Optical Networks for joint teaching programme of BUT and VSB-TUO

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1 Transmission properties of optical fibres

The transmission properties of optical fibres depend in the first place on the type of fibre design. In this respect, three types of fibre are distinguished:

- multimode fibres with constant refractive index of the core and step refractive index of the jacket; these fibres are simple to manufacture and handle, and of a comparatively simple design but their drawback is greater attenuation and dispersion, and small transmission capacity. They feature large core and jacket diameters. An example of this type of fibre can be seen in Fig. 1.1.

![Multimode step-index fibre.](image)

Some characteristics of this type of fibre: $D_j = 50\text{–}200 \mu\text{m}$, $D_p = 120\text{–}300 \mu\text{m}$, dispersion $50 \text{ ns} \cdot \text{km}^{-1}$, attenuation $5\text{–}20 \text{ dB} \cdot \text{km}^{-1}$, and bandwidth $60 \text{ MHz}$.

Fibres of this type are mostly used in short-haul links, in particular for automation purposes, short data transmissions, local networks, etc.

Multimode fibres with varying refractive index in transversal section of the core, which have feature lower dispersion, lower attenuation, somewhat more complicated manufacture and thus more complicated fibre design and splicing. The fibre has been standardized according to the ITU-T recommendation: $D_j = 50 \mu\text{m}$, $D_p = 125 \mu\text{m}$. An illustration of the refractive index pattern is given in Fig. 1.2.

![Multimode fibre with varying refractive index.](image)
Some selected characteristics of this type of fibre are: dispersion at 0.85 µm is 1 ns·km⁻¹, attenuation 2.5-5 dB·km⁻¹, transmitted bandwidth 600 MHz.

In view of the above parameters, this type of fibre is particularly suited for telecommunication purposes, namely for short-haul links.

Single-mode fibres with constant refractive index of the core and step refractive index of the jacket, which feature low dispersion, very low attenuation, and large transmission capacity. They mainly find application in long-haul transmissions. In this case there is only one mode propagating in the fibre, in the direction of the axis. To be able to achieve this state it is necessary to reduce the core diameter to a value equal to only a few light wavelengths. The diameter range is D_j = 7-9 µm, D_p = 125 µm, as shown in Fig. 1.3.

![Fig. 1.3: Single-mode step-index fibre.](image)

Fibre characteristics: dispersion ca. 0.3 ns·km⁻¹, attenuation below 0.2 dB·km⁻¹ at a wavelength of 1.55 µm, and a bandwidth of 10 GHz.

In cases when the refractive index changes stepwise, the term layered lightguides is often used. In these cases the transmission is based on the principle of total refraction at the core-jacket interface. In the second type, the lightguide with continuously varying refractive index (so-called gradient-index lightguide), the path of the ray has the form of elliptic or circular helix.

Since the transmission properties of optical fibres depend on the pattern of refractive index distribution, various manufacturers apply further variants of different refractive index profiles, as illustrated in fig. 2.4.

Thus, for example, Fig. 2.4a illustrates a fibre lightguide that is used with success as an alternative to single-mode lightguides. Frequently occurring are two-layer lightguides and gradient-index lightguides with the curve of refractive index close to the parabolic curve. As will be given below, a more complicated pattern of refractive index can yield a shift in the dispersion characteristic, etc..
1.1 Attenuation of optical fibres

Attenuation of optical fibres is mainly due to:

- absorption by the medium in which the radiant energy is propagating,

- radiation from the fibre,

- diffusion on inhomogeneities.

Absorption losses in the UV and visible regions are due to the transitions between atomic levels and, in the infrared region, between molecular levels of the basic material, admixtures and impurities, of greatest effect among which are ions of Fe, Cu and Cr, whose resonance at certain frequencies is accompanied by thermal losses. The resonance frequency of OH ions, which represent the main part of the losses, corresponds to a wavelength of 2.8 µm so that it lies outside the band used for transmission over optical frequencies but the second harmonic, 1.38 µm, and the third harmonic, 0.94 µm, are in the band region that is used. Typical resonance curves due to OH ions are evident from Fig. 2.5. For the manufacture of fibres with low specific attenuation it is necessary to ensure a low concentration of OH ions and ions of metals.

Radiation losses are due to the refraction of propagating rays on the interface of two dielectric media of different properties, when part of the energy escapes out of the core.

Dispersion losses are due to the fact that molecules randomly distributed in amorphous material actually form micro-inhomogeneities of the refractive index of the material. If these

Fig. 1.4: Examples of different refractive index profiles.
inhomogeneities and minor impurities are dimensionally small in comparison with the wavelength, the dispersion losses appearing on them are called Rayleigh’s scattering losses. The losses are inversely proportional to the fourth power of the wavelength of propagating radiation and they rapidly increase towards the UV region. The characteristic feature of Rayleigh’s scattering is its omnidirectionality.

From the practical viewpoint, the above losses can be extended with losses due to imperfect geometry, distorted shapes and dimensions of the boundary between the core and the cladding. Small cracks in the core material also play a role. Last but not least, the so-called microbends should be mentioned, which include defects in the rectilinearity of lightguide axis.

Fig. 1.5 illustrates the losses described above and, at the same time, gives the development of the reduction of attenuation in fibre lightguides. In the most recently developed fibres the effect of OH ions has been eliminated, in particular between the 1.3 and 1.55 µm wavelengths, i.e. between the so-called 2nd and 3rd “windows”.

Attenuation, an important transmission quantity, can be defined as follows: Radiant power of wavelength λ at a distance z from the fibre beginning at an input power $P(0, \lambda)$ is given by relation 1.1:

$$P(z, \lambda) = P(0, \lambda) \exp \left[ 2xz \gamma(\lambda, z') dz' \right],$$  \hspace{1cm} (1.1)$$

where $\gamma(\lambda, z')$ is the attenuation coefficient per unit of length, which can in general depend on the distance from the fibre beginning. It is therefore of advantage to introduce the average coefficient of fibre attenuation

$$\bar{\gamma}(\lambda) = \frac{1}{2} \int \gamma(\lambda, z') dz',$$  \hspace{1cm} (1.2)$$

which simplifies dependence (1.1) to the approximate relation (1.3),

$$P(z, \lambda) = P(0, \lambda) \exp \left[ -\bar{\gamma}(\lambda)z \right].$$  \hspace{1cm} (1.3)$$
This relation is the starting point for measuring the attenuation of optical fibre by the differential method. When it is necessary to measure the transmitted power at two different points, we obtain from equation (1.3) the relations

\[ P(z_1, \lambda) = P(0, \lambda) \exp \left[ -\overline{\gamma}(\lambda) z_1 \right], \]

\[ P(z_2, \lambda) = P(0, \lambda) \exp \left[ -\overline{\gamma}(\lambda) z_2 \right], \quad (1.4) \]

from which after rewriting we obtain the attenuation coefficient

\[ \overline{\gamma}(\lambda) = \frac{1}{z_2 - z_1} \ln \frac{P(z_1, \lambda)}{P(z_2, \lambda)}. \quad (1.5) \]

The term derived shows that the average attenuation coefficient only depends on the ratio of input and output powers.

For practical reasons the attenuation coefficient is given in units of dB·km\(^{-1}\) according to the relation:

\[ \alpha(\lambda) = \frac{1}{z_2 - z_1} 10 \log \frac{P(z_1, \lambda)}{P(z_2, \lambda)}. \quad (1.6) \]

The methodology itself of measuring the attenuation will be described below.

There are also other parameters that influence the attenuation characteristic. For example, in current operating conditions, changes in the temperature will not have any major effect on attenuation. In severe frost, however, some fibres will exhibit higher attenuation (at \(-30^\circ\text{C}\) ca. 2 dB·km\(^{-1}\)). Attenuation also gets increased at higher positive temperatures, as shown in Fig. 1.6.

![Fig. 1.6: Temperature dependence of lightguide attenuation.](image)

**Fig. 1.7** illustrates what the attenuation pattern looks like in a fibre of “drowned” cable (i.e. a cable flooded with water) after eight months.
In conclusion, let us sum up the knowledge gained about lightguide attenuation and current trends. Fig. 2.8 gives the attenuation characteristic with OH already eliminated on a wavelength of 1380 nm. At the same time, new wave windows are described.

1\textsuperscript{st} window (850 nm) belongs to multimode propagation. Here, the attenuation characteristic is steeply falling and the achieved values of specific attenuation are too high to be used in long-haul transmissions in particular. Thanks to very cheap sources of radiation the transmission is used in optical access networks.

2\textsuperscript{nd} window (1280 to 1335 nm) is the lowest and historically the first window that can fully be used for single-mode transmission over fibres with 9/125 µm diameters. The specific attenuation value achieved is typically just below 0.35 dB·km\(^{-1}\). This window is used for long-haul transmissions.

3\textsuperscript{rd} window (1530 to 1565 nm) is a window in which the minimum specific attenuation appears for standard quartz fibre, typically in the range from 0.19 to 0.22 dB·km\(^{-1}\). This window is used for long-haul transmissions (i.e. transport and global networks).

4\textsuperscript{th} window (1565 to 1625 nm) is already beyond the absolute minimum of specific attenuation. It is, however, so flat that the attenuation parameters differ only minimally from the 3\textsuperscript{rd} window. It is the advances in the WDM technology and in optical amplifiers that allow, in the transmission of the joint spectrum of the 3\textsuperscript{rd} and 4\textsuperscript{th} windows, almost doubling the transmission capacity.

5\textsuperscript{th} window (1335 to 1530 nm) has been available for transmission applications only since the late 1990s, when the technology of manufacturing optical fibres without OH admixtures was mastered to such a degree that the local maximum attenuation fades out at 1380 nm. Joint 2\textsuperscript{nd} to 5\textsuperscript{th} windows form a continuous transmission channel of 50 THz in bandwidth.

The current trend in transmission over optical fibre is characterized by a shift to the 2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th} and 5\textsuperscript{th} windows, with single-mode lightguides being used. Today, the growth of these transmissions in comparison with multimode lightguides leads to reductions in their prices.
A new designation of wavebands has been introduced, as shown in Tab. 1.1.

**Tab. 1.1: Individual wavebands of single-mode optical fibres.**

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<thead>
<tr>
<th>Waveband</th>
<th>Name</th>
<th>Range [nm]</th>
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<tr>
<td>O</td>
<td>Original</td>
<td>1260-1360</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
<td>1360-1460</td>
</tr>
<tr>
<td>S</td>
<td>Short</td>
<td>1460-1530</td>
</tr>
<tr>
<td>C</td>
<td>Conventional</td>
<td>1530-1565</td>
</tr>
<tr>
<td>L</td>
<td>Long</td>
<td>1565-1625</td>
</tr>
<tr>
<td>U</td>
<td>Ultra-long</td>
<td>1625-1675</td>
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For these transmissions there are, according to the ITU-T recommendations (group G), the following single-mode fibres:

**Type G.652 fibre** is standard optical single-mode fibre 9/125 µm, sometimes designated by the abbreviation USF (Unshifted Fibre) according to the specification of the Corning Company. These fibres are referred to as Matched Cladding (MC) in view of the typical change in the refractive index at the interface of the fibre core and cladding. There is a special group of fibres with the so-called depressed refractive index, in which the refractive index of the cladding near the core is lower than in the cladding proper of the optical fibre made of pure silicate glass without any added admixtures.

**Type G.652.C fibre** is a currently available new type of fibre which, unlike the ordinary fibre G.652, can be used over the whole wavelength range; all the available transmission bands, inclusive of band E (1360-1460 nm), can thus be exploited. Formerly it was not possible to use this band because conventional optical fibres have increased insertion attenuation in this region due to resonances on absorbed water ions OH⁻, which permeated the fibre during manufacture.

**Type G.652.D fibre** is an all-wave fibre, which is compatible with all the H.652 fibres.
Type G.653 fibres have been developed with the aim of suppressing chromatic dispersions for the 1550 nm wavelength. These fibres are referred to as DSF (Dispersion Shifted Fibre) fibres. They are used for higher transmission speeds over great distances with a single wavelength in operation. However, when the need arose in practice to deploy systems of wavelength multiplex DWDM with several wavelengths, it was found that these fibres had a side effect. It consists in the overlapping of individual wavelengths and the appearance of parasitic neighbouring channels and cross-talk.

Type G.654 fibres have been developed as a special variant of the G.652 fibres. These fibres are optimized for the lowest possible insertion attenuation in the 1550 nm band and have the cut-off wavelength shifted (wavelength up to which they perform as single-mode fibres). They are expensive and are used almost exclusively for extreme long-haul transmissions over submarine cables without amplifiers along the route.

Type G.655 fibres with shifted non-zero dispersion (NZ-DSF, Non-Zero Dispersion Shifted Fibre) are optimized for the transmission region in the 1550 nm band. Today, these fibres are mainly used in wide-range optical networks; unlike type G.653 fibres, they do not have zero dispersion for the 1550 nm wavelength. Low non-zero dispersion is necessary lest non-linear side-effects should show here too much. This type of fibre is designed for the operation of DWDM technology and for high transmission speeds.

Type G.656 fibres with shifted non-zero dispersion (NZ-DSF, Non-Zero Dispersion Shifted Fibre) are optimized for the transmission region in the 1460-1625 nm band. These fibres are designed for the DWDM and CWDM wavelength multiplex systems. In the S band they enable up to 40 channels in the DWDM system. The maximum chromatic dispersion is set to be from 2 to 14 ps·nm/km-1, the maximum polarization dispersion is 0.20 ps/√km.

Type G.657.A fibre is for inside/internal cabling and for optical access networks.

Type G.657.C fibre is a new type of fibre, which is resistant to microbending up to a radius of 5 mm.

When fibres are spliced, reflections appear on connectors and, generally, on all inhomogeneities in the fibre. This gives rise to random resonators of different frequencies, which can interfere with the performance of lasers and optical amplifiers or cause interferometric noise. The recommendations admit total route reflections of no more than -27 dB.

The behaviour of actual fibres may differ in dependence on the glass purity and dopants used but the characteristic behaviour on the respective wavelengths will prevail.

1.2 Dispersion in optical fibres

Dispersion in optical fibres is the main cause of distortion of the transmitted signal; it is defined as the difference of pulse width at half the height of the fibre at its beginning and end. The frequency dependence of refractive index, which gives rise to the frequency dependence of the group and phase velocities of wave propagation in the material of the lightguide, is the cause of material dispersion.

In the lightguide the material dispersion of the mode is combined with the waveguide dispersion, which is due to the changes in the mode geometry and thus also changes in the group and phase velocities of propagation when the frequency changes. The resultant effect of material and waveguide dispersions is usually referred to as chromatic dispersion.
If the propagating energy is divided into several modes, then in addition to the chromatic dispersion there is also the mode dispersion, due to the different propagation velocities of individual modes. The distortion of transmitted signal caused by chromatic dispersion can be reduced by narrowing the signal frequency spectrum while the effect of mode dispersion can be reduced by reducing the number of modes participating in the transmission. This is done by choosing suitable design parameters of the lightguide, and the reduction can in extreme cases be to a single mode, i.e. single-mode lightguide. The single-mode lightguide has only the chromatic dispersion. Another possibility how to reduce mode dispersion is to equalize the group velocities of propagation of individual modes via a suitable arrangement of the waveguide structure.

Dispersion belongs to the most important parameters of optical lightguides: it determines the width of the transmitted band and thus also the speed of transmission. Because of its importance, we will discuss it in greater detail later.

Material dispersion is caused by the different velocities of the propagation of rays of different wavelengths, which in turn is due to the non-linearity of the frequency behaviour of refractive index, as can be seen in Fig. 1.9.

![Pattern of frequency dependence of refractive index on group refractive index n_s for SiO_2.](image)

**Fig. 1.9:** Pattern of frequency dependence of refractive index on group refractive index n_s for SiO_2.

In general, it holds that the phase velocity is given by the relation

$$v_p = \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} = \frac{c_0}{n}$$

while the group velocity is given by the relation

$$v_g = \frac{d\omega}{dk} = \frac{1}{d\omega} \frac{c_0}{n + \frac{dn}{d\omega}} = \frac{c_0}{n_s},$$

where n_s is the group refractive index. Further we derive
Let us assume that there is a source of radiation of spectral breadth $\lambda$ on the input. Due to the different propagation velocities there will be at a unit distance from lightguide beginning a time gap between the components, which differ by $\Delta\lambda$. The gap is given by the difference of their group delays (see Fig. 2.10).

\[
\Delta t_{\text{mat}} = t_{s1} - t_{s2} = \left( t_s + \frac{dt_s}{d\kappa} \right) - t_s = \frac{dt_s}{d\kappa} \Delta \kappa.
\]  

Substituting from the well-known relations for delay

\[
t_f = \frac{1}{v_f} = \frac{n}{c_0}
\]  

and for group delay

\[
t_s = \frac{1}{v_s} = \frac{n}{c_0} = \left( n - \lambda \frac{dn}{d\lambda} \right) \frac{1}{c_0},
\]  

after rewriting we obtain

\[
\Delta t_{\text{mat}} = \frac{\lambda \Delta \lambda}{c_0} \frac{d^2n}{d\lambda^2} \left( \text{ps} \cdot \text{km}^{-1} \cdot \text{nm}^{-1} \right).
\]  

Fig. 1.10: Pulse broadening due to material dispersion.

Non-zero material dispersion for the inflection point of the curve will be $n = f(\lambda)$, i.e. $n_s = f(\lambda)$ for the local minimum of the curve, as is evident from the result of differentiation (see...
Fig. 1.8). For silicon dioxide, $\text{SiO}_2$, the pattern of the dependence of material dispersion $\Delta t_{\text{mat}}$ on wavelength is plotted in Fig. 1.11. For $\lambda = 1.28 \, \mu\text{m}$ the material dispersion is zero. If silicon dioxide is doped with germanium dioxide, $\text{GeO}_2$, the zero point of material dispersion is shifted towards higher wavelengths. It follows from practical implementations that the typical value for a $\text{SiO}_2$ multimode fibre with $\lambda = 0.85 \, \mu\text{m}$ is $\Delta t_{\text{mat}} = 100 \, \text{ps} \cdot \text{km}^{-1}$ and thus a laser with a spectral breadth of 3 nm will cause a material dispersion of 300 ps km$^{-1}$ in the lightguide.

Waveguide dispersion is also responsible for broadening the pulses transmitted by lightguides. This is because the propagation constant is different for every mode so that its frequency is changed, which results in a change of the speed of propagation. In multimode lightguides with step- and gradient-index profiles the effect of waveguide dispersion can be neglected. It must, however, be taken into consideration in single-mode fibres, where it has a substantial share in the total dispersion of this fibre. For a wavelength of 1.3 $\mu\text{m}$ the dispersion value is around 2 ps km$^{-1}$.

Dimensionless waveguide dispersion coefficient $D_{\text{wln}}$ comes to be introduced as the measure of waveguide dispersion:

$$D_{\text{wln}} = c_0 \int t_{s1} \Delta \frac{dT_s}{df},$$

(1.14)

where $t_{s1} = n_{s1}c_0^{-1}$ is the group delay of the wave propagating in the lightguide axis, with group refractive index $n_{s1}$, $T_s = (t_s - t_{s1})(\Delta t_{s1})^{-1}$ is the normalized group delay.
Chromatic dispersion, which is formed by material and waveguide dispersions, is thus due to the non-linear frequency dependence of the group velocity of mode propagation in the lightguide. The bandwidth of the lightguide is inversely proportional to the bandwidth of the radiation source. For example, a semiconductor laser with the typical value of relative spectral breadth $S_{z}f_{0}^{-1} = 0.0001$ enables transmitting a 400 times broader band than a light-emitting diode (LED) with a typical relative spectral breadth of 0.04. The chromatic dispersion coefficient is defined as

$$D_{chr} = c_0 \int \frac{dt_s}{df}.$$  \hfill (1.15)

It is possible to choose for the lightguide such an operating frequency that chromatic dispersion in the middle of the transmitted band is zero. A practical consequence in the single-mode SiO$_2$ fibre is the shifting of the operating mode from the 1.28 µm wavelength, at which the material dispersion is zero, to a wavelength of ca. 1.33 µm, where the chromatic dispersion is zero. In this way, the transmitted band of single-mode lightguides can be extended.

Mode dispersion is the main factor that limits the width of transmitted band in multimode lightguides with homogeneous core. For these lightguides, the mode dispersion can be explained using the method of geometrical optics. The larger the angle between the ray trajectory and the lightguide axis (the higher the mode), the longer the path between the lightguide input and output; the ray’s longitudinal velocity in the lightguide axis direction is lower. This is the reason why higher modes, which are closer to their cut-off frequencies, propagate more slowly than lower modes do. At a unit distance from the lightguide beginning there will be a time gap between individual modes, which will be given by their group delays. For a mode propagating in the lightguide axis and a mode whose trajectory contains an angle with the axis it holds

$$\Delta t_{vid} = \frac{t_s}{\cos \vartheta} - t_s = t_s \left( \frac{n_1}{n_2} \right) = t_s \Delta = \frac{n}{c_0} \Delta.$$  \hfill (1.16)

In gradient-index lightguides the ratios are better. With optimum profile of the refractive index the magnitudes of the mode and the material dispersions are of the same order and it holds

$$\Delta t_{vid} = \frac{n(0)}{c_0} \left( \frac{1 - \Delta}{\sqrt{1 - 2\Delta}} - 1 \right).$$  \hfill (1.17)

The typical value for multimode step-index fibre is 20 ns·km$^{-1}$, which allows transmitting bandwidths of up to tens of MHz·km; for gradient-index fibre it is 50 ps·km$^{-1}$ with bandwidths of units of GHz·km while for single-mode fibre the dispersion is almost zero and the bandwidth is up to ca. 200 GHz·km. The concrete value of mode dispersion for gradient-index fibre and parabolic profile of refractive index of $n(0) = 1.51$, and $n(a) = 1.5$ is

$$\Delta t_{vid} = 111 \text{ ps·km}^{-1}.$$  

The total number of propagating modes in gradient-index fibre lightguide is given by the relation

$$M = \frac{\xi}{\xi + e^2} a^2 k_0^2 \Delta.$$  \hfill (1.18)
For the parabolic profile of refractive index \((\xi = 2)\) the number of propagating modes is half the number of modes for the gradient-index profile of two-layer lightguide with homogeneous core \((\xi \to \infty)\), with identical values of \(a, \Delta\). For example, for the parabolic profile with the parameters \(\xi = 2, n(0) = 1.51, n(a) = 1.5, \lambda = 0.84 \mu m, a = 80 \mu m\) and the total number of propagating modes is \(M = 1040\).

Mode dispersion does not play any role in the single-mode lightguide; its transmission properties are given by the material dispersion alone.

The above views on the respective problems are given illustratively in Fig. 2.12. It shows the patterns of input and output pulses after passing through one of the three basic types of lightguide.

It should be noted that, from the practical point of view, it is not always the most important thing to achieve the maximum parameters of lightguide because it might involve increased prices of fibres, complicated splicing and connecting of fibres, etc.

![Figure 1.12](image)

**Fig. 1.12:** Pulse propagation in lightguide: a) multimode step-index fibre, b) multimode gradient-index fibre, c) single-mode step-index fibre.

### 1.2.1 Chromatic dispersion

As stated in the preceding chapter, chromatic dispersion makes itself felt in single-mode fibres too. Single-mode fibre transmission is given by the condition of transmission of the first root of the Bessel function, i.e.
The wavelength is given. Current technological potentials make it possible to change the core and thus influence the process of chromatic dispersion.

Until recently, chromatic dispersion was not in fact measured. The need to measure it came with the increasing demand for transmission capacities and with the arrival of systems that use the DWDM multiplexes (Dense Wavelength Division Multiplex). In such transmissions, different spectral components of the signal (of different wavelengths) propagate simultaneously through the optical fibre at different velocities. The signal always contains several spectral components. In this case some components of the input signal pulse will be time-delayed when passing through the optical fibre. Due to the passage through optical fibre the pulse will extend in time and this deformed pulse will get into the neighbouring bit gaps and the transmitted information will be distorted. The magnitude of chromatic dispersion is characterized by the so-called chromatic dispersion coefficient

\[ D(\lambda) = \frac{d t_g(\lambda)}{d(\lambda)}, \]

which gives the change of the group delay \( t_g \) of a signal passing through the fibre, in dependence on wavelength \( \lambda \). The maximum values of chromatic dispersion coefficient according to ITU-T G.695 are given in Tab. 1.2. The coefficient value gives the extension of the (Gaussian) pulse in ps for a radiation source of 1 nm spectral half-width, after passing through a 1 km fibre.

Tab. 1.2: Limit values of chromatic dispersion according to ITU-T G.695

<table>
<thead>
<tr>
<th>Wavelengths ( \lambda ) [nm]</th>
<th>Chromatic dispersion coefficient ( D(\lambda) ) [ps.nm(^{-1}).km(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1291-1351</td>
<td>5.7</td>
</tr>
<tr>
<td>1311-1371</td>
<td>6.8</td>
</tr>
<tr>
<td>1391-1451</td>
<td>11.5</td>
</tr>
<tr>
<td>1531-1591</td>
<td>19.9</td>
</tr>
<tr>
<td>1471-1611</td>
<td>21.1</td>
</tr>
</tbody>
</table>
A classical pattern of chromatic dispersion is given in Fig. 1.13. As mentioned above, the fibre can be prepared technologically such that also in the wavelength region 1.55 µm the dispersion values are reduced to zero. These cases of DS (Dispersion Shifted) fibres are given in Fig. 1.14: a) concerns the so-called fibre with shifted dispersion characteristic while b) concerns the fibre with flat dispersion characteristic.

The arrival of DWDM has entailed the problem of how to compensate chromatic dispersion in older, already installed fibres. Most frequently, passive optical compensation is used, which employs special compensation fibres DCF (Dispersion Compensation Fibre) of
high negative chromatic dispersion value. The method consists in connecting a “coil” of this fibre at the end of the route (about 1/6 of the actual length) and this will compensate the dispersion value. Examples of route compensation are given in Fig. 1.15 and Fig. 1.16.

Today, new types of compensation fibres are available, with sufficient negative slope of the dispersion characteristic, suitable for the compensation of conventional and NZDF (Non Zero Dispersion Fibre) fibres. This compensation can also be achieved using the special HOM (High Order Mode) multimode fibres. Moreover, the chromatic dispersion of these HOM fibres is ca. three times higher than in classical DCF fibres so that it suffices to use only a third of the length of compensation fibre in comparison with the DCF fibre. HOM fibres have a low specific attenuation and are resistant to non-linear events. Another compensation possibility consists in using the Bragg gratings. Such a grating with varying grating period can be used for a function similar to compensation fibre, but usually for only a narrow spectral region of a few nm (up to ca. 6 nm). To compensate the chromatic dispersion of several spectral channels it is in this case necessary to employ a cascade of such gratings. Today, of course, wide-spectrum compensators with the Bragg gratings are available for bands of up to 35 nm.

A typical, practically applied fix compensator of chromatic dispersion for high-speed optical networks, based on the Bragg grating technology, can be used for single-channel or broadband transmission, either in real time or for static compensation.

Typical properties:
- it compensates one or several channels simultaneously,
- insertion attenuation is less than 3.5 dB,
- it balances the slope of the dispersion curve of transmission fibre,
- it has small dimensions.
Typical applications:
- as an alternative to dispersion compensation fibre DCF,
- in metropolitan and long-haul DWDM networks,
- SSSDH/SONET and CATV transmission routes,
- compensation at terminal or transmission point of transmission route,
- correction of residual chromatic dispersion and dispersion curve slope.

1.2.2 Polarization mode dispersion (PMD)

With the transmission speeds in individual optical fibres increasing to over 2.5 Gb/s the need to measure PMD has increased. When passing through the optical fibre, the mode propagates in two mutually perpendicular planes. This phenomenon deteriorates with any circular asymmetry of optical fibre; this may be due, for example, to microbends formed in the course of installation or directly to the manufacture or faulty installation of the cable, on which all sorts of external pressure then act. All this can result in that the two polarizations propagate at different rates and thus in signal distortion or pulse widening.

The polarization mode dispersion is expressed by the PDM coefficient. Over short distances, approximately to 10 km, PMD is roughly linear and is expressed by

\[
\text{PMD} = \frac{\Delta \tau}{L} \quad [\text{ps.km}^{-1}],
\]

where \( L \) – is the length of route, \( \Delta \tau \) – is the signal delay. Over long distances it does not propagate linearly but with the square root of the distance

\[
\text{PMD} = \frac{\Delta \tau}{\sqrt{L}} \quad [\text{ps.km}^{-1}].
\]

PMD is shown illustratively in Fig. 1.16 and its values are given in Tab. 1.3.

<table>
<thead>
<tr>
<th>transmission speed Gbit.s(^{-1})</th>
<th>0,155</th>
<th>0,622</th>
<th>2,500</th>
<th>10,000</th>
<th>40,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDH</td>
<td>STM-1</td>
<td>STM-4</td>
<td>STM-16</td>
<td>STM-64</td>
<td>STM-256</td>
</tr>
<tr>
<td>duration 1 bit [ps]</td>
<td>6430,00</td>
<td>1610,00</td>
<td>401,88</td>
<td>100,47</td>
<td>25,12</td>
</tr>
<tr>
<td>limit PMD [ps]</td>
<td>640,0</td>
<td>160,0</td>
<td>40,0</td>
<td>10,0</td>
<td>2,5</td>
</tr>
<tr>
<td>limit PMD declaration 1/10 [ps]</td>
<td>643,00</td>
<td>161,00</td>
<td>40,10</td>
<td>10,00</td>
<td>2,51</td>
</tr>
<tr>
<td>( \text{PMD}_{\text{coef. per 400km}} ) [ps/( \sqrt{\text{km}} )]</td>
<td>&lt; 32,00</td>
<td>&lt; 8,000</td>
<td>&lt; 2,000</td>
<td>&lt; 0,500</td>
<td>&lt; 0,125</td>
</tr>
</tbody>
</table>

PMD values can only be limited by the selection of cable fibres that are of guaranteed quality. If the largest participation in PMD is by only a part of the optical cable route, there is
another possibility, namely exchanging the cable run (more in the chapter on measurement – POTDR).

**Non-linear phenomena in optical transmission**

In recent years, problems of non-linear phenomena have come to be solved from both the theoretical and practical points of view. Only the basic concepts will be given below since a detailed treatment would be beyond the scope of this publication.

The appearance of non-linear phenomena is conditional on great densities of light output power in the fibre. The problem is that fibres have a very small cross-section of the core, and with the arrival of wavelength multiplex systems optical amplifiers began to be incorporated in longer routes that multiply increase the power in the fibre. If we have a system operating with several tens of channels, the power of all lasers must be added up. In the design of routes with transmission speeds of 10 Gbits or more per channel these problems have to be solved.

*Stimulated scattering* – is a non-linear physical phenomenon in which the light wave is scattered by collisions with acoustically or thermally oscillating atoms of the fibre. During the scattering the wavelengths get slightly shifted towards higher values.

*The Brillouin scattering* – is called forth by the longitudinal wave caused by electrostriction and the scattered wave is spectrally shifted by ca. 10 GHz. The size of scattering depends on the angle of scattering; maximum energy is scattered in the back direction. The Brillouin scattering is particularly important for signals with narrow line width and this phenomenon can be suppressed effectively by reducing the coherent length of signal, or by broadening the signal spectrum.

*The Raman scattering* – its essence consists in the mutual interaction between light propagating in a certain medium and this medium, the result of which is a frequency shift. Scattered light wave propagates in both directions. Critical power depends again on the material and on the number, average output power and mutual spacing of optical channels. A practical application of the Raman phenomenon had to be waited for till the mid-1980s, when research into stimulated Raman phenomenon led to its practical deployment as an amplification element in the medium of single-mode fibres.

*Own phase modulation* – is the result of the optical pulse acting on itself. The increase and decrease of power on the edges of optical pulse lead to changes in its propagation phase and thus to its shape being distorted and its spectrum being broadened; in a dispersion medium the spectrum can retroactively affect the pulse shape. With excessive pulse broadening the pulses overlap in intersymbol interference and, subsequently, transmission errors occur.

*Cross phase modulation* – is in principle a phenomenon similar to own phase modulation but in conditions when the signal of one wavelength modulates the signal of another wavelength. Therefore it only appears in multichannel optical systems.

*Four-wave mixing* – is a non-linear phenomenon where the interaction of signals of two or more wavelengths gives rise to signals of new wavelengths. It is similar to the electrotechnical effect where intermodulation products arise during modulation.
1.3 Theory of transmission over lightguides

In any real transmission medium, thus in lightguides too, the signal gets distorted. The distortion is due to two basic causes. On the one hand, it is the irregularity of the frequency response of the fibre itself, which is responsible for the change in the spectrum and time behaviour of the signal. The other cause of the distortion and impaired propagation capacity of the signal is noise.

The level of lightguide noise is determined from the power on the input. Most important is quantum noise, with thermal noise also playing a role.

An analysis of propagation is very complicated, in multimode lightguides in particular. The aim of the analysis is to determine the pulse of transition function of the lightguide or the frequency response

\[ K(\omega) = |K(\omega)| \exp[j\varphi(\omega)]. \]  

(1.21)

Based on the knowledge of these characteristics the shape of the output signal can be found in dependence on the input signal. In practical cases and in the optical fibre transmission mode we are mostly not interested in the exact shape of the output signal but only in its elongation in comparison with the input signal. This enables determining the parameter of optical communication route – the transmission speed or the width of transmitted band.

The frequency response is determined in the modulation frequency spectrum \( \omega = 2\pi f_m \) and it is

\[ K(\omega) = P_2(\omega) \exp[j\varphi_2(\omega)]/P_1(\omega) \exp[j\varphi_1(\omega)]. \]  

(1.22)

where \( P_1(\omega) \) and \( P_2(\omega) \) are the input and output powers. The absolute value

\[ |K(\omega)| = P_2(\omega)/P_1(\omega) \]  

(1.23)

is the frequency response, and

\[ \Psi(\omega) = \varphi_2(\omega) - \varphi_1(\omega) \]  

(1.24)

is the amplitude characteristic. It is of advantage to normalize the amplitude characteristic such that

\[ |K(0)|^0 = 1. \]  

(1.25)

In this case we are concerned with normalized amplitude characteristic.

The width of the pass-band is determined by the drop of amplitude characteristic by 3 dB, or the drop of normalized characteristic to the value 0.5

\[ |K(\omega)|^0 = 0.5. \]  

(1.26)

The starting point of measuring is the frequency \( f_m = 0 \) and the band is denoted as width \( S \). The relation between input signal \( P_1(t) \) and output signal \( P_2(t) \) is given by the relation

\[ P_2(\omega) = K(\omega) P_1(\omega), \]  

(1.27)

where \( P_1(\omega) \) and \( P_2(\omega) \) are the Fourier images of the input and output signals \( P_1(t) \) and \( P_2(t) \).
where

\[
P(\omega) = \int_{-\infty}^{\infty} P(t) \exp[-j\omega t] dt.
\]  

The output signal P2(t) is obtained by performing the transformation of the signal P1(t). Multiplying the obtained input signal image \( P_1(\omega) \) by the function \( K(\omega) \) yields the output signal image \( P_2(\omega) \). Reverse transformation according to the relation

\[
P(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} P(\omega) \exp[j\omega t] d\omega,
\]

gives the output signal \( P_2(t) \). In the majority of practical cases the integration must be performed numerically. With regard to the usual transmission mode the analysis of the transmission signals is the most important. The characteristic of the response to the input signal in the form pulse can be used to calculate the response to the input signal of any arbitrary form. The best method of examining the transmission properties of lightguides is to use a pulse in the shape of Gaussian curve or the Dirac pulse, denoted \( \delta \) function; the Dirac pulse is in practice realized by a very short rectangular pulse. Using the Dirac pulse enables determining the width of the transmitted band. Denoting the Dirac pulse \( P_1(t) \), its Fourier image is

\[
P_{ii}(\omega) = \int_{-\infty}^{\infty} P_{1i}(t) \exp(-j\omega t) dt = \int_{-\infty}^{\infty} \delta(t) \exp(-j\omega t) dt = 1.
\]  

The image of the response to the Dirac pulse is

\[
P_{2i}(\omega) = K(\omega) P_{1i}(\omega) = K(\omega).
\]  

Fig. 1.17: Lightguide transmission of signals: a) normalized characteristic, b) response to the Dirac pulse.
The input signal as a response to the unity pulse is

\[ P_{2i}(t) = \int_{-\infty}^{\infty} K(\omega) \exp(j\omega t) d\omega. \] (1.32)

The response to the unity pulse on the lightguide input is thus given by the reverse transformation of the frequency response. It is apparent that the lower the \( P_{2i}(t) \) curve on the prescribed level, the wider the pass-band of the lightguide. The response to unity pulse is called the pulse response. Its qualitative evaluation is done by determining its width \( \tau \) on the level of half the amplitude. This point is made clear in Fig. 1.17. It can be proved that the product \( S\tau \) depends only very little on the concrete shape of frequency response and is within the bounds

\[ 0.45 < S\tau < 0.6. \] (1.33)

The speed of information transmission \( C \) is given in bits per second and in the digital transmission of binary signals it is numerically approximately equal to the maximum modulation frequency \( f_{m\text{ max}} \), which is close to the width of transmitted band. Thus we have

\[ C \approx f_{m\text{ max}} = S \] (1.34)

and

\[ \frac{0.45}{\tau} < C < \frac{0.6}{\tau}. \] (1.35)

Relation (1.35) is used to estimate the transmission speed but, of course, on the assumption that the value of \( \tau \) is known. It is evident from the above that the basic problem in determining the width of lightguide pass-band or the transmission speed is the determination of the frequency response. It can be established either by measurement or by calculation.

Direct measurement of the lightguide frequency response is complicated. Such a measurement requires exciting successively individual modes on the input and determining their frequency responses or exciting the whole spectrum of modes with uniform power distribution among individual modes.

It is simpler to measure the frequency response of a system made up of lightguide source and detector. In this case it suffices to have at one’s disposal a frequency-tuned source of optical radiation and a detector with a known voltage dependence of emitted or incident power. The frequency responses can be used only for the source and detector with which the measurement was carried out.

The frequency characteristic can also be established indirectly, by measuring the response to the Dirac pulse and its reverse Fourier transform. Also in this case, however, it is necessary for the energy of input pulse to be distributed exactly and definably into individual modes.

The frequency responses measured can be used to determine the response to an arbitrary input signal and the width of transmitted band but this will not reveal the connection with the lightguide design parameters.

To propose an optimum lightguide design it is necessary to know the dependence of frequency response on design parameters. Such dependence can only be established via calculation starting from the fact that the shape of frequency response is in direct relation to chromatic and mode dispersions. The calculation is therefore closely linked with a detailed examination of the theory of the mechanism of originating individual dispersions.
The analysis of the propagation over real lightguides resulted in the following possible widths of the transmitted band:

- multimode lightguide with constant refractive index of the core and arbitrary source of radiation $10 < S < 15 \text{ [MHz⋅km]}$,
- gradient-index lightguide with semiconductor laser operating at non-optimum frequency (with respect to material dispersion) $10 < S < 2000 \text{ [MHz⋅km]}$,
- gradient-index lightguide with semiconductor laser operating at optimum frequency $0.2 < S < 10 \text{ [GHz⋅km]}$,
- single-mode lightguide with constant refractive index of the core with semiconductor laser operating at optimum frequency $S$ of up to $1000 \text{ [GHz⋅km]}$.

From the above data it is obvious that the development in optical transmission over longer distances will take the path of introducing single-mode optical fibres.

Problems of energy propagation in optical fibres can be solved by two approaches: either on the basis of geometrical optics or on the basis of wave optics. Geometrical optics gives clear and simple results but they are valid only in the first approximation. The results are suitable above all for multimode fibres and their physical interpretation is easy but does not give a complete picture of the processes in the fibre.

Wave optics gives results that are more exact. However, their physical interpretation is more difficult and frequently the relations derived cannot be solved analytically. A clear picture can be obtained of field distribution in both the transverse and the longitudinal directions, and conditions of the propagation of individual components can be derived.

Geometrical optics of transversely homogeneous fibres. Geometrical optics starts from the assumption that light energy propagates in the medium along certain curves, the light rays. At the same time it assumes that the wavelength of propagating energy is negligibly short ($\lambda \to 0$). The ideal fibre, i.e. fibre without interference, is considered as the model. Its effect on the layout of the field in the fibre and on energy propagation cannot therefore be expressed well.

The basic relation of geometrical optics that determines the nature of the propagation of light rays is the eikonal equation

$$\left| \grad S(r) \right|^2 = n^2(r). \quad (1.36)$$

where $r$ is the radius-vector of the point considered, $n$ is the refractive index of the medium, and $S$ is the phase function (eikonal).

The wave fronts of propagating radiation are determined by the condition of the constancy of phase function $S$, i.e. the condition

$$S(r) = \text{konst.} \quad (1.37)$$

It also follows from equation (1.36) that the phase function $S(r)$ can be determined when the spatial arrangement is known of the refractive index of the medium in which the rays propagate. In the transverse homogeneous fibre optics, equation (1.36) becomes simpler because of the step dependence of refractive index on transverse coordinates of the fibre. We assume the longitudinal coordinate to be identical to the fibre axis. Further simplification of equation (1.36) results from the circular symmetry of the fibre, when the refractive index is only a function of the radius. With cylindrical coordinates, the solution of equation (1.36) is given generally, by the relation
\begin{equation}
S(r, \varphi, z) = \int_0^r P(r) dr + h \varphi + kz,
\end{equation}

where \( P(r) = \left[ n^2(r) - k^2 - h^2 / r^2 \right]^{1/2} \), \( h \) and \( k \) are the integration constants that depend on the conditions of the entry of ray into the fibre and remain constant for the period of propagation.

From the physical viewpoint, \( P, h \) and \( k \) are proportional to the radial, azimuthal and longitudinal components of the wave vector of the plane wave at the given point

\begin{equation}
k(\vec{r}) = \left[ \frac{2 \pi}{\lambda}, \frac{2 \pi}{\lambda}, \frac{2 \pi}{\lambda}, k \right].
\end{equation}

Using the relations

\begin{equation}
r = r(z), \quad \varphi = \varphi(z), \quad Z = z
\end{equation}

as parametric equation of the ray in the fibre, equation (1.33) will give the differential equations

\begin{equation}
k^2 \left( \frac{\delta r}{\delta z} \right)^2 = P^2(r), \quad kr^2 \frac{\delta \varphi}{\delta z} = h.
\end{equation}

With polar coordinates we derive relations for \( P(r), h \) and \( k \) using simple trigonometric formulae, according to which it holds

\begin{equation}
\frac{\delta r}{\delta z} = \tan \Theta \cos \varphi, \quad \frac{\delta \varphi}{\delta Z} = \tan \Theta \sin \delta,
\end{equation}

where \( \Theta \) is the angle between the ray and the axis, and \( \varphi \) is the azimuthal coordinate \( r \). Substituting these relations into equation (1.37) we obtain, after rewriting, the following simple relations

\begin{equation}
P(r) = \left[ n^2(r) - \frac{h^2}{r^2} - k^2 \right]^{1/2},
\end{equation}

\begin{equation}
h = n(r) r \sin \Theta \sin \varphi,
\end{equation}

\begin{equation}
k = n(r) \cos \Theta,
\end{equation}

which enable classifying the rays into sets by the parameters \( h \) and \( k \) and in dependence on the conditions of the entry of rays into the fibre, i.e. in dependence on the angles \( \varphi, \Theta \), on radius \( r \) and on the value of refractive index at the point of entry \( n(r) \). The term that determines the value \( P(r) \) can be real positive or negative. The former corresponds to guided waves, the latter to decaying waves. Geometrical optics is only concerned with guided waves.

The preceding relations make it possible to assume that rays propagate in the fibre as a result of reflections on the interface of two mediums of different refractive index values. The relation between incidence angle \( \Theta_1 \) and refraction angle \( \Theta_k \) is given by the Snell law

\begin{equation}
n_1 \sin \Theta_1 = n_2 \sin \Theta_k.
\end{equation}

The total reflection of ray on the interface occurs when \( \sin \Theta_k = 1 \), from which it follows

\begin{equation}
\sin \Theta_i = \frac{n_2}{n_1}.
\end{equation}
The maximum angle (with respect to the fibre axis), at which rays can enter the fibre and propagate in it, is defined by the so-called numerical aperture (NA). This dependence is expressed by the relation
\[ \text{NA} = \sin \Theta_{\text{max}} = \sqrt{n_1^2 - n_2^2}. \]  
(1.46)

Geometrical optics gives a simple but only approximate relation for the dispersion of guided rays.

Wave optics of transversely homogeneous fibres starts from the solution of Maxwell’s equations. With a view to the fibre geometry, it is of advantage to solve the equation in cylindrical coordinates. The solution of these equations enables finding the spatial arrangement of the electromagnetic field inside and outside the core, and determining the propagation conditions for individual modes of the electromagnetic field. The exact solution of Maxwell’s equations is known and so is the solution under simplifying assumptions and with the introduction of linear polarized modes, inclusive of relations with the components of electromagnetic field.

An analysis of electromagnetic field using linearly polarized modes (LP modes) is simpler than a description using the electromagnetic field components. The derived results make it also possible to assign the denotation of electromagnetic field components (TM, TE, EH, HE) to the corresponding denotation in the terminology of linear polarized modes. On the basis of the derivation a simple form of the dispersion equation of LP modes can be obtained
\[ \frac{J_{l-1}(u)}{J_l(u)} = -w \frac{K_{l-1}(w)}{K_l(w)}, \]  
(1.47)

which is in agreement with the dispersion equation derived via simplified solution of Maxwell’s equations. For dimensionless parameters it holds that the critical values of the constant of propagation in the direction of axis \( z \) are equal to \( n_2k \) while the parameter \( w \) is in that case equal to zero. Under these conditions, dispersion equation (1.47) will be fulfilled only for \( J_{l-1}(u) = 0 \). From this value we can determine the values of argument \( u \) that corresponds to the critical values of the constant \( \beta \) and the denotation of linear polarized modes. The roots of Bessel functions \( J_1(u) \) and \( J_0(u) \) correspond to the following denotation of linear polarized modes. For \( J_1(u) \) and arguments \( u = 0 \) and 3.85 the corresponding modes are LP_{01} and LP_{02}. For \( J_0(u) = 0 \) and arguments \( u = 7.015, 2.40, 5.52 \) and 8.67 the corresponding modes are LP_{03}, LP_{11}, LP_{12}, and LP_{13}. 
Fig. 1.18: Curves for Bessel functions $J_0$ and $J_1$ and propagation boundaries of corresponding modes.

When the condition $0 < u < 2.4$ is fulfilled, only one transverse mode LP$_{01}$ will propagate through the fibre. Fig. 1.18 gives the curves of Bessel functions $J_0$ and $J_1$ in dependence on the value of argument $u$, together with the regions beginning from which the respective LP mode can propagate.

The propagation constant will be determined from the relation

$$\beta/k = n_2 (\Delta b + 1),$$

(1.48)

where

$$b = 1 - u^2/v^2 \quad \text{and} \quad \Delta = \frac{n_1 - n_2}{n_2}. \quad (1.49)$$

Fig. 1.19: Propagation constant $\beta$ in dependence on normalized frequency.
Propagation constants for various field lay-outs are illustrated in Fig. 1.19. The direct detection of light signals distinguishes only the envelope delay caused by the change in group velocity, which is given by the relation

$$\tau_{sk} = \frac{L}{c} \left( \frac{d \beta}{dk} \right).$$

(1.50)

When differentiating relation (1.48), the dependence of $n$, $\Delta$ and $b$ on the wave vector $k$ must be respected. With small differences between the refractive indices of the core and the cladding, $\Delta$ does not depend on $k$, and for the majority of materials used for fibres it holds

$$k \frac{dn}{dk} << n.$$  

(1.51)

Respecting these relations, we obtain the group velocity

$$\tau_{sk} = \frac{L}{c} \left[ \frac{d(nk)}{dk} + n \Delta \frac{d(bk)}{dk} \right].$$

(1.52)

The wave vector $k$ can be expressed by the relation

$$k = \frac{\nu}{a \left( n_1^2 - n_2^2 \right)^{\frac{1}{2}}}.$$  

(1.53)

Relation (1.52) can then be rewritten in the form

$$\tau_{sk} = \frac{L}{c} \left[ \frac{d(nk)}{dk} + n \Delta \frac{d(bv)}{dv} \right].$$

(1.54)

The first part of this term characterizes the material dispersion, which is the same for all modes. The second part expresses the mode delay due to waveguide dispersion. Of decisive effect in this term is the coefficient $d(bv)/dv$, which after modification can be written in the form

$$\frac{d(bv)}{dv} = 1 - \frac{u^2}{v^2} \left( 1 - 2 \frac{v}{u} \right).$$

(1.55)

In Fig. 1.20, this dependence is given for different linearly polarized modes. It is obvious from these curves that far from the critical frequency the term $d(bv)/dv$ approximates the value 1, and with increasing index of the first mode its group delay also increases.
The obtained theoretical results were verified experimentally and very good agreement was confirmed.

Up to now, the results of analysis assumed propagation in the ideal optical fibre. Real fibres, however, differ from ideal fibres by various inhomogeneities such as changes in refractive index, diameter, etc. In that case we speak of fibres with defect and even for such cases theoretical conditions of energy transmission have been determined. From the results it follows that the consequence of defects is a change in the distribution of transmitted energy and the appearance of mutual coupling of modes.

In transversely inhomogeneous optical fibres, when the profile of refractive index is close to the parabolic index, guided rays oscillate about the fibre axis without reaching the region of the core/cladding interface. Losses in these fibres will therefore be substantially lower than losses in step-index fibres. From the viewpoint of geometrical optics, rays in these fibres in an area distant from the axis travel through a medium of lower refraction index and their rate of propagation in this area is higher than in the direction of the axis. Consequently, the dispersion of these fibres will also be substantially lower.

The theoretical solution of these problems is complicated and is carried out under certain simplifications. Because of the limited scope of this chapter, we will only give some of the conclusions.

Scalar theory of transversely inhomogeneous fibres determines the propagation constant $\beta$ according to the relation

$$\beta_{nm} = \frac{\omega}{c} \sqrt{\frac{1}{H_0}} \left[ n + \frac{1}{2} \left( \frac{H_2}{H_0} \right)^{1/2} - \left( m + \frac{1}{2} \right) \left( \frac{H_2}{H_0} \right)^{1/2} \right].$$ (1.56)

The group velocity of propagation is $v_g = \frac{d\omega}{d\beta}$. According to this result, in scalar theory approximation this $v_g$ does not depend on the type of propagating mode (i.e. indices $m$
and \( n \). Thus it can be expected that the dispersion of fibres with quadratic profile of the refractive index is negligibly small, which is their main advantage.

Wave theory of transversely inhomogeneous fibres again starts from Maxwell’s equations, when solution can only be realized for some fibre profiles while in the other cases approximate solutions must be sought. For example, using the WKB (Wenzel-Kramers-Brillouin) method, the propagation constant can be determined with an accuracy better than 1 % according to the relation

\[
\beta_n^2 = H_0 k_0^2 - (2n + 1) k_0 H_1^{1/2}.
\]

(1.57)

Also in these cases it is possible to analyze fibres with defects.

### 1.4 Polymer optical fibres – POF

The development of glass fibre transmission was accompanied by efforts to realize transmissions over plastic fibres. The problem posed by these fibres was and is their great attenuation. Initially it was in the range of hundreds of dB·km\(^{-1}\); in more recent years it has come down to 10 dB·km\(^{-1}\). This value is acceptable for networks of the type of fibre to the home. The dependence of attenuation on wavelength is given in Fig. 1.21. The curve for the higher value corresponds to the year 1990 while the curve with lower attenuation corresponds to the present-day state of development. At the same time, success has been achieved as regards increasing the thermal resistance of these fibres. Today’s fibres can withstand temperatures of 200 to 300 °C.

![Dependence of attenuation on wavelength in POF.](image)

Fig. 1.21: Dependence of attenuation on wavelength in POF.

A great advantage of these fibres is the simple and easy installation, and easy and rapid preparation of connectors in the field. If the attenuation values of these fibres could be further lowered, their deployment might be considered a “revolution” in optical transmissions, on the one hand because of the above advantages and, on the other hand, because of the expected radical price reduction.
At this point, fibres of the type of PCS (plastic-core-silicon) should be recalled, which were also used.

As regards the design and transmission, POF is analogous to glass fibre. The core is made of polymethylmethacrylate (PMMA) and the cladding is made of fluorinated PMMA (fluoropolymer). The refraction index of the core is \( n_i = 1.492 \), that of the cladding is \( n_p = 1.416 \), and NA = 0.47. Schematic diagram and dimensions are given in Fig. 1.22.

Currently manufactured fibres have cores of 50, 62.5 and 120 µm in diameter and claddings of 490 µm in diameter. Gigabit Ethernet or multi-gigabit transmissions can be realized to a distance of ca. 200 m, in typical transmission windows of 850 and 1300 nm.

![Fig. 1.22: POF fibre.](image)

The transmission problematic is solved by mode theory, and dispersion and other effects, described above, also manifest themselves. Standards issued for POF include IEEE 1394, ATM Forum, etc.

### 1.5 New technologies of fibre manufacture

**Doped fibres**

Next chapter will deal with optical amplifiers. One of the design possibilities for these amplifiers is the application of the principle of erbium- (or ytterbium-) doped fibre for the wavelength 1.53-1.61 µm of laser amplifier (EDFA – Erbium Doped Fibre Amplifier). Use is made of the method of multi-point excitation of active medium in double-cladding (DC) fibres. Excitation is connected to the area of multimode inner cladding of large diameter (not only to the area of single-mode fibre) and thus a power laser diode of large radiation area and low radiant intensity is used for the excitation. The signal itself is then transmitted by the central single-mode doped fibre.

The principle of the method is shown in Fig. 1.23. The principal problem of the method consists in the way the excitation and signal are coupled to the active fibre.

**Polarized fibres** are designed for special application such as PDM compensators, future coherent transmissions, testing of equipment. They can also be used in metrology, gyroscopes, Doppler speed indicators, and other sensor applications.

Single-mode fibres of this type are delivered in yardages or already provided with connectors. A “PANDA” shape section through the fibre with strength members and indicated
polarization is shown in Fig. 1.24. Axis X is the so-called fast axis, axis Y is the slow axis. The so-called telecommunication polarized fibre, which is specially designed for the polarization multiplexing EDFA excitation laser, is available on the market today.

Fig. 1.23: Principle of excitation into doped fibre, using fused fibre splice element.

Fig. 1.24: Polarization.

Fig. 1.25: Microstructure optical fibre.
Microstructure optical fibres (MOF) bring new revolutionary changes in the design of fibres. Theoretical knowledge was obtained via computation but it is only the present-day technologies that have made it possible to manufacture these fibres of various remarkable properties. These new fibres enable, for example, positive waveguide dispersion in single-mode fibres, guidance of light in hollow cores using the prohibited photonic band, sensor and interferometer applications, and reduction of polarization dispersion.

Their design realization is in the form of 2D photonic crystal, which is formed by periodically placed air openings (instead of air, gas, polymer or liquid can be used) extending along the optical fibre length. Hexagonal or plastic structure with circular openings is usually used. The number, lay-out type and size of openings and the spacing of their centres are chosen in dependence on the purpose the given MOF has been designed for. The outer jacket of the fibre is of pure SiO$_2$; the whole MOF is of the same outer diameter as conventional optical fibres, i.e. 125 µm.

Fig. 1.25 gives an indication of the fibre (after magnification) and of the technology of its manufacture by means of preforms (to be explained in the following chapter), when the preform itself (from which the fibre is drawn in subsequent operation) is obtained by fusing the indicated glass tubes around the core.

These fibre types are manufactured and supplied under various designations in different modifications for special applications. They mainly belong to the group of Photonic Crystal Fibres (PCF), which is a frequently used label. There are also designations like Holey Fibre (HF), Solid Core PCF, and others, depending on their properties.

Let us now go back to the original denotation MOF. Depending on the technology used, MOF can be manufactured with specific dispersion properties. Ultra-flat dispersion characteristic can be obtained in them (Fig. 1.26).

![Graph](image)

**Fig. 1.26:** MOF with ultra-flat dispersion characteristic.
Highly nonlinear MOF (Highly Nonlinear Crystal Fibre) can be used for optical switching or pulse regeneration. MOF gratings, the so-called Bragg gratings, are used in wavelength multiplexes to lead one channel from the transmitted spectrum; they are suitable for sensor applications, for equalizing the gain in erbium fibre amplifiers, and also for the compensation of dispersion.

Double-core MOF, where light is coupled to one of the cores while from the other core it is coupled to a conventional fibre; power can be seen on the output to flow from one core into the other, with minima and maxima appearing in the transfer function. They are used in fibre filters and sensors.

These questions are in the stage of research: new structures, manufacturing technologies and methods of fibre splicing are sought, as well as ways of reducing costs since application in the area of transport (long-haul) networks is, for the time being, very costly.

A different situation seems to be emerging in the area of transmissions over short distances, ca. up to 50 m.

POF brings many advantages for this type of transmission. Connecting the fibre to the connector-converter is simple. It suffices to cut the fibre with a knife as need be and “clasp” it down. The systems operate in the region of visible radiation – the state can be checked immediately. In comparison with “glass” optics the costs are very low.

Some companies already offer such products for indoor transmission.

The trend in the development is evidently towards taking the (SI) fibre to the home (FTTH) and realizing further PC, TV and other connections by means of plastic fibres (POF).
2 Manufacture of optical fibres

In principle, there are two methods for manufacturing optical fibres: either via drawing from a glass preform, whose surface layers are suitably doped with various oxides (so-called gaseous phase – modern manufacturing technology) or as multicomponent fibres (liquid phase method).

The preform is essentially a glass intermediate in the shape of a cylindrical rod, from which optical fibre is drawn. The profile of the rod represents an enlarged profile of the optical fibre. After intensive local heating, the fibre is drawn from this preform. It is immediately coated with a layer of polymer of several micrometres in thickness, so-called primary coating, to be mechanically protected. Then it is spooled.

The principle of drawing fibre from a preform is depicted in Fig. 2.1.

This facility is ca. 7 metres tall and relatively quite complicated, provided with precise measurement and control technology using a microcomputer. A feeding mechanism brings the preform into the drawing zone with either a resistance furnace or a burner. On leaving this zone, the fibre is measured immediately below the melting zone and the value measured is sent to the control system. The respective response must not be slower than 0.1 to 0.03 s, and the resultant diameter deviations from the required values must be less than 2%. Then the coating nozzle applies the primary coating layer to the fibre. In the case of silicone resin a thermal hardening furnace is used while in the case of acrylate UV light is used for hardening. The number of furnaces, or the total length of hardening zone, depends on the rate of drawing. In the deposition of primary coating, rates of up to 5 m s\(^{-1}\) are achieved. The fibre provided with primary coating is introduced into a drawing machine controlled by the control system. The speed of the drawing machine is controlled on the basis of information about the fibre diameter. The last component of the line is the spooling device, ahead of which a tester of fibre strength is sometimes placed.
The preparation of the preform (gaseous phase method) is based on the oxidation of silicon tetrachloride

\[ \text{SiCl}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + 2\text{C}_2 \]

and other similar oxidation reactions, during which very fine particles of solid oxides are formed. These particles settle on the surface of a suitable carrier and form a porous layer, which due to increased temperature melts into the so-called preform, from which the optical fibre is drawn in the next stage. Different technologies are used in the manufacture of preforms, which differ either in the direction in which the reaction components cross or in the reaction mechanisms. The preparation of the preform is the most important operation in the whole manufacturing process since all the fibre properties are given by the properties of this preform.

In the preparation of the preform by the method of chemical vapour deposition (CVD) the following technologies are used:

- **OVD (Outside Vapour Deposition)**, outside deposition from the gaseous phase by way of lateral deposition on the core, which rotates at a constant rate,
- **MCVD (Modified Outside Vapour Deposition)**, which belongs to the inside methods, in which oxides are deposited on the inside wall of rotating silicon tube,
- **PCVD (Plasma Chemical Vapour Deposition)**, in which, the same as with MCVD, oxides are deposited on the inside wall of rotating silicon tube but the reaction according to the starting equations is initiated by microwave plasma,
- **VAD (Vapour Phase Axial Deposition)**, which differs from the preceding technologies in that oxides are deposited in axial direction on a rotating target from the carrier material.

And now some details about the individual technologies.

**OVD technology** is an original technology of the Corning Glass Works Company (which in 1970 made the first optical fibre with an attenuation of less than 20 dB-km\(^{-1}\)) and is used by the Company in the manufacture of optical fibres. This method uses lateral deposition on the core, which rotates at a constant rate. Usually, the core is of 0.5 cm in diameter and made of Al\(_2\)O\(_3\) or graphite. Fuel, SiCl\(_4\) and the respective dopants are fed into the burner. The principle of this method is shown in Fig. 2.2. The hydrolysis of halogenide vapours in the flame gives rise to solid soot of oxide or mixture of oxides, part of which settles on the core, forming a porous matter, whose density is about 1/3 of silicon glass density. Doped onto the carrying rod are layers that form in the drawn fibre both the core and the cladding. After doping, the carrier rod is, due to different thermal expansivity, carefully removed and the porous perform will sinter into a clear vitrified preform in the furnace at temperatures around 1500 ºC (Fig. 3.2b). The burning of fuel gas is accompanied by the formation of OH groups. During sintering, the flow of He with a few per cent of Cl\(_2\) will remove the OH groups relatively effectively. This method makes heavy demands on the protection against impurities from the surroundings. Controlling the OVD technology is also demanding: it is necessary to maintain constant speeds of the flow of raw materials and fuel, preform revolutions and constant burner temperature. During vitrification the speed of drying gas and perform revolutions and the burner temperature must be constant. During vitrification there are chemical reactions between dopants and drying gas and this leads to changes in the refraction index profile. These changes are corrected in advance, i.e. by such doping that after the reaction with gas the profile is correct. More than 10 km of fibre of 125 μm in diameter can be drawn from a preform. Currently achieved rates of settling are higher than 2 g-min\(^{-1}\), which
corresponds to 75 m of fibre per minute. The attenuation values achieved are low, the bandwidth is greater than 1 GHz·km⁻¹.

**Fig. 2.2:** Principle of preform manufacture by the OVD method.

**MCVD technology** is based on internal oxidation of the gaseous phase in the reaction zone inside the rotating tube of silicon dioxide, along which the oxy-hydrogen flame is travelling. This technology was developed in the Bell Laboratories and put into practice by the Western Electric Company. It spread gradually into Japan and Europe and today it is the most frequently used method. The production principle is indicated in **Fig. 2.3**. An advantage of this method consists in the great purity of the basic process; contamination from the surrounding medium is practically out of the question. The preform is prepared by heating a silica tube with a layer of sintered soot at a temperature of about 1900 ºC, when shrinkage to the shape of rod occurs. In the manufacture, a deposition rate of 0.4 g·min⁻¹ is used, which corresponds to 40-160 m of fibre per minute, with the possibility of drawing a total of 10 to 15 km of fibre.

**Fig. 2.3:** Principle of preform manufacture by the MCVD method.

Using the preform made by the MCVD technology, multimode and single-mode lightguides with step-index and gradient-index profiles can be made, whose parameters are good on the whole. The multimode fibre attenuation is given as ca. 3 dB·km⁻¹ for the 0.85 μm wavelength, and 1 dB·km⁻¹ for 1.3 μm, with the bandwidth in units of GHz·km⁻¹. Peak values are substantially better, with attenuation below 1 dB·km⁻¹, bandwidth in tens of GHz·km⁻¹. In
single-mode fibres, the attenuations achieved for 1.55 μm are below 0.2 dB·km⁻¹, bandwidth 10 GHz·km⁻¹.

**PCVD technology** was developed in the Philips Research Laboratory and production started in the Philips Glass Division. The method is shown schematically in Fig. 2.4. The method is also ranked among the inside methods and is characterized by the application of non-isothermal plasma, in which the reaction proper takes place. A pressure of 1330 Pa is maintained in the tube, which is placed horizontally in the furnace at a temperature of 1200 ºC. Inside the furnace, a microwave generator is moving around the tube at a rate of 8 m·min⁻¹ along a length of 70 cm, operating with 2.45 GHz frequency. This generator generates microwave plasma, in which a heterogeneous reaction is taking place on the tube walls, with no soot being produced. For SiO₂ the deposition efficacy is almost 100 % while for GeO₂ it is ca. 85 %. The method described yields very thin layers (up to 700 layers of about 0.5 μm), which is of advantage for fibres with gradient-index profile in particular. This is due to the fact that energy for the reaction is supplied directly and not through tube walls. After the deposition of the core materials the furnace temperature is raised to 2000 ºC followed by the collapse of silica tube. The manufacturing rate of deposition is 0.5 g·m⁻¹.

![Fig. 2.4: Preform manufacture by the PCVD technology.](image)

The control of PCVD is easier than that of the other methods. Heavy demands are made on the amount of raw materials; the other parameters such as pressure in the tube, furnace temperature, plasma energy, resonator speed, etc. do not affect the resultant parameters substantially. The collapse is the same as with the MCVD method.

**VAD technology** was developed in Japan by the NTT Company, and production was started in Fujikura Cable Works Ltd., Sumitomo Electric Industries Ltd, and in other companies. The basic schematic diagram of this method is given in Fig. 2.5. With this method, the particles, which later form the core and the cladding, are deposited on a substrate in axial direction and thus a cylinder without central opening is formed. Important is not only the absence of any central opening, which leads to a reduction of losses, but mainly the possibility of continual preparation of the preform. Vitrification takes place in an electric furnace at 1500 ºC in a He-CO₂ or He-SiCl₂ atmosphere, in which water is repulsed. In the course of vitrification the preform volume is reduced eight times and the preform diameter is ca. 2.5 cm. It is then elongated to a diameter of 1 cm and placed in the silica tube, and the tube collapses. With this technology, no central dip appears in the refractive index profile. A typical deposition value is 0.4 g·min⁻¹ and the preform can yield over 100 km of fibre. Using this method, both multimode and single-mode step-index and gradient-index
lightguides can be prepared, with very low attenuation (below 1 dB·km⁻¹) and large bandwidth. The tensile strength of the fibre is also good.

![VAD process diagram]

**Fig. 2.5:** Preform manufacture by the VAD technology.

Controlling the VAD process is very demanding. The refractive index profile is affected by the temperature distribution on the preform surface, flame position and angle. The flow rate of raw materials, fuel and exhaust, the rotation rate of porous preform, and the position of the growing end must be constant. Increasing the deposition rate entails problems. Efficacy of SiO₂ deposition is 60 to 80%. In the manufacture of single-mode fibres one burner is used for the deposition of core and one or more burners for the deposition of cladding.

**Liquid phase methods.** In these methods the so-called multi-component fibres are based on classical glass-making methods. These methods were used when the manufacture of optical fibres was launched. The basic manufacturing operations are the preparation and melting of initial bulk glass and the drawing of fibre.

The first phase consists in preparing ultra-pure starting materials, mostly powder oxides and carbonates. These materials are prepared by using diverse purification methods and by combining them. One of the methods for obtaining silicon dioxide of required purity is to refine the natural raw material via washing in acid solutions, in particular concentrated hydrofluoric acid and nitric acid in 1:1 ratio, and also hydrochloric acid. Synthetic SiO₂ powder is prepared by hydrolysis of tetraethoxysilane or silicon tetrachloride; it can be purified via repeated distillation and subsequent drying in dry gas atmosphere. Sodium carbonate is comparatively easy to purify by filtering a 25% solution on filter paper, chip filtration on cellulose acetate membrane and also by electrolysis with mercury cathode.

The second phase is melting, when homogeneous glass without bubbles is obtained; difficulties may arise due to the danger of glass being contaminated with crucible material and furnace medium. Crucibles made of aluminium oxide and platinum are responsible for contamination with iron; the solution is to use raw materials with low melting temperature and, consequently, crucibles of pure silica can be used. But then the crucible material starts dissolving and striae appear. This can be prevented by high-frequency heating of bulk glass
and simultaneous cooling of crucible. Drying gases are made to bubble through the bulk glass in order to reduce the content of hydroxyl ions. After cooling, the glass is machined to the required dimensions or it is allowed to cool only partially and a rod is drawn from its surface; this will eliminate contamination stemming from machining but at the cost of lower glass homogeneity.

For the fibre-drawing itself, two basic methods are used: the method of “rod in the tube” and the method of “double crucible”.

**Fig. 2.6:** The “rod in the tube” method of manufacturing optical fibre.

The **“rod in the tube” method** is particularly simple and productive. A rod of extremely pure glass or fused silica is inserted into a tube of glass of low refractive index and subsequent heating allows a fibre to be drawn (see **Fig. 2.6**). A disadvantage is that geometrical and structural imperfections of the inner surface of the rod can show as defects of the core-cladding interface, which cause diffusion losses. The method is used for the preparation of cheap multimode step-index lightguides, comparatively large attenuation and great numerical aperture. The lowest attenuation of the lightguides is ca. 6 dB·km⁻¹ and the numerical aperture is 0.6. The prepared initial material of 25 mm in diameter and 500 mm in length can yield about 20 km of fibre.
The double crucible method. The core and cladding materials are melted separately in a double crucible as shown in Fig. 2.7. A structure is thus produced which after drawing gives a fibre of the required refractive index profile. The method enables continual drawing of fibres of great lengths at a high rate of drawing. A charge of 100 kg would be enough to draw a fibre 1000 km long. Practical experience is not as good though. Fig. 2.8 shows a practical implementation of this method, inclusive of the heating furnace.

Similar to the fibres made by drawing from a preform, fibres manufactured by the liquid phase must also be provided with primary coating (plastic covering based on silicon, epoxy resin, etc.) protecting the fibre against chemical effects and increasing its tensile strength.
Optical fibre PCS is a multimode step-index fibre. The core is of silicon dioxide, the cladding is of hardened silicon resin. In comparison with other types of fibre, the advantage of the PCS fibre is its larger core diameter and higher numerical aperture, which provides for easy handling when connectoring, splicing, etc.

2.1 Characteristics of manufactured optical fibres

*Single-mode fibre with matched refractive index profile (Matched Clad, MC) – manufacturer ofs (US manufacturer)*

General characteristic

Single-mode optical fibre with adapted refractive index profile is made up of germanium-doped core and cladding of pure silica glass. The refractive index profile is shown schematically in Fig. 3.9. The fibre is designed for all applications where low attenuation and high transmission bandwidth are required. The fibre can be operated on the two wavelengths used, i.e. wavelengths 1310 and 1550 nm. Its further advantages include:
- very low attenuation on both wavelengths,
- outstanding geometrical parameters that enable obtaining very low attenuation values of splices and connectors,
- double primary coating D-LUX 100<sup>®</sup> gives the fibre excellent mechanical and climatic resistance,
- if the fibre is in an ofs cable, the manufacturer guarantees for both the fibre and cable outstanding parameters as regards polarization dispersion. Guaranteeing this parameter is of particular importance in analogue applications (cable TV).

![Refractive index of SM fibre](image)

**Fig. 2.9:** Refractive index of SM fibre.

*Geometrical parameters*

**Fibre**

Core diameter: 8.3 µm (nominal value)

Cladding parameter: 125 ± 1 µm

Core non-circularity: <1%

Core-cladding eccentricity: ≤ 0.8 µm
**Primary protection**

- Primary coating diameter: 245 ± 10 µm
- Primary protection-cladding eccentricity: <12 µm

**Transmission parameters**

- Mode field diameter (MFD): 9.3 ± 0.5 V (1310 nm)  
  10.5 ± 1.0 µm (1550 nm)
- Cut-off wavelength ($\lambda_{\text{cut-off}}$): 1150-1350 nm (for 2 m fibre length)
- Cut-off wavelength in cable: ≤ 1260 nm
- Attenuation (customer specifies maximum value from the range): 0.35-0.40 dB·km⁻¹ per nm, 0.21-0.30 dB·km⁻¹ per 1550 nm
- Spectral change in attenuation: ≤ 0.1 dB·km⁻¹ in the interval 1285-1330 nm  
  ≤ 0.05 dB·km⁻¹ in the interval 1525-1575 nm
- Longitudinal homogeneity of attenuation: no point discontinuities > 0.1 dB
- Attenuation on wavelength of absorption maximum of OH-ions (1383±3 µm) ≤ 2 dB·km⁻¹

**Chromatic dispersion**

- Wavelength of zero chromatic dispersion $\lambda_0$: 1300-1322 nm (typically 1312 nm)
- Dispersion between 1200 and 1600 nm can be calculated according to the relation
  \[ D(\lambda) = 0.25 \cdot S_0 \cdot \lambda \cdot (1 - \lambda / \lambda_0)^4 \]
- Maximum dispersion on 1550 nm: 18 ps/nm⁻¹·km⁻¹
- Maximum slope of dispersion characteristic on the wavelength of zero chromatic dispersion: $S_0$ ≤ S: 0.092 ps·nm⁻²·km⁻¹ (typically 0.088 ps·nm⁻²·km⁻¹)
- Losses due to macrobends:
  - Less than 0.5 dB on one turn of 32 mm in diameter on $\lambda = 1550$ nm.
  - Less than 0.05 dB on 1310 nm and less than 0.1 dB on 1550 nm on 100 turns of 75 mm in diameter
- Polarization mode dispersion: 0.5 ps/√km on 1310 nm (in of§ cable).

**Mechanical parameters**

- Tensile strength (Proof Test): 0.7 GPa
- Stripping force of primary coating: <8.9 N, ≥ 1.3 N

**Climatic resistance**

- Temperature dependence of attenuation: ≤ 0.05 dB·km⁻¹ within the range -60 °C to +85°C.
- Static fatigue: static value coefficient is > 20 if D-LUX 100K protection is used.
- Endurance of colour marking:
Colour-marked fibres in the D-LUX 100R primary coating do not exhibit any changes in colour after the following aging tests:
- 30 days at 95 °C and 95% relative air humidity
- 20 days in dry heat of 125 °C

The other characteristics

Relative refractive index difference: $\Delta_1 = 0.33\%$

Effective group refractive index: 1310 nm 1.466
1550 nm 1.467

Numerical aperture: 0.12

Rayleigh’s back-scattering coefficient: 1310 nm -49.6 dB
1550 nm -52.1 dB

Fibre curl: curl radius $\geq 2$ m

**Single-mode fibre with depressed refractive index profile (Depressed Clad, DC)**

General characteristic

Single-mode optical fibre with depressed refractive index profile is made up of germanium-doped core, inner cladding with reduced refractive index profile, and outer cladding of pure silica glass. The refractive index profile is shown schematically in Fig. 2.10. The fibre is designed for all applications where low attenuation and high transmission bandwidth are required. The fibre can be operated on the two wavelengths used, i.e. wavelengths 1310 and 1550 nm. Its further advantages include:
- very low attenuation on both wavelengths,
- outstanding geometrical parameters that enable obtaining very low attenuation values of splices and connectors,
- the depressed refractive index profile provides excellent resistance of attenuation to microbends and macrobends, even in the case of changing to the 1550 nm wavelength,
- double primary coating D-LUX 100R gives the fibre excellent mechanical and climatic resistance,
- if the fibre is in an ofs cable, the manufacturer guarantees for both the fibre and the cable outstanding parameters as regards polarization dispersion. Guaranteeing this parameter is of particular importance in analogue applications (cable TV).

![Refractive index profile](image)

**Fig. 2.10:** Refractive index profile.
**Geometrical parameters**

**Fibre**
- Core diameter: 8.3 µm (nominal value)
- Cladding parameter: 125 ± 1 µm
- Core non-circularity: <1%
- Core-cladding eccentricity: ≤ 0.8 µm

**Primary protection**
- Primary coating diameter: 245 ± 10 µm
- Primary coating-cladding eccentricity: <12 µm

**Transmission parameters**
- Mode field diameter (MFD): 8.8 ± 0.5 V (1310 nm)  
  9.7 ± 0.6 µm (1550 nm)
- Cut-off wavelength (\(\lambda_{\text{cut-off}}\)): 1170 – 1310 nm (for 2 m fibre length)
- Attenuation (customer specifies maximum value from the range): 0.35-0.40 dB-km\(^{-1}\) per 1310 nm, 0.21 – 0.30 dB-km\(^{-1}\) per 1550 nm
- Spectral change in attenuation: ≤ 0.1 dB-km\(^{-1}\) in the interval 1285-1330 nm  
  ≤ 0.05 dB-km\(^{-1}\) in the interval 1525-1575 nm
- Longitudinal homogeneity of attenuation: no point discontinuities > 0.1 dB
- Attenuation on the wavelength of absorption maximum of OH-ions (1383 ± 3 µm):  
  ≤ 2 dB-km\(^{-1}\)

**Chromatic dispersion**
- Wavelength of zero chromatic dispersion (\(\lambda_0\)): 1310 ± 10 nm (typically 1310 nm)
- Dispersion between 1200 and 1600 nm can be calculated according to the relation  
  \(D(\lambda) = 0.25 \cdot S_0 \cdot \lambda \cdot (1-\lambda/\lambda_0)^4\)
- Maximum dispersion on 1550 nm: 18 ps-nm\(^{-1}\)-km\(^{-1}\)
- Maximum slope of dispersion characteristic on the wavelength of zero chromatic dispersion (\(S_0\)):
  0.092 ps-nm\(^{-2}\)-km\(^{-1}\) (typically 0.088 ps-nm\(^{-2}\)-km\(^{-1}\))
- Losses due to macrobends:
  Less than 0.5 dB on one turn of 32 mm in diameter on \(\lambda = 1550\) nm.
  Less than 0.05 dB on 1310 nm and less than 0.1 dB on 1550 nm on 100 turns of 75 mm in diameter
- Polarization mode dispersion: 0.5 ps/√km on 1310 nm (in Lucent Tech. cable).

**Double-layer primary coating of optical fibres D-LUXR 100**

When selecting a suitable optical fibre, it is important from the user’s viewpoint to what degree the attenuation of fibres can increase due to diverse mechanical or climatic effects.

Increased attenuation is often caused by microbends on optical fibres. The D-LUX 100 double-layer primary coating (Lucent Technologies) maximally prevents the appearance of microbends and increases the quality of optical fibres and cables made by Lucent Technologies. The D-LUX 100 primary coating is made up of two acrylate layers of roughly the same thickness, applied to the fibre such that the total diameter of the fibre with primary coating is 245 ± 10 µm. The inner layer exhibits a lower Young’s modulus and thus forms a sort of “cushion”, which protects the fibre against external effects and prevents the
appearance of microbends. The outer layer with a higher Young’s modulus better protects the fibre against the action of external factors.

The advantages of double-layer primary coating D-LUX 100:

1. Minimization of microbends. The soft inner layer of primary coating enables a relatively loose seating of the fibre and thus eliminates the action of external forces leading to the appearance of microbends. This property is very important for the fibre behaviour at low temperatures.
2. Increased resistance to effects of external forces.
3. Easy removal of primary coating from the fibre (e.g. for fusing and connecting).
4. Outstanding stability and long service life of fibres.

The D-LUX 100 two-layer primary coating is designed such that it has maximum resistance to degradation caused by either hydrolysis or oxidation. Fibre with the above primary coating exhibits excellent stability of parameters and long service life in humid and in dry environments. This stability and long service life are responsible for the following advantages:

- colour marking does not change throughout the whole service life of fibre,
- the fibres do not get mutually stuck,
- for the whole service life of fibres the primary coating does not lose adhesion, and the stripping force necessary for the removal of coating does not markedly change either,
- high resistance of fibres to static fatigue.

The D-LUX 100 primary coating is used with all types of ofs fibres.

All Wave Fibre (ofs)

This is a fibre with suppressed OH “peak” between the second and the third windows of the attenuation characteristics of optical fibre. It is denoted ZWP (Zero Water Peak) single-mode fibre, which enables transmission in the waveband of 1260-1625 nm. The fibre is suitable for CWDM and DWDM transmissions as well as for access networks (FTTx), etc.

It also exhibits very low PDM values. The fibre is manufactured in compliance with the ITU-T G.652D standard.

Geometrical parameters

Fibre
Core diameter: 8.3 μm
Cladding diameter: 125 ± 0.7 μm
Core-cladding eccentricity: ≤ 0.5 μm
Primary coating diameter: 235 – 245 μm

Transmission parameters

Attenuation
1310 nm ≤ 0.34 dB·km⁻¹
1385 nm ≤ 0.31 dB·km⁻¹
1490 nm ≤ 0.24 dB·km⁻¹
1550 nm ≤ 0.21 dB·km⁻¹
1625 nm ≤ 0.24 dB·km⁻¹

Chromatic dispersion: \( S_0 \leq S: 0.09 \text{ ps·nm}^{-2} \cdot \text{km}^{-1} \) (typically 0.087 ps·nm⁻²·km⁻¹)

Polarization mode dispersion: < 0.06 ps √km

Temperature range: -60 °C - +85 °C
**All Wave FLEX Fibre (ofs)**

It is designed for the installation of FTTH (or FTTx) networks. Its specification corresponds to that of the preceding fibre but exhibits greater reliability and very low transmission losses. It complies with the ITU-T G.657 recommendations.

**EZ Bend Optical technology**

This technology represents new possibilities in laying and installing optical fibres (in cables) with bend resistance up to a bend radius of 5 mm (an ITU-T G.657C recommendation is being prepared for the fibre).
3 Manufacture of optical cables

The term optical cables refers to cables that contain at least one optical fibre, irrespective of whether they also contain other conductors (Cu, coax) for the purpose of transmission, supervision or repeater supply. The design of optical cables must provide protection against external mechanical, climatic and thermal effects. The quality of the transmission properties of optical fibres can be impaired in particular by pressure, bending, torsional stress, and shear microbends.

![Design of a simple optical cable](image)

**Fig. 3.1:** Design of a simple optical cable: 1 – core, 2 – cladding, 3 – primary coating, 4 – secondary coating.

The basic building block in the manufacture of the optical cable core or of a simple cable for indoor purposes is an insulated optical fibre, as can be seen in **Fig. 3.1**. The figure shows the core, the cladding, and the primary protective coating which gives the core and the cladding mechanical ruggedness. Then comes coating, usually thick-walled and made of plastic. Its diameter is usually 0.8-1 mm and gives the fibre mechanical ruggedness. Plastics used as secondary coating are of high strength module such as polyester, polypropylene and nylon. The process of extruding and simultaneously cooling the fibre that is being extruded must be checked carefully in order to prevent impairment of optical transmission properties. These impaired properties are due to the stresses present in the fibre as a result of thermal contraction of the fibre and also to the morphological changes in the plastic. Coatings are preferred that do not contract the fibre too much because it has been found that with a small coating contraction and tight coating adhesion to the fibre the fibre gets twisted with a small twist, which increases optical losses in the core. This is often referred to as micro-deformation. A very effective means for limiting micro-deformation losses is the use of double cladding formed by an inner layer of low elasticity modulus, and an outer layer of a relatively high elasticity modulus. An example of such an arrangement is given in **Fig. 3.2**. A more complicated cable structure is given in **Fig. 3.3**. In this case, a cushion (damping layer) is used, followed by a layer of Kevlar (this is the strength layer) and cable jacket of softened frost-resistant PVC.
Fig. 3.2: Optical cable: 1 – optical fibre, 2 – outer plastic cladding, 3 – PVC jacket.

Fig. 3.3: Single-fibre optical cable: 1 – optical fibre, 2 – cushion, 3 – Kevlar, 4 – PVC.

Optical cables are manufactured in runs of 1 000 m, 2 000 m, up to a maximum length of 10 000 m.

Another example of a light single-mode optical cable is given in Fig. 3.4. The optical fibre is in the centre of cable core, surrounded by strength members of Kevlar and then a plastic jacket.

Fig. 3.4: Single-fibre optical cable: 1 – optical fibre, 2 – Kevlar reinforcement, 3 – plastic jacket.
**Fig. 3.5** shows schematically a single-fibre optical cable combined with Cu pairs.

**Fig. 3.5**: Schematic illustration of combined single-fibre optical cable with Cu pairs added.

A more complicated multi-fibre version is shown in **Fig. 3.6**. It is based on the classical structure where the strength member (Kevlar) is in the centre of cable core while the next layer contains the respective variable number of optical fibres (inclusive of loose cavities since the design is the same for different numbers of fibres because optical fibres make up a considerable part of the price of cable), and then comes the PVC jacket.

**Fig. 3.6**: Six-fibre optical cable: 1 – 19 strength members of Kevlar, 2 – optical fibres, 3 – filler, 4 – jacket.

A similar design variant is shown in **Fig. 3.7**.

**Fig. 3.7**: Two-fibre optical cable: 1 – strength member, 2 – optical fibres, 3 – filler, 4 – cushion, 5 – PVC jacket.
Another possible variant has the fibres in the centre of cable core while the cladding and possibly strength members are in the next layers (see Fig. 3.8 and Fig. 3.9).

![Fig. 3.8: Seven-fibre optical cable.](image)

Another possible variant of the lay-out of strength members in the cable design is shown in Fig. 3.10.

![Fig. 3.9: Seven-member optical cable: 1 – optical fibre, 2 – Kevlar cladding, 3 – strength members (Kevlar), 4 – jacket.](image)

![Fig. 3.10: Optical cable (different location of strength members): 1 – optical fibres, 2 – strength members, 3 – jacket.](image)

Of a completely different design are cables with optical fibres placed loose in special tubes or grooves. In this case the fibre is completely free from any pressure, it lies loose. A disadvantage of this design is a sort of “floating” and thus increased tensions in cases when the cable rises steeply. An example of this design is shown in Fig. 3.11.
This design group also covers the so-called slotted cables, where one or more fibres can lie loosely in individual cavities (see Fig. 3.12) and cables with the so-called cellular structure, where a great number of fibres can be placed clearly arranged (see Fig. 3.13).

The profiles of slots and cells can be different. Loose placement thus assures the least possible mechanical loading of fibres and thus a minimum added attenuation and long service life, and the properties of optical fibres are in no way changed by cabling. The disadvantages are that in the case of vertical placement of cable the fixed position is not preserved, and that in the case of freezing over the fibres get bent and thus losses increase, possibly damaging the whole cable.

Another possible variant is the ribbon cable. First, ribbons with fibres placed next to each other are made. These ribbons are then joined into a matrix, which is twisted and thus
enables the cable to withstand bends of usual radii. **Fig. 3.14** shows one such design variant with a 6 x 3 matrix (in real execution the number of fibres in the matrix is usually greater, e.g. 12 x 12 = 144 fibres). The main advantage of this design is the quick connecting of cable runs because cable run ends are connected (which is of advantage in the case of access networks).

![Figure 3.14](image)

**Fig. 3.14**: Ribbon arrangement of optical cable: 1 – optical cables led out to connector, 2 – armouring, 3 – jacket.

In addition to the above types of optic cable there are also other types designed mostly for special applications. For example, self-supporting optical cables are suitable for military purposes. Power engineers embed optical fibres in VHV conductors (buried cables) for the transmission of information data for dispatching centres. Optical cables are available for local networks with a unit design of 4000 fibres. The range of cable design is from light cables to heavy-duty armoured cables (submarine cables). An example of armoured optical cable is given in **Fig. 3.15**.

![Figure 3.15](image)

**Fig. 3.15**: Armoured type of optical cable – submarine seven-fibre cable: 1 – optical fibres, 2 – inner cladding, 3 – armouring, steel wires (Kevlar), 4 – copper wires, 5 – jacket.

Demands made on cables:

The manufacture of optical cables has to meet certain demands resulting from the particular application cases. It is necessary to take into consideration mechanical parameters, effect of temperature, heat resistance, and prevention of the appearance of products of dangerous gases.

The central member, the so-called strength member (Kevlar – aramid fibres) is of high tensile strength and copes with the tensile stress of optical fibres.

Filler gels also prevent tension from being transferred onto fibres, reduce the breaking of tubes, and protect the cable against dampness and flooding with water. Cables fall into two classes, indoor and outdoor cables. Indoor cables do not require extreme tension protection and need not be very resistant to dampness.

Some of the materials used, and their abbreviations:
- Polyvinylchloride (PVC) – is used in cable cladding (resistant, soft, withstands tensile forces).
- Polyuretan – material for heavy-duty jackets (up to 50 °C), poorly flammable.
- HDPE (High-Density PolyEthylene) – material for the manufacture of protection pipes
- LSF (Low Smoke and Flame) – low flammability and smokiness.
- LSF/OH (Low Smoke and Flame Zero Halogen) – low smokiness and flammability without halogens.
- LSHF (Low Smoke Halogen Free) – low smokiness without halogens.
- LSZH (Low Smoke Zero Halogen) – low smokiness without halogens.

There are also special cables manufactured for aggressive chemical environments, cables for very high temperatures (up to 900 °C), cables resistant to radiation, and cables for other unconventional environments.

### 3.1 Properties of selected type sof optical fibre

The SPCER TYPE 8 cable, manufactured by Sumitomu Electric Industries, is shown in cross-section in Fig. 3.16 (it was the first cable in our country; it connected the ATU Dejvice and ATU Prague Centre exchanges). The strength member is a steel wire of 2.6 mm diameter, insulated with PE insulation. The diameter inclusive of insulation is 5 mm. In four segments there are always 2 optical fibres, i.e. 8 fibres altogether, and between these segments are quads with copper wires of 0.9 mm in diameter, with PE insulation. The core is protected with polystyrene foil of corrugated PE, which is fused to the outer jacket. The total cable diameter is 19 mm. An aluminium foil plays an important role because it hinders the penetration of water vapours, which are very dangerous from the viewpoint of aging and impaired attenuation.

![Fig. 3.16: SPCER TYPE 8 cable](image)

1 – steel strength member, 2 – chamber protection of fibres, 3 – optical fibres, 4 – core coating, 5 – PE cladding, 6 – steel armouring, 7 – anticorrosive compound, 8 – outer jacket.

Technical parameters of the cable: fibre attenuation at 0.85 µm is better than 4 kdB.km⁻¹, at 1.3 µm better than 0.6 dB.km⁻¹, bandwidth 500 MHz, NA 0.2, and the range of operating temperatures from -15 to 60 °C.

This type of cable was used in the first Czechoslovak optic route in Prague in 1984. The cable was laid as follows: a polyethylene tube was pulled into the cable duct and the cable
itself (specific weight 380 kg·km⁻¹) was pulled into this tube. This guaranteed a minimum friction coefficient and thus a comparatively low tensile stress in the cable during pulling.

After the installation the whole line was measured; the whole line (twelve fused splices) exhibited an attenuation of 2.5 dB·km⁻¹, which was a far better result than that declared by the manufacturer (manufacturers include an allowance for aging).

Some optical cables are given below:

**OPTION1 (Lucent Technologies)**

**Fully dielectric dry optical cable**

**Application**

Optical cable OPTION1 (Outside Plant to Indoor Optical Network) is a fully dielectric universal (outdoor and indoor applications) optical cable with dry inside of the cable core. The design of OPTION1 cable is similar to the design of outdoor cables, providing the required tensile and mechanical properties of this cable for outdoor application. The dry design of cable core enables protecting the cable with a flameproof coating without halogen elements (LSZH – Low Smoke Zero Halogen). The cable is therefore suitable for the outdoor to indoor cable transition, to be used inside buildings.

![Cable OPTION1](image)

**Fig. 3.17:** Cable OPTION1: 1 – optical fibres, 2 – dielectric central member, 3 – protection tube, 4 – water-blocking elements, 5 – rip cord, 6 – aramid yarn, 7 – polyethylene jacket.

**Cable description**

The design of cable OPTION1 ([Fig. 3.17](image)) is based on the well-known Loose Tube design. In this design the optical fibres are protected by a tube of loose secondary coating, whose diameter is several times larger than the fibre diameter so that several fibres can be held in the tube. In some cases the tubes are filled with a special gel, which prevents water from penetrating to the fibres and, at the same time, provides relative mechanical independence of the fibre and cable. The protection tubes and fibres are easy to distinguish by the colour marking.

The tubes are wound around the central dielectric strength member. In contrast to the common cables of the Loose Tube type, the core is not filled with gel; protection against water is provided by dry strips impregnated with SAP (Super Absorbent Polymer) material. The absence of gel inside the cable markedly simplifies the preparation of the cable for
splicing. The required tensile resistance is provided by the aramid yarn placed under the cable jacket made of an LSZH material. Thanks to this design the OPTION1 cable meets all the requirements put on indoor and outdoor cables. Cable OPTION1 is used with advantage in routes with outdoor-to-indoor transition. Installation costs are greatly reduced because no transition from outdoor cable to indoor cable is necessary.

Properties
- optical cable for outdoor and indoor application, capacity up to 144 fibres,
- fully dielectric design,
- LSZH jacket resistant to UV radiation,
- inside the cable are absorption strips of SAP material, which prevent water from spreading along the cable,
- for the transition from outdoor to indoor it is not necessary to change the cable,
- the ROL reverse oscillation technique used in stranding the tubes during cable manufacture enables easy access to fibres and simple splicing,
- the rip cord makes the removal of individual jacket layers easy,
- the cable can be used in the temperature range from -40 to 70 °C,
- the cable fulfils all the demands placed on outdoor cables, inclusive of preventing water penetration,
- the dry design of cable core makes installation and maintenance more effective,
- the low weight of cable provides for further reduction of installation costs (blowing, pulling in, transport, etc.),
- quality certificates ISO 9001 and Bellcore CSQP have been awarded to the manufacturer.

Cable designations for the purpose of ordering
AT – S1, S2, SF, S3, S4, S5, S6 – up to 144 fibres
S1 – Operational wavelength
1 = only 1310 nm
2 = the same attenuation on 1310 and 1550 nm
3 = attenuation on 1550 nm is by 0.1 dB/km lower than on 1310 nm
6 = 1550 nm (TrueWave™ fibre)
R = transmission over 850 and 1300 nm (multimode fibre)
S2 – Maximum attenuation on 1310 nm
Conventional single-mode fibre
B = 0.35 dB/km
4 = 0.40 dB/km
Dispersion shifted fibre (TrueWave™ fibre)
2 = 0.25 dB/km (1550 nm only)
3 = 0.30 dB/km (1550 nm only)
Multimode fibre
S = 3.5/1.0 dB/km 160/500 MHz.km (minimum transmission band)
U = 3.4/1.0 dB/km (850/1300) 200/500 MHz.km (minimum transmission band)
Sf – Type of fibre
0 = Lucent DC (Depressed Clad) M = Lucent MC (Matched Clad)
D = Lucent DS (Dispersion Shifted SMF)
9 = 62.5/125 µm multimode fibre
T = TrueWave™ fibre
S3 – Dielectric central member
1 = D-P
S₄ – Tensile strength
2 = 2700 N
S₅ – Solution of fibre protection
O = OPTION1 Loose Tube
S₆ – Number of fibres in one tube
2 = 2 fibres
4 = 4 fibres
6 = 6 fibres
8 = 8 fibres
N = 10 fibres
T = 12 fibres
Notes
P = Flameproof jacket
D = Dielectric strength member

**POWERGUIDE™**

**Fully dielectric self-supporting optical cable**

**Application**

Optical cable PowerGuide™ is a fully dielectric self-supporting optical cable suitable for up to 1000 m distances between the carrier supports. Thanks to its design, which guarantees high resistance to weather effects, and because of the simple installation of the cable, which minimizes installation costs, the PowerGuide™ optical cable represents a favourable-price solution for suspension optical routes (Fig. 3.18).

![Self-supporting optical cable diagram](https://via.placeholder.com/150)

**Fig. 3.18:** Self-supporting optical cable: 1 – optical fibres, 2 – dielectric central member, 3 – protection tube, 4 – rip cord, 5 – polyethylene inner jacket, 6 – aramid yarn, 7 – polyethylene jacket.

**Description**

In the design of the PowerGuide™ cable, use is made of tested and highly reliable loose tube protection (Loose Tube), which is known from the design of outdoor cables. In this design, optical fibres are protected by a tube of loose secondary coating of a diameter that is several times larger than that of the fibre. Several fibres can thus be held in the tube. In
addition, the tubes are filled with a special gel, which prevents water from penetrating to the fibres and, at the same time, provides relative mechanical independence of the fibre and cable. The tubes are wound around the central dielectric strength member and the whole core is also filled with gel to prevent water penetration. The protection tubes and fibres are easy to distinguish by their colour marking. The cable jacket consists of two polyethylene protection layers, between which there are strength members of aramid yarn. This design provides sufficient tensile resistance and does without auxiliary carrying elements that are known in other designs of suspension cables. The small diameter, smooth round shape and integrated strength members provide high resistance to weather effects (wind and ice) and reduce the cable sag and the loading of support poles.

**Properties**
- simple installation,
- every cable is custom-built for individual applications,
- the distance between carrying supports is up to 1000 m,
- tested technology of loose tube protection,
- the cable is made with up to 144 fibres,
- the ROL technique of reverse oscillation used in stranding the tubes during cable manufacture provides easy access to fibres and simple splicing,
- the strength members are made of dielectric aramid (Kevlar) yarn.
- the rip cords make the removal of individual jacket layers simple,
- quality certificate ISO 9001 has been awarded to the manufacturer.

**Installation**
Optical cables PowerGuide™ can be suspended from the towers of power distribution networks without any effect of the electromagnetic field on the signal being transmitted. In power engineering applications the act of suspending the cable does not require interrupting the power supply. Installation can proceed quickly and simply even in highly populated areas:
- low installation costs,
- simple installation,
- it is not necessary to interrupt power supply during installation,
- quick and simple installation in populated areas.

**Optical cable, type Mini-LXE**

*General characteristic*

Type Mini-LXE cables are a reduced-weight version of LXE (Lightguide Express Entry) cables of simpler design. Their core is formed by a single central PE tube with 3.9 mm outer diameter. The tube is filled with gel and can hold up to 3 bundles of 6 fibres each, i.e. 18 fibres at the most. Each bundle is held together and at the same time identified by a colour thread. Individual fibres also differ in colour (**Fig. 3.19**).
Optical Networks for joint teaching programme of BUT and VSB-TUO

Fig. 3.19: Optical cable Mini-LXE: 1 – fibre bundles, 2 – filler gel, 3 – central PE tube, 4 – armouring (steel), 5 – strip to prevent water penetration, 6 – PE jacket.

Mechanical protection of the cable is provided by armouring (bellows) of chrome steel and two strength members of steel. This combination gives the cable a tensile strength of 1800 N, which is sufficient for most installation methods. The outer jacket of the cable is formed by polyethylene of middle density (MDPE).

The Mini-LXE cable is an economical and space-saving solution for all optical networks that do not require a high number of fibres. They find application particularly in subscriber networks or in cable TV networks.

The Mini-LXE cable is fully compatible with the other accessories supplied by the Lucent Technologies Co. (splices, distribution boxes, etc.) and together with these accessories it offers the user a complete solution of end-to-end optical network.

Summary of basic properties of type Mini-LXE cable:
- optimized cable design for a maximum of 18 fibres,
- colour identification of fibres and fibre bundles (6 fibres in a bundle),
- type Lightpack core (a single central tube with fibres), type LXE jacket (steel armouring + two steel strength members),
- small diameter and small weight, tensile strength 1800 N, simple and very quick access to fibres,
- available with either DC (Depressed Clad) fibres or MC (Matched Clad) fibres,
- D-LUX 100 primary coating of fibres gives the fibres and cable excellent mechanical and weather resistance.

Optical cable GRP (Tyco Electronics)

Description

The cable is ideal for sites where pressure force can act on the cable. Installation into ground without protection piping is a matter of course. The design of the GRP cable is one of the strongest on the market. A great advantage is the absence of any metallic elements.
Properties
- GRP bars provide protection against rodents and external damage (from pressure, impact and shear),
- installation tensile strength of up to 6000 N,
- suitable also to be laid directly in ground,
- increased wear resistance,
- without metallic components,
- ULSZH or PE jacket,
- resistant to water, both longitudinally and transversely,
- fibre colours according to TIA/EIA coding for simpler identification,
- Temperature range:
  - single-tube: transport/storage: -20 °C to +70 °C, installation: -5 °C to +50 °C,
  - operation: -30 °C to +70 °C,
- Resistance in shear:
  - 2000 N for cables with up to 24 fibres,
  - 4000 N for cables with more than 24 fibres,
  - 4 to 288 fibres, OM1, OM2, OM3+(OM4), OS1, OS2, ...

Indoor optical cable ACCUMAX

Thanks to its outstanding mechanical properties the ACCUMAX indoor optical cable can be used in practically any indoor applications that do not require a great number of fibres. In telecommunications it can be used, for example, to connect the cable room, where it is usually connected by an optical splice to outdoor cable, and the repeater station, where it can terminate in an optical distribution box or be connected directly to a transmission device. It is particularly suited for FTTO (Fibre to the Desk) applications (Fig. 3.20).
Type ACCUMAX cables contain single-mode optical fibres with double primary coating D-LUX 100 and with tight secondary protection of 0.9 mm outer diameter. The fibres can be either of the DC type (Depressed Clad – depressed refractive index profile) or the MC type (Matched Clad – matched refractive index profile). Fibre identification is provided by coloured tight secondary coating. The maximum number of optical fibres in the ACCUMAX cable is 72. The optical fibres are surrounded by Kevlar fibres, which give the cable its tensile and mechanical strengths. The outer PVC jacket is of yellow colour.

Parameters
- Fibre type: Lucent Technologies SM DC or SM MC,
- primary coating: D-LUX 100, diameter 245 ± 10 μm,
- diameter of tight secondary coating: 0.9 mm,
- attenuation (maximum attenuation of fibre in cable): 1310 nm ≤ 0.4 dB/km, 1550 nm ≤ 0.3 dB/km.
- Chromatic dispersion: 1310 nm ≤ 2.8 ps/km·nm. 1550 nm ≤ 18 ps/km·nm,
- cut-off wavelength: ≤ 1230 nm,
- operational temperature: -20 °C to +70 °C.

Cable for FTTx networks – Multi Loose Tube Cable
As an example, the cable manufactured by the company PRYSMIAN will be given. This is a conventional cable with central strength member. The fibres are held in tubes (MM or SM), the maximum capacity is 720 fibres.

Ribbon cable – Fusion Link™
This cable, with a capacity of up to 216 fibres, is made up of ribbons of 12 fibres each, and is suitable for access networks. The fibres are placed in the centre of the cable core, inserted in a tube and armoured with a steel tube. The strength members are held in the jacket. Cable by the PRYSMIAN Company.

Self-supporting optical cables A-Dxx
These types of cable with a maximum number of fibres 48 are made with a self-supporting strength member or with the strength member inside the cable core. There are maximally 6 fibres in a tube. The cable has a PE jacket. The maximum spanning distance is 200 m. Ice coating must be taken into consideration. These cables are suitable for the interconnection of buildings.
FIZZER

This is the designation under which the company CDT Optius, Děčín-Podmokly, manufactures and supplies a fireproof cable (without halogen) with fibres (up to 24 of them) placed in a tube in the centre of cable core. The other elements serve as protection and strength members.
4 Splicing technicne, connectors and couplers

The same as metallic cables, optical cables, too, are delivered in (considerably larger) runs, which need to be connected, i.e. individual fibres and then the jacket need to be joined. To join optical fibres is much more complicated than to join metallic cables; jacket splices are in principle identical to splices of plastic cables.

On sites where it will often be necessary to interrupt the optical route, e.g. for the purpose of measuring, optical connectors are used.

Splices in fibre optics can from this viewpoint be divided into:
- non-demountable splices,
- demountable splices.

Couplers are then used for routing, coupling and separating optical radiation.

4.1 On general problems of splicing

Generally speaking, any connection in optical communication can be regarded as a coupler which, in comparison with metallic conductors, introduces considerable attenuation into the splice. The connection of the coupler between two fibres is illustrated in Fig. 4.1. Insertion attenuation can then be defined by the relation

\[ A = -10 \log \frac{P_1}{P_2} \text{ (dB)}, \]

where
- \( P_1 \) is the power measured at the fibre end,
- \( P_2 \) is the power on the fibre input.

![Fig. 4.1: Coupler.](image)

It is obvious that in the case of splice it is no problem to measure power \( P_1 \) but to measure \( P_2 \) is more difficult. For this reason in practice we measure power \( P_2 \) only after it has left the fibre, at a point \( x \).

It is necessary to take into consideration additional attenuation of the fibre, which has to be subtracted in order to get the real value of the splice. In the case of a very small piece of fibre to be measured it is possible to neglect the value of additional attenuation.

The magnitude of losses in splices is generally varied and depends on the type of splice, fibres and, above all, on precision and quality.
In first approximation in Fig. 4.2 we can see what potential errors may occur in the position of two fibres, when they are being spliced (imperfect flatness of front faces, roughness of the left fibre, axial misalignment, etc.). The reasons can mainly be sought in the small diameters of optical fibres (comparison with the human hair) and they will evidently increase from type PCS fibres (large diameter) through gradient-index fibres to single-mode fibres: the smallest diameter requires adequately greater precision and perfection in the course of splicing.

Fig. 4.2: Position of two fibre ends prior to splicing.

Developing a perfect technology for the splicing of optical fibres is very important because optical losses appear in every splice. Their origin can be seen in the different properties of the fibres being spliced (internal effects) and in the imperfect geometry of the splice (external effects). Internal effects are due to:

- changes in the diameters of the core and primary coating of the fibres being spliced,
- mismatch of refractive indices,
- mismatch of numerical apertures,
- ellipticity and non-concentricity of the core and primary coating.

External effects on losses in the splice are the following:

- transverse displacement,
- longitudinal displacement,
- axial misalignment of fibres,
- quality of the fibre end preparation,
- Fresnel reflections.

External effects can be reduced by first-rate splicing technology. It holds for multimode fibres that the greatest losses are caused by axial refraction and transverse displacement. Longitudinal displacement effects are less pronounced. Fresnel reflection losses at the glass-air-glass interface can be reduced using a suitable filler material whose refractive index is similar to that of the core. The quality of the fibre end is of minimum effect on losses as long as suitable techniques of cleavage and, possibly, grinding and polishing of the front faces of optical fibres are used.

In connection with the above division of splices into those that cannot be demounted and those that can be demounted there are a number of techniques, which will be indicated in
the following. The choice of a concrete technique depends on the properties required from the connection.

These properties can be sorted as follows:

a) Design solution, which includes:
   - multiple or single splice,
   - splice durability,
   - density of inner lay-out,
   - installation universality,
   - magnitude of optical losses,
   - complexity of the method.

b) Installation properties include:
   - stability of splice losses,
   - mechanical robustness,
   - resistance to environment.

c) Economic factors include:
   - cost of material per splice,
   - tools and their cost,
   - cost of training the installers.

All these important viewpoints need to be taken into consideration. There will be some differences depending on whether multimode or single-mode fibres are concerned.

In the following we will show the dependence of some parameters on potential faulty splices.

**Difference in core and fibre diameters**

This is the case when two fibres of different diameters are joined and the fibres are axially identical. The dependence of insertion losses is established from relation (5.1)

\[
a_d = -10 \log \left( \frac{d_1}{D_1} \right)^2,
\]

and is graphically illustrated in Fig. 4.3. Substituting into relation the maximum deviations of fibre diameters according to the ITU-T recommendation, \( d = 2a = 50 \, \mu\text{m} \pm 3 \, \mu\text{m} \), we obtain the deviation \( a_d = 1.05 \, \text{dB} \).
Fig. 4.3: Dependence of attenuation on different diameters and NA of optical fibres.

Unless specified otherwise, the following formulations of losses hold for multimode fibres.

**Difference in NA fibre sizes**

In this case the core of the transmitting fibre and the core of the receiving fibre have different numerical apertures NA. Again according to the ITU-T recommendation, for the GI fibre the difference should be $\text{NA} = 0.2 \pm 0.02$.

The calculation can be performed according to the relation

$$a_{\text{NA}} = -10 \log \left( \frac{\text{NA}_R}{\text{NA}_T} \right)^2.$$  \hspace{1cm} (5.3)

The graphical illustration is almost identical to the preceding case and so the result is also obvious from Fig. 4.3.

**Transverse displacement of fibre axes.**

This concerns two fibres that are axially displaced. For the step-index fibre the losses can be expressed according to the relation

$$a_{\text{OS}} = -10 \log \left\{ \frac{2}{\pi} \arccos \left( \frac{e}{2a} \right) - \frac{e}{\pi a} \left[ 1 - \left( \frac{e}{2a} \right)^2 \right]^{1/2} \right\}.$$  \hspace{1cm} (5.4)

and efficiency according to the relation

$$\eta_e = 1 - \frac{2e}{\pi a} \frac{g+2}{g+1}.$$  \hspace{1cm} (5.5)
For the gradient-index fibre the losses can be expressed according to the relation

\[
a_{OG} = -10 \log \left\{ \frac{2}{\pi} \arccos \left( \frac{e}{2a} \right) - \frac{e}{\pi a} \left( 4 - \left( \frac{e}{a} \right)^2 \right)^{\frac{1}{2}} \left[ 1 - \frac{1}{12} \left( 2 + \left( \frac{e}{a} \right)^2 \right) \right] \right\}.
\]

(5.6)

Graphical representation of these dependence relations can be seen in **Fig. 4.4**.

**Fig. 4.4**: Dependence of attenuation on transverse displacement of fibre axes.

**Fig. 4.5**: Dependence of attenuation on angular misalignment and longitudinal displacement of fibre axes.
Angular misalignment

Losses due to the misalignment of opposite fibre axes (acc. to Fig. 4.5) can be expressed for the step-index fibre as

\[
a_{US} = -10 \log \left\{ \frac{2}{\pi} \arctg \left( \frac{\sin^2 \Theta_c}{\sin^2 \alpha/2} - 1 \right)^{\frac{1}{2}} - \frac{\sin^2 \alpha/2}{\sin^2 \Theta_c} \left( \frac{\sin^2 \Theta_c}{\sin^2 \alpha/2} - 1 \right)^{\frac{1}{2}} \right\} \tag{5.7}
\]

and for the gradient-index fibre as

\[
a_{UG} = -10 \log \left\{ \frac{2}{\pi} \arccos \left( \frac{\sin \alpha}{2 \sin \Theta_2} \right) - \frac{\sin^4 \alpha}{8} \left( \frac{\sin^2 \Theta_c}{3 \sin^2 \alpha/2} - 1 \right)^{\frac{3}{2}} \right\} \tag{5.8}
\]

It is obvious from the graphs that for the gradient-index fibres the losses are larger.

Longitudinal displacement of fibres

Longitudinal displacement appears in the connector joining of fibres. Particularly in the case of connector failures this attenuation increases. The dependence is plotted in the graph in Fig. 4.5. The graph shows considerable scatter in the loss values, which have been plotted on the basis of different sources that give practical results of measurements. No theoretical relation has as yet been found for this dependence. Based on measurements, the following term has been determined explicitly for the calculation

\[
a_{PS} = -10 \log \left( 1 - \frac{4 \ell}{3 \pi a} \tan \Theta_c \right) \tag{5.9}
\]

for gradient-index fibres it is necessary to subtract the correction factor

\[
K = 1 - \frac{1}{2 \pi}. \tag{5.10}
\]

Losses due to reflection

They appear above all in the case of connected splices but also in permanent joints on the interface fibre - air (glue, immersion liquid) – fibre. These losses are caused by the Fresnel reflections. The value of these losses is usually not high; it strongly depends on the quality of the surface of fibre ends.

For the calculation a relation can be used that makes use of the well-known reflectance coefficient

\[
a_{RS} = -10 \log \left[ 1 - 2 \left( \frac{n_j - n_0}{n_j - n_0} \right)^2 \right]. \tag{5.11}
\]

For a recommended value \( n_j = 1.47 \) the outcome is \( a_{RS} = 0.32 \) dB. The graphical representation of the fibre-air-fibre losses is shown in Fig. 4.6.
Fig. 4.6: Dependence of reflection losses on refractive index of core.

For gradient-index fibres the determination of insertion losses is more difficult in view of the varying refractive index. It is possible to introduce the average value of refractive index

\[ \bar{n} = \frac{1}{a} \int_{0}^{a} n_{k}^{2} \left[ 1 - 2 \Delta \left( \frac{r}{a} \right) \right] dr, \quad (5.12) \]

where the parameter \( g \) with regard to the design of gradient-index fibre is equal to 2.

The for the reflection attenuation it holds

\[ a_{RG} = -20 \log \left[ 1 - \left\{ \frac{n_{j} \left( \frac{1 - 2 \Delta}{g + 1} \right)^{\frac{1}{2}} - n_{0}^{2}}{n_{j} \left( \frac{1 - 2 \Delta}{g + 1} \right)^{\frac{1}{2}} + n_{0}^{2}} \right\} \right], \quad (5.13) \]

When choosing the parameters \( \Delta = 0.01 \), \( g = 2 \) and \( n_{0} = 1 \) (air) the resultant absolute value of losses is 0.01 dB.

**Splicing of single-mode fibres**

In the splicing of single-mode fibres it is possible to start from analogies to the splicing of multimode fibres. Thus, for example, from the viewpoint of internal losses, when the two fibres to be spliced are of different diameters, e.g. 9 μm and 10 μm, we obtain losses in the value of 0.05 dB. The dependence is illustrated by the graph in Fig. 4.7.
Losses due to angular misalignment are illustrated in Fig. 4.8. The function $\alpha/\alpha_0$ given in the graph depends on the wavelength $\lambda$ and is expressed by the relation

$$\alpha_u = \frac{\lambda}{\pi \ n_u \ W_G}.$$

(5.14)

For $\lambda = 1.3 \ \mu m$, $w_{G1} = w_{G2} = 5 \mu m$ and angular misalignment $\alpha = 0.5^\circ$ the losses are $a_{ij} = 0.05$ dB.

Finally, the dependence for longitudinal displacement between fibres is plotted in Fig. 4.9.
Fig. 4.9: Dependence of attenuation on longitudinal displacement of single-mode fibres.

Losses due to reflection are identical to losses given above for multimode step-index fibres.

For the maximum deviation tolerance for optical fibres an ITU-T standard has been accepted.

**Application of lenses in communications**

In many cases in optical communication it is of advantage to use conventional lenses. Lenses find application when splicing two fibres of different diameters or shapes. They are also used when coupling light to the fibre. Last but not least, they are employed in connectors.

Using them in connectors helps eliminate deviations that arise when splicing two fibres, as described above. Lenses are indispensable at sites of strong vibrations, for example in connectors of railway carriages, car trailers, etc.

Fig. 4.10: Principle of lens positioning in a splice.
The principle of incorporating lenses in a splice is given in Fig. 4.10. The figure clearly shows the direction and broadening of the optical beam on the input, subsequent transmission (through the connector) and the narrowing of the beam and its coupling to the fibre on the output. In the physical version the lenses are replaced by balls of corresponding focal lengths.

The focal length is given by the relation

\[ f = \frac{n_L}{2(n_L - 1)}, \]

(5.15)

where \( R \) is the lens radius (mm), \( n_L \) is the refractive index of ball lenses.

For coupling efficiency it holds

\[ n_{opt} = 1 - 0.21 \left[ \frac{1}{8} \left( \frac{n_L}{(n_L - 1)^2} - 1 \right) \frac{f \cdot NA_S^2}{a} \right]. \]

(5.16)

Examples of another effect on losses due to lenses used in the splice are given in the following two figures. Fig. 4.11 gives the dependence of attenuation on transverse displacement for the connection of two fibres with and without lenses being applied in the splice. A pronounced decrease in the attenuation is evident.

Fig. 4.11: Dependence of attenuation on transverse displacement of fibre axes.

Fig. 4.12 gives a similar dependence for angular misalignment, and Fig. 4.13 for longitudinal displacement.
The problem of single-mode splices with lenses would be solved analogously to the above examples of splices of multimode fibres.

In all the methods of splicing, the jacket must be stripped off the core. The length of the stripped part is different in individual methods. Jacketing systems differ from manufacturer to manufacturer. The secondary coating of the jacket is removed mechanically while the primary layer is mostly removed mechanically and chemically. The removal of primary coating must be perfect otherwise we could not make a good cleavage, which is a condition of good splice. Fibre ends are cleaved in a special jig – the cleaver. It is required that the fracture surface should make with the fibre axis an angle of more than 89º. In this operation, a tool with a very fine cutting edge is used such that at the point of cleavage a small crack appears. Axial pulling will then yield a sharp and clean perpendicular fracture surface. If in this operation torsional stress in the fibre can be avoided, the perpendicularity is better than 89.5º.

A good cutting tool must fulfil these requirements:
- good control of cutting edge pressure on fibre to obtain a crack of constant size,
- cutting edge must act on the fibre perpendicularly,
- possibility of controlling the length of the fibre being cut,
- constant pressure on the fibre held in the tool,
- simple and smooth sequence of operations.

One of the simpler tools for fibre cleavage is a pair of pliers. The surface formed by cleavage must be smooth like mirror, undamaged and without burrs. The cleavage is checked under microscope and if the fracture surface shows any defect (see Fig. 4.14), the process must be repeated. To have well-cleaved fibres, special single-purpose mechanical cleaver is used. The quality of the splice depends on the quality of cleavage.

A fibre prepared in this way is now ready for being spliced (fused). For connectoring it is necessary to grind and polish the front faces. Very pure and highly efficient grinding and polishing agents are used; using suitable grinding and polishing tools these agents enable obtaining the required shape and very good surface. The whole process is divided into the following steps:

- grinding (bonded diamond) 9 µm,
- lapping (bonded diamond) 1 µm,
- polishing (cerox solution) 0.3 µm.

The polished surface has some specific peculiarities. A small layer of different composition than the material itself, so-called Beilby layer, can be found on the polished surface. This layer will close the scratches on the surface of fibre face such that they cannot be perceived and positively influence the magnitude of losses caused by the Fresnel reflection.

For practical installation work, unit-designed connectors are supplied; they can be implemented via certain simplified operations (inclusive of cleavage, grinding, etc.) described above.
4.2 Non-demountable splices

This group includes the most frequently applied method of fusion splicing, methods of joining optical fibres by gluing, and most recently the method of fixed metallic splices.

Fusion splicing

Arc welding has become the most widely spread among the existing methods. The method of gas welding and the CO₂ laser method are used less frequently. Since the fibre cross-section must not be narrowed in the fusion splice, the fibres are moved against each other during fusing. These operations are very important for the splice quality and are usually checked automatically (using a microprocessor with I/O circuits). To get a good fusion splice, we must also know the melting point of glass. Depending on the type of glass the time of adjusting the fibre end and the time of welding must be set.

This is followed by cleavage of the fibre and removal of the primary coating.

To maintain axial alignment of fibres prior to fusion, wedge-shaped grooves are used, which guarantee the required fibre geometry during fusion. Surface tension in the area of the fusion zone provides for equal diameter of the fibres and the melt. The adjustment of fibres and the course of fusion phase can be followed under a microscope or on a screen. A simplified schematic diagram and principle of fusing optical fibres can be seen in Fig. 4.15. The fusion proper occurs at the moment when the distance between the fibres is ca. 20 µm. In about 0.2 s, when the fibre ends start melting, the fibres start moving towards each other and are pressed against each other with an overlap of ca. 15 µm. The total time of arc discharge is ca. 2.5 s. For example, for the fusion of multimode fibres, Ericsson Company gives an arc current of 16.25 mA/50 Hz and a total fusion time of 4 s.

![Fig. 4.15: Principle of fusing optical fibres.](image-url)
After fusing the splice, the strength of the splice is tested and the splice is measured for attenuation.

Detailed technologies of fusing are kept secret by individual companies and exact data on arc current values and fibre spacing during individual fusion stages are difficult to get at.

Modern fusing facilities are equipped with computers and corresponding software. To obtain a good fusion, it is necessary to take into consideration what kind of fibre is concerned; the best welding machines themselves determine what fibre comes into consideration. They are also provided with automated adjustment facility for sea-level altitudes of up to 2000 m since arcing depends on the amount of oxygen. The built-in GPS module can record the site of fusion (splice) directly on a map.

Setting the position of fibres under microscope has also advanced to automatic setting. In principle, two systems are used:

**Evaluation of video image L-PAS** (Lens-Profile-Alignment-System). Fibres in the x and y planes are observed using a CCD video-camera. The video image is shown on a contrastive 4” LCD colour screen enabling the evaluation of positioning, assessment of end surfaces and determination of L-PAS attenuation.

**System LID** (Local Injection and Detection) uses the procedure of measuring the transmitted light and contains two flexible couplers. Light of 1300 nm wavelength is transmitted into the left flexible coupler (transmitter) and is received by the coupler on the right-hand side (receiver). Equipped with a microprocessor facility the LID system provides precise core-to-core positioning in the x, y and z directions and automatic control of fusion time (AFC). When AFC is used, the optical power transmitted (through the splice) is measured during the melting stage. When the transmission maximum has been reached, the fusion process is terminated. In addition, the LID system enables a precise recognition of refraction angle and also the measurement of splice attenuation after fusion and in the manufacture of attenuation splices.

Further details and technical data are given in the respective manufacturers’ manuals (Corning, RXS, Siemens, Fujikura, Ericsson, etc.).

Worth mentioning among the latest new developments is the FUSE-LITE (RXS) system, so-called connector system for connecting fibres. Here, a factory-polished ceramic ferrule (connector) is placed in the welding machine and the fibre is fused to it. A disadvantage of the system is that if the fusion is faulty, a new connector must be inserted.

A fusion principle is also known with one fibre end rotating, which enables fusing type “PANDA” fibres, etc.

Perhaps the latest new development is the welding machine equipped with GPS, which records cartographic data about the site of fusion/splice directly on a map.

If the fused fibre exhibits any flaws, established by visual inspection, mechanical inspection or attenuation examination, the splice must be broken and the whole process must be repeated. The most frequent causes of fusion defects are the narrowing or the bulging of fibre profile, imperfect fusion of glass along the whole profile, appearance of bubbles and axial misalignment, as illustrated in Fig. 4.16.
When the fusion has been completed, the primary coating of fibre must be renewed, e.g. using special silicone. The secondary coating is restored, for example, by applying a contractible plastic tube to the fusion site and heating it; the fibre thus gets firmly fixed at the fusion site and near it.

Mechanical strength of splices is about 70% of the strength of fibre, and the average value of optical attenuation is about 0.02 dB.

Glued splices
In these splices, glue is used to fix the fibre to the substrate and to connect fibres to each other. The glue has the following functions:
- its refractive index is very similar to that of the fibre,
- it protects the splice against environment,
- it fixes permanently the fibres in required position,
- it prevents splice deformations and provides tensile strength.

The most frequently used type of splice consists of a sleeve whose inner diameter corresponds to the outer diameter of the fibres being joined, and in which the touching fibre ends are glued together. Alternatively, the sleeve may contract thermoplastically or contain adhesive material that will set when exposed to UV radiation (see Fig. 4.17).
The technique of hardenable splice is based on the introduction of ultraviolet light into the fibre after the splice geometry has been set. Due to the light, the glue polymerizes and meets all the above requirements.

Losses in these splices are about 0.1 dB, sometimes even less. The splices are sensitive to temperature changes. An additional loss of 0.1 dB may appear following the temperature cycle -30 °C - +70 °C.

**Mechanical splices**

It is obvious from the name itself that axial alignment of the fibre is obtained using various mechanical structures such as V-grooves (see Fig. 4.18), tunnels formed between blocks of bars, cylinders and corners of square profiles (Fig. 4.19). It is important that fibres prepared in this way should be fixed firmly to the flattening surface since they must withstand handling and environmental effects.
To obtain permanent optical losses below 0.3 dB it is necessary to use optical filler material between the fibre ends. This material is chosen depending on the optical properties of glass. They are usually silicone gels, epoxy resins and ultraviolet glues. Filler materials must remain in contact with both fibres even if the gap is changed. These materials serve at the same time as primary coating of bare core. In the case of glues, also the mechanical strength of the splice is ensured.

Optical losses of mechanical splices usually depend on temperature. At room temperature the characteristic value is 0.1 to 0.15 dB. A good splice has an additional loss of 0.05 dB after the temperature has changed from -40 °C to +60 °C, for less good splices it is 0.1 to 0.2 dB. Fast push-down metallic splices are the latest novelty introduced by Tyco Electronics under the name Record Splice and by 3M Company under the name Fibrlok, for splicing multimode and single-mode fibres. After five years of development, a device has been fabricated that is cheap and easy to handle, giving very good splices with less than 0.1 dB attenuation, guaranteed for any splice; in fact, some 30% of splices achieve values below 0.02 dB. The device does not require any supply; it operates on the mechanical principle and can thus be deployed with advantage in explosion-hazard environments.

Installation of the splice proceeds sequentially in a device in the form of a portable suitcase. The first operation consists in removing insulation and primary coating, followed by making a cut in the fibre and cleavage. Gel is then applied to fibre ends (this reduces losses on the glass-air transition and also removes superficial defects from the fracture surface), which are then inserted into the push-down splice and, finally, joined by (hand-) exerted pressure. Splices realized in this way are of high quality, precise, fast and do not require much training on the part of personnel.

The price of this device is ca. one tenth of the purchase cost of a welding facility.

4.3 Demountable splices

Demountable splices, so-called connector splices, are mostly used in exchanges or at sites of repeater amplifiers, to a less degree in cable routes where cables with ribbon structure are used.

The principle of connectors again consists in guiding precisely the respective ends of fibre lightguides against each other but the problem is complicated here in that the optimum position needs to be secured by a suitable mechanical stop and by joining the two connector parts. The fibres to be spliced must not touch each other in order to prevent abrasion of the front surfaces. Initial adjustment of the position of fibre ends with respect to the reference positions of the respective connector part plays an important role. Special fixing jigs or fast automatic micromanipulators are used to this end. The contact element is the main functional part of the connector and determines its quality and price.

ensure precise axial alignment of the fibres being spliced both rigid and flexible installation in the connector body are used. Most connectors use as the main design element inserted between the fibre and the adjustment mechanisms a suitable sleeve or pin or both. Losses in connectors of this type range between 0.2 and 0.6 dB, depending on the given design and the material used. There are diverse connector solutions differing in technology, design and material.

The principle of a simple co-axial connector is illustrated in Fig. 4.20. As can be seen, axial alignment is obtained using a calibrated quartz stone and a silicone rubber cone. The spacing between the ends of the two fibres in the stage of splicing is set by means of
a metallic tube such that in the final position there is a small micrometer gap between the fibre ends. The fibre is fixed in the correct position by means of a plastic protection layer and by gluing. The connector in question is the first connector developed in the Czech Republic, in the Research Institute of Communication Technology in Prague.

**Fig. 4.20:** Principle of the function of single-mode connector for splicing two optical fibres.

Example of another possible connector solution is in **Fig. 4.21.** Arrow heads represent reference surfaces.

**Fig. 4.21:** Principle of fibre connector.

The principle of single-mode connector is given in **Fig. 4.22.** The connector is terminated by a precise planar polished surface (quartz). In order to reduce losses the fibre is fixed with glues based on quartz – epoxy, which provide good mechanical integrity and broad thermal stability.

**Fig. 4.22:** Principle of precise (single-mode) connector.

**Fig. 4.23** shows a practical implementation of connector.

**Fig. 4.23:** Practical connector implementation.
Connectors with ball lenses have recently come to be increasingly used because of their excellent transmission properties. The principle of the operation of this connector is shown in Fig. 4.24.

![Fig. 4.24: Principle of connector with lenses.](image)

**Fig. 4.24**: Principle of connector with lenses.

Fig. 4.25 shows a ribbon connector of the MT type, which can also cope with 2, 4, 6, 12, and 24 fibres. There are many variants of ribbon connector. Tyco Electronics supplies up to 72 fibres in one connector.

![Fig. 4.25: Ribbon connector.](image)

**Fig. 4.25**: Ribbon connector.

Our leading manufacturer of optical connectors, OPTOKON Co. Ltd. Jihlava, manufactures various types of optical connector. One among the first types was type SMA optical connector. Connectors are fixed to the cable by the technology of pressing; they are all-metallic with stainless-steel guiding system. The terminal surface is polished and optically conducting. The connection thread is inch thread 1/4 - 36 – UNS – 28. Example of the connection part of optical connectors can be seen in Fig. 4.26. Examples of the current most frequently used connectors of the SC type by OPTOKON Co., Ltd., a leading manufacturer of connectors, are shown in Fig. 4.27.
Fig. 4.26: Optical connector.

It is obvious from the figure how precise the requirements are that are placed on the mechanical and optical reference planes. An optical splice has a lifetime minimum of 1000 cycles. Attenuation of the connector is less than 0.3 dB.

Fig. 4.27: SC connector in PC version and adaptor.

Connecting two connectors by a fibre or cable gives rise to an optical splicing fibre module. The optical splicing cable module is usually supplied in runs of 1, 2, 3, 5, 7, 10, 15, 20, 30, 50, and 70 m. An example can be seen in Fig. 4.28.

Fig. 4.28: Optical splicing module.

Type FC connectors (complying with the IEC 86-B recommendation), designated 2WF 862, are designed for multimode fibres 50/125 GI. They are provided with a cylindrical
guiding system of 2.5 mm in diameter and 7.5 mm in length. The joining parts are provided with M 8 x 0.75 thread. The connectors are provided with a stud that prevents their rotation. They are made of stainless steel, the elastic sleeve is of beryllium bronze, and the surface has nickel finish. The schematic diagram of the connector is given in Fig. 4.29. Connector attenuation is less than 0.3 dB till the end of mechanical lifetime, i.e. 1000 cycles.

![Fig. 4.29: Optical connector, splice GI.](image)

The strict requirements on the manufacture of connectors are evident from the above data. In the last decade further types of optical connector have appeared on the market. It is not possible to describe here in detail individual connectors as has been done hitherto; only some types of connector will be given below.

Since the time when connectors began to be used, their manufacturing technology has experienced many changes, which has primarily shown in the reduction of insertion attenuation and cost, increased resistance to polarization properties, and back scattering.

There are now more materials suitable for the manufacture of connectors, more methods of polishing, and a greater variety of designs.

Some simple types of connector can be installed on the fibre in the field (toolkit for the manufacture of connectors) while more complicated connectors are mostly bought from the manufacturers (OPTOKON, QOS, etc.) with a pigtail, which is fused to the route.

Ferrule types:
- Aluminium ferrule – brittle material, difficult polishing, great thermal expansion.
- Zirconia ferrule – frequently used material, 4 times greater strength than in aluminium, very good polish, small dimensions of ceramic grain, low friction wear.
- Plastic ferrule – the cheapest type, easy polishing, higher attenuation, shorter lifetime
- Composite ferrule – the best, most precise and most expensive ferrule, small insertion attenuation losses.
- ARCAP ferrule – cheap, easy polishing, low friction wear, long lifetime.

Possible ferrule terminations are shown in Fig. 4.30.

![Fig. 4.30: Ferrule terminations.](image)

The effect of polishing on the value of back reflection is indicated in Fig. 4.31. The last to be given here, the APC (Angle Polish Connector) connector belongs to the best (and most expensive) connectors. The figure gives a detailed view of the PC and APC connector faces.
Fig. 4.31: Fibre terminations.

Connector types:
- Bionic – one of the first connectors (1980) supported by the AT&T Co., conic ferrule, insertion attenuation 0.5 – 0.6 dB.
- SMA – also an older type of connector, ferrule not protected against rotation, aluminium or ARCAP ferrule, threaded cap nut.
- FC – standard for telecommunications, ceramic or composite ferrule of 2.5 mm in diameter, threaded cap nut with positioning.
- ST – standard for telecommunications, pin arrest against rotation, spring-mounted ferrule, bayonet splice, insertion attenuation 0.2 – 0.3 dB.
- SC – supported by AT&T, ISO/IEC11801, push-pull version, ceramic or composite ferrule, insertion attenuation 0.15 dB.
- FDDI – paired connector for FDDI networks, push-pull version, ceramic ferrule, insertion attenuation 0.2 dB.
- ESCON – similar to FDDI, supported by IBM.
- E2000 – European standard for telecommunications, developed by DIAMOND Co., push-pull version, spring-mounted cover overlapping the ferrule, insertion attenuation 0.2 dB.
- LC – represents a new generation of connectors (in execution it resembles the SC connector) whose design takes up 50% less space in comparison with SC. It is manufactured in MM and SM variants. In the duplex version it is compatible with the dimensions of RJ-45 connectors.
- MT-RJ double-fibre connector, compatible with RJ 45, supported by AMP, HP, Fujikura, and Siecor.
- MTP – designed for ribbon cables 4, 6, 12, 24, and 36 to 72 fibres.
- VF 45 – double-fibre connector, for PC connection, supported by 3M Co. for the Volition system.

Some connector versions were given above; further typical connectors are shown in Fig. 4.32.
The following connectors are designed for special applications:

- **HMA connectors**, in which the optical ray is extended over a system of lenses so that splicing takes place on a large area. The connector is resistant to vibrations, dust, and water. Its application is in the armed forces, heavy industry, mining, and oil industry but also in TV transmissions, etc.

From the viewpoint of the type of application (a maximum of 6 fibres, SM-MM) two basic types of interconnection modules are used:

a) **Tactical military LD cable** with OHMA connectors of the plug type at both ends, suitable for interconnecting network nodes (length 200 – 500 m).

b) **Hybrid modules** for interconnection between OHMA connectors and standard optical connectors of the types SC, ST, LC, etc., designed for connection at terminal points of networks with standard outputs.

- **HFOC** is a classical SC connector in robust encapsulation. It is designed for FTTH projects, where the connector may also be placed in outdoor location (for details see the technical specification on OPTOKON web pages).

In view of the great number of connector types we cannot avoid in practice the application of so-called leadthroughs (adaptors), which enable connecting two different kinds of connector (e.g. ST/E2000 adaptor, etc.). Naturally, to connect two identical connectors we will use the splice.

To conclude this section a detailed technical description of the frequently used E2000 connector will be given. This connector type was introduced by the DIAMOND Company – SQS.

**Properties**

- integrated protection flap protects the ferrule against pollution and prevents emissions of laser radiation,
- integrated spring for reliable closure of the protection flap,
- is supplied in the Standard or the Premium variant,
- in SM and MM versions, polished also angularly (APC),
- pawl system resistant to spontaneous disconnection, full ceramic ferrule,
- positioning in 60° steps,
- colour and mechanical marking,

**Technical specification**

- insertion attenuation (IL): type 0.10 dB,
- reverse attenuation (RL): > 60 dB,
- tensile load: 40 N,
- temperature range: -40 °C to +85 °C,
- connection frequency: a minimum of 1000 cycles,
- method of manufacturing: gluing and polishing,
- connection: physical contact,
- mechanism: pawl,
- standard: EN 186-270,
- ferrule material: full ceramic zirkonia,
- connector material: UL 94-V0,
- splice material: UL-04 V0, ceramic sleeve,

**Application**
- telecommunications,
- LAN, WAN,
- CATV, supervision systems, measuring technology,
- services, railways, power engineering, etc.

### 4.4 Optical couplers

Depending on the configuration of optical network, it is often necessary to separate optical power from the main direction; in other cases it is necessary to combine optical radiation, perform decoupling, switching and rerouting. Optical couplers are used to this purpose. They can be implemented in many ways.

General requirements for these couplers include:
- low insertion losses,
- high losses in the reverse direction,
- independent separation of modes into individual directions,
- simple adjustment,
- easy manufacture,
- low price.

Since in most cases the four-port couplers are concerned, it is of advantage to define them in matrix notation as dependence between input power $P_i$ and output power $P_j$. For the case of four-port coupler according to **Fig. 4.33** we can write

$$
\begin{bmatrix}
P_{1a} \\
P_{2a} \\
P_{3a} \\
P_{4a}
\end{bmatrix}
= \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} \\
P_{21} & P_{22} & P_{23} & P_{24} \\
P_{31} & P_{32} & P_{33} & P_{34} \\
P_{41} & P_{42} & P_{43} & P_{44}
\end{bmatrix}
\begin{bmatrix}
P_{1e} \\
P_{2e} \\
P_{3e} \\
P_{4e}
\end{bmatrix}
$$

(5.17)
In practical implementations, the members of this matrix are reduced. The relation between the input and output of optical power on an $n$-port coupler can generally be expressed by

$$A_{ij} = -10 \log \frac{P_j}{P_i}, \ (i, j = 1, 2, 3, \ldots).$$

(5.18)

**Couplers implemented by optical fibres**

These belong to the simplest couplers, which are implemented by gluing or fusing together two optical fibres.

An example of coupler with evanescent field is given in **Fig. 4.34**. The coupling between the fibres is obvious from the figure.

![Coupler with evanescent field](image)

**Fig. 4.34:** Coupler with evanescent field.

An example of biconical coupler is given in **Fig. 4.35**. The coupling enables dividing the luminous flux into two directions.

![Biconical coupling of optical fibres](image)

**Fig. 4.35:** Biconical coupling of optical fibres.

Frequently applied couplers are directional couplers in the form of Y, as shown in **Fig. 4.36**. They are used to couple and decouple light in optical routes and in measuring technology. Light can be delivered either from fibre 1 to fibres 2 and 3 or vice versa. Fibres 2 and 3 are ground to the shape of Y.
The optical parameters are expressed by the matrix

\[
P_S = \begin{bmatrix}
0 & 3.8 & 3 \\
3.8 & 0 & 34 \\
3.7 & 34 & 0
\end{bmatrix} \text{ (dB)}. \tag{5.19}
\]

The slight difference in the division of powers in fibres 2 and 3 is due to the non-uniformity of grinding and gluing the two fibre halves.

Various couplings can be obtained by displacing the fibres axially against each other. In the case of step-index fibres, the coupling depends on the overlap of surfaces (see Fig. 4.37). Optical relays, switches, etc. operate on this principle. Fixing a fibre (fibres) to a metallic reed controlled by magnetic field (analogy to reed relays) will enable switching optical power in this way (see Fig. 4.38).

**Fig. 4.36:** Y-coupler.

**Fig. 4.37:** Optical switch.
A part of optical power can be separated by directional splitting coupler, as indicated in Fig. 4.39. The division of luminous flux is proportional to fibre diameters $D_1$, $D_2$ and $D_3$ according to

$$D_3 = D_1 + D_2.$$  \hspace{1cm} (5.20)

Losses are below 0.5 dB.

Other frequently used couplers are mirror (Fig. 4.40) and partially transmissive mirror (Fig. 4.41).
Fig. 4.40: Mirror used as coupler.

Fig. 4.41: Partially transmissive mirror used as coupler.

Fig. 4.42 shows a transit coupler (star coupling). It operates as a mode scrambler of light coming via lightguides from individual optical transmitters. On the output side are lightguides leading to the receiver. The coupler shown in Fig. 4.43 operates on a similar principle. These couplers find application in local optical networks, acting as connection circuits.
A coupler that enables separating (merging) luminous radiation of different wavelengths is shown in **Fig. 4.44**. The coupler employs an interference filter, which separates one wavelength. The principle is clear from the figure. Losses are below 1 dB.
These couplers can be used to implement duplex operation between two stations. They are sometimes referred to as wavelength division multiplexing (WDM). Most frequently used wavelengths are $\lambda_1 = 850 \text{ nm}$ and $\lambda_2 = 1300 \text{ nm}$.

This brings us to the problems of mixing and separating various wavelengths from optical fibre. These problems will be dealt with in greater detail later.
5 Source of light

Radiation sources are one of the basic parts of optoelectronic telecommunication link. Although any source of light can in principle be used as a source of optical radiation, the application, for example, of an electric bulb is for present-day requirements out of the question because of its low energy and unfavourable radiation characteristics. In laboratories concerned with sources of radiation very intensive studies are therefore conducted into sources based on the solid phase that generate radiation at room temperature. These are semiconductor sources, with the focus on light-emitting diodes and laser diodes.

The main requirements placed on optical sources are the following:
- maximum efficiency of the conversion of electrical energy to radiant energy,
- generation of radiation on such wavelengths where the attenuation of current optical fibres is the lowest,
- generation of radiation at room temperature,
- high reliability and long lifetime (problem of lasers),
- easy modulation over a wide range, above all via changing the injection (supply) current,
- high monochromatism or coherence of generated radiation,
- the narrowest possible directional characteristic of out-going radiation,
- easy connectibility of generated radiation to optical fibre,
- small dimensions and weight.

For optical telecommunications the following types of sources come into consideration:
- incoherent – light-emitting semiconductor diodes (LED - Light Emitting Diode)
- coherent – lasers: mainly semiconductor diodes (LD – Laser Diode), for special purposes also gas, solid-state, and multiline lasers.

In first approximation, light-emitting diodes (LED) are cheap and easily available, with long lifetime and easy to modulate. However, they have a large divergence of the output beam and radiate a lower output (in comparison with LD) on all wavelengths that are suitable for telecommunication transmissions.

Laser semiconductor sources (LD) feature higher radiated output, lower spectral width, high efficiency of coupling to fibre, and the possibility of modulating to higher frequencies (GHz, Gbit·s⁻¹). On the other hand, they require higher supply and temperature stabilization; they are the most likely cause of errors in optical routes (stand-by redundancy is introduced but their lifetime is steadily increasing) and are more expensive.

From the viewpoint of small dimensions, easy connection to optical fibre and easy modulation, the two elements (LED and LD) are frequently used in the telecommunication practice. For less demanding applications, where it is not necessary to maintain directionality of optical beam, and for transmissions over shorter distances the LED semiconductor sources are used. For transmissions over longer distances, where it is necessary to radiate in a narrow beam and where several wavelengths need to be transmitted (wavelength division multiplexing – WDM) the laser semiconductor diodes (LD) are used.
5.1 Light-emitting diodes

Semiconductor infrared electroluminescence diodes (LED) are P-N structures, mostly on the basis of GaAs, polarized in the forward direction. On the P-N junction minority carriers are injected, part of which do not combine radiantly. The simplest structure is shown schematically in Fig. 5.1.

![Diagram of PN structure with energy diagram](image)

**Fig. 5.1:** Schematic diagram of PN structure with energy diagram.

Energy generated by current passing through the diode forms electron-hole pairs in the active region. It follows from the energy diagram that the electrons are in the conduction band of energy $E_V$ and the hole in the valence band of energy $E_L$. Thus in the process of recombination the energy radiated into the surroundings is

$$\Delta E = E_V - E_L \quad (\text{eV}).$$

(5.1)

The relation that holds between the energy $\Delta E$ and the radiated frequency is

$$\Delta E = h \cdot f,$$

(5.2)

where $h$ is Planck’s constant ($h = 6.62 \times 10^{-34}$ Ws$^2$),

$f$ is the frequency in [Hz].

From the well-known relation for frequency

$$f = \frac{c}{\lambda},$$

(5.3)
where \( c \) is the speed of light propagation in vacuum \((c = 2.998 \times 10^8 \text{ m} \cdot \text{s}^{-1})\), we obtain for the wavelength of optical radiation

\[
\lambda = \frac{1.242}{\Delta E} \text{ (\mu m; eV)}.
\]  

(5.4)

If for the base material of optical radiation source we use the already mentioned and widely used gallium arsenide (GaAs), where the distance between the valence and the conduction bands expressed as the difference of energy levels (forbidden region) is ca. \( \Delta E = 1.4 \text{ eV} \), the wavelength of emitted optical radiation is 0.89 \( \mu \text{m} \). The choice of base material and other components will affect the generated wavelength and spectral bandwidth. For example, for the 1.3 \( \mu \text{m} \) region the InGaAsP structure is used.

The response to the current pulse of electroluminescence diodes is given by the lifetime of spontaneously recombining injected minority carriers. For type GaAs semiconductors this time is short and the leading edge of light pulse is only several ns. These extremely short leading edges are obtained by replacing the common P-N junction by a simple or double heterojunction with narrow active region. In this way, very powerful incoherent generators can be made for telecommunication systems even for longer distances. These sources are small, cheap, of good efficiency and suitable wavelength for the telecommunication region. They enable modulation also by analog signals up to 500 MHz, with radiated power about 1000 W∙cm\(^2\) and long lifetime (up to 107 hours).

The applicability of LED diodes has, however, its limitations. It is, above all, their broad omnidirectional radiation diagram that is an obstacle to efficient adaptation to optical fibre (in particular fibre with small numerical aperture NA). Another limitation results from the relative broad emission spectrum (30 nm), which brings about a distortion that is given by the dependence of the speed of light propagation in the fibre on the wavelength.

**Fig. 5.2** gives the schematic of the design of GaAs-based light-emitting diode with front emission and direct coupling to the optical fibre. Such a design, implemented at the manufacturer’s, yields great efficiency of the coupling between LED and the fibre. The required fibre length is provided with a connector. This will save the customer problems with coupling optical radiation to the fibre.

![Fig. 5.2: Front-emitting LED with coupling to optical fibre.](image-url)
**Fig. 5.3** illustrates the other possible variant of LED, namely edge-emitting diode. This is a super-luminescent diode with stripe geometry of contacts. The diode radiates in a narrow band on one side only, with high power. This gives a narrower-band source of radiation, where the amount of modes appearing in the fibre is reduced. This enables increasing the transmission speed and range of this diode.

![LED with stripe geometry](image)

**Fig. 5.3**: LED with stripe geometry.

Typical LED properties and characteristics will be given below.

So far we have considered only in general that on the basis of recombination optical power is emitted. Not all the kinds of recombination contribute equally to the total emitted optical power $P_{LC}$. Let the power assigned to concrete wavelengths $\lambda$ be denoted $P_{L}(\lambda)$. The dependence of power $P_{L}$ on the wavelength

$$P_{L} = f(\lambda), \quad (5.5)$$

will be denoted spectral characteristic $PL - \lambda$. to which The predominant mechanism of recombination process has the wavelength $\lambda_{M}$, to which the maximum value of emitted power pertains, $P_{LM} = f(\lambda_{M})$. **Fig. 5.4** gives the typical spectral characteristic of LED.
Fig. 5.4: Spectral characteristic of LED.

The width of spectral characteristic at half the maximum power is denoted $\Delta\lambda_{\text{HP}}$. This quantity is sometimes given as a criterion of monochromatism of light. But the situation is better expressed by the so-called measure of monochromatism $m_m$, for which it holds

$$m_m = \frac{\Delta\lambda_{\text{HP}}}{\lambda_{\text{M}}}.$$  \hspace{1cm} (5.6)

On the basis of the numerical value of $m_m$ sources fall into those we consider monochromatic and those we do not. Conditions for the monochromatism of GaAs have been determined as follows: $\Delta\lambda_{\text{HP}} \leq 50,0 \text{ nm} : \lambda_{\text{M}} \geq 855,0 \text{ nm} > m_m \leq 0,059$.

Integral optical power $P_{\text{LC}}$ is determined according to

$$P_{\text{LC}} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} P_L(\lambda) \, d\lambda.$$  \hspace{1cm} (5.7)

and is proportional to the area delineated in Fig. 6.4 by the curve, i.e. coordinates for power and wavelength at the extreme points, and by the line segment on the $\lambda$ axis between points $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$. It holds

$$P_{\text{LC}} = P_{\text{LM}} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{P_L(\lambda)}{P_{\text{LM}}} \, d\lambda.$$  \hspace{1cm} (5.8)

Spectral purity $p_s$ is the greater, the smaller the powers transmitted by lateral waves $\lambda < \lambda_{\text{min}}$ and $\lambda < \lambda_{\text{max}}$, and the greater the power $P_{\text{LM}}$ on the medium wavelength $\lambda_{\text{M}}$.

Expressed mathematically

$$p_s = \frac{P_{\text{LM}}}{P_L(\lambda < \lambda_{\text{min}}) + P_L(\lambda > \lambda_{\text{max}})}, \quad p'_s = \frac{P_{\text{LM}}}{P_{\text{LC}}}.$$  \hspace{1cm} (5.9)

For the relation between $p_s$ and $p'_s$ it holds
\[ p_s = \frac{p'_s}{1-p'_s}. \] (5.10)

A set of spectral characteristics of different radiation sources, sensitivity of the human eye and detector given in Fig. 5.5 offers an interesting comparison. Curve a represents the spectral characteristic of LED, curve b represents the sensitivity of the human eye on the visible wavelength (the region of LED emission is for the human eye zero), curve c is the characteristic of tungsten electric lamp, curve d gives the dependence for Si-phototransistor (the maxima of Si-phototransistor and AgAs LED are identical; we say that they are optically matched and this is a precondition of mutual action of the source in the transmitter part and the detector in the receiver part of optical telecommunication system).

![Relative spectral characteristics](image)

**Fig. 5.5:** Relative spectral characteristics.

Electrooptic characteristic \( P_L = f(P_D) \) renders the dependence of optical power \( P_L \) on electrical input of the diode \( P_D = U_{id}I_F \). Typical dependence is given in Fig. 5.6.
Quantum efficiency is established from the relation

$$\eta = \frac{P_L}{P_D} \tag{5.11}$$

Polar radiation plot of diodes is given as an example in Fig. 5.7.

**Fig. 5.6**: Optical power vs. Current.

**Fig. 5.7**: Polar radiation plot of LED.
Of no less importance are the dynamic properties of LED, defined by the response of light to a jump in current. Rise time is the time necessary for the optical power to increase from the 10% of peak value of $P_{LM}$ to 90% (it is usually about 1 ns). Delay time is the time between the pulse beginning and the moment when $P_L$ reaches 10% of the maximum value. These times depend on the dynamic of recombination processes, on the junction capacity and on parasitic capacities of the casing and leads.

To a certain extent, light-emitting diodes depend on the supply current (spectral characteristic gets shifted towards higher wavelengths), which may lead to a change in temperature.

Exact values of the parameters and characteristics for individual types of light-emitting semiconductor diodes can be found in manufacturers’ catalogues.

5.2 Laser diodes

The laser diode (LD – Light Amplification by Stimulated Emission of Radiation Diode) is based, as the name itself suggests, on the amplification of light via stimulated emission of radiation.

In its design the laser diode does not differ much from the lay-out of edge-emitting LED but, in addition, it must meet some requirements that enable emitting coherent radiation.

In the following, only the basic principle of the laser function will be described;

The laser consists of two basic parts:
- wavelength amplifier,
- feedback resonator.

In the interaction of electromagnetic field with a solid, three basic types of junction between the fundamental and the excited state appear, namely absorption of radiation (junction to a higher energy state) and spontaneous and stimulated emissions (junction from the excited state to the fundamental state). Spontaneous emission of radiation begins spontaneously and randomly some time (about $10^{-8}$ s) after excitation. Stimulated emission is triggered by direct interaction with the standing electromagnetic field. Due to this interaction the optical radiation originating in the element in which this type of junction predominates is coherent.

To achieve this effect, external energy must be applied to ensure such an out-of-equilibrium state where the number of atoms or molecular systems of the active region in excited state will be greater than in the basic state. Then in such a structure of the active region the predominant interaction between the field and the substance is stimulated emission and not absorption, and the optical radiation propagating in this region is amplified. This state is referred to as population inversion.

In population inversion the speed of emission transitions $W_{emission}$ must be greater than the speed of absorption $W_{absorption}$. In keeping with the energy levels the speed of emission will be proportional to

$$W_{emise} \sim \int n_\gamma(W) F_c(W) n_\gamma(W-h\nu)[1-F_\gamma(W-h\nu)] \, dW. \quad (5.12)$$

$$W_{absorpe} \sim \int n_\gamma(W-h\nu) F_c(W-h\nu) n_\gamma(W)[1-F_c(W)] \, dW, \quad (5.13)$$

where $F_c$ and $F_\gamma$ are the Fermi-Dirac distribution functions
\begin{equation}
F_c(W) = \frac{1}{1 + \exp\left(\frac{W - W_{Fc}}{kT}\right)} p.
\end{equation}

(5.14)

\begin{equation}
F_v(W - h\nu) = \frac{1}{1 + \exp\left(\frac{(W - h\nu) - W_{Fv}}{kT}\right)} ,
\end{equation}

where $h\nu$ is the energy of emitted photons, $n_c, n_v$ are the state densities in the conduction and valence bands, $W_{Fc}, W_{Fv}$ are apparent Fermi levels valid for the conduction and valence bands.

An important relation follows from conditions (5.12) and (5.13) for the amplification of optical radiation

$W_{Fc} - W_{Fv} > h\nu$.  \hspace{1cm} (5.15)

The above relation is generally valid for semiconductors or for a medium that can amplify light of frequency $\nu$. At the same time it is a necessary condition for light amplification but not sufficient for light generation. For the latter it is necessary to satisfy the feedback condition for the appearance of oscillations, i.e. to prepare a structure that enables introducing positive feedback with a sufficient feedback factor. The resonance properties of the Fabry-Perot cavity (see Fig. 5.8) are used for this purpose. In principle, this cavity is formed by two parallel partially transmitting mirrors placed at a distance $L_R$ on opposite sides of the semiconductor material, with the active region between them.
The feedback condition can be written as

$$\ell \frac{n}{R} = (g - \alpha) L_R,$$  \hspace{1cm} (5.16)

where $R$ is the coefficient of mirror reflection, $\alpha$ is the coefficient of optical losses, $g$ is the gain of active medium, and $L_R$ is the length of resonator.

Equation (5.16) is used to establish the threshold gain of active medium necessary for the generation of coherent light

$$g_{\text{prah}} = \alpha + \frac{1}{L_R} \ln \left( \frac{1}{R} \right).$$  \hspace{1cm} (5.17)

With the simplification that the Fabry-Perot cavity is a one-dimensional resonator in which the optical wave propagates in axial direction, the basic selection of modes is given by the requirement of integer number of half-waves between the reflection surfaces.
\[ m \frac{\lambda}{2n} = L_r, \]  

(5.18)

where \( m \) is 1, 2, 3, …,

\( \lambda \) is the wavelength,

\( n \) is the refractive index of cavity medium.

For practical applications, for the purpose of achieving radiation directionality, the resonator is usually partially transmitting from one side only. Inciting the semiconductor laser structures by injection on the P-N junction is the simplest and most efficient method of achieving population inversion. Of practical importance are lasers based on double heterojunction. The optical field and the minority carriers are concentrated very effectively in a very narrow active region. The Fabry-Perot resonator is often replaced by a better resonator, as is the case of laser with distributed feedback (DFB) or laser with the Bragg reflection (Distributed Bragg Reflector); the schematic of the latter is given in Fig. 5.9. The indicated optical grating forms a frequency-selective reflector.

![Figure 5.9: Semiconductor laser with Bragg reflection.](image)

It is evident that the design of LD will affect the characteristics of radiant energy balance, spectral dependence, temperature dependence, etc.

A typical spectral characteristic of laser diode is shown in Fig. 5.10. Even in the case of sharp resonator tuning to the wavelength \( \lambda_M \) the radiant intensity does not pertain to only a single wavelength (absolute monochromatism) but is divided continuously in a certain interval of wavelengths. The radiant intensity (power) increases with increasing current. Increasing temperature will shift the spectral characteristic to higher wavelengths.
Another important laser characteristic is the dependence of emitted optical power on the amplitude of current. The graph of this function, $P_L = f(I_M)$, is given in Fig. 5.11. It is apparent from the graph that with increasing temperature the characteristic gets shifted. It can also be seen that the characteristics are almost ideally linear so that in pulse operation the current amplitude modulation of luminous flux can be used.

**Fig. 5.10:** Spectral characteristic of laser.

**Fig. 5.11:** Dependence of emitted optical power on current amplitude.
Naturally, in a more profound study of laser processes it is necessary to deal with free-space radiation, voltage characteristics, dynamic properties, etc.

As regards the wavelength, laser-generated radiation covers the whole region necessary for telecommunications (0.85 µm to 1.55 µm), with typical bandwidth below 5 nm and lower than 1 mm (multimode, single-mode) and optical power of ca. 10 mW.

The narrow directional radiation characteristic of elliptical shape and with ca. 5° acceptance angle enables the emitted power to be effectively coupled to the fibre (much more effectively than with the LED).

The efficiency of the coupling of optical source to the fibre (see Fig. 5.12) can be expressed as

\[
\eta = \frac{P_{\text{fiber}}}{P_{\text{diode}}} = T \frac{A_{\text{fiber}}}{A_{\text{diode}}} (NA)^2 ,
\]

where \( P_{\text{fiber}}, P_{\text{diode}} \) are power transmitted to fibre and diode power,
\( A_{\text{fiber}}, A_{\text{diode}} \) are fibre input area and diode output area,
\( T \) is the luminous transmissivity of medium
\( NA \) is the numerical aperture of fibre

**Fig. 5.12:** Radiation source coupled to optical fibre.
5.3 Optoelectronic transmission components

Leading world manufacturers (Siemens, GE Solid State, Optral, OKI, Sony, and others) offer a variety of semiconductor sources of radiation for the area of telecommunications. To name all of them would take up a major part of this publication. It is imperative for potential users (designers) to obtain the respective catalogues from the manufacturers. In the catalogues, individual types are listed in detail; in addition to the main parameters, data on spectral characteristics, radiation diagrams, power and current relations, etc. are given there.

The offer includes a whole range of various types of fixed optoelectronic coupling elements (one component forms both the transmitter and the receiver, so-called coupler, which is the result of coupling optically the GaAs light-emitting diode, the transmitter and a silicon NPN phototransistor as the receiver) employed to galvanically separate current circuits.
6 Light modulation and detection

It is clear that transmitting information by means of optical radiation is only possible if the luminous flux is influenced one way or another. In keeping with the signal transmitted we speak of modulation while the reverse process is called demodulation. At the receiver end an optical detector must be connected which converts optical radiation back to electric signal.

6.1 Modulation methods

In optical transmission, too, generally known modulation methods are used, such as amplitude, frequency, and phase modulations. In the transmission of analog signals amplitude modulation with direct modulation of radiant intensity (AM-IM) is mostly used or also frequency modulation using the carrier frequency. Analog transmission methods are used with advantage in the transmission of TV signal. In the receiver it is then necessary to evaluate the changes in intensity, and in the demodulator to restore the original signal. For the transmission the original analogue signal can be converted to digital signal and the PCM-IM, PFM-IM, and PWM-IM modulation principles can be used.

When analogue modulation of the transmitting element is used, the relatively good linear dependence of transmitted power on excitation current is made use of. In comparison with digital transmission the requirements for signal-to-noise ratio are stricter and, also, the linearity of the attenuation and the phase characteristics need to be taken into consideration.

Modulation properties of LD

An advantage of semiconductor lasers is that direct modulation can be used, i.e. modulation current can be superimposed directly on the constant injection current, which sets the operating point on the output characteristic.

In analogue modulation it is of advantage to set the bias voltage just above the threshold current. In analyses made for a small modulation signal, a mathematical representation was proposed, which is given by a system of two non-linear differential equations. From the two equations the following conclusions can be drawn: in the modulation characteristic a resonance peak can be expected as a result of the interaction of photon population and concentration of injected electrons. For excitation current $I$ the resonance frequency $f_r$ is given approximately by

$$f_r = \frac{1}{2\pi} \left( \frac{1}{\tau_e \tau_f} \frac{I - I_p}{I_p} \right)^{\frac{1}{2}} \text{ (MHz)}, \quad (6.1)$$

where $\tau_e$ is the lifetime of electrons,
$\tau_f$ is the lifetime of photons,
$I_p$ is the threshold current.

If typical values for the semiconductor laser are considered, e.g. $I_p = 190$ mA, $\tau_e = 4$ ns, $\tau_f = 1$ ps, and the laser is excited by the constant current $I = 205$ mA, we obtain from (6.1) $f_r = 7.07 \cdot 10^8$ Hz. The frequency response of a laser with the above parameters is shown in Fig. 6.1.
Pulse modulation is seen as the most advantageous laser operation regime. But even here, due to increasing bit rates, specific problems arise that limit the pulse modulation potentials. The reason is, on the one hand, the lag of output signal behind input pulse modulation and, on the other hand, the potential rise of relaxation oscillations, whose frequency may reach into the region of modulation frequencies. The problem of inner modulation of semiconductor laser thus consists in setting the operating conditions such that the above two parasitic phenomena are maximally suppressed and that time and temperature stability of operation is obtained.

It follows from the above that the linear part of the characteristic (Fig. 6.1) needs to be selected for the laser operation region. On the basis of equivalent laser diagram and also on the basis of measurement the maximum laser modulation rate can be established. The upper limit is again given by the appearance of relaxation oscillations. For the magnitude of these oscillations it holds

$$f_r \approx \frac{1}{2\pi} \left( \frac{I-I_p}{I} \frac{1}{\tau_e \tau_f} \right)^{\frac{1}{2}} \text{ (MHz)}.$$  \hspace{1cm} (6.2)

Substituting the typical values (see relation (6.1)) we obtain $f_r = 685 \text{ MHz}$. The amplitude of relaxation oscillations can be suppressed by choosing a suitable quiescent current $I_0$ if it is permanently set above the threshold value $I_p$. For a laser with the above parameters, with $I_0 = 200 \text{ mA}$ and with the bit rate $250 \text{ Mbit} \cdot \text{s}^{-1}$, the relaxation oscillations almost disappeared. Technologically high-quality lasers enable obtaining bit rates of hundreds of Mbit$\cdot$s$^{-1}$ to units of Gbit$\cdot$s$^{-1}$.

Current sources are used to set the laser operating point. Transistor current sources are the most widely used.

Let us now have a case when a number of modes, about 10 to 20, appear in the spectral characteristic. These modes are attenuated on either side of $\lambda_M$ (in the region of lower
wavelengths a greater number of modes and a less abrupt slope of the characteristic) as shown in Fig. 6.2. This is because for a period of a few nanoseconds lasers exhibit a very broad radiation spectrum if they are operated with pulse modulation with bias voltage below the threshold of stimulated radiation. It is the result of the big jump in electron density in the time intervals between peaks of attenuated output oscillations of the laser. This high density of electrons provides sufficient gain to give rise to a number of modes. This phenomenon can be prevented by introducing a constant injection current whose value is just above its threshold.

![Fig. 6.2: Spectral characteristic of laser.](image)

**Modulation properties of LED**

Light-emitting diodes can with advantage be modulated also internally, i.e. with the aid of injection current. Extensive use is made of the linear static modulation characteristic, which gets curved only at higher current values, due to thermal phenomena (see Fig. 6.6).

Due to the dynamic properties of LED (lifetime of injected electrons, voltage dependence of the p-n junction capacity) there is a delay in the diode response with respect to the injection current, and the leading and trailing edges of input modulation pulses are slowed down. These phenomena then limit the modulation frequency band. The maximum modulation frequency is approximately determined from the relation

$$f \ll \frac{1}{2\pi \tau_e}.$$  \hspace{1cm} (6.3)

Substituting again the typical values $\tau_e = 1$ to 2 ns (lifetime of injected electrons) yields the maximum modulation frequency of LED in the range from 100 to 200 MHz.

In order to achieve higher modulation limits in pulse modulation, and for this purpose also to shorten the time delay $t_e$ between the excitation jump current $I_e$ and the appearance of output radiation, it is necessary to polarize the LED with a voltage whose value is close to the
diffusion voltage $u_d$. The modulation properties of LED are determined to a great extent by the design of the LED itself. And last but not least, it is necessary to properly match the generator output impedance with the low input impedance of the diode.

If the modulation does not require a linear characteristic, the depth of modulation can be reduced, which, however, has an unfavourable effect on the value of signal-to-noise ratio, or the non-linearities of the characteristic can be compensated.

Any of the methods given below can be used for the linearization of characteristics.

The *pre-distortion method* is based on the principle that prior to the modulation itself on the transmitter diode the electric signal is led through circuits that cause inverse non-linear distortion.

The phase modulation method is based on simultaneous modulation of two LED of identical characteristics, with the signals being the same but phase-shifted by $\pi/2$. After the emitted powers have been combined in the optical fibre, the second harmonics, i.e. components of the type of $2\omega t$ and $\cos (\omega T + \pi)$ are suppressed.

The negative feedback method, which is frequently applied in electronic circuits, can also be used in optical transmissions and is advantageous from the viewpoint of implementation. It is based on the principle of diverting into the feedback a part of emitted power, from which a part of the current for transmitter diode is formed.

Besides the modulations given above, there are also other types of modulation for specific purposes. Depending on the type of modulation, these external modulators may be based on the principles of electro-optics, magneto-optics, acoustics, and absorption. Since all practically significant implementations are primarily built on the principles of integrated optics, some of these implementations will be given in the one of next chapter.

### 6.2 Detection of radiation

Elements called detectors are used to detect radiation. Radiation detectors that are necessary for the demodulation of optical signal in optoelectronic systems must fulfil certain requirements from the viewpoint of parameters, compatibility with the other elements, execution, and costs. Only semiconductor detectors are used for telecommunication purposes. Interest is focused on semiconductor diodes, in particular type PIN photodiodes and avalanche photodiodes (APD). The detectors must satisfy the following requirements:

- high sensitivity in the waveband of the light sources described above, i.e. for $\lambda = 0.8$ to 1.55 μm,
- sufficient width of the frequency band being transmitted,
- fast time response,
- low intrinsic noise,
- minimum dimensions, suitable for connection to optical fibre,
- insensitivity to temperature changes, supply voltage changes, etc.
The detectors used are thus mostly elements with p-n junction. They are based on separating pairs of charge carriers, i.e. electrons and holes, which result from optical radiation being absorbed by the detector. Materials that have sufficient light absorbance in the above wavelength band are Ge, Si, GaAs, InGaAsP, and InGaAs. Their spectral coefficients of absorption $\alpha_a$ are given in Fig. 6.3. The figure also gives the corresponding depth of radiation penetration into the material $x_0$, which is defined by the relation

$$x_0 = \frac{1}{\alpha_a}. \quad (6.4)$$

When radiation of power $P_0$ hits the detector surface, the process of absorption is given by the relation

$$P(x) = (1-R)P_0(1-e^{-\alpha_a x}), \quad (6.5)$$

where $R$ is the coefficient of detector surface reflection. This coefficient gives the magnitude of the part of incident power that does not penetrate into the semiconductor and is thus lost for useful processing. To prevent this and to enhance the overall detection efficiency, an antireflection layer of $\lambda/4$ thickness is applied to the functional surface of detector. The layer acts like an impedance transformer.

Relation (6.5) reveals the physical significance of penetration depth $x_0$: it is a depth for which (6.4) holds, i.e. it is the distance from the detector surface, where 63% of incident power is absorbed.

From Fig. 6.3 we can also read the frequency limitation of application for individual materials. All the materials mentioned have a clearly expressed limit wavelength of application. For GaAs it is about 0.9 $\mu$m, for Si 1.1 $\mu$m, for InGaAsP 1.2 to 1.6 $\mu$m, and for Ge 1.7 $\mu$m.
Fig. 6.4: Principle of operation of PIN photodiode.

In the following we will describe the principle of operation of the PIN diode. Fig. 6.4 gives schematically the PIN diode and the waveform of the intensity of electric field in the middle layer (i). It can be seen from the figure that the PIN diode consists basically of three semiconductor layers:

- a heavily alloyed layer p of thickness \(w_p\),
- a heavily alloyed layer of thickness \(w_n\),
- a middle layer i, which is weakly alloyed and has type p or type n conductance.

The above waveform of the intensity of electric field in layer I results from the voltage that polarizes the diode in the reverse direction. The site of contact between layers p and I gives rise to a junction. A junction also arises at the site of contact between layers i and n. Due to incident light, electron-hole pairs can generally appear in all the three regions of the diode. Due to the effect of strong electric field, electrons and holes formed in the region i diffuse in mutually reverse directions, electrons towards the \(n^+\) region and holes towards the \(p\) region. Electrons formed in the \(p\) region close to the \(p-I\) junction diffuse through this junction into the i region and continue travelling at drift velocity towards the \(n^+\) region. Holes formed near the \(n^+\)-i region behave in a similar fashion.

Fig. 6.5: Structure of PIN photodiode (lateral incidence of radiation).
PIN photodiodes are widely used detectors of radiation, which have a high quantum yield (60-80%) and fast response. On wavelengths where both Si and Ge diodes can be used it is of advantage to give preference to silicon diodes since they are thermally less dependent and have a smaller dark current.

![Structure of PIN photodiode](image)

**Fig. 6.6:** Structure of PIN photodiode (frontal radiofon incidence).

*Avalanche photodiodes*

Avalanche photodiodes are used in telecommunication practice because in comparison with the above PIN diodes they can achieve higher sensitivity. While the PIN diodes are based on optical excitation of free charge carriers and on the recombination processes, in the case of avalanche photodiodes there is an added process of free carriers being multiplied on the basis of ionization in a strong electrical field.

A disadvantage of avalanche photodiodes is that their manufacture is complicated, that they are more expensive and require bias voltage, and that the above advantageous process of multiplication simultaneously increases the level of noise voltage.

A schematic representation of avalanche photodiodes can be seen in **Fig. 6.7**. As is evident from the figure, alloying is performed such that the intensity of electrical field in the junction region has a high value. Charge carriers that are drifting in the region can be accelerated to velocities that are sufficient to generate new electron-hole pairs due to collision ionization. These newly generated pairs are the origin of the generation of further pairs. This is how the process of avalanche increase of charge carriers originates. This process of multiplication is a random event and is therefore accompanied by the appearance of additive noise. The magnitude of the multiplication coefficient ranges from several tens to several hundreds.
Fig. 6.7: Principle of avalanche photodiode operation.

An illustration of the design of silicon avalanche photodiode with protection annulus is given in Fig. 6.8. A feature of the design is the protection ring in the form of $n$ region, diffused at the interface of regions $n^+$ and $p$. Its purpose is to reduce the high intensity of electric field at the site of this junction. The time in which the avalanche is produced is extremely short, a few ps. These photodiodes are therefore suitable for wideband detection of optical signals. Values of the product of photoelectric gain and bandwidth are in tens of GHz (up to 100 GHz).

Fig. 6.8: Design of avalanche photodiode.

6.3 Parameters of radiation detectors

An important parameter of semiconductor detectors of radiation is the quantum efficiency. It is defined as that part of incident electron flow which is absorbed in the semiconductor and generates current carriers, which are collected along the p-n junction. The magnitude of the current (photocurrent) generated by the absorption of optical radiation of average power $P$ (corresponding with the amount of incident photons $P/h\nu$) is given by the expression
\[
I = \eta \frac{q}{h \nu} P \quad (\text{A}),
\]

where \(\eta\) is the quantum efficiency. Relation (6.6) allows estimating the sensitivity of a typical PIN diode: expressing the sensitivity \(A_d\) as a ratio of incident photocurrent to optical power, then

\[
A_d = \frac{I}{P} = \eta \frac{q}{h \nu} \quad (\text{A.W}^{-1}).
\]

(In the expression, \(h = 6.626 \cdot 10^{-34}\) is Planck’s constant, \(q = 1.6 \cdot 10^{-19}\) C is the charge of electron.)

The frequency properties are influenced primarily by the photodiode design. From the viewpoint of detector connection it is necessary to know the impedance and time constants of the detector.

Relative spectral sensitivity is a dimensionless quantity. It gives the ratio of spectral sensitivity at a given wavelength to spectral sensitivity at maximum dependence.

No less important parameters are the dark current with non-illuminated detector, and the temperature dependence of detectors.

Another important parameter is the level of noise voltage. It determines the minimum value of detected power of incident radiation. The quantity \(P_{\text{NEP}}\) (NEP – Noise Equivalent Power) is introduced for this purpose. This power is defined as the power of incident radiation that generates on the detector the same effective voltage value as the noise voltage. The incident radiation is assumed to be sine-modulated. The value of \(P_{\text{NEP}}\) is established by measuring the noise properties of detector and is obtained from the relation

\[
P_{\text{NEP}} = \frac{P_D U_s}{\sqrt{\Delta f} U_f} \quad (\text{W.Hz}^{-1/2}),
\]

where \(U_s\) is the effective value of noise voltage (V), \(U_f\) is the effective value of photovoltage (V), \(\Delta f\) is the amplifier bandwidth (Hz), \(P_D\) is the optical power incident on detector surface; effective value is considered (W).

The effective value of noise voltage depends on the bandwidth of selective amplifier. In most cases it is recalculated for the 1 Hz width. For practical purposes and for the comparison of detectors the concepts of detectivity \(D\) and normalized detectivity \(D_n\) have been introduced, which are given by the relations

\[
D = \frac{1}{P_{\text{NEP}}} : \quad D_n = D \sqrt{S},
\]

where \(S\) is the detector surface (m\(^2\)).

In Tables, for example, the designation \(D\) (0.85; 800; 1) means that the value \(D\) is considered for a wavelength of 0.85 \(\mu\)m, incident radiation was interrupted at a frequency of 800 Hz, and the bandwidth of selective amplifier considered is 1 Hz.
Let us return to the avalanche photodiode. The increased sensitivity is proportional to the multiplication factor and it holds

\[ I = M_O \cdot I_f, \quad (6.10) \]

where \( I_f \) is the primary photocurrent corresponding to incident optical power, given by relation (6.6). The relation holds for small photocurrents.

For \( M_0 \) it further holds

\[ M_O = k \frac{1}{1 - \left( \frac{U}{U_D} \right)^n}, \quad (6.11) \]

where \( U \) is the reverse voltage of diode, \( U_D \) is the breakdown voltage, \( n \) is a constant covering the basic properties of material and the alloying profile, etc., and \( k \) is the proportionality constant. The dependence of multiplication coefficient on voltage in reverse direction is given in Fig. 6.9.

![Dependence of multiplication constant on diode voltage in reverse direction.](image)

**Fig. 6.9:** Dependence of multiplication constant on diode voltage in reverse direction.

The multiplication coefficient is further dependent on the modulation frequency of optical radiation, and approximately it holds

\[ M(\omega) \approx \frac{M_O}{1 + j \omega M_O}, \quad (6.12) \]

where \( \omega \) is the modulation frequency of optical radiation, and, \( M_O \) is the multiplication coefficient for \( \omega = 0 \).

The same as with sources of radiation, leading manufacturers offer a wide variety of radiation detectors. In prospectuses and catalogues, the required detector type can be chosen by detector parameters given in the preceding chapter and for the required applications.
7 Optoelectronic telecommunication systems

A range of optoelectronic telecommunication systems are in operation today, whose technical solution depends on the nature of the signal being transmitted (for example, digital signal of telephone call, data signal, image signal, FDM transmission signal, etc.). The nature of the device also depends on the application and it is different in devices for local access networks, WAN, transport and global networks. In the case of trunk communication over long distances it is necessary to connect repeaters or amplifiers after certain sections. The distance between them depends on the type of optical fibre, type of source and optical detector and, last but not least, on the nature of the signal being transmitted.

Transmission of digital signal over optical fibres is seen as particularly advantageous. In comparison with metallic conductors it is necessary to respect certain differences, in particular the fact that light intensity cannot acquire negative values; this is the reason why the source of light must be modulated by unipolar code during transmission. For these reasons an optical link interface is inserted after the signal source or after the multiplex device, to be followed by optical cable.

If analogue modulation of the transmitter element is used, the relatively good linear dependence of transmission power on excitation current is used. The requirements for signal-to-noise ratio are substantially stricter in comparison with digital transmission. It is further necessary to take into consideration the linearity of attenuation and phase characteristics or the waveforms of differential gain and phase. In most cases the modulation of radiant intensity (AM-IM) or the frequency modulation is used. Analogue-type transmissions are used with advantage in image signal transmissions.

The basic schematic diagram of an optoelectronic telecommunication system is shown in Fig. 7.1. In the electrical part (E) of the system the signal being transmitted is adapted for input into the optical part (O), where the respective source of radiation emits information into the fibre. At the receiver side in the optical part (O) the light is converted by the respective optical detector back to electrical signal (E), which is then appropriately modified to correspond to the nature of input device.

![Fig. 7.1: Basic connection of optoelectronic system.](image)

In the case of longer distances between the terminal devices it is necessary to employ optical repeaters (see Fig. 7.2a). In the repeater, optical radiation is again converted to electrical signal, which is appropriately amplified, adapted and delivered to repeater output. The light source on the repeater output is again coupled to another section of optical fibre. In recent years, optical amplifiers (OA) (see Fig. 7.2b) have been introduced into practice, which amplify incoming optical radiation without converting it to electrical signal (e.g. the EDFA optical repeater, to be discussed in the following).
Fig. 7.2: Optoelectronic transmission system a) with repeater, b) with optical repeater.

On OLT (optical link terminals), repeaters and amplifiers the fibres are of course connected by means of connectors (not indicated in schematic diagrams, for simplicity). In this way the basic unidirectional optoelectronic transmission has been described. Since in most cases two-way transmission is required, it is necessary to use two fibres between the input (A) and the output (B). A schematic representation is given in Fig. 7.3.

Fig. 7.3: Two-way optoelectronic transmission.

Another solution can be had, when using two wavelengths, $\lambda_1$ and $\lambda_2$, for A-B and B-A directions for transmission over a single fibre (so-called wavelength division multiplexing). This solution is illustrated in Fig. 7.4.

Fig. 7.4: Two-way optoelectronic transmission with wavelength multiplex.

Further increases of transmission capacity potentials in the case of optical fibre transmission are feasible if multiplexers are used.
There are three methods of simultaneous transmission:
- electrical multiplex, which is the most widely used method in telecommunication practice, when the signal is first electrically multiplexed and then transmitted over optical fibre (see Fig. 7.5),

![Fig. 7.5: Electrical multiplex.](image)

- wavelength multiplex, in which several radiation sources of different wavelengths are coupled to a single optical fibre for the purpose of transmission (see Fig. 7.6),

![Fig. 7.6: Wavelength multiplex.](image)

- fibre multiplex, where each signal has its own fibre (this is justified by the micro-dimensions of separate fibres – see Fig. 7.7),

![Fig. 7.7: Fibre multiplex.](image)
Comparing these three multiplexes it can be said that the electrical multiplex is currently the most frequently used. The wavelength multiplex exceeds the electrical multiplex as regards capacity but it is very demanding as regards the technology of the components used.

The above examples form the basis of optoelectronic telecommunication systems. Systems that operate on their basis are higher-order digital systems, analogue systems, broadband systems (enabling both voice and video transmission), data transfer systems, etc. They are used not only in telecommunications but also in other sectors such as transport, automation, power engineering, etc.

In view of the application of these systems it is obvious that besides transmission parameters their reliability, supervision, location and error suppression must also be dealt with.

In the following sub-chapters we will be concerned with the basic problems of these systems and made familiar with some real systems.

### 7.1 Basic problems of optoelectronic systems

In this part we will outline some important problems concerning the reliable operation of optoelectronic systems. From a systems point of view, there are the following options in the design of a real device.

- **Type of signal being transmitted, from the viewpoint of the system:**
  a) Digital
    - corresponding bit error rate,
    - bit rate.
  b) Analogue
    - corresponding width of transmitted band,
    - distortion.
  c) Radio
    - corresponding width of transmitted band,
    - distortion.
  d) Image
    - width of transmitted band,
    - distortion.

In all the above cases it is necessary to consider the range of operating temperatures. **Transmitter parameters:**

- input impedance,
- maximum values of input signal,
- radiation wavelength,
- value of optical power,
- corresponding power of supply source.
Radiation source parameters:
- radiation wavelength,
- spectral bandwidth,
- forward current,
- overall optical power,
- range of operating temperatures,
- rise time and fall time.

Fibre parameters:
- type of fibre,
- refractive index,
- fibre attenuation,
- numerical aperture,
- distortion,
- jacket and core diameters,
- mechanical properties of fibre.

Cable parameters:
- number of fibres (groups),
- diameter of fibre with coating,
- cable diameter,
- weight (in kilograms per kilometre),
- minimum bend diameter.

Detector parameters:
- forward current,
- operating wavelength,
- output power,
- range of operating temperatures,
- rise time and fall time.

Receiver parameters:
- output impedance,
- input level of signal,
- optical sensitivity,
- dynamic range,
- rise time of output signal (analogue, digital),
- corresponding power of supply source.

It is obvious from the above overview that when designing a system it is necessary to take into consideration many factors. In the first place, it is necessary to know the nature of
information signal, i.e. digital or analogue signal. Another important factor is the route length, i.e. the distance between the transmitter and the receiver. Signal parameters need to be known too. What is a sufficient signal-to-noise ratio in the case of analogue signal? What is the bit error rate in digital signal? If the basic parameters are known, it is possible to proceed with the design of the system.

The design of an optoelectronic system is based on the following steps:
- determination of the type of signal for information transmission,
- definition of the bandwidth,
- determination of the signal-to-noise ratio if analogue signal is used,
- definition of the probability of error occurrence if analogue signal is used,
- definition of the probability of error occurrence if digital signal is used (the minimum value for digital transmission is $P_E = 10^{-9}$),
- determination of transmission length,
- selection of suitable optical fibre with respect to splice attenuation,
- calculation of the fibre bandwidth for the system under consideration (the value is in terms of MHz·km$^{-1}$),
- calculation of the power reserve (difference between output power and input sensitivity of receiver),
- determination of overall fibre attenuation with respect to length,
- addition of losses on connectors,
- addition of losses on splices,
- reserve for temperature changes (1 dB),
- reserve for time changes (2 dB),
- the sum of the above attenuations gives the total system attenuation

$$P_D = P_Z - (P_{K1} + P_{01} + P_{SP} + P_{02} + P_{K2} + P_R),$$ (7.1)

where $P_D$ is the detector power, $P_Z$ is the source power, $P_{K1,K2}$ are the losses on the connectors, $P_{01,02}$ are the attenuation losses in the fibre, $P_{SP}$ are the losses on the splice, and $P_R$ is the reserve of the system (temperature and time reserves). Also taken into consideration are losses given by the optical source-fibre and fibre-detector junctions; sources and detectors are currently manufactured directly with fibre and detector, as a single component. Attenuation conditions are illustrated in Fig. 7.8.
The suitability of the system design is assessed with respect to the minimum value of the system’s reserve \( R_R \) in the distance between the transmitter and the receiver: in the case of negative result it is necessary to change the transmitter and receiver parameters, in particular improve receiver sensitivity; further possibilities include choosing a fibre with lower attenuation, reducing the number of splices and connectors or using the repeater-amplifier.

The last step consists in determining the value of dispersion on the whole splice, i.e. getting to know the pulse broadening after its passage through the system (in the first place it is necessary to take into consideration the source of radiation, fibre dispersion, material dispersion, and optical detector). These critical values are used to determine the average value, which is in practice multiplied by the coefficient 1.1 or 110% according to the following expression

\[
D = 1.1 \left( T_1^2 + T_2^2 + T_3^2 + T_4^2 + \ldots \right)^{\frac{1}{2}}.
\]  

(7.2)

### 7.2 Transmitter and receiver parts of optical system

Optical sources and detectors were dealt with in detail in Chapters 5. For practical application, these elements have to be complemented with appropriate circuits.

An example of a simple circuit for digital signal transmission is given in Fig. 7.9. The digital signal on the input passes directly through a LED, which is the source of radiation.

At the receiver side it is necessary to tackle the problem of modulation amplifier of the non-linearity of light emitting diode, which is most frequently obtained via negative feedback or compensation in forward direction.
Fig. 7.9: LED connection for modulation of digital signal.

The circuit with feedback is shown in Fig. 7.10.

Fig. 7.10: Modulation amplifier with feedback.

The feedback is obtained directly from the photodiode via resistor $R_z$ while current in the LED is set by choosing $R_i$. In the case of high frequencies there may be problems with the feedback loop.

Optical compensation in the forward direction is based on the principle of distortion component of a signal appearing in a non-linear element and its subsequent addition as an error signal in the optical coupler.

An example of possible laser diode circuit is given in Fig. 7.11. This connection is more complex because it requires permanent excitation of the laser and it is only to this value that the modulation pulse pattern is superimposed. Such a connection enables increased switching rate and, at the same time, suppresses the susceptibility to overshoots in output light pulses. Laser diodes are further dependent on temperature and aging. The connection therefore includes a feedback loop, which controls the value of quiescent current or, depending on the modulation depth, also the amplitude of modulation pulses. The quiescent current of laser diode is controlled in dependence on the average transmitted optical power. Lest the control current should increase the quiescent current above the threshold value in the absence of
modulation signal, the detector output is compared with the reference voltage derived from the modulation signal.

Fig. 7.11: Modulation amplifier for laser diode.

For practical reasons the whole modulation amplifier is usually implemented by one hybrid circuit with preset elements and the optical fibre led out. End-user’s work is thus limited to connecting to the fibre, which is mostly done using a connector.

The receiver part of optical system in the basic block-type execution is shown in Fig. 7.12. It consists of a photodetector, low-noise pre-amplifier, amplifier, and filter. Automatic gain control by feedback is often led out to the photodetector.

Fig. 7.12: Schematic diagram of optical receiver.

From the viewpoint of the receiver as a whole we are primarily interested in the noise problematic. In the receiver there is quantum noise (given by the primary detection process), noise caused by photodetector (multiplication noise, dark current, surface leakage, series resistance of photodetector), and noise caused by the subsequent amplifier. In many cases the predominant component is the noise caused by the subsequent amplifier, in which case it is of advantage to use for the detection photodetectors with internal avalanche amplification. Because amplification by avalanche photodiodes is of statistical nature, noise at the output is multiplied on the one hand by the multiplication factor $M$ but also by another additive factor $F$, which is a function of $M$. It can be derived and it approximately holds that while signal
power is multiplied by $M^2$, noise in silicon diodes is multiplied by $M^{2.3}$ and in germanium diodes by $M^3$.

![Equivalent diagram of input circuit of receiver.](image)

**Fig. 7.13**: Equivalent diagram of input circuit of receiver.

Equivalent diagram of the input circuit of optical signal receiver with direct detection is given in **Fig. 7.13**. It consists of a photodetector with internal amplification $M$ and a load circuit. For the signal-to-noise ratio it holds

$$
\frac{P_s}{P_n} = \left( \frac{1}{2} \left( m I_s \right)^2 \left| M(\omega) \right|^2 \right)
\left[ 2q \left( I_t + I_b + I_d \right) M(\omega)^2 F(M) + 4K \frac{v_{et}}{R_{eq}} \Delta f \right],
$$

(7.3)

where $P_s/P_n$ is the ratio of signal power to noise power,

$m$ is the modulation index,

$M(\omega)$ is the multiplication factor of photodiode,

$i_s$ is the photoelectric current (of both signal and background) (A),

$I_t$ is the current excited by signal (A),

$I_b$ is the current excited by background,

$I_d$ is the photodetector dark current (A),

$\Delta f$ is the electrical bandwidth of detection system (s$^{-1}$),

$F(M)$ is the factor of noise increase due to internal amplification process,

$R_{eq}$ is the equivalent resistance of photodetector and input circuit of amplifier ($\Omega$),

$v_{et}$ is the effective thermal noise, inclusive of thermal noise of detector, load resistance, and subsequent amplifier (K),

$I_v^2$ is the average quadratic value of noise spike

$I_v^2 = 2q \left( I_t + I_b + I_d \right) \Delta f$,

$I^2$ is the effective value of the square of thermal noise $I^2 = 4k \frac{v_{ef}}{R_{eq}} \Delta f$,

$q$ is the elementary charge $1.6 \cdot 10^{-19}$ C.

Relation (7.3) can be used to determine the minimum $P_s/P_n$ ratio in dependence on the multiplication factor $M$, with which the noise spike caused by the average optical signal, background and dark current is multiplied to a level identical to the level of the thermal noise.
of subsequent amplifier. The calculation can also be made for photodiodes without internal amplification, in which case $M = 1$.

The $P_s/P_n$ ratio is an important value in the design of optical system. In view of the absolute level of optical signal powers this ratio is a limiting factor from the viewpoint of the cut-off frequency of the system. This dependence is for the PIN photodetector shown in Fig. 7.14.

![Dependence of required average optical power at receiver input on frequency with $P_s/P_n$ parameter for PIN photodiode.](image)

**Fig. 7.14:** Dependence of required average optical power at receiver input on frequency with $P_s/P_n$ parameter for PIN photodiode.

For the case when an avalanche photodiode is used as the detector, the dependence is shown in Fig. 7.15.
Comparing the dependence in the two cases makes it obvious that the avalanche photodiode is in the design of optical system of greater advantage. In analogue signal transmission the required signal-to-noise ratio is 40 to 60 dB. From the known optical power at the receiver output and the optical route attenuation the maximum spanning distance can be determined.

In digital signal transmission we again start from the equivalent diagram of receiver; with all the sources of noise taken into consideration the minimum required energy of input optical pulse for a given error probability is determined. Also, the problem of optimum shape of input pulse needs to be considered. It follows from the above considerations that the optimum receiver properties can be obtained if a pre-amplifier with high input impedance, a photodetector, and a pre-amplifier with the lowest possible capacitance are used. The drop in attenuation characteristic caused by the integrating member at receiver input (capacitance of photodiode and pre-amplifier, input resistance of pre-amplifier) must be balanced after partial amplification. These so-called integration amplifiers are most frequently found with PIN-FET combination at the output and are used for wavelengths of 1.2 to 1.6 µm. The amplifier enables obtaining maximum sensitivity but in view of the fact that signals are integrated at its input, the amplifier is followed by a group-delay equalizer, which somewhat degrades the noise conditions.

For wavelengths of 0.8 to 0.9 µm the transimpedance amplifier (feedback amplifier connected as current transducer) is mostly used, whose sensitivity is 1 to 2 dB lower but its dynamic range is greater and thus there is no need to use a group-delay equalizer. The amplifier can be implemented on a chip together with silicon PIN diode.
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7.3 Optical link codes

The selection of an appropriate code is an important step in the design of systems with optical fibres. The simplest solution would be to choose the same codes as for metallic lines. Light, however, has a peculiar property in that it cannot have negative values as is the case in standard codes. The negative polarity of AMI or HDB3 bipolar codes thus cannot be represented directly but in a round-about way: either by a ternary code with permanent bias voltage or by a unipolar code with information content higher than or equal to the ternary code. Another possibility is to convert bipolar signal to its equivalent binary form with subsequent transition to a suitable link code.

The selection itself and the design of code are part of the overall conception of the transmission system. The codes currently form a relatively large category so that proposing a new coding rule for a new system is practically out of the question. The following requirements are put on a link signal generated on the basis of a given rule:

- high content of the clock cycle component,
- constant dc component,
- minimum bandwidth,
- simple detection of bit error rate,
- simple encoder and decoder circuitry,
- system compatibility.

Because of the nature of optical transmission, there are additional requirements: power and linearity of the modulation characteristic of radiation source, attenuation and bandwidth of optical cable, sensitivity and noise conditions of radiation detector.

Because of their simplicity the NRZ (no return to zero) and RZ (return to zero) codes are frequently used. To eliminate the long sequence of zeros and ones an encoding and
a decoding device is installed in the transmitter and receiver, where code rewriting takes place. Automatic measurement of the coefficient of bit error rate is performed via parity check sum.

Higher-order signals are transmitted using the mBnB codes, in which each word of the message being transmitted, $m$ bits long, is recoded via a defined rule into an $n$-bit word ($n > m$).

For example, for second-order transmission systems type 1B2B link code has been chosen, which requires a two-fold transmission bandwidth but its solution of the encoder and decoder circuitry is relatively simple.

In the selection of the type of 1B2B code the following codes can be considered: CMI (Codec Mark Inversion), DMI (Differential Mark Inversion), MCMI (Modified CMI) and MDMI (Modified DMI). An example of the waveforms of link codes is given in Fig. 7.17.

![Waveforms of link codes](image)

**Fig. 7.17:** Waveforms of link codes.

It follows from the definition of codes that the CMI and DMI codes are assigned to the binary code while the MCMI and MDMI codes are assigned directly to the HDB3 code. On the basis of an analysis of the functional diagrams of code converters the application of the 1B2B code with direct assignment to HDB3 has been found advantageous. When choosing
between the MCMI code and the MDMI code it is preferable to choose the MCMI code because the clock phase signal $T$ is directly coupled to the trailing edge of MCMI signal (see Fig. 7.17).

The MCMI link code is used by many manufacturers (Siemens for example) in digital systems. A comparison of the normalized spectrum of MCMI code with other codes is given in Fig. 7.18, where $P$ is the average power, and $f = 1 \cdot T^{-1} = 8448$ kHz.

![Fig. 7.18: Normalized power spectrum for different codes.](image)

Type mBnB codes form a range of codes. Code efficiency is calculated using the relation

$$\eta_K = \frac{n}{n+1} \cdot 100\%$$

(7.4)

It increases with increasing $n$. The efficiency of the 1B2B code is thus 50%. With higher $n$ the efficiency increases less than the cost of converter implementation. When writing this link code, $2^5$ code combinations of five-bit words must be encoded in six-bit words, i.e. $2^6$ combinations. The writing of the code proceeds such that each five-bit code combination is assigned two code combinations, preferably in such a way that one combination is a positive word (the number of ones in a six-bit word is greater than the number of zeros) and the other combination is a negative word (the number of ones is smaller than the number of zeros).

The so-called running digital sum (RDS) is the parameter of the word created. It can be established using the relation

$$RDS_{(i)} = \sum_{n=1}^{i} b_n + RDS_{(0)} \cdot b_n = +1: -1,$$

(7.5)

where $b_n$ has the value +1 when the code mark has the value “1”; $b_n$ has the value -1 when the code mark has the value “0”. $RDS_0$ expresses a suitably chosen initial value. If RDS at the end of the word is negative, the following word is transmitted with the positive sign, and vice versa. In this way a constant unidirectional value is ensured during signal transfer.
Six-bit words are formed such that the average multiplication coefficient of error is as small as possible, which assumes the least possible difference between the input signal and the output signal when an error occurs in the transmission.

### 7.4 Optical link range

The range of optical link depends on the attenuation of optical fibre, on the type of optical source and detector, on splices, magnitude of system reserve, temperature, etc. The range of optoelectronic link is then given by the size of repeater spacing section and the number of repeater amplifiers or optical amplifiers.

The design starts from the length of optical link, to which the respective corresponding type of fibre is assigned, respecting, of course, the respective bandwidth. When choosing the type of fibre, it should already be clear what wavelength the system is to be operated on. Then the source and radiation detector need to be selected. Last but not least, it is necessary to decide on the kind of modulation and coding.

When LD and LED are compared as sources of radiation, LD has a higher power coupled to the fibre and, also, the smaller spectral width balances the substantially shorter lifetime of laser sources. PIN photodiodes and APD avalanche photodiodes are used as detectors in receivers. Because in many cases the predominant component in receivers in optoelectronic systems is the pre-amplifier noise, the application of APD increases the receiver sensitivity by about one order in comparison with PIN.

By combining the above sources and detectors of radiation, various link lengths are obtained. An example for the design of optical link can be seen in Table 8.1, where the possibility is considered of deploying an optical digital system with 34 Mbit·s⁻¹ transmission speed on wavelengths 0.85 μm and 1.3 μm for fibre GI, and 1.31 and 1.55 μm for fibre SM. Assumed cable lengths are 2000 m and an attenuation of 0.03 dB per splice is considered. From the results it is obvious that the maximum link length is in the case of LD-APD combination (see Tab. 7.1).

**Tab. 7.1**: Length of optical link for digital system 34 Mbit·s⁻¹ for different combinations of sources and detectors, and for different fibre types.

<table>
<thead>
<tr>
<th>Source and Detector Combination</th>
<th>LD/APD</th>
<th>LD/PIN</th>
<th>LED/APD</th>
<th>LED/PIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power of light source</td>
<td>+7 dBm</td>
<td>+7 dBm</td>
<td>0 dBm</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Average power of light source</td>
<td>+1 dBm</td>
<td>+1 dBm</td>
<td>-6 dBm</td>
<td>-6 dBm</td>
</tr>
<tr>
<td>Receiver sensitivity (P_E = 10⁻⁹)</td>
<td>-55 dBm</td>
<td>-40 dBm</td>
<td>-55 dBm</td>
<td>-40 dBm</td>
</tr>
<tr>
<td>Total attenuation</td>
<td>56 dBm</td>
<td>41 dBm</td>
<td>49 dBm</td>
<td>34 dBm</td>
</tr>
<tr>
<td>Connector losses</td>
<td>1.0 dBm</td>
<td>1.0 dBm</td>
<td>1.0 dBm</td>
<td>1.0 dBm</td>
</tr>
<tr>
<td>System’s reserve</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
</tr>
<tr>
<td>Length of link with fibre:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GI 0.85 μm, 3.5 dB.km⁻¹</td>
<td>15 km</td>
<td>10 km</td>
<td>13 km</td>
<td>8 km</td>
</tr>
<tr>
<td>GI 1.3 μm, 1.2 dB.km⁻¹</td>
<td>43 km</td>
<td>31 km</td>
<td>37 km</td>
<td>25 km</td>
</tr>
<tr>
<td>SM 1.31 μm, 0.7 dB.km⁻¹</td>
<td>74 km</td>
<td>53 km</td>
<td>64 km</td>
<td>43 km</td>
</tr>
<tr>
<td>SM 1.55 μm, 0.3 dB.km⁻¹</td>
<td>173 km</td>
<td>123 km</td>
<td>150 km</td>
<td>100 km</td>
</tr>
</tbody>
</table>
In an actual design it is important to know the dispersion values for the whole link, as discussed earlier. Of no less importance is the function of signal restoration and digital transmission check is of no less importance.

7.5 Deployment of optoelectronic systems

Up to now we have divided optoelectronic systems by their functional potentials but their division by distance and territory is also important.

When the link length is from the viewpoint of attenuation no longer satisfactory, it is imperative to employ repeaters or optical amplifiers. They need to be supplied and this brings certain complications in the case of optical fibre. To provide this supply it is necessary to either insert metallic conductors into the cable profile or choose the route such that there are sources at sites of expected repeaters. In the latter case the route is chosen in such a way that it goes through telecommunication objects.

When selecting the route, maximum use should be made of cable ducts, cable trenches, conduits, overhead lines, etc. If any “excavating” is done these days, it is advisable to lay a plastic pipe in the excavation, into which an optical cable can be pulled at some later stage.

Short-haul transmissions cover these areas: data transfer, computer-to-computer transfer, measuring technology, control of automated machines, airborne systems, military applications, etc.

Long-haul transmissions cover telecommunication trunk lines, submarine cables, long-haul data transmission, etc.

It is in digital signal transmission over great distances that the virtues of optical transmission stand out, namely very good transmission parameters, great functional reliability and low (and constantly decreasing) cost.

Problems that have been indicated above will be treated in detail in subsequent sub-chapters.

7.6 Optoelectronic link track of 8 Mbit·s⁻¹ digital system

The optoelectronic link track is designed for the transmission of digital signal at a transmission speed of 8.448 Mbit·s⁻¹ and enables the transmission of 120 telephone channels. In this country the system is deployed in conurbation networks.

The system is made up of eight first-order multiplexing devices (mul dexes) MX1, two second-order mul dexes MX₂, and one optoelectronic link tract OLT₂. The link track consists of two optoelectronic link terminations OLT₂, the transmission medium formed by optical cables, and second-order optoelectronic repeaters OO₂. The digital equipment complies with the CCITT G.742 recommendation while the interface of optoelectronic link termination complies with the G.703 recommendation.

The block diagram of optoelectronic link termination is shown in Fig. 7.19. In addition to the above mentioned transmission speed, the basic electrical characteristics include the HDB3 code (see Chapter 7.3), the shape and nominal voltage of pulses at the output, the maximum attenuation of the cable coupled to the optical link termination, cable impedance (non-symmetrical, 75 Ω), etc. The radiation source in the optoelectronic link tract is usually a laser diode, and the detector is an avalanche photodiode. The MCMI code is used as the link
code so that HDB3 to MCM and MCM to HDB3 code converters are necessary in the device.

**Fig. 7.19**: Schematic diagram of second-order digital optical system.

**Optoelectronic transmitter and receiver**

The basic problems concerning the optoelectronic transmitter and receiver were given in Chapter 7.2. In the design of circuit solution it is necessary to start from the basic information given there. Depending on the choice of LD and APD many variants of the circuit solution can be proposed, which in essence start from the same basis. When repeaters are used, the transmitter and receiver circuits are usually identical.

The functional schematic of optoelectronic receiver with avalanche photodiode is depicted in **Fig. 7.20**. Incoming optical signal is converted in the APD to electrical signal. With error occurrence probability $P_E = 10^{-9}$ the input sensitivity is ca. -55 dBm. The APD is supplied from a controlled source. The APD is followed by a low-noise pre-amplifier. Subsequent controlled amplifier has automatic gain control; to obtain a wider control range the voltage dependence of APD gain is also used for the control. The voltage for automatic control of amplifier gain is obtained via peak signal detection at the filter output, which determines the resultant frequency bandwidth. The last block after the filter is a threshold detector with output at the TTL level.

**Fig. 7.20**: Optoelectronic receiver circuit.

**Optoelectronic link termination**

The optoelectronic link termination is designed to connect the digital system muldex to the optical cable. Its task is also to convert the code prescribed at the multiplex interface (HDB3 code) to a link code that is suitable for transmission over optical route, and vice versa. Circuits for supervision and signal check form part of the link termination.

The functional schematic of optoelectronic link termination is given in **Fig. 7.21**. The input signal flows through the decision circuit to the regenerator of the shape and amplitude of the HDB3 signal. Automatic control in the input circuit enables connecting an arbitrary length
of station cable. The block designated FZ represents the circuit of the phase lock loop. Part of regenerated signal comes to the check circuit. The signal is then delivered into the HDB3/MCMI code converter. After the conversion of level TTL to ECL the subsequent amplification takes the signal to the “optical transmitter” to be coupled to the optical fibre.

In the receiving direction the signal comes from the optical fibre to the optical receiver, where optical radiation is converted to electric signal, which is then amplified, and the level of logical 0 or 1 is determined. Clock cycle signals are formed from the received signal and they are used for both the operation of regeneration circuits and the MCMI decoder. The decoder converts the binary signal to the signal of HDB3 code; subsequent amplification delivers the signal to the output of optical link termination, i.e. to the interface according to the respective recommendation ITU-T, G.703.

Check circuits (CC) serve the supervision and signal checking. Checking concerns the presence of input signal, the presence of output signal emitted into optical fibre, at the receiver side also the presence of signal from the optical route, error rate, and the supply for optoelectronic link termination (not shown in the schematic).

For example, if there is no signal within an interval of ≥250 s, the supervision circuit after the input turns on the disturbance signalling. Supervision of the laser is provided by connecting the LD block, which detects radiation and the respective circuits that monitor the 50% current difference against nominal values and raise urgent alarm. As regards the error rate of the code coming from the optical route, it is monitored according to the coding rule of the HDB3 code. This is made possible by using the MCMI/HDB3 code converter, which operates without transition via the binary signal form. If the code error rate is greater than $10^{-3}$, urgent alarm is raised; if the error rate is greater than $10^{-6}$ but less than $10^{-3}$, non-urgent alarm is raised.

The signalling of urgent and non-urgent signal is usually coupled to the alarm signalling unit of the rack; signalling is optical (LED) and acoustic.

**Optoelectronic repeater**

The optoelectronic repeater makes it possible to span large distances between the receiver and the transmitter in the digital system. One or more repeaters can be deployed, depending on the track length in both directions.
The functional schematic of repeater is given in Fig. 7.22. Here the input optical signal is converted to electric signal, amplified and regenerated. Then it is prepared for conversion to optical signal (the same circuits as in the optical link termination).

Repeater operation needs supply. Supply is either from a local source or by means of metallic conductors, which are attached in the cable core together with optical fibres. An example of the supply for the repeater and also remote supervision of the repeater is illustrated in Fig. 7.22. Using a metallic line, the laser output is signaled and checked and the repeater input is also checked, inclusive of the rate of error occurrence. In the repeater the MCMI code is again converted to the HDB3 code, which then initiates the respective circuits; after amplification and transmission over the metallic line it is evaluated as an alarm signal in the respective terminal station.

New elements, so-called optical amplifiers, have recently come to be applied in optical transmissions; they do not require the O/E and reverse E/O signal conversion. These are universal elements. They will be dealt with in greater detail in next chapter.

![Fig. 7.22: Schematic of optoelectronic repeater with remote supervision.](image)

### 7.7 Optoelectronic link track of 34 Mbit·s⁻¹ digital system

The digital optoelectronic track is designed for two-way transmission of digital signals at a transmission speed of 34.368 Mbit·s⁻¹ along two optical fibres. It is part of a third-order digital transmission system, which enables the transmission of 480 telephone channels, as well as transfer of data, radio modulation, and TV signal.

The optoelectronic track is formed by two third-order optoelectronic link terminations, optical medium, and, depending on the link length, repeaters. At each end the whole system is composed of 16 first-order multiplex devices, 4 second-order multiplex devices, and one third-order multiplex device.

The code prescribed for digital systems is HDB3 with a transmission speed of 34.368 Mbit·s⁻¹. The functional and electrical parameters of contact circuits for multiplex interface are defined in the ITU-T G.703 and G.823 recommendations.

Again, the optical transmitter and receiver are part of the link termination. The design of the termination is usually such that optoelectronic converters (LD, LED, APD, and PIN) and various transmission wavelengths can be changed easily.

**Optoelectronic link termination**

The functional schematic of the transmitter and receiver of optoelectronic link termination is given in Fig. 7.23.
The input signal (from the multiplex device) is delivered into the regenerative circuits of the HDB3 block, where the signal is first processed in an automatic corrector. Its task is to remove the frequency-dependent attenuation of the connecting cable between the multiplex device and the optoelectronic link termination and to obtain in the decision circuit a pulse shape that is optimum from the viewpoint of resistance to disturbance and symbol interference.

The signal is then converted to unipolar signal suitable for optical transmission and conducted via a scrambler to the HDB3/5B6B code converter.

The task of the scrambler is to convert the non-uniformly distributed ones and zeros of the binary block to pseudorandom signals with more or less uniform temporal distribution of energy. In the HDB3/5B6B coder the input signal is first converted in the HDB3/NRZ converter to NRZ code according to the coding algorithm.

The practical implementation of the NRZ/5B6B code converter is such that the signal encoded in NRZ is first delivered to a series/parallel converter. Five-bit parallel-arranged words come from the converter output to the addresses of PROM memory, where the conversion itself of five-bit words to six-bit words takes place. A parallel/series converter is inserted at the PROM memory output, which provides for the conversion of the six-bit word back to the series form.

Via the next block of the optical transmitter, information in the form of radiation is transmitted into the optical fibre. Time-base circuits, check circuits (CC), supervision circuits, supply circuits, etc. form part of the transmitter of optoelectronic link termination.

In the receiver the optical signal is converted back to an electrical signal, which is conducted to the amplifier whose gain can be controlled by the voltage of automatic sensitivity balance. In dependence on the optical power at the receiver input the gain is changed such that the level of output signal of optoelectronic receiver remains almost constant. The signal is then conveyed to a low-pass filter, which corrects the frequency response of optical receiver to an optimum from the viewpoint of symbol interference of output pulses. At the output of optical receiver we again obtain a unipolar signal encoded in 5B6B, at a level of 1 V and 75 Ω load, which characterizes the internal interface of the optoelectronic and electrical part of receiver.

The task of the next block of 5B6B code regeneration is the time, shape and amplitude regeneration of the signal of this code. The presence or absence of the signal is evaluated in the check circuit.
Analogously to the transmission side, the last three blocks are blocks that ensure decoding, i.e. the conversion of the 5B6B code, via descrambler, to the HDB3 code, which is required for the defined interface.

### 7.8 Optoelectronic link track of 140 Mbit·s⁻¹ digital system

The optoelectronic link track is designed for the 140 Mbit·s⁻¹ transmission speed, with transmission over gradient-index fibre or single-mode fibre, operating most frequently on the 1.31 μm wavelength. In the design it is essentially an analogy to the preceding solution.

Using the LD source and type GI fibre, repeater spacing of almost 30 km can be obtained; with the SI fibre the utmost limit is about 120 km.

Again in compliance with the ITU-T recommendations, the incoming input signal from the electrical interface, encoded in CMI, is corrected for transmission over optical fibre. For this reason the input signal is processed in the automatic corrector, regenerated, decoded, and conveyed to the scrambler. Then it is converted to the 5B6B binary link code. In the optoelectronic transmitter block the electrical signal is transformed into optical signal.

### 7.9 Optoelectronic link track of 565 Mbit·s⁻¹ digital system

Digital systems of the fifth order markedly enhance the economic aspect of information transmission but at the cost of more demanding requirements placed on the technical level of devices. These systems are suitable for long transport routes. Their transmission speed is 565 Mbit·s⁻¹, they are deployed on single-mode fibres, and they use the operating region of the 1.31 μm and 1.55 μm wavelengths. In essence, they are a multiplex of 4 systems of 140 Mbit·s⁻¹ transmission speed using the time or wavelength division multiplex. The application of single-mode fibre puts increased demands on coupling the radiation to the fibre, on connectors, splices, etc. On the other hand, the high transmission speed places high demands on the optical transmitter, which must generate pulses of extremely narrow spectral width.

The functional schematic of the system is given in Fig. 7.24. The multiplexer (MUX) mentioned earlier combines 4 x 140 Mbit·s⁻¹ systems; the remaining blocks are basically identical to the third-order system described above. The difference is only in the design of circuitry, which must provide higher transmission speeds. The application of scrambler (descrambler) is mostly limited and integrated to 140 Mbit·s⁻¹. Synchronization is performed via phase lock. Supply, signalling and supervision circuits also form part of the optoelectronic link termination.
The 565 Mbit·s⁻¹ transmission speed corresponds to 7680 telephone channels or eight colour TV channels.

Similar circuits for optical interface – OLT “plate” (optical link termination) are implemented for SDH systems, specifically for STM-1 with 0.155 Gbit·s⁻¹ transmission speed, STM-4 with 0.622 Gbit·s⁻¹ transmission speed, STM-16 with 2.5 Gbit·s⁻¹ transmission speed, possibly also STM-64 and STM-256 with 10 and 40 Gbit·s⁻¹ transmission speeds, respectively.

The design of OLT will, of course, be different from different manufacturers but at the inputs and outputs they must respect the relevant ITU standards. The dominant parameters are distortion and error rate, above all in dependence on the required higher transmission speeds.

Further increases in the transmission capacity of fibres in the order of tens of Gbit·s⁻¹ or more are implemented on the principles of wavelength multiplexes (see Chapter 7.16).

7.10 Optoelectronic systems for transmission of analogue modulation

Current world trends in the digitization of telecommunication networks give strong preference to the transmission of digital signals over optical fibres but even so the transmission of analogue signals has and will have its justification. In some respects the transmission of analogue signal over fibre is problematic while in the case of TV signal transmission its advantageous features stand out.

Problems appearing in the transmission of analogue signals arise from the non-linearity of elements. Under regular conditions in optical fibre with non-linear properties they need not be taken into consideration. Problems only begin to appear at higher powers. The case of detectors is in this respect similar. The main problem consists in the output characteristics of semiconductor sources of radiation. From the viewpoint of these transmissions it is imperative to linearize the operating part of the characteristic.

The most frequently used modulations are the direct intensity modulation IM and the pulse frequency modulation PFM – IM.

The IM method is suitable when power superluminescence diodes are used, which have a relatively good linear characteristic for less demanding applications, for example short-haul
links. For more demanding links (greater distance, higher frequency, TV signal) the characteristic of the system must be linearized, for example via preliminary correction of the distortion of diode excitation current, possibly by subsequent correction of distortion at the receiver output. Correction can also be performed by means of negative feedback.

A frequently used modulation is the above PFM modulation. It can be regarded as the counterpart of regular analogue frequency modulation where instead of the carrier frequency (of harmonic signal) a sequence of pulses is used. For systems with PFM modulation it is best to use a broadband receiver and, after detection, to apply the regeneration of individual signal pulses by means of limiter and monostable multivibrator before the pulse is conveyed to the input of low-pass filter. The schematic diagram of the suggested system is shown in Fig. 7.25. The input block (G) is a voltage-controlled generator whose output is formed by a sequence of rectangular pulses. The swing of repetition frequency \( f_g \) is controlled by the magnitude of input modulation voltage, i.e. \( f_g = k \cdot V_{\text{mod}} \). This generator has essentially the function of modulator. The exciter (B) is basically a power amplifier. The optical part is formed by an LD source, fibre with connectors, and APD photodiode. The optical detector is followed by the pre-amplifier, whose input circuit determines to a considerable degree the noise properties of the receiver. The pulse limiter and shaper come next. The shaper is formed by a monostable multivibrator and its task is to generate pulses of constant width, irrespective of their repetition frequency. The spectrum of this pulse sequence contains the modulation signal component that has been filtered on low-pass filter. The last block is the output image amplifier of the receiver.

![Fig. 7.25: Block diagram of analogue system with PFM modulation.](image)

In order to obtain a maximum signal-to-noise ratio it is appropriate to introduce the maximum possible \( \Delta f_g/f_g \) ratio, where \( f_g \) is the carrier frequency. In the system, the effect of noise shows as jitter, which causes a reduction in the signal-to-noise ratio. This ratio can be expressed by the relation

\[
\frac{S}{N} = \frac{3(T_0 \Delta f \cdot r \cdot M \cdot P_0)^2}{(2\pi B)^2 \cdot i_n^2},
\]

where \( T_0 \) is the (non-modulated) nominal value of pulse period, \( \Delta f \) is the frequency swing, \( r \) is the sensitivity of detection diode (A/W), \( M \) is the average value of photodiode gain, \( P_0 \) is the peak value of received optical power, \( \tau \) is the rise time of pulse front at the input into regenerative repeater. It results from the above relation that a large S/N ratio can be obtained with very short leading edges of detected pulses.
7.11 Optoelectronic systems for transmission of television signal

In the description of these systems it is in principle necessary to start from what was said in the preceding chapter in respect of analogue optoelectronic systems. The devices should comply with the ITU-T G.567 recommendation for the transmission of image information over TV channel. In the design of the system, the problem of non-linear characteristic of optical source comes again into the foreground. Direct intensity modulation cannot be adopted because this non-linearity is not adapted to the non-linear channel. The image signal is therefore first converted (modulated) to the 70 MHz frequency, which is then used to modulate the optical transmitter. To put it more precisely, the basic image signal band of 0 to 6 MHz is modulated to an intermediate frequency of 70 ± 4 MHz, and vice versa. It is only now that the transmitting optical element in the receiver block can be modulated by intensity modulation. For these purposes the GI fibre of 0.85 μm wavelength is used most frequently. An example of the system, its functional connection, is shown in Fig. 7.26.

![Fig. 7.26: Functional schematic of TV signal transmission over optical fibre.](image)

The receiving side, the optical radiation is converted back to intermediate frequency, which is then converted to the basic band in the demodulator. For the image signal transmission the signal quality is defined according to the S/N ratio at the receiver output according to the relation

\[
S/N = \frac{(2m P r a)^2}{2e P r B + i^2_{lep}}, \tag{7.7}
\]

where \(i^2_{lep}\) is the average value of thermal noise current, \(P\) is the average value of received optical power, \(m\) is the modulation index (ca. 0.8), \(r\) is the diode response (0.5 A/W for the PIN diode), \(a\) is the ratio of the brightness component of image signal to the total TV signal (0.7), and \(B\) is the receiver noise bandwidth (typically 5 – 6 MHz). From the practical viewpoint good results for the S/N ratio are obtained with input power into receiver \(P_s = 0.2 – 0.3\) W. Transmitted optical power \(P_t = 1\) mW can be considered. If connector losses of 1 dB and a system reserve of 6 dB are considered, an optical fibre attenuation of 28 dB can be considered, to which a distance of 7 km between transmitter and receiver would correspond in the case of GI fibre. The radiation source used is laser. If single-mode fibres are used, the spanning distance is increased.

7.12 Optoelectronic transmission systems for short distances

These systems are designed for (from the viewpoint of bandwidth and transmission speed) less demanding transmissions, in particular in local networks. The aim has been to design universal devices for the transmission of both analogue and digital signals, up a transmission rate of 2 or 8 Mbit·s\(^{-1}\), possibly also digital telephone transmission for four subscribers.
These systems are also designed for transmission over short distances. They make full use of the advantages of transmission via optical radiation and are designed for data (signal) transmission in computer and automation technologies, transport, and at sites with a high level of electromagnetic interference (high-voltage switching stations), etc.

These systems are designed as separate transmitter and receiver blocks, with dimensions slightly greater than a matchbox. Inputs and outputs are compatible with TTL logic; some systems are designed for the transmission of analogue signals. The source of radiation is usually an LED and the receiving element a PIN photodetector. The transmission range achieved is up to 1–3 km. Of course, other combinations of optical components can also be chosen. A schematic representation of the system can be seen in Fig. 7.27. Both the receiver and the transmitter are usually provided with connectors and thus to establish a link a connectorized optical fibre (cable) is only necessary.

![Fig. 7.27: Schematic representation of system for industrial applications.](image)

Some manufacturers make these blocks with multiplexers for several channels, mostly 8 to 16.

In some cases the signal is required to be divided into two (or more) directions or, on the contrary, to be combined. In such cases an optical splitter or coupler is connected between the transmitting and the receiving modules. An example of the case when it is necessary to transmit signals to two receivers is shown in Fig. 7.28, the reverse process is shown in Fig. 7.29.

![Fig. 7.28: Connection with signal split into two directions.](image)
With the current rapid development of automation in industries these systems gain in significance. Converters ELO and Exx are designed for both multimode and single-mode fibres. Links of 40 km in length can be achieved. Using the wavelength multiplexer a full duplex can be implemented over a single fibre. Repeaters (splitters) and options of connecting via RS interface, bus, USB port, etc. are on offer.

7.14 Local optical networks

Historically, the local optical network (LON) has evolved from the local area network (LAN), with the metallic transmission medium being replaced by optical fibre. Although the nature of the network does not change, there are certain differences, both advantages and drawbacks, inherent in optical transmission.

The local network as such refers to a transmission or communication system that guarantees data transmission among a theoretically infinite number of stations over a common transmission medium, and the whole of which is installed on the premises of a single user. These networks are mostly installed in industrial enterprises, schools, business companies, etc.

In comparison with metallic lines used in LAN (coaxial cables or shielded pair) the optical fibre offers higher transmission speeds, larger bandwidth, perfect resistance to electromagnetic interference, and galvanic separation of inputs and outputs. A disadvantage can be seen in the difficult splicing and in large optical power losses in directional couplers.

The local network can be characterized by the following basic criteria:
- transmission medium,
- transmission speed,
- network topology,
- method of user access to the network,
- architecture.

Transmission medium

Most frequently, multimode media of larger core diameter and larger numerical aperture are used. This choice will yield high-quality fixed and demountable fibre splices, easy handling, and effective coupling of radiant energy from radiation sources to the fibre. On the other hand, all this is at the expense of the attenuation values and bandwidth of such fibres. The dimensions of frequently used fibres are 50/125 µm, 62.5/125 µm, 100/140 µm, and
others. In some cases single-mode fibres are also used, in particular for larger distances and higher transmission speeds.

**Transmission speed**

According to transmission speed, local networks are divided into three groups:
- up to 10 Mbit/s (low-speed networks),
- up to 100 Mbit/s (medium-speed networks),
- over 100 Mbit/s (high-speed networks).

In low-speed networks the application of optical fibres cannot be seen as most advantageous, unless a medium with strong electromagnetic field is concerned or perfect galvanic separation of both ends is required. An important LON requirement is a low price of transmission facilities. For this reason the 850 nm operating wavelength is mostly used, with LED diodes as radiation sources and PIN diodes as receivers.

In medium-speed networks and, in particular, high-speed networks the pros of optical transmission become significant. It should be noted that maximum transmission speed is not identical to information throughput of the network. The actual values mainly depend on the network access methods and usually they are about 70% of the transmission speed given. With higher transmission speeds the integration of data, video, voice, and services can be taken into consideration.

**Network topology**

The fundamental question of network topology is the connection of the terminal (station). In the case of metallic conductors, high-impedance connection of terminals is possible, but this connection cannot be implemented optically because it results in extremely high power losses in the directional coupler. An example of passive connection to the terminal is shown in Fig. 7.30a. In the case of connecting several terminals it is necessary to use active connection, which is in essence formed by a repeater with connected terminal (see Fig. 7.30b).

![Fig. 7.30: Terminal connection a) passive, b) active.](image)

For small LON the passive star topology can be used. The principle is clear from Fig. 7.31. The active star topology can be implemented on a similar principle.
The ring topology is frequently used with advantage in LON. Examples of the passive and the active rings are given in Fig. 7.32 and Fig. 7.33, respectively. From the viewpoint of secure transmission it is of advantage to use ring topology with two fibres. The connection of terminal device to such a network is shown in Fig. 7.34. When there is a failure in the first fibre, operation is re-directed to the second, backup, fibre. In the case of fibre outage between terminals fibre looping (dashed line) is performed on neighbouring terminals and operation may continue without break. The optical relay in the figure provides for “bypassing” the terminal, be it for passivity reason or in the case of failure.

Fig. 7.31: Passive star topology.

Fig. 7.32: Passive ring topology.
Fig. 7.33: Active ring topology.

Fig. 7.34: Secured ring topology.

An example of typical optical bus is given in Fig. 7.35. The bus can also be implemented in the passive form.

Fig. 7.35: Bus topology.

So-called mixed topologies, implemented from passive and active topologies, are often used.

So-called hybrid topologies in local networks take advantage of metallic conductors for lower transmission speeds and lower network levels (buses) while for higher levels and higher transmission speeds they use optical fibres (ring topology). An example of this topology is given in Fig. 7.36.
In the design of topologies it is of advantage to give preference to the wavelength division multiplexer.

LAN are used with advantage in administrative buildings, institutes, schools, etc., where mixed and hybrid topologies find application, most frequently of the star-ring or star-bus type.

Network reliability is then one of the most important parameters.

**Access methods**

The term medium access control (MAC) is taken to mean a communication protocol that assures that the transmission capacity of a common transmission device is shared by and allocated to the connected active stations. MAC is a protocol of the physical layer or the link layer (will be dealt with later) and thus fundamentally influences the capacity of local networks.

Allocation of the time frame is one of the most widely used methods. The methods of user access to the network are divided into two groups: deterministic methods (when the sequence of network access is determined) and random methods. Two most frequently used deterministic methods are: method of allocating time frames to individual subscribers (Cambridge Ring), where each subscriber transmits a short message at a determined instant of time, and the so-called method of allocating the control token (Token Passing), when the right to transmit is passed among subscribers. This right is limited in time lest the subscriber should block the network.

The method of allocating time frames in the network requires a control station; the method of token passing does not require a control station but for a number of functions (determining the network clock cycle, equalizing the time shift, and coping with exceptional states) one station becomes the so-called active monitor.

The above methods have been standardized, e.g. the Token Passing method in ISO DIS 8802/4, DIS 8802/5. There are also methods with register insertion, selection methods, methods of call and reply, methods of time-division multiplexing (TDMA) and the method of rotating minipackets (ISO DIS 8802/7).
Random (stochastic) methods are referred to by abbreviations CSNA/CD or CSMA/CA (for Carrier–Sensing Multiple Access/Collision Detected or Collision Avoided) methods when collision is detected (or avoided) from the signal level, i.e. a situation when two subscribers simultaneously start transmitting. In optical networks collision is detected from the signal shape, not from the signal level. The methods are advantageous mainly for low-speed transmissions; at higher speeds the transmission redundancy is increased. From the viewpoint of network the bus and tree topologies are better suited to these methods. Standardization has taken place in this area too; for example, ISO DIS 8802/3 defines the CSMA/CD access method.

**Architecture**

Similar to data and computer networks, local networks start from the well-known ISO-OSI (Open Systems Interconnection) layer model. The model contains seven layers, the so-called physical, link, network, transport, relation, presentation, and application layers. Communication between systems takes place between identical layers while communication in the system takes place in the form simple commands and acknowledgements between the layer under consideration and the nearest higher and lower layers. The physical transmission medium itself is mostly included in the physical layer.

The OSI layer model was initially developed for data networks with packet commutation; for local networks there are some differences. In the first place, the link layer is different; it is divided into two parts (sub-layers). The lower layer is called medium access control (MAC) while the upper part (sub-layer) is the logic link control. In parallel with all the layers is the control of subscriber station (or the SMT/NMT network). At the input (output) of the LLC layer to the higher layer there must always be a buffer store. If the store is common for both receiving and transmitting transmissions, the so-called semiduplex architecture is concerned; if there are separate stores, the station has a duplex architecture. As regards the higher layers (relation, presentation, and application layers) they form part of the computer equipment of the network and in the local network they can be included in the intelligence of the devices served.

Let us now have a closer look at the lowest four layers:

**Physical layer**

The physical layer of LON includes the MAC (which may include CNL (connection of the type of CNL – connectionless)). The CNL service consists in the ability to transmit separate data units (blocks, packets, frames) from one source point of access service to one or more addressed source points of service access without establishing a connection. Another variant of the service, type CON (Connection Oriented), assumes establishing connection between stations. This solution assumes a larger header volume, the throughput of the network is reduced and the implementation is more demanding.

**Link layer**

Two types of link protocol are distinguished: logic link control LLC with CNL (type LLC 1) and CON (type LLC 2). Type CNL service is represented, for example, by the TOP/MAP architecture while LLC 2 is a costly and complicated protocol. The complicated header is compensated by high transmission speed and is not therefore critical.

**Network layer**

The well-known protocol X.25 is in this layer; it is of the CON type because of its universal application in public data networks. A counterpart to X.25 is the CNL network.
protocol designed in DIS 8473, where either the zero function (non-active protocol) or the full protocol can be chosen, depending on the type of functions that are to be provided.

*Transport layer*

Five classes of type CON protocol are defined in the recommendations (ISO 8073 and ITU-T X.24), which differ in the manner of providing different functions. The simplest is class 0 and is satisfactory in the case that the link layer protocol (LLC) provides the control of data flow, security, and multiplex. If terminal multiplexing is not available in the link layer, higher layers (2, 3 or 4) must be implemented. The selection of the class of transport protocol depends on the service provided by the network layer. In principle, if the network layer service is of the CON type, an arbitrary protocol can be used but preference is given to classes 0 and 2 because of header length minimization. For the CNL service only class 4 is necessary.

Type CNL transport protocol is the subject of standard proposal (DIS 8473) with two procedures: via the CNL network service and via the CON network service (optional).

The choice of layers and type of service (CNL/CON) is in principle a matter of application and a compromise between cost and performance. Disregarding the simplest solution based only on the physical layer, the basic LON variant may contain the second layer with LLC 1 or LLC 2 protocol (two variants). If the network or transport layer is included, again with type CON or CNL service, we obtain another 8 variants. Because of this potentially great number of variants it is in the case of LON suitable to perform a certain reduction in order to reduce the number of possibilities. The choice is made with a view to application needs in such a way that all the necessary functions are assured. For practical implementation, 4 to 8 out of 18 possible variants are recommended.

The simplest LON is built on the basis of type CON and CNL link protocols, which provide interconnection via a bridge for local networks. If large networks need to be interconnected, interconnecting in the network layer is more advantageous than in the transport layer. The best network protocol of the CON type is the X.25 packet protocol. The packet protocol also enables interconnecting with the public data network and, at the same time, implementing the higher layers of standard protocols without any or only minimum modification.

The development of technologies for LON keeps going on and new networks are constantly being put into operation. The most frequently occurring topologies today are active ring topologies with the deterministic access method and also passive star topologies with the stochastic access method. Active star topology with the CSMA/CD access method is also often used. In most cases the wavelength of the radiation of the first window, i.e. 0.85 μm is used but in the case of longer distances the region of the second window, i.e. 1.3 μm is used. Different wavelengths can be used also for the wavelength division multiplexer.

LD diodes are used as radiation sources for these extreme cases and for high-speed transmissions while LED diodes are mostly used for the other applications. The receivers are PIN or APD photodiodes.

Attenuation was reduced in both symmetrical and unsymmetrical T-, Y-, and X-directional couplers. In the region of passive star topology, type 100 x 100 matrix has been realized.

For the evaluation of the network the following parameters need to be taken into account:

- transmission speed,
- maximum span of network,
- topology, access method,
- probability of error occurrence,
- number of stations,
- number of terminals,
- code used (NRZ, RZ, Manchester),
- type of fibre,
- transmission window,
- type of radiation source and power (LD, LED),
- type of detector and its sensitivity (PIN PD, APD),
- couplers,
- switches (optical), reliability,
- network cost (last but not least).

Most of these parameters were discussed above, some of them in preceding chapters.

As regards reliability, it generally depends on several factors, above all on the transmission medium, topology and also on the access method and interface logic.

For the average time of network failure with active bus and \( n \) stations it holds

\[
T_s = \left(2(n-1)\lambda\right)^{-1},
\]

where \( \lambda \) is the failure density (includes transmitter, connector, fibre, connector, receiver).

The relation assumes that in the relevant range the error rate is characterized as an error rate with exponential distribution, i.e. with constant failure density.

For a network with ring topology the relation for average time between two failures holds

\[
T_s = \left(n\lambda\right)^{-1}.
\]

For the active star topology it holds

\[
T_s = \left((n+s)2\lambda\right)^{-1},
\]

where \( s \) is the number of repeaters in branches that need to be lengthened.

For the tree topology it holds

\[
T_s = \left(2s\lambda\right)^{-1},
\]

where \( s \) is in this case the number of strings used for the implementation of one half of the tree network.

For the active loop topology it holds for the average time between failures

\[
T_s = \left((2n-1)\lambda\right)^{-1}.
\]

In order to increase reliability, the network is often doubled.
Some practical implementations of local optical networks

C&C Net Loop 6830

This local optical network was designed by the Japanese company NEC Corporation. The doubled optical fibre network consists of a central station (CS) and several terminal data stations (TDS), which are interconnected by this network. The basic schematic of this ring topology is given in Fig. 7.37. CS mostly has the function of network control while TDS forms the interface for the connection of various terminal devices.

![Concept of NET LOOP 6830 network](image)

**Fig. 7.37:** Concept of NET LOOP 6830 network.

Basic characteristics of the network:
- transmission speed 32 Mbit·s\(^{-1}\),
- network range 2 km,
- double-ring topology,
- synchronous or asynchronous operation,
- maximum number of TDS stations 64,
- RZ code,
- multimode gradient fibre (50/125 \(\mu\)m),
- first transmission window,
- radiation source NDL 4103 A (NEC), GaAlAs DH LED,
- radiation detector NDL 2102 (NEC) Si PIN FD,
- error occurrence probability \(P_E = 10^{-10}\).

Transmission is realized using the TOKEN method, data are transferred by means of packets (HDLC procedures), and transmission of video signals is also possible.

Schematic diagram of the module of optical interface is given in Fig. 7.38.
Example of FDDI (Fibre Distributed Data Interface) network
FDDI defines ring topology LON with these parameters:
- transmission speed 100 Mbit$^{-1}$
- network range as much as 100 km,
- double-ring topology,
- maximum number of stations 500,
- code 4B/5B,
- gradient multimode fibre 62.5/125 $\mu$m or 85/125 $\mu$m,
- wavelength regions of first or second transmission windows,
- radiation source LED, LD,
- radiation detector PIN PD.

FDDI enables building a high-capacity bus of computers or other LAN networks on the premises of industrial plants, institutions, etc. The conversion of different protocols, speeds, data formats, etc. of these networks is performed by the so-called gateway. One variant of the FDDI network is shown in Fig. 7.39. As can be seen in the figure, various local networks are connected to this network (ETHERNET acc. to IEEE 802.3 recommendation, TOKEN RING acc. to IEEE 802.5 recommendation) as well as a private branch exchange (PBX). Building such networks enables easier integration of PBX exchanges and computers, and also simultaneous integration of LAN, LON and ISDN networks (integrated services digital network).
High transmission speed also enables creating links among computers, between computers and peripheral units (multiprocessor systems, systems CAD, CAE, and CAM) using the FDDI “Back-end” network.

When the double-ring topology is used, the second fibre is used not only for the reserve but also for transmission, and network throughput can thus be increased to 200 Mbit·s⁻¹. In practical implementations the first fibre mostly interconnects all the subscribers (primary line) while the second fibre interconnects only selected subscribers (secondary line), as shown in Fig. 7.40. Type A station (connection to both fibres) contains one MAC (Media Access Controller) block and two PHY/PMD (Physical Media Dependent) blocks, which provide connection to both fibres. Type B stations lack this feature; they can only be connected to one ring (1 MAC block and 1 PHY/PMD block). Type B stations are less important stations.

The cable itself contains two optical fibres provided with a connector. In the case of station A one fibre forms the above-mentioned primary network, the other fibre forms the
secondary network. In the case of station B the same cable transmits incoming signals along one fibre and outgoing signals along the other fibre.

When there is a failure in one fibre (not necessarily a mechanical failure, also increased error rate, etc.), operation passes onto the other fibre within a few milliseconds. When there is a failure in the cable between stations, alternate operation is chosen depending on the topology shown in Fig. 7.41.

![Fig. 7.41: Change in configuration in case of cable failure.](image)

FDDI uses the 4B5B code, which allows obtaining a lower modulation speed of 125 Mbit·s⁻¹ and using cheaper components, manufactured by the LED technology, in the implementation of the transmitter and receiver.

The network itself is formed by stations connected in series in closed ring. Information is successively transmitted from one station to another. The station has the right to transmit as soon as it receives the “carrier”, which is a special packet that circulates along the ring after the last information packet. Its format is given in Fig. 7.42. Each station in the network supervises the carrier circulation time, from which the network load can be inferred. In the case of heavy load it is possible to transmit only the group of high-priority packets (designated synchronous). The other transmissions can only take place when the circulation time of the “carrier” is shorter than an agreed time value.

<table>
<thead>
<tr>
<th>PA</th>
<th>SD</th>
<th>FC</th>
<th>DA</th>
<th>SA</th>
<th>INFO</th>
<th>FCS</th>
<th>EDF</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INFORMATION STORAGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>PA</th>
<th>SD</th>
<th>FC</th>
<th>EDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARRIER</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 7.42: Carrier and information packet formats:** PA – PREAMBLE separator for synchronous receivers, SD – separator for indicating the packet beginning, FC – control bits for ensuring priority access to transmission medium, DA – address of station receiver, SA – address of station transmitter, INFO – information (data, 4500 bytes at the most), FCS – protection, EDF – separator for indicating the end of transmitting information, EDT – separator for indicating the end of transmission on the carrier, FS – control bits for indication of transmission errors.
The time of “carrier” run $t_{RT}$ is directly proportional to the operational load on the ring. For ordinary operation it is guaranteed that the value of $t_{RT}$ never exceeds $2 \cdot t_{opr}$ ($t_{opr}$ is the reference quantity of carrier circulation). Stations with synchronous operation are guaranteed at least one transmission in every interval $2 \cdot t_{opr}$.

The total synchronous operational load is given by the sum of synchronous operational loads of all stations. If $t_{RT} < t_{opr}$ the operational load is small and at that moment asynchronous operation can start. Operation importance is given by the priorities. This solution of time supervision represents a simple and efficient means of controlling the operation on the ring, with the possibility of dynamic priority in dependence on operational load.

All failure functions are revealed when $t_{RT} > 2 \cdot t_{opr}$. In such cases it is necessary to launch procedures for failure localization as well as procedures for network reconfiguration.

The circuits AM 7984 and AM 7985 implement the functions of the PHY block, i.e. parallel-to-series data conversion for optical transmitter, series-to-parallel data conversion, 4B/5B coding, and compensation of the time shift of synchronization clock pulses.

The circuit AM 79083 implements access to transmission medium, inclusive of carrier restoration. It contains the detector and address generator, register of normal and error reports from transmission medium, generator and canceller of own carriers, detector and generator of CRC protection polynomial, and register of status word and failure states.

FDDI is a powerful network that offers great possibilities and was expected to become number one in LON but it failed to achieve supremacy. Specific design elements for this network (optical cables, connectors) were to have ensured the production of and market for these elements but the development took an easier path – towards Ethernet.

**LON FIBERCOM**

This local optical network is designed for industrial applications, offices, laboratories, schools, the military, and others, enabling mutual interconnection of microcomputers, PC, terminals, printers, modems, and other devices provided with standard interface. It is a follow-up to the Ethernet standard, i.e. a compatible device.

Basic network characteristics:
- transmission speed 100 Mbit\cdot s^{-1},
- network range 2 km,
- ring topology,
- maximum number of stations 1024,
- access method CSMA/CD,
- compatible operating systems: MS-DOS, CP[M, Unix,
- gateways: SNA/SDLC, Ethernet, X.25, HDLC.

The network is shown in Fig. 7.43.
7.15 Current trends in optical access networks

The development of new technologies and related telecommunication services makes increasing demands on the transmission speed. One of the means of providing the required bandwidth is the application of optical technologies and installing optical access networks (OAN). For the end user this connection an abbreviation has appeared that is increasingly used today, namely FTTx (Fibre to the...), which refers to the solution of access networks exactly on the basis of optical fibres. It is obvious that optical transmission will predominate also in access networks, as is the case in Japan, for example. A common technical solution of this situation will employ just the above-mentioned FTTx, which will be dealt with in the next chapter. Optical access networks gradually cease to be the preserve of big companies (FTTO – fibre to the office) and data centres. The situation is beginning to change and the all-pervasive Ethernet technology has a chance of advancing the development also in this area. Although the development of future access networks is bound to differ depending on the specific operator, country, etc., it is obvious that in the long run they will be based on optical technologies. Thanks to the FTTx technology, optical fibre will spread from backbone to access networks and to the end user.

A number of optical transmission solutions are available from different vendors today, from simple electro-optical converters (media converters) through AON to APON, GPON and EPON. In the following text the suitability of point-to-point or multipoint solution for diverse applications will be discussed. In the case of passive optical networks there is the dilemma of whether to use the GPON conception in accordance with the ITU-T recommendation or the Ethernet-based EPON (sometimes also GEPON). Although the cost of optical network components is in general gradually falling, in our local conditions it still represents a formidable barrier. Which solution is then better? The answer depends on many factors, including the existing infrastructure, bandwidth requirements and requirements on services the network will offer.

Optical solution can be based on transmission between two points (point-to-point, PTP, P2P) with individual fibres from the operator’s central unit or on branching with the application of intermediate active elements (AON) or on multipoint architecture (point-to-multipoint – PTMP, P2MP) with passive branching (PON). Each of the above solutions can use either two fibres, i.e. separately for each transmission direction, or one fibre with wavelength division, i.e. with wavelengths reserved for each transmission direction.
PON (Passive Optical Network)

Passive optical network (PON) is composed of OLT (Optical Line Termination) located in the CO (Central Office) and a set of interconnected ONT (Optical Network Terminal), which serve to terminate the fibre and convert optical signal to electric signal (usually located on the customer’s premises). Both devices (PLT and ONT) require voltage supply. PON got its name due to the fact that on the route between OLT and ONT it does not use active elements that need to be supplied but uses splitters and couplers to divide and distribute the fiber transmission capacity among end users – usually 32 end users over a distance of 10-20 km. And since this is a shared network, it is sometimes also referred to as P2MP (Point To Multipoint).

AON (Active Optical Network)

Active optical network (AON) is very similar to passive optical network (PON) although there are three main differences. Along the route it does not use passive elements; it uses elements of the Ethernet network for outdoor application, which provide access to the fibre and aggregation.

Instead of sharing the transmission bandwidth among several end users, this solution prefers a reserved channel for each user so that the channel is fully bidirectional, unlike in ADSL, where upload does not equal download. Because of its technology, this architecture is often referred to as P2P (Point To Point).

The third difference in comparison with PON is the maximum route length. In PON the most remote end user must be 10 to 20 km from CO (in dependence on concrete conditions and the number of splitters used). On the other hand, the distance limit for AON is ca. 80 km, in dependence on the number of users that are to be served. In this case the number of users is given by the number of switches used and not by the infrastructure itself, as was the case of PON.

The basic functional units forming the optical access network are:
- Optical line termination (OLT), which is provided by the function of network interface between the access network and the network providing telecommunication services,
- Optical distribution network (ODN), which is a set of optical transmission devices between OLT and ONU,
- Optical network units (ONU), which provide the functions of interface between the optical and the metallic parts of access networks,
- Optical network terminals (ONT), which provide the functions of subscriber interface between subscriber terminals and access network (VoIP, video, data), see Fig. 7.44.

Fig. 7.44: Block diagram of access network.

From the viewpoint of optical network units (ONU) in optical access networks and the manner of their execution, i.e. depending on where in the network the optical fibre is terminated, different types of optical access networks are distinguished; the following are usually given as the basic types:
- FTTC (Fibre To The Curb), optical fibres are brought to the subscriber’s optical switchbox and the terminal points of the network are connected to it via metallic cables,
- FTTB (Fibre To The Building), optical fibres are brought to the subscribers’ buildings and individual subscribers are connected via internal network,
- FTTO (Fibre To The Office), optical fibres are brought to a device (PC),
- FTTH (Fibre To The Home), optical fibres are brought as far as subscriber sockets,
- FTTCab (Fibre To The Cabinet), optical fibres are brought to rooms of subscribers with great demands for transmission capacity.

The main function of access networks consists in providing transport services in the duplex mode. Signal transmission in both directions can be provided in several ways:
- *Simplex with SDM (Space Division Multiplex)*; transmission in either direction is provided along one optical fibre,
- *Duplex with WDM (Wavelength Division Multiplex)*; along one optical fibre, with 1550 nm wavelength for downstream, and 1310 nm wavelength for upstream,
- *Duplex with FDM (Frequency Division Multiplex)*; one optical fibre and one wavelength are used for signal transmission in both directions, transmission directions are frequency-divided.

The parameter that determines the nature of access network is the type of transmission track used in the distribution part of network:
- point-point P2P (Point-to-Point), e.g. direct connection of OLT and ONT,
- multipoint P2M (Point-to-Multipoint), e.g. passive optical network.

*Optical splitters*

Optical splitters are network elements that enable optical transmission medium to be shared by a great number of subscribers. In the FTTH systems, which are operated in PON networks, they are usually bidirectional passive elements that have one input port and several (2 – 128) output ports. In downstream direction, the signal coming from the OLT to the input port of splitter is divided into the required number of partial signals, which are then distributed via output ports to individual ONU units. In the opposite (upstream) direction the splitter combines the signals coming from individual ONU units into a single signal, which is further distributed to OLT.

Splitters are passive network elements that only perform the splitting or merging of optical signals, without any further modification. Depending on the type and manufacturing technology, they can operate either in a certain transmission band or over its whole width. Using a splitter will insert attenuation in the optical route, whose value depends on the number of output ports and is given in dB, see Table 8.2 (for a division ratio of 1:32)].

**Tab. 7.2:** Values of insertion attenuation for PLC splitter Telecordia GR-1209.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>1 x 4</th>
<th>1 x 8</th>
<th>1 x 16</th>
<th>1 x 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>1260 – 1650</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of insertion attenuation [dB]</td>
<td>6,6</td>
<td>9,8</td>
<td>12,7</td>
<td>15,8</td>
</tr>
<tr>
<td>Maximum value of insertion attenuation [dB]</td>
<td>7,1</td>
<td>10,2</td>
<td>13,2</td>
<td>16,6</td>
</tr>
</tbody>
</table>
Splitters can be cascaded in dependence on network topology. But it is necessary to comply with the ITU-T recommendations, which regulate the attenuation values inserted in the optical route due to splitter application.

The application and deployment of these passive splitters is of advantage (in comparison with active elements) because it is not necessary to solve the problem of supply along the optical route.

According to manufacturing technology, splitters can be divided into two groups:
- PLC (Planar Lightwave Circuit),
- FBT (Fused Bionic Taper).

PLC splitters are manufactured using the planar technology. By means of a technological procedure the required structure is produced on silicon substrate. Using this technology, splitters with as many as 128 output ports can be manufactured. This technology is used for splitters with a higher number of output ports (see Fig. 7.45). Manufacturers: SQS-FIBER.

FBT splitters are made by splicing optical fibres at a high temperature and pressure, when the fibre jackets get fused and the cores of the fibres being spliced get very close to each other. This technology is used to manufacture bundles of 2 to 4 fibres; to have a greater number of ports, the fibres are cascaded. This technology is mainly used for a smaller number of output ports (see Fig. 7.45). Manufacturers: OPTOKON.

![Principles of splitter](image)

**Fig. 7.45:** Principles of splitter a) PLC technology, b) FBT technology.

*Specification of PON networks for FTTx systems*

In the year 1995, seven largest world telecommunications operators formed a corporation called Full Service Access Network (FSAN), whose goal was to standardize and develop PON networks. The specifications were designed such that they provided for the users full broadband services such as transmission of voice, data, and video. The following wavelengths were assigned by the FSAN organization for the distribution of these services: For downstream transmission of voice and data the 1490 nm wavelength, for upstream transmission of the same the 1310 nm wavelength. For downstream transmission of video the 1550 nm wavelength was assigned.

*APON, BPON*

Specification G.983.1 APON (ATM Based PON) was approved by ITU-T in the year 1998. This is a passive optical network that uses ATM (Asynchronous Transfer Mode) cells for the transmission of information. Transmission speeds are offered in two variants: symmetrical service at a speed of 155.52 Mbit·s⁻¹, and asymmetrical service at a speed of 622.08 Mbit·s⁻¹ (downstream) and 155.52 Mbit·s⁻¹ (upstream).
Additionally, symmetrical service at a speed of 622.08 Mbit-s\(^{-1}\) was provided. In the year 2001, ITU-T approved the G.983.3 BPON (Broadband PON) standard, which was in fact an extension of the preceding standard and which uses the same transmission speeds. It uses one or two optical fibres G.652 as the transmission medium. Two-way communication along one fibre is ensured by wavelength division.

**GPON**

In the year 2003, ITU-T approved the specification G.984.1 GPON (Gigabit Capable PON), which starts from the G.983.X specification. It enlarges the G.983.1 specification as regards the speed while preserving the principles of broadband access system. For transmission it employs ATM cells and also the GEM (GPON Encapsulation Method) method. This method is used to transmit GPON frames, which are of variable lengths. ATM cells and GEM frames or their fragments are transmitted together in frames of fixed 125 \(\mu\)m length. This enables making use of packet-oriented services such as Ethernet or IP (Internet Protocol). Transmission speeds are offered in two variants: symmetrical service at speeds of 1244.16 Mbit-s\(^{-1}\) and 2488.32 Mbit-s\(^{-1}\), and asymmetrical service (downstream) at speeds of 1244.16 Mbit-s\(^{-1}\) and 2488.32 Mbit-s\(^{-1}\), and upstream at 155.52 Mbit-s\(^{-1}\), 622.08 Mbit-s\(^{-1}\), and 1244.16 Mbit-s\(^{-1}\).

**EPON**

By endorsing the IEEE 802.3ah specification, IEEE assured the introduction of Ethernet in access networks. This specification is usually referred to as EPON (Ethernet Based PON) or also EFMF (Ethernet In First Mile Fibre). The aim was to bring the Ethernet standard to the very user and thus to simplify the coupling of local networks. For the transmission in both directions Ethernet frames of fixed 2 ms length are used. EPON is designed for the multipoint network sharing one transmission medium but point-to-point communication can be emulated (P2PE Point To Point Emulation). The IEEE 802.3ah standard specifies two types of interface, which differ in the dynamics and optical powers. Type 1000Base-PX10 is designed for application over distances of up to 10 km, with maximum branching 1:16. Type 1000Base-PX20 is designed for distances of up to 20 km, with maximum branching 1:32. The transmission speed was set at 1244.26 Mbit-s\(^{-1}\), symmetrical.

**Triple Play Services in FTTH Systems**

The current trend among telecommunications operators and providers of broadband services is to offer the end user the broadest possible transmission band and the related services. Growing competition and desired cost-effectiveness makes operators implement ever new services. One of them is the “Triple Play” service. This is a new generation of services that offer transmission of voice, data, and video. The basic services are not billed singly since they are included in the flat rate for the connection to broadband network. Services that are beyond the frame of basic services are billed.

**Methods of distributing video signal**

Offering a wide choice of video and voice services is the main trend among telecommunications operators. No wonder, because they form a major part of their income. Much effort is therefore invested not only in deploying new services but also in seeking the most suitable transmission form that could introduce more services at the same time, without the need of extending the transmission bandwidth; this would increase the provider’s income. Video services offered within the frame of “Triple Play” are distributed among users in two
For video transmission, overlay PON networks use the 1550 nm wavelength, which has been reserved for this service by ITU-T. The signal together with the data flow (data and voice) is transmitted to the user along one optical fibre, for which the 1490 nm wavelength is reserved using the wavelength division multiplex WDM. Both analogue and digital signals can be transmitted. At the user side the video signal is separated in the ONT unit (by means of so-called triplexor) and converted to radio-frequency signal. In the case of classical analogue signal, the signal is delivered by coaxial cable from the ONT unit straight to the TV set. If the signal is digital, a set top box (STB) must be used, which will convert digital signal to analogue signal. The overlay network offers providers flexibility and enables them offering a wide choice of video services. These networks can offer homes a capacity that often exceeds their requirements. The backward channel uses the 1310 nm wavelength.

The other possibility how to distribute video services over a PON networks is IPTV, or switched video. In this case the video signal is transmitted to the user via a packet network. At the side of network termination the video signal is first digitized and then compressed. Binary data are entered into IP datagrams. This compressed signal together with the data flow (data and voice) is transmitted via ATM cells or Ethernet frames to ONT, which uses the 1490 nm wavelength. The set top box with IP interface is inserted in the transmission path between the TV set and the ONT unit. The connection of IP STB to ONT is accomplished using the CAT-5 structured cabling. The TV set is already connected to STB by coaxial cable.

**Choice of appropriate transmission method**

As already mentioned, overlay PON uses for downstream transmission of video signal the 1550 nm wavelength; the video signal is thus separated from the data flow, which is transmitted downstream on the 1490 nm wavelength. This wavelength has not been chosen by ITU-T ad hoc but because the value of insertion loss of optical fibre is for this wavelength the lowest. Since in the initial stage analogue video was transmitted, this property played a decisive role. To assure the required quality of transmitted analogue signal it is necessary to ensure a maximum carrier-to-noise ratio (CNR). The Federal Communications Commission (FCC) set the minimum CNR value at 44 dB. With this value, the elimination of the so-called “snow” in the image is guaranteed. The value used in FTTH systems should, of course, be higher than 47 dB; the value 48 dB is usually used. Present-day ONT can assure a CNR value of 48 dB for the received signal level between -5 and -6 dBm. To assure obtaining a CNR of 48 dB, sources of large optical power (lasers, EDFA) need to be used. With these powers, the so-called Brillouin scattering (BS) shows in the optical fibre, when part of reflected light ray returns back to the source and thus causes interference. This scattering occurs as a result of the interaction of optical radiation (photons) with virtual grating, which is formed by acoustic waves (phonons) generated by a laser source or EDFA amplifier at large powers. Earlier, this phenomenon manifested itself already at powers of 7 dBm but today this limit has been shifted beyond 20 dBm, thanks to improved technology.

**Optical converters**

Due to the current increase in LAN networks, data networks, and access networks, network elements called media converters are applied. They are manufactured by many manufacturers (Cisco, IC Plus Corp., Tyco/Electronic, Optokon, etc.), in compliance with interface standards IEEE 802.3 & IEEE 802.3u for Ethernet 10/100 Mbit·s⁻¹, IEEE 802.3z for 1000Base Gigabit.

The range of optical link depends on the transmitting (LED, LD) and receiving (PIN, APD) optical elements and on the type of the chosen optical fibre (MM, SM). Termination is
provided by standard connectors ST, MT-RJ, and SC. Let us have as an example the CS-120 connector supporting the 10/100 Mbit·s⁻¹ Fast Ethernet. If multimode fibre is used, a range of 2-5 km is possible while with single-mode fibre the maximum distance is 120 km. The converter can also be used in FTTH networks and wavelength division multiplex CWDM is also possible.

These converters have a data integrated circuit IP113A LF, which enables transmitting packets of up to 1600 bytes, using the EPROM interface.

The CS-1200 series supports 1 Gbit·s⁻¹, Gigabit Ethernet. It fulfils the recommendations IEEE 802.3zD2 GBIC (Gigabit Interface Converters) and MSA (Multi Source Agreement).

In the VCSEL (Vertical Cavity Surface Emitting Laser) transmitting part the 850 nm wavelength can be used. For single-mode transmission on the 1310 nm wavelength the FP (Fabry-Perot) laser is used while for the 1550 nm wavelength the DFB (Distributed Feedback) laser is used, which allows the deployment of the CWDM multiplex, with 20 nm channel spacing in the 1310-1610 nm waveband. For the MM fibre the range is up to 550 km, for the SM fibre it is as much as 120 km. Optical output can be solved using duplex connectors SC and LC or Bi-Di (bidirectional) single connectors LC and SC.

The receiving part consists of a high-sensitivity GaAs PIN or InGaAs Pin photodiode, with high sensitivity, possibly also with application of optical amplifier. The receiver enables using the waveband of 1100 to 1600 nm.

The converters also satisfy the respective standards for the supply and for the diagnostics of function and failure conditions.

At the exchange side the converters are mounted in switchboards (box – chassis) with connection via UTP cables to switches. A network made up in this way can be monitored from the viewpoint of failure conditions (supervision system).

Work is currently continuing on changing over to higher speeds, 10 Gbit·s⁻¹, with commensurably increased range. Standards XENPAK, X2, XFP, and SFP+.

### 7.16 Optoelectronic multiplex systems

The present information explosion makes increasing demands on the number of transmitted channels and this is the reason why signals are multiplexed on links. The following methods of multiple transmission are in existence:

- **frequency division multiplex**: individual signals are transferred to higher frequency bands and so-called modulation groups are formed which are modulated to an optical signal generated by laser or light-emitting diode. The whole multiplex system remains in the region of electronic circuits; the potentials of this multiple transmission are limited by the parameters of sources of optical radiation,

- **time division multiplex**: each signal is assigned a time interval in which at the transmitting side the transmitter and at the receiving side the receiver of the given signal are connected,

- **electronic multiplex**: not a binary signal but a multiple signal is transmitted along one fibre, which increases the transmission speed n-times,

- **space division multiplex**: it uses several fibres to transmit different signals,

- **wavelength division multiplex**: it makes use of the possibility of radiation from various sources of light of different wavelengths, which are modulated by
individual information sources (the respective “windows” in regions of minimum fibre attenuation are used for the transmission),

- **hybrid multiplex**: it represents the combination of wavelength division multiplex with electronic multiplex (enabling maximum exploitation of the transmission potentials of fibre).

In view of the fact that as regards the exploitation of transmission capacity of optical fibre the most advantageous is the wavelength division multiplex (hybrid multiplex) we will deal with it in detail below. The other principles, given earlier, are generally known and some of them trivial (see space division multiplex).

The classical optoelectronic link, described on several earlier occasions, enables one-way operation between the transmitter and receiver (simplex link); when more fibres are used, the space division multiplex can be formed (Fig. 7.46a). If two-way operation along one fibre is needed, connection according to Fig. 7.46b can be used, i.e. duplex connection. In such a connection, transmitter V₁ and receiver P₁ operate together on wavelength λ₁, transmitter V₂ and receiver P₂ on wavelength λ₂. Wavelengths from the fibre are combined and divided in a duplexer. In the case of using several radiation emitters on different wavelengths, coupled by means of multiplexer to one optical fibre, we speak about wavelength division multiplexer. At the receiver side, the demultiplexer is connected, whose task is to divide the respective wavelengths for individual receivers (Fig. 7.46c). To implement an n-channel link it is necessary to have n modulators, n optical sources and n detectors, one WDM (Wavelength Division Multiplexing) multiplexer and one demultiplexer (the pair is referred to as WDM mulpex). Simple non-selective optical termination can be used in the function of multiplex. Optical demultiplexers, which must be implemented as optical filters, are more complex.
Optical carrier waves corresponding to individual channels can be distributed more or less uniformly over the whole lightguide throughput band with regard to the minimum of its attenuation and dispersion, availability of light sources for the respective wavelengths and attainable selectivity of optical filters. Possible position of $n$ channels in the region of 1st, 2nd and 3rd “windows” on typical optical fibre attenuation curve is given in Fig. 7.47.
Current technical facilities enable implementing ca. 40 wavelength transmission facilities. The channel spacing is given by:

- spectral width of emitted light, $\Delta \lambda$, if light-emitting diodes (LED) are used,
- accuracy and stability of average wavelength value of emitted light, $\lambda_{str}$, if laser diodes (LD) are used,
- wavelength selectivity of optical filters in the demultiplexer.

It is obvious that when laser diodes are used (the spectrum of multimode lasers, LD1, is about 20 times, and that of single-mode lasers, LD2, up to 1000 times narrower than the spectra of LED diodes), more channels can be placed in the operating region. The effect of the spectra of various light sources on the implementation of wavelength division multiplex is evident from Fig. 7.48. But the value of average wavelength $\lambda_{str}$ depends critically on the material composition of LD structure and, in addition, it varies with temperature and time. It is also necessary to bear in mind that the lower part of radiation spectrum even in single-mode lasers is far from $\lambda_{str}$ because it is due to spontaneous optical radiation, similar to LED diodes. It is also evident from the figure that the spectra of individual channels in both LED and LD sources may overlap, leading to cross-talk, i.e. inter-channel interference. The interference can be either inside or outside the channel. It is obvious that, for example, reaching inside the $k$-th channel are spectra from neighbouring channels (hatched areas), which would give rise to intra-channel interference. To have the least possible channel spacing it is necessary to suppress this type of cross-talk in the multiplexer already, because filters in the demultiplexer transmit all light in the band of wavelengths reserved for the given channel, i.e. the desired signal and also the spurious signal that would fall into this band. Seen from another angle, insufficient selectivity of the filter in demultiplexer will result in extra-channel interference.
On the basis of what has been said we can define channel spacing as the difference of two close wavelengths of optical radiation

\[ \Delta \lambda = \lambda_{j+1} - \lambda_j. \]  \hspace{1cm} (7.13)

The value \( \Delta \lambda \) depends on the radiation sources used and on the design of optical multiplexers and demultiplexers.

The spacing and wavelength selectivity of WDM multiplexer and demultiplexer are given by the pass-band width and the steepness of the sides of optical filter attenuation characteristics.

An important parameter of multiplexers is their insertion loss. Insertion loss defines the losses that arise due to the passage of optical radiation through multiplexer or demultiplexer; they can be expressed by the relation

\[ a_j = 10 \log \frac{P_{i, \text{vst}}}{P_{i, \text{výst}}} \text{ (dB)} \]. \hspace{1cm} (7.14)

It is obvious that the value of insertion loss will be different for each wavelength. Optical multiplexer or demultiplexer is defined (evaluated) by the maximum value of insertion attenuation for the given type of system.

Another parameter for the evaluation of WDM multiplexer is cross-talk attenuation. It is expressed by the ratio of power \( P_{\lambda_j, \text{vst}} \) to power \( P_{\lambda_i, \text{výst}} \), where \( P_{\lambda_j, \text{vst}} \) is the power of radiation entering the system on the wavelength \( \lambda_j \) while \( P_{\lambda_i, \text{výst}} \) is the power of radiation on the wavelength \( \lambda_j \) on the output for the wavelength \( \lambda_i \).

\[ a_{ji} = 10 \log \frac{P_{\lambda_j, \text{vst}}}{P_{\lambda_i, \text{výst}}} \text{ (dB)} \]. \hspace{1cm} (7.15)

The main task of the WDM multiplexer is thus to multiplex light beams from individual sources into a single lightguide. With small channel spacing the multiplexer must also contain wavelength-selective members (optical filters) for the purpose of suppressing intra-channel interference. The division of light beam into individual rays by wavelength is performed in demultiplexer. Demultiplexer must always contain wavelength-selective members; in some cases just the selectivity of photodetectors is made use of.

In duplex links, when the transmitter and receiver are connected to the same end of optical fibre, at least a coupler must be inserted between this pair and the fibre otherwise cross-talk would appear between the transmitter and receiver.
Wavelength-selective members used in muldex design are in most cases reciprocal, i.e. they can be used for both multiplexing and demultiplexing by simply interchanging the inputs and outputs. Depending on the method they use for their function, they can be divided into two groups:

- interference members,
- dispersion members.

**Interference selective members** make use of interference filters, which make light waves either reflect from the filter or pass through the filter, depending on the wavelength of light. The filter itself is formed by 10 to 40 thin layers of dielectric material with alternately changing refractive index. A high reflectance for certain wavelengths is obtained by a suitable structure of the filter. The design of a demultiplexer with interference filters is shown in **Fig. 7.49**. The lenses are formed by glass cylinders, in which refractive index decreases from the axis to the rim so that the passing light beam gets focused. Insertion attenuation of muldaxes with such filters increases roughly in proportion to the number of channels.

![Interference demultiplexer](image)

**Fig. 7.49**: Interference demultiplexer.

\[ a_i = n \quad \text{dB}, \quad (7.16) \]

\( a \) can therefore be used for multiplexers with a lower number of channels. Attenuation increases by \( n \)-fold reflection or by the passage of light through filters. The radiation sources may be both LED and LD diodes.

**Dispersion filters** make use of the separation of light, for example, by a prism or various optical gratings.

When light passes through a prism (**Fig. 7.50**), then due to the double refraction on border surfaces there is a refraction angle \( \nu \)

\[ \phi_{\text{min}} = 2 \arcsin \left( n \sin \left( \frac{\alpha}{2} \right) \right) - \alpha, \quad (7.17) \]
where

$$\alpha < 2 \arcsin \left( \frac{1}{n} \right).$$ \hspace{1cm} (7.18)

Fig. 7.50: Prism demultiplexer.

In view of the dependence of refractive index on wavelength $n = f(\lambda)$, different light wavelengths are refracted at different angles. The location of optical detectors $P_1$, $P_2$ and $P_3$ depends on angular refraction, which is given by the relation

$$\frac{d \varphi}{d \alpha} = \frac{\sin \alpha}{\left[ 1 - (1+n)^2 \sin^2 \left( \frac{\alpha}{2} \right) + n^2 \sin^2 \left( \frac{\alpha}{2} \right) \right]^{1/2}} \cdot \frac{d n}{d \lambda}. \hspace{1cm} (7.19)$$

The application of gratings is of greater advantage. Their advantage is that they enable processing a greater number of channels but, by contrast, they cannot be used with LED because their broad spectrum causes increased cross-talks and insertion attenuation. Additional attenuation of multideses with optical grating changes only a little with the number of channels

$$a_j = 2 + 0.25 \times n \text{ (dB)}. \hspace{1cm} (7.20)$$

An example of multiplexer is illustrated in Fig. 7.51a while a possible variant of demultiplexer is given in Fig. 7.51b. A feature of this solution is the potential direct connection of fibres to the demultiplexer. The angular dispersion is given by the relation

$$\frac{d \varphi}{d \lambda} = -\frac{m}{d \cos \varphi}, \hspace{1cm} (7.21)$$

where $m$ is an integer and $d$ is a constant determining the grating dimensions.
WDMs begin to find practical application mostly on the principle of optical gratings or on the principle of interference filters. A practical preview of the implementation of radiation sources of different wavelengths, which from the technological viewpoint is possible, and of the corresponding radiation detectors is given in Fig. 7.52. It is obvious from this figure that for the simpler variants of multiplex (two-channel) links the easiest way of connecting can be implemented by locating one channel to the lower border of the throughput “window” of optical fibre ($\lambda = 0.8$ to $0.9 \mu m$) and the other channel in the region of the second and third “windows”, i.e. $\lambda = 1.2$ to $1.6 \mu m$. In view of the large spacing between WDM channels the multiplexer does not have to be wavelength selective. Moreover, the demultiplexer does not have to contain any filters because the silicon photodetector, which is used to detect light in the first channel, is insensitive to wavelengths $\lambda > 1.1 \mu m$ while detectors for wavelengths of over $1.1 \mu m$ (e.g. germanium, GaAs or InP detectors) suppress shorter-wavelength light, as is also obvious from Fig. 7.52. Because of their functional simplicity, these systems find increasing application in practice.

Simple WDM systems of a small number of channels ($n \leq 3$) can also be implemented by using sources that emit light on several wavelengths or using combined photodetectors, whose structure contains two active layers sensitive to various light wavelengths. The quantum efficiency of these combined sources and the sensitivity of photodetectors are, for the time being, lower than when they are implemented separately. Moreover, thermal and electrical coupling may give rise to cross-talk.
These wavelength multiplexers (couplers) are manufactured by many companies, e.g. OPTOKON, FITEL, etc., which employ the wavelengths 830, 850, 1300, 1310, and 1550 nm. They are implemented in the form of “small boxes” with output to the fibre and provided with the connector as ordered. An example of one such variant is given in Fig. 7.53.

Fig. 7.53: Wavelength multiplexer.
In transport networks, use is made of more wavelengths, primarily by using the 3rd extended transmission window; in the most recent systems the number of wavelengths has been increased into the removed “hump” on the attenuation curve (type All Wave fibres) as indicated by dashed line in Fig. 7.52.

Let us in the following have a look at these wavelength systems.

The initial wavelength multiplex uses for the transmission only two or three wavelengths, mostly in two-way operation on one optical fibre. The passive wavelength multiplexer WDM is a simple and cheap device.

**WWDM Technology**

The wide wavelength division multiplexing (WWDM) mostly uses four wavelengths in the 850 nm region (multimode optical fibres) or in the 1300 and 1310 nm regions (multimode or single-mode optical fibres). Most frequently, the WWDM technology is employed for the transmission of Gigabit and 10 Gigabit Ethernet. Individual wavelengths of the WWDM multiplex have typically a spacing of 25 nm.

**DWDM Technology**

The dense wavelength division multiplexing (DWDM) uses minimum spacing between individual channels so that it can implement tens of wavelengths in one fibre. Single-mode lasers and narrow-band interference filters are used in these cases. In addition, it is necessary to assure sufficient frequency stability and extremely narrow spectral lines. Laser stability is ensured either from outside (via injection synchronization, phase lock) or using distributed feedback or the Bragg mirrors. Since the selectivity of optical filters is of the order of 10 THz at best, the division of channels must be performed on intermediate frequency by means of electric filters, i.e. the receiver must contain a scrambler and a local oscillator in the form of frequency-stabilized highly coherent optical source.

In practical designs it is necessary to bear in mind that the range of individual channels will be different (the differences are quite large) and the worst transmission properties of a particular channel in the multiplex must be considered (or the worst channels not used).

The deployment of DWDM systems in commercial operation was conditional on the development and economically mastered production of key components such as erbium-doped fibre amplifiers (EDFA), multiplex and demultiplex units, and narrow-band laser transmitters. Thanks to the progress in the field of development and production but also thanks to the considerable demand for transmission capacity, the DWDM systems at the beginning of the 20th century began to be deployed in backbone transmission routes. The first functional DWDM devices came to the Czech Republic in the spring of 1999.

**ITU-T Recommendation G.694.1** “Spectral grids for WDM applications: DWDM frequency grid” specifies individual transmission channels in the wavelength region from 1490 nm (200.95 THz) to 1620 nm (186.00 THz) (so-called S, C and L bands). ITU-T recommendation G.694.1 specifies the spacing of individual channels in the range of 100 GHz, beginning on 186.00 THz (spacing ca. 0.8 nm) or twice as many channels with 50 GHz spacing (ca. 0.4 nm). In DWDM transmissions the required signal-to-noise ratio increases with increasing transmission speed in the channel. For example, for STM-16 (2.5 Gbit·s⁻¹) 18 – 20 dB SNR is sufficient for good-quality transmission; for STM-64 (10 Gbit·s⁻¹) 22 dB are required while for STM-256 (40 Gbit·s⁻¹) ca. 25 dB are required. For good-quality transmission it is necessary for the actual wavelength of the channel (so-called maximum power wavelength) not to deviate from the prescribed wavelength (i.e. the nominal
wavelength) by more than ± 0.2 of the spacing of carriers. For a 100 GHz spacing of the carriers it follows that the actual wavelength must be within the ± 20 GHz tolerance (this corresponds to ± 0.16 nm). The bandwidth of an optical signal transmitted in one channel depends on the bandwidth of the original modulating signal and it can be further impaired (extended) by using an inappropriate modulation technique.

**CWDM technology**

Coarse wavelength division multiplexing (CWDM) came into being as a cheaper variant of DWDM. The CWDM technology is a form of wavelength multiplexing that uses a larger spacing between individual transmission channels than is the case in the classical DWDM technology. In the recommendation ITU-T G.671 it was specified that the spacing of individual channels should be less than 50 nm; for the 1550 nm wavelength it should be 8 nm. It was only the advent of fix specification of individual wavelengths that provided a basis for the extensive development and mass deployment of this technology. In the year 2002, the Standards Commission of ITU issued the recommendation ITU-T G.694.2 “Spectral grids for WDM applications: CWDM wavelength grid.” Standard G.694.2 defines the size of spacing of individual wavelength channels for use in CWDM technology such that laser diodes could be used as radiation sources without cooling being required. Also, the individual wavelengths were chosen such that they were compatible with the conventional wavelengths 1310 nm and 1550 nm.

All the wavelengths of the CWDM technology (18 channels are available) can only be used with type “Metro” fiber, in other words with full spectrum according to the G.652.C standard. “Metro” is a type of fibre that is manufactured without increased attenuation in the region of the 1360 to 1450 nm wavelengths. In current cases of the existing optical routes, however, only the standard single-mode fibre 9/125 μm is mostly available, which corresponds to the ITU-T G.652 standard; 12 channels are available, with wavelengths of 1290, 1310, 1330, 1350, 1470, 1490, 1510, 1530, 1550, 1570, 1590, and 1610 nm.

CWDM finds the application in metropolitan optical networks and in the optical-fibre solution of the “last mile” problematic. In access networks, xDSL providers can use CWDM to connect the digital loop carrier (DLC) to the central exchange. CWDM is most often used in point-to-point communication or in ring topologies of up to four nodes. CWDM can transmit Gigabit Ethernet over distances of up to 80 km; at STM-16 speeds (2.5 Gbit·s⁻¹) the range is about 50 km.

**Optical amplifiers**

Optical amplifiers are used with advantage in wavelength division multiplexing systems. Unlike repeaters, they enable restoring luminous flux in the fibre without the necessity of converting it to electric form. These amplifiers are universal elements that amplify both analogous and digital signals of arbitrary transmission speed.

**Optical fibre amplifiers EDFA (Erbium Doped Fibre Amplification)**

A simplified block diagram of the EDFA amplifier is given in Fig. 7.54. The amplifier is formed by the so-called laser pump and a special optical fibre, which is doped with rare-earth elements (erbium, et al.). Due to the laser pump emission (of 980 nm or 1480 nm wavelength) coupled to a special fibre of several metres in length, atoms of doped element are excited to a higher energy level. The energy obtained from the laser pump radiation is thus temporarily stored in the atoms. This energy is released due to the presence of the signal being transmitted, whose energy calls forth stimulated emission of radiation, which is of the same wavelength and phase as the signal transmitted. This amplifies the transmitted optical signal. Optical fibre amplifiers enable increasing the signal level by as much as 50 dB (one channel,
C – band). Via internal arrangement of the amplifier a wide range of the amplified band can be obtained and thus the signal can be amplified in the C and L bands simultaneously. Various possibilities of deployment in an optical transmission system result from the principle of EDFA function. Basically, the amplifiers can be applied in four manners:

- **Booster** – which is located right after the optical transmitter; it serves to amplify its signal to a maximum level that can be coupled to the fibre. It must be capable of accommodating a relatively large input signal from optical transmitter.

- **In-line amplifier** – which is located on the optical fibre route; it amplifies a small input signal to a maximum output signal.

- **Pre-amplifier** – serves to amplify very low signal levels to a level that is sufficient for a correct functioning of optical amplifier at the end of transmission route. The requirement put on the pre-amplifier is to have a minimum internal noise.

- **Compensation of losses in optical networks (CATV)** – in optical community antenna television the reduction of signal level is primarily due to the requirement to divide the optical signal into several fibres. Before being divided the signal is amplified by means of EDFA such that the same signal level is obtained in output fibres as in the original fibre.

These amplifiers are manufactured as single-channel EDFA amplifiers, WDM amplifiers, and CATV amplifiers.

**Optical Raman amplifiers**

The Raman type of amplifiers is used to amplify an optical signal. It is practically just a laser source of radiation connected to the optical route. To amplify the optical signal the Raman scattering on particles of the waveguide material is used. With this scattering there is, among other things, a shift of energy from the lower wavelengths (wavelength of Raman pump radiation) to higher wavelengths (wavelengths of the signal being transmitted) and consequently an amplification of the signal. A simplified connection diagram is shown in Fig. 7.55.

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**Fig. 7.54:** Principle of optical EDFA amplifier.
The amplification of optical signal thus takes place directly in the transmission route fibre. No special fibre is necessary here; any communication fibre can be used. Amplification values obtained with this type of amplifier are not as high as with EDFA. The signal level can be increased by ca. 15-20 dB.

The Raman amplifier is located at the end of optical transmission fibre and radiation from the laser pump propagates against the signal being amplified. This amplifier can be used to amplify an arbitrary wavelength, provided the appropriate wavelength of laser pump is chosen (e.g. 1450 nm for the 1550 nm band). The EDFA amplifier and the Raman amplifier can with advantage be combined. However, these amplifiers also amplify distortion and thus in the case of long routes it is necessary to connect the classical repeater to restore the signal.

Example of four-wavelength multiplexer - is a frequently demanded multiplexer for rapidly increasing the network capacity at a relatively low cost. It is based on the principle of cascading interference filters with 8 nm spacing (see Fig. 7.56).

Example of dense wavelength division multiplexer (DWDM) – leading manufacturers of the DWDM device include Lucent Technologies, Alcatel, Nortel, NEC, and others. Currently marketed DWDM have 16, 20, 40, 60 and up to 100 spectral channels.

The Wave Star OLS 806 device by Lucent Technologies will be given as an example. It employs 16 wavelengths, spanning attenuation 33 dB, which corresponds to a distance of 120 km without amplification (non-zero dispersion fibre True wave is assumed). The device can be used with advantage when creating ring topologies, as can be seen in Fig. 7.57.
Effects influencing the quality of multiplex transmissions

For a good quality transmission it is necessary to meet the respective limits, which are verified by measuring and which include:

- the average wavelength, which must meet the respective standards; accurate measurement must be assured with respect to temperature changes, laser instability, and back reflections,
- the bandwidth must also meet the criteria of spectral characteristics,
- the insertion loss must provide the most favourable transmission conditions,
- in DWDM installations, the cross-talk must satisfy the cross-talk quantities between neighbouring wavelengths, as was earlier the case with metallic conductors,

\[\text{Fig. 7.57: OLS 806 in “ring application”.}\]

- the back reflection may be different in individual channels and the values need to be kept within tolerances, mainly with a view to system stability,
- the peak power of individual channels must satisfy the respective tolerances,
- the type of fibre used is a separate and very important consideration.

An example of the spectral characteristics of four-wavelength multiplexer is shown in Fig. 7.58. In the case of new installation, when the deployment of DWDM system is assumed, the technical parameters can be selected to meet the operator’s requirement. This principle is currently implemented in the construction of transport networks of many operators, using the so-called “Telehouses”.

A substantially more difficult situation exists as regards the future exploitation of already installed fibres for the needs of DWDM.

In the first place, earlier fibres (ITU G.652) are not ideal for DWDM. Relatively large chromatic dispersion in the 1550 nm band limits the link range and compensation is necessary for longer routes.
All the effects given above influence transmission and they must be taken into consideration in the design of networks.

*Application potentials of wavelength division multiplexers in academic computer network of universities*

One of the first applications is the deployment of two-wavelength multiplexer in the experimental network of the Department of Telecommunications (DT). The system demonstrates its functionality and enables the measurement of elements. The system was used to demonstrate its application in the supervision for optical cables. Its connection is shown in Fig. 7.59.

**Fig. 7.58:** Spectrum of wavelength division multiplexer.

**Fig. 7.59:** Implementation and connection of WDM in DT network.
Experimental DWDM transmission in CESNET project

Given as an example will be the results of a DWDM transmission that was realized by CESNET workers. The experiment was to prove, and it did prove, the possibility of two-way transmission by (2x4) 10 Gbit∙s⁻¹ Ethernet (GE) channels over a distance of 210 km without the necessity of connecting the EDFA link amplifier. This is the distance between Prague and Brno and the fibre used was standard single-mode fibre (G.652).

At the receiving and the transmitting sides 4 DWDM channels were combined (divided) by means of multiplexers (demultiplexers) with a phased series of waveguides. Following the transmitter, the signals were amplified in EDFA with 22 dB output power, and transmitted via polarization-independent insulators into a 210 km long standard single-mode fibre (G.652); the wavelength complied with the ITU-T standard, channels 34-37; channels 31, 32, 33, and 38 for reverse direction. Optical power of transmitters ca. 1 mW.

At the receiving side 4 DWDM channels were separated by polarization-independent optical circulator and amplified by low-noise EDFA pre-amplifier (P_vyst = 10 dBm). Chromatic dispersion of the fibre was compensated using the temperature-tuned DWDM Bragg grating (FBG); individual channels were demultiplexed via AWG (Array Waveguide Grating) and delivered to XENPAX receivers.

The results were evaluated by measuring the channel spacing and error rate. On the basis of analysis the hypothesis was formulated of potential 16 x 10 Gbit∙s⁻¹ transmission over a distance of up to 250 km (using EDFA with higher output power).

Further prospects of DWDM multiplexers

Increasing the speed will continue to be the main trend in further development. The maximum number of channels is being increased to 128 – 160. In experimental work as many as 1024 channels have been achieved. Other parallel bands, C and L, begin to be used. The universality of transmission medium increases, enabling e.g. the Gbit, 10 Gbit, Ethernet, and STM 64 transmissions. If systems with a capacity of 1.6 Tbit∙s⁻¹ are deployed today in backbone networks, this value can be expected to increase to 20 Tbit∙s⁻¹. As regards the distance, the use of Raman scattering and soliton transponders will increase the DWDM range to thousands of kilometres.

Network flexibility will be markedly increased by the application of Cross-Connects; they enable assuring the reconfiguration and stand-by of spectral channels in several milliseconds. These elements are currently implemented with a switching capacity of 1024x1024, the switching being performed on a chip by means of micro-electromechanical mirrors; the switching is 16 times faster than in current electronic switches.

Summing up we can say that these new technologies markedly enhance the offer of new services and transmission potentials in optical communications.

7.17 TV optical fibre links

The principle of cable television (CATV – Community Antenna Television) consists in that the TV centre receives television programmes from TV transmitter, satellite or directly from local studio and converts them to ordinary television bands and channels. The latter are then distributed through a single broadband branched cable with amplifiers. Every house or home can subscribe to the whole television programme on offer. Abroad, this service is used extensively. Not only does it enable increasing the number of channels, inclusive of satellite
reception, but it also assures high quality reception of the signal, in particular at sites of weak reception (valleys, cities, etc.).

It is obvious that this service primarily attracts the interest of subscribers, in particular today, when operators offer Internet and telephone services.

Interest in the construction of these links also poses the question whether it would be of greater advantage to use optical fibre instead of the currently used coaxial cable. Fundamentally, the same problem is concerned here as outlined in the solution of FTTH networks.

Optical fibres are currently used by CATV operators for long-haul transmissions between the centre and a city (urban satellite); subscribers continue being connected via cheaper coaxial cables.

Already in present-day conditions we can see that three areas, namely telecommunications, radio-communications and computer technology begin to fuse, being increasingly dependent on one another.

However, the situation today is characterized by lack of coordination from the technical viewpoint and also as regards standardization, software, etc. The need will thus arise for systems with different internal architectures to cooperate. At the interfaces of these networks adapters will have to be installed that will interconnect and adapt the individual systems.

7.18 Submarine optical transmission

With the first major successes in transmission over optical fibres it became obvious that it would not take long before interest was shown in their application in the construction of submarine networks. Until the achievement of major progress in optical transmission it seemed that submarine communication would cease to be used or survive and be gradually replaced by satellite links. But the arrival of optoelectronic systems has completely changed the situation.

Reasons for the subsequent rapid development of submarine communications can primarily be seen in the following aspects: Optical cable has a low mass, which greatly facilitates its installation. Low fibre attenuation enabled the first implementation of submarine optical cables over short distances (e.g. between islands) without the use of repeaters, which greatly affected the simplicity of installation, cost, reliability, etc.

Unlike with satellites, there is no eavesdropping and interference, which has greatly advanced the construction of submarine optical communications.

As already mentioned, the first submarine optical cables were laid to provide short submarine links mainly in the US, Japan, France, and England after 1985. Systems that can span below sea level a distance of 100 – 300 km are currently being installed in various countries. In the year 1988 the first Trans-Atlantic optical cable system (TAT-8) and a year later the Trans-Pacific cable system (TPC-3) were put into operation.

Further optical cables followed in the subsequent years, namely TAT 9, 10, and 11. The latest cable that has been laid is TAT 12/13.

Characteristics of the TAT 12/13 system: it consists of two rings with four terminations (2 x US, 1 x UK, and 1 x France), see Fig. 7.60. The STM 16 2.5 Gbit·s⁻¹ system is deployed here, with a total capacity of 10 Gbit·s⁻¹. The route is 6321 km long. One section, 4 127 km,
was built by the firm AT&T, the other section, 2194 km, by the firm Alcatel. Optical amplifiers are installed every 74 km (Fig. 7.60).

**Fig. 7.60:** Submarine optical cable TAT 12/13 (2 x US, 1 x England, 1 x France).

The cable can be laid as deep as 7000 m. The service life of the system is expected to be 25 years, with a maximum of 3 reliability failures within this period. Elements that are most susceptible to failure are laser diodes and therefore they were installed with triple redundancy. Save minor exceptions, the facility has been designed in accordance with the respective ITU-T recommendations. As a result, similar facilities could be built in the US, France and UK, which can communicate with one another. The system has its own check and failure modes.

Submarine optical cable TPC 5 interconnects the US, Japan, and Hawaii. FLAG (Fiberoptic Link Around the Globe), a cable-optic system of over 27 000 km in length, interconnects the UK, Egypt, India, Thailand, Hong Kong, China, Korea, and Japan.

The latest major achievement is the AFRICA TWO optical network interconnecting 40 countries around the African continent, length over 40 000 km.

Optical fibres for submarine cables undergo special testing. The design of the cable is more or less classical; optical fibres are in the centre of cable core (mostly in tubes or chambers), after which there is the protective tube (Cu, Al), and then the strength and protection elements. The cable diameter ranges between 20 and 50 mm. Cable manufacturers can deliver cables in runs equal to repeater section lengths, i.e. about 70 km.

### 7.19 Installation of optical routes

The same as with “classical” transmission systems, the installation of an optoelectronic transmission facility can be divided into the indoor (exchange) part and the outdoor (cable) part.
As regards the indoor installation of optical link termination, this is essentially a matter of providing the rack with blocks (cassettes). The optical transmitting element (the same as the receiving element) has its output connected via fibre directly to the connector. A direct connection to the optical distribution box is thus made possible. The optical distribution box (provided it is deployed) is used to terminate the optical cable and distribute the individual fibres to the respective optical link terminations.

The construction of the outdoor part will now be dealt with in detail. What is concerned here is the interconnection of two terminal devices by a cable. Optical cable (similar to the metallic one) can be laid in the following mediums: air, earth, cable duct, conduit (tunnel), cable trench (pipes), water, residential and industrial buildings.

Conditions for laying the cable may be quite different even within the individual mediums. Extreme conditions in which the cable will be operated without changes in transmission parameters are therefore always considered. Each of the above mediums offers specific possibilities of cable damage. For example, a cable laid in earth can be damaged by extreme temperature changes, severe frost causing soil movement, vicinity of hot springs, presence of oil, animals, earthquakes, landslides, and other circumstances.

In the case of overhead lines some of the above factors need to be considered but, in addition, also wind, rain, snow, ice, sunshine, falling stones, birds, and insects.

All the factors given above are of natural character. But there are also artificial factors, where we include the effects of fire and smoke, road transport, action of oil and vapours, building activities, and vandalism.

It is therefore evident that the cable should resist all these effects and this may be helped by suitable cable-laying and selection of the route.

The very laying and handling of optical cable can be of minimum or small but also severe effects on transmission parameters. Impairment may stem from bending the fibre, fibre microbends, fibre deformation, and admission of moisture. The ideal state would be if the optical fibre in the installed cable had the same properties as the individual fibres before being twisted to form the cable core in the factory.

The above fibre microbends are a failure caused by normal forces acting on the cable. The longitudinal axis of the fibre is not straight, it is wavy. The deviation of the actual axis from the ideal one is usually ca. 1 μm and the period of axis ripple is in millimetres to centimetres. Normal forces acting along the fibre can arise during manufacturing but also, not infrequently, during cable laying or due to changes in cable dimension caused by temperature fluctuation. The problem with temperature appeared, for example, in the Czechoslovak optical cable (at extreme negative temperatures). Susceptibility to microbending also depends on the refractive index difference between the core and the jacket, and also on the diameters of the optical fibre core and jacket.

In the case of fibre (cable) bends, optical losses increase from certain limits onwards. There is also a danger that cracks will eventually appear in the fibre, leading to its rupture. In the course of bending, longitudinal forces appear in the fibre, and normal forces also act on it.

An even higher degree of fibre degradation is its deformation, no matter whether due to twisting, bending, handling, stressing, etc.

Moisture also reduces the tensile strength of fibre and cuts the time to static failure. Increased optical losses can be the consequence. In winter, cable moisture may freeze up and make the fibre break.
Protecting the fibre against moisture is difficult because filler materials are not fully impermeable. The following measures are therefore taken, either separately or in combination:

- protection by air pressure,
- barrier against moisture,
- filler material.

All the above factors need to be considered when selecting the cable route and when laying the cable.

While being laid, the cable is exposed, for a short-time, to high tensile stress. It is important not to exceed the tensile force limit as declared by the manufacturer; otherwise the fibres will start cracking. The cable is manufactured in very long runs (1 000-2 500 m, sometimes 10 000 m) and thus it is opportune to use such a laying technology that the runs do not need to be cut. When pulling the optical cable in, it is necessary to use an automatic power-cutting device (dynamometer), which will stop the pulling procedure when the tensile force increases.

Currently the most frequently used method is blowing the optical cables by air pressure into HDPE protection tubes. The cable is thus better protected against external effects and damage. In the case of failure, the damaged run is easy to replace. The principle consists in the cable being borne by air pressure. In Italy, for example, they have cables borne by water. Depending on the terrain, 2 to 6 km (maximum 10 km) of cable can be blown in (for longer runs, a tandem blower must be used).

In towns, cable ducts are used for laying cables in order to avoid frequent digging up of pavements and roads. The ducts are made up of pipes, into which the HDPE tube is pulled, and the optical cable goes into the latter. In recent years, cable ducts (multichannels) by the SITEL company have proved to be good (Fig. 7.61).

All types of cable can be laid in multichannels (four-, six- or nine-way ducts). The system is designed for the dry process of construction, without the necessity of using concrete, and it can be used for the construction of both subsurface and deep-buried cable ducts. Square cross-sections enable cables to be pulled in faster and more easily thanks to lower friction forces acting on the cable itself. The whole system is installed section by section, with individual splices being sealed with rubber packing and locked by four elastic steel clips.

The basic features of this technology include: materials stability and robustness, potentially high concentration of cables in a small space, speed of installation, possibility of parallel installation, and reduction of piping to individual tubes.
Apart from these classical methods of laying the cable, some “novelties” have come to be used.

**MCS (Micro Cabling System) method**

Micro cabling systems NSC are an expedient alternative to laying and installing optical cables and optical cable joints in the construction of new access networks. Optical cables designed for these systems are laid in roads or pavements (MCS-Road) or in sewage drains (MSC-Drain). The MSC-Road and MSC-Drain micro cabling systems are mutually compatible and also compatible with the existing conventional optical cable networks.

**MSC-Road Micro Cabling System**

This is a system of special micro cables, which are made up of a thick-walled copper tube with optical fibres; the tube is protected by polyethylene (PE) jacket, see **Fig. 7.62**.

**Fig. 7.62**: Optical cable in MSC-Road version.

Outside diameter of micro-cables is 7 mm (for a maximum of 60 optical fibres) or ca. 9.6 mm (for a maximum of 120 fibres). Micro-cables contain 2, 24, 26, 48, 60 or 144 optical fibres. Individual fibres are identified by their colour marking.

For optical micro-cables to satisfy the parameters declared by the manufacturer it is necessary to respect the minimum admissible radius of micro-cable bending (ca. 70 mm) and the maximum admissible tensile force (1 000 N). For the splicing of optical micro-cables, underground waterproof cable joints of the type of U-60 and U-144 were developed; they are made of stainless steel and placed in roads, pavements, etc. These cable joints can resist heavy loads. The two types of cable joints enable straight (continuous) joining of optical micro-cables to a maximum capacity of 60 fibres (U-60) or 144 fibres (U-144).

In the installation, the optical micro-cable is laid in a groove milled in the road, pavement or another type of surface. The depth is chosen between 60 and 120 mm. After milling (cutting, grinding) the groove, it is cleaned and dried, e.g. by hot air blown into the groove under pressure. The optical micro-cable is placed in the groove and, using a thrust
ring, it is pressed to the groove bottom. A cord of foam polyethylene (functioning as filler material and thermal insulator) and then a cord of foam rubber (functioning as a thrust element) are pressed onto the micro-cable in the groove. Eventually, the groove is filled with a suitable sealing compound.

The above is a Siemens patented system. It is suitable for installation in high-quality roads, in large-area facilities, where up to 1 km of cable can be laid in a day (excavation work not included).

**MCS-Drain Micro-Cabling System**

This special optical micro-cable is formed by a thick-walled aluminium tube with optical fibres, armoured with a continuous layer of steel wires. This armouring arrests the tensile forces and protects the cable against rodents. There is a polyethylene (PE) jacket over the armouring. Outside diameter of the aluminium tube is about 6 mm, the diameter of the whole cable (including PE jacket) is ca. 10.6 mm. For the optical micro-cables to satisfy the parameters declared by the manufacturer it is necessary to respect the minimum admissible radius of micro-cable bending (ca. 100 mm) and the maximum admissible tensile force (1 500 N).

In the installation, the optical cable is laid in sewage drains, which are first cleaned with water under high pressure. After cleaning, the optical cable is smoothly pulled into the drains, where it is fixed in the upper part of the piping.

**Overhead optical cables**

In the course of constructing optical routes, it is sometimes necessary to mount the cables on poles. This is done using self-supporting cables or bearer wires. Spacing between poles must be chosen such that the cable is not exposed to tensile stress beyond admissible limit. Ice accretion, wind and temperature changes must be considered in this choice. The line must be suitably anchored to prevent any motion of the poles. It is a good practice to locate the optical cable at the top of the pole because there it is best protected against damage during line maintenance. If there is a danger that the jacket might be damaged by rodents, the cable must be armoured.

The choice of a suitable method for stretching the cable is also important. During installation, attention must be paid to keeping the minimum radius of bending. It is recommended to suspend the cable from a bearer wire that has been stretched in advance.

**Underwater cable laying**

Another possibility of laying cables is underwater laying. The cable is laid under or on the bed of creeks, rivers, lakes or shallow waters. The cables can be installed loose in trenches or in pipes or they can be laid from ships as floating cables. In most cases they are mechanically covered. The cables are armoured to be additionally protected against the river stream and their waterproofness is usually increased by the filling material. Cables laid in waters where fishing is practised need double armouring.

**Application of microtubes**

This is the latest trend in the construction of optical networks of the type of FTTH, when a PE microtube is brought to the subscriber, into which one or two optical fibres are then blown. Fibres can be blown to a distance of 2 to 6 km. Cable joints and directional couplers for micro tubes have been worked out.
When the respective runs have been installed in the proper places, their splicing can start.

The splicing of optical fibres was dealt with in detail in Chapter 5.

The methods for splicing optical cable jackets are based on the usual methods of splicing metallic cable jackets. The cable joint must:

- restore the integrity of cable jacket, inclusive of the mechanical continuity of the strength member,
- protect spliced optical fibres against the effects of cable environment,
- provide appropriate conditions for housing the spliced fibres and their reserves.

In keeping with the criteria for the splicing of cables with plastic jackets, it will hold for optical cables:

- the sleeve material must be compatible with the jacket material, and the temperature used in splicing should not fundamentally affect the physical structure of the plastics, metals, and glues used,
- the proposed technologies must enable laying the cables in earth, swamp or an available cable chamber,
- it must be possible to use the technology in heat, frost and moisture,
- the method must allow opening the cable joint and closing it again without interrupting the links in operation,
- the cable joint must be robust as regards mechanical effects,
- economic criteria need to be taken into consideration too.

Fibres in the cable joint are arranged in such a way that fibre reserve is located in the fibre space for possible repairs and adaptations in the cable joint. Already in the process of installation it is in most cases necessary to repeat fibre splicing until the required splice attenuation is obtained. The radius of the laid fibre must be small with respect to the cable joint dimensions but not so small that the fibre should be damaged due to static fatigue. This necessarily leads to specific requirements for laying the fibre in the cable joint cavity. The methods of implementation differ depending on the cable joint design and number of fibres.

The splicing of optical cable jackets is based on the application of contractible thermoplastic materials. The sleeve can be made of this material in the form of tube, longitudinally combined tube or strip. The internal side of the sleeve and strip can be coated with a material which melts under heat and thus a waterproof closure is obtained between the contracted sleeve and the cable jacket.

The quality of cable joints is evaluated in order to assess their resistance to failure in the given medium. This resistance is usually examined by testing. The respective tests fall into three basic groups:

Mechanical requirements
- cable joint resistance to pressure,
- cable joint resistance to impact,
- resistance to tension,
- resistance to bending in sleeve neck,
- resistance to vibrations.

Electrical requirements
- resistance to induced (short-circuit) voltages,
- electrical capacitance.

Environmental effects
- cyclic temperature changes,
- immersion of cable joint in water,
- resistance to chemicals,
- resistance to fungi and blight,
- resistance to overpressure in the cable joint.

The programme of testing should cover the whole range of manufactured cable joint sizes and configurations.

The basic cable section usually includes several manufacturing runs. When determining the transmission parameters of a section it is necessary to take into consideration not only the properties of the cable runs used but (in addition to other factors) also the effect of splices and connectors, and the effect of the coupling of modes that affect the bandwidth and attenuation size.

The transmission properties of manufacturing runs, splices and connectors have a certain occurrence probability, which often needs to be taken into consideration with a view to an economic design of the route.

Attenuation of the basic cable section is given by the sum

\[ a = \sum_{n=1}^{m} \alpha_n L_n + a_s \cdot x + a_c \cdot y, \quad (7.22) \]

where \( \alpha_n \) is the attenuation coefficient of \( n \)-th fibre, \( L_n \) is the length of \( n \)-th fibre, \( m \) is the total number of fibres, \( a_s \) is the average splice attenuation, \( x \) is the number of splices in the section, \( a_c \) is the average connector attenuation, and \( y \) is the number of connectors.

The values \( \alpha_{n_0}, a_s \) and \( a_c \) can be obtained as average values or they can be calculated using the standard deviation.

Two approaches can be used to form the basic cable section:

1. To select fibres from one category given for the manufacturing runs and assume the highest value of the selected category.
2. To select fibres from various categories on condition that attenuation of the basic section will not exceed the required attenuation. In that case the real attenuation coefficient is equal to the attenuation coefficient of \( n \)-th fibre.

From the practical viewpoint it is necessary to maintain certain reserve attenuation for potential additional splices and cable branching devices, for losses due to aging and temperature changes. For losses in splices and connectors the average value is considered. In
the design of concrete routes it is necessary to take into consideration statistical changes of these parameters.

When the cable has been laid and is connected at both ends to optical link terminations, it is possible to address the final measurements.

Results of the measurement of link routes must correspond to the respective technical conditions and recommendations of ITU-T. Also, the stability of the values measured and the overall reliability of the system must be proved.

The most widely monitored route parameters include the sensitivity of optical receivers (in loop operation), measurement of bandwidth, measurement of attenuation, and measurement of error rate.

Detection (search for) optical cables

Metallic pair can be embedded in the core (or jacket) of optical fibre to enable measuring the cable insulation state and detection of a buried cable. But many cables are fully dielectric and then there are difficulties with the detection of the buried cable.

For this reason, markers are added to the cable after certain distances. The markers are easy to identify by a locator and the cable can be traced. The location and depth of the cable can be established with very high precision.

Cable systems

This group covers mechanical technologies for the splicing and termination of optical cables.

Optical cable joint (splicing module), type 2500LG, is a separate optical cable joint for universal application. Its cover is made of reinforced thermoplastic material, which provides the cable joint with very good mechanical, climatic, and chemical protection. In the basic version, the cable joint is provided with three cassettes for storing fused or mechanical splices of optical fibres. Equipped with the cassettes, the cable joint has a capacity of 24 fibre splices (fused or mechanical). An additional extension cassette D-182563 can be included in the cable joint. From among the available cassettes, 3 cassettes of the type UC-54 can be located in the cable joint. These cassettes enable extending the cable joint capacity up to 54 fused splices while using the mechanical sandwich protection of splices. The basic splice package contains all the components necessary for installing two cables (o.d. 10 ÷ 21.6 mm) into the main cable joint inputs. The only consumable that needs to be ordered for cable joint installation separately is the filler material, so-called encapsulant, which is used to fill up the cable joint and which prevents water from penetrating into the inner space of the cable joint (see Fig. 7.63).

Basic properties and features:
- universal application,
- capacity 24 optical fibre splices, with extension cassettes up to 30 or 54 splices,
- possible application of: mechanical fibre splices, fused fibre splices with thermally contractible protection of splices, fused fibre splices with mechanical sandwich protection of splices.

Type 3000 optical cable joint can hold up to four such cassettes (36 splices each), with a resultant capacity of 144 fibre splices.
Optical distribution boxes, LGX series

Optical distribution boxes of the LGX series are designed to terminate or interconnect optical cables inside buildings. Together with accessories, optical distribution boxes form a modular, easy-to-extend unit. They can be placed in 19", 21" (ETSI) or 23" racks or they can be fixed directly on a wall. The basis of LGX series is formed by individual racks. By their function, the racks fall into:

- termination racks – are used to terminate fibres on connectors,
- storage racks for splices – are used to store fused fibre splices and their reserves, either when fusing pigtails or when directly fusing fibres from different cables,
- storage boxes for connection modules – are used to store redundant runs,
- optical connection modules,
- combination racks – serve as a combination of storage and termination racks.

Racks thus enable the fusing of pigtails and their termination on connector panels. The capacity of individual boxes can be 24, 72 or 144 fibres. The boxes are 43.2 cm (17") wide and 27.9 cm (11") deep. The height differs from type to type, and it ranges from 12.7 cm (5") to 53.4 cm (21").

Some distribution boxes are installed in the Laboratory for transmission media (see Fig. 7.64).
7.20 **Free-space optical communication**

Free-space optical links are implemented as links in closed spaces, free space (the atmosphere), and outer space.

*Free-space optical links in closed* spaces are implemented via optical fibreless modems (two-point modems or with connection to LON, etc.), which make servicing much more comfortable. Transmission to headphones is possible, e.g. TV sound accompaniment or in facilities for video-conferencing or interpreting. This area also includes wireless telephony, remote control of TV sets, and supervision and control of other devices. In all these cases the transmission is of high quality and without interference; in the case of interpretation facility there is the added advantage that eavesdropping outside the room is impossible (in contrast to similar electromagnetic facilities). IR radiation cannot get out of a closed space. Energy transmission between the transmitter and the receiver can proceed:

- directly, by directional radiation,
- indirectly, by diffuse radiation (e.g. reflection from wall surfaces).

Directional radiation is made use of when establishing point-to-point links. Diffuse radiation is used to establish connection among several terminals.

In the transmission using IR radiation a sufficiently strong field must be created in the closed space with receivers. High-quality transmission is conditional on uniform and sufficient radiation. The required optical emitted power is of the order of units to tens of watts. In large spaces it is advisable to have decentralized radiation, i.e. to use a greater number of radiators and these should be located as high as possible. It is good practical experience to install radiators close to the ceiling and tilt them into the space.

*Directional radiation*

Radiant energy propagates from the source of radiation in all directions at the velocity of light \( c \); radiant energy crossing a surface per unit time is called radiant flux through surface. Radiant flux \( P_e \) gives the power transmitted by IR radiation and is measured in watts.
Radiant intensity $I_e$ of a point source in a certain direction from this source is taken to mean the differential ratio of radiant flux $P_e$, which emanates from the source in this direction into a small solid angle $\Omega$, and this solid angle

$$I_e = \frac{dP_e}{d\Omega} \quad (\text{W} \cdot \text{s} \cdot \text{r}^{-1}).$$

(7.23)

Radiant intensity $E_e$ gives the differential ratio of radiant flux $P_e$ incident on an elementary part of an area $A$ to the size of this area

$$E_e = \frac{dP_e}{dA} \quad (\text{W} \cdot \text{m}^{-2}).$$

(7.24)

where

$$d^2P_e = L_e \frac{dA_1 \cos \varepsilon_1 dA_2 \cos \varepsilon_2}{r^2} \Omega_o,$$

(7.25)

$L_e$ is the radiation (W s r$^{-1}$ m$^{-2}$),

d $A_1$ is the element of transmitter surface (m$^2$),

d $A_2$ is the element of receiver surface (m$^2$),

$\varepsilon_1$ is the radiation angle of transmitter,

$\varepsilon_2$ is the radiation angle of receiver,

$r$ is the distance between transmitter and receiver (m),

$\Omega_o$ is s r.

The intensity of the radiation incident on an area from isotropic point source changes, by the cosine law, with radiation direction deviation $\varepsilon$ from the normal to this area and with the square of distance $r$

$$E_e = \frac{I_e \cos \varepsilon}{r^2}.$$ 

(7.26)

In the case that the area of receiver inlet opening is larger than the area formed by the radiant beam, it holds that the intensity of radiation incident on the receiver decreases with the square of distance $r$

$$E_e \approx \frac{1}{r^2}.$$ 

(7.27)

The passing beam of radiant intensity $E_e$ is further reduced by energy $dE$ per distance $dx$

$$\frac{dE}{E_e} = -k \, dx.$$ 

(7.28)

By solving differential equation (8.28) for initial and boundary conditions we obtain relation (8.29), which gives the losses due to absorption by environment along the whole distance $r$ between the transmitter and the receiver

$$E_e = E_o \, e^{-kr}.$$ 

(7.29)

Since in practice we will never achieve a situation that the area of inlet opening of receiver $A$ is at least equal to the beam trace $A_1$ ($A_1 > A$), the energy losses due to the difference between inlet opening area of receiver and beam trace area will be expressed by the ratio of these areas
\[
\gamma = \frac{A}{A_1}.
\]  
(7.30)

The quality of reflection areas of receiver and transmitter (if used) are expressed by reflectance coefficients \( \rho_p \) and \( \rho_v \), with \( \rho_p \) and \( \rho_v < 1 \). After substituting we obtain the expression for energy incident on receiver in directional radiation

\[
E_c = E_O \cdot \gamma \rho_p \rho_v \frac{e^{kr}}{r^2},
\]  
(7.31)

where \( E_c \) is the energy incident on receiver (W),
\( E_O \) is the transmitted energy (W),
\( \gamma = A \cdot A_1^{-1} \),
\( A \) is the area of receiver inlet opening (\( m^2 \)),
\( A_1 \) is the area of transmitter beam trace (\( m^2 \)),
\( \rho_p \) is the reflectance coefficient of receiver area,
\( \rho_v \) is the reflectance coefficient of transmitter area,
\( \rho_k \) is the extinction coefficient = 3.90 \( \times \) 10\(^{-4} \) m\(^{-1} \) (for \( \lambda = 0.9 \mu m \)),
\( r \) is the distance (m).

These relations can be used when solving problems of information transmission using sharply directed IR radiation over large distances. In transmissions in closed spaces the atmosphere attenuation can be neglected since it has been established that attenuation in the range of currently used wavelengths does not exceed the value 0.6%, even in the case of 100% humidity [8.21].

**Diffuse radiation**

The total power of IR radiation depends to a considerable degree on the room dimensions and the material of surfaces. The higher the reflectance coefficient of material surface \( \rho \), the lower the necessary IR radiant power is. The reflectance coefficient \( \rho \) is a function of incidence angle \( \alpha \), wavelength \( \lambda \) and polarization \( p \), i.e. \( \rho = f (\alpha, \lambda, p) \). The reflectance coefficient decreases with increasing incidence angle. Typical values for the region of the 1\(^{st} \) window:
- white wall 0.75-0.85,
- red wall 0.40-0.50,
- blue wall 0.05-0.20,
- black wall 0.01,
- white paper 0.80-0.85,
- black velvet 0.005,
- white wood 0.35-0.50,
- dark wood 0.10-0.20

Let us assume that the reflectance coefficient of all the surfaces that delineate the given space is the same, equal to \( \rho \), and that in time \( \Delta t \), which is the average time of wave propagation on the path between the radiator and the reflection surface of reflectance \( \rho \), average power \( P_{str} \) is emitted. After the first reflection, part of the emitted power, which is
equal to \( \rho \, P_{\text{str}} \), remains inside the space. At the instant of second reflection \( 2\Delta t \) the power has the value \( P_{\text{str}} + \rho \, P_{\text{str}} \) and therefore power \( P_2 \) inside the space has the value \( P_2 = \rho \, (P_{\text{str}} + \rho \, P_{\text{str}}) \). At the instant of \( k \)-th reflection \( k\Delta t \) the power inside the space is

\[
R_k = P_{\text{str}} + \rho \, P_{\text{str}} + \rho^2 \, P_{\text{str}} + \cdots + \rho^k \, P_{\text{str}}.
\]  

(7.32)

Since the reflectance coefficient is \( 0 < \rho < 1 \), we can write

\[
P_k = \frac{P_{\text{str}}}{(1-\rho)}.
\]  

(7.33)

In a closed space volume the state of equilibrium occurs: power emitted from the radiator will compensate the absorption by delineating surfaces. The average IR radiation inside the closed space will be \( 1/(1-\rho) \) times greater than emitted power.

If several different materials of different reflectance coefficients are used inside a closed space (which is often the case in practice), then it is necessary in relation (7.33) to substitute for the value of reflectance coefficient \( \rho \) the average value \( \bar{\rho} \) of all the inner surfaces. This value is calculated from the relation

\[
\bar{\rho} = \frac{A_1 \rho_1 + A_2 \rho_2 + \cdots + A_n \rho_n}{A_1 + A_2 + \cdots + A_n},
\]  

(7.34)

where \( A_1, A_2, \ldots, A_n \) are the areas of individual surfaces,
\( \rho_1, \rho_2, \ldots, \rho_n \) are the reflectance coefficients of individual surfaces.

It will be proved in the following that in the transmission via IR radiation the closed space behaves as an inertia element, which eventually turns out to be a limiting factor of the whole transmission system. The radiation velocity is finite. Information transmission is made possible by changing an arbitrary parameter of radiation. Technically the simplest thing is to modulate the intensity of radiant flux, which means that the instantaneous emitted power \( P_o \) is a function of time. It is obvious that in time \( t + dt \) the instantaneous power \( P_o \) will already have a different value and all the preceding signals, which after multiple reflections strike the receiver at this instant \( (t + dt) \), will show as disturbance signals.

Let us assume that in an arbitrary system for information transmission inside a closed space by means of IR radiation there is attenuation, which is caused by \( m \) reflections, with the \( m \)-th reflection not representing the disturbance value of reception. The attenuation is the result of \( k \)-th reflection, after which the value of radiant power in a closed volume equals

\[
\frac{P_o}{m} = P_o \, \rho^k,
\]  

(7.35)

where

\[
k = -\frac{\log m}{\log \rho} \quad \rho < 1 \Rightarrow \log \rho < 0, k > 0.
\]

Let the period of modulation frequency of transmission system be equal to \( T \). In time \( T \) there will be

\[
k = \frac{T}{\Delta t}
\]  

(7.36)

reflections. The average time of wave propagation in a closed volume is tied by the geometrical dimensions of the closed space by the mutual relation
where \( V \) is the volume of the room (m\(^3\)),
\( A \) is the total area of surfaces delineating the given volume (m\(^2\)),
\( c \) is the velocity of light propagation in vacuum (m\(\cdot\)s\(^{-1}\)),

substituting (7.35) and (7.36) and solving (7.37) for \( f_{\text{max}} = \frac{1}{T} \) we obtain

\[
f_{\text{max}} = \left[ \frac{c \cdot A}{4 \cdot V} \right] \left[ \frac{\log \rho}{\log m} \right] \text{ (Hz)}. \tag{7.38}
\]

This relation enables determining the maximum carrier frequency for single- and multi-channel systems of information transmission by means of IR radiation inside a closed space.

From relation (7.38) it is also evident that the highest carrier frequency is largely affected by the closed space dimensions, more exactly by the ratio of the room surface to the room volume.

Another factor that influences the result is the reflectance coefficient of all surfaces inside a closed space. The actual number of reflections \( m \) inside a closed space is difficult to establish but it can be assumed to range between 100 and 100 000. With increasing reflectance coefficient \( \rho \) the number of reflections increases, and vice versa.

Modulation of optical radiation

For optical transmitters in the 0.8 to 0.9 \( \mu \)m wavelength range LED diodes with direct modulation of the modulation signal are used. Emitted radiation does not propagate evenly over the whole space; most energy is emitted in the direction of optical axis, i.e. the straight line normal to the chip plane or passing through its centre. An idea of the distribution of radiant energy can be obtained from the radiation characteristics. For practical purposes it is of advantage to determine the graphic dependence of output optical power on the distance from the source and on the angle (from the optical axis), as shown in Fig. 7.65.
To obtain higher radiant powers several LED diodes are placed in one plane, which forms the so-called radiator. The number of diodes in the radiator can be 6, 12 or even much more.

For example, a radiator for monophonic and stereophonic transmission of signals can be set up, for example TV sound accompaniment in flats. The radiator can have six LEDs with cooler and reflector on each diode.

The power radiator is formed by 12 IR LEDs with cooler and reflector. The total emitted power is 200 mW, which guarantees good reception within ca. 15 m. The radiation characteristic of radiator is given in Fig. 7.66.

Fig. 7.65: Power vs. distance curves for free-space transmission.

Fig. 7.66: Radiation characteristic of radiator.
For transmissions over greater distances (also in the case of a higher number of channels) an even higher power is necessary. For example, a radiator with 167 LEDs can be used, whose radiation angle is 60°.

![Diffuse coverage: a) in a meeting room, b) around a table.](image)

**Fig. 7.67:** Diffuse coverage: a) in a meeting room, b) around a table.

For the detection of radiation a silicon-based PIN photodiode is usually used, whose characteristic has sensitivity on the same wavelength as that of the above radiation source.

In the design it is necessary to take into account also potential reception disturbance due to light sources in the room (fluorescent lamp, etc.). In all such cases simple filters are used, which filter the undesirable radiation components (simple filters such as film, special glass, etc.). Without filtering, an increase in noise of up to 50% can appear in some bands.

The frequently used modulation methods include FM modulation and FSK modulation. In many devices the PSK-IM modulation is used.

For the diffuse coverage of a space it is necessary to place a radiator in each corner as close to the ceiling as possible and to tilt them under 20° - 40° into the space. Radiators must be installed such a way they cover the whole space by partial overlapping of the radiation characteristics of individual radiators. An example of the coverage in a meeting room and “around a table” is given in **Fig. 7.67**.

In diffuse coverage, the reflectance coefficient of light areas $\rho > 0.2 - 0.9$ assures an even distribution of radiation intensity $E_e$ over the whole space.

In directional coverage we start from the directional characteristic of the respective radiator; to cover the same area, ca. 66% of the LED radiant power in comparison with diffuse coverage is sufficient.

By contrast, if ragged spaces with recesses, dark walls and strong interference from another light are involved, the number of radiators must be increased 1.5 times. If strong solar radiation is assumed that enters the room through a window or glass wall, additional radiators must be placed such that they radiate in the direction of the interfering solar radiation.

A suitable lay-out of radiators inside the closed space can be checked using the receiver. The minimum distance between receiver and radiator is 2 m. Decisive for the assessment of the transmission quality is the SNR measured on the low-frequency receiver output, expressed
in dB. In practical realizations we distinguish SNR of 40, 30 and 20 dB, endeavouring to achieve the value 40 dB.

**Optical free-space modem**

The solution in Fig. 7.68 gives one of the possible applications of these transmissions. The modem is most frequently made up of two parts, the so-called satellite head (transmitter and receiver) fixed on the ceiling, and the terminal itself, which includes the directional optical part. This way the terminal can be connected at any point in the room. The connection of terminal to satellite is shown schematically in Fig. 7.68. The respective block diagram is in Fig. 7.69.

![Diagram of optical free-space modem](image)

**Fig. 7.68:** Installation of optical free-space modem.

In practical implementations, diffuse radiation with a range of over 10 km is used. The devices achieve 100 Mbit·s⁻¹ transmission speeds. The type of modulation used is FSK-IM (PSK-IM). The radiation sources are usually LED diodes of the wavelength $\lambda = 0.88 \, \mu m$, and PIN PD detectors. The modem operates in half- or full-duplex. An approximate direction-adjustment of the facility is made for the terminal – satellite transmission.
Optical free-space links in free space

These links are designed, above all, for rapidly establishing communication without the necessity of laying cables. These links are "line-of-sight" links, i.e. highly directional and, in comparison with radio links their operation is not conditional on frequency allocation by CTU. Using these links, it is no problem to span roads, valleys, etc. The disadvantages of these links include the difficulty of bringing transmitter into phase with receiver, and the not always 100% reliability of the links, which depends on fog, flying flocks of birds, etc. Development in this area is focused on seeking methods that increase the resistance of transmission to atmospheric events.

This kind of transmission is currently implemented by the laser beam, with the optical power divided among several parallel beams for the sake of increased reliability.

Transmissions are most frequently realized at speeds of 155 Mbit·s⁻¹ over distances from hundreds of metres to 1.2 to 3 km. The wavelengths used are 785 nm, 850 nm, and 1550 nm. Wavelength multiplexers with speeds of up to 10 Gbit·s⁻¹ have already been installed.

The total link attenuation between the transmitter and receiver can be expressed by the relation

$$a_c = a_v + a_{12} + a_{atm} + a_p \quad [\text{dB}]$$

(7.39)

where

- $a_v$ is the attenuation in transmitter system,
- $a_{12}$ is the attenuation by propagation,
- $a_{atm}$ is the attenuation due to atmospheric phenomena,
\( a_0 \) is the attenuation due to receiver system.

Attenuation due to propagation \( a_{12} \) is given by the ratio of optical intensities on the beam axis at the receiver and transmitter sites. In the remote radiation zone the divergent Gaussian beam can be approximated by spherical wave. For attenuation due to propagation the following relation can be derived

\[
a_{12} = 20 \log \left(\frac{L_0}{L_0 + L_{a2}}\right) \text{ [dB]}
\]

where \( L_0 \) is the so-called auxiliary length.

To be able to express \( L_0 \) the diameter of optical transmitter system \( D_{TXA} \) and the planar angular width of transmitted beam \( \phi_1 \) must be known. The two quantities are obtained by measuring.

Atmospheric attenuation \( a_{\text{atm}} \) is divided into two components: constant attenuation, i.e. attenuation in the “pure” atmosphere, and random additive attenuation of the real atmosphere.

In the power balance in free-space links it is necessary, the same as in fibre links, to consider the reserve, error rate, signal-to-noise ratio, and, in addition, short-time fading, and wave interference in turbulent atmosphere. Certain problems arise with vibrations of fixing brackets and when these links are deployed in new buildings, which may have the tendency to “slide” (before they “settle”), etc.

It is obvious that not all of the negative effects will come about at the same time and everywhere. It depends on the respective localities, buildings, and flocks of birds flying above the town centre, etc.

These facilities are offered by many firms under firm names such as CANON – ANOBEM, CBL-Laser Link, SONA-SONA beam. The current top product in this area is Tere Scope 10GE (10 Gigabit Ethernet) of the MRV Company, with an operation range of up to 850 m. Those interested can find more details on the respective web pages.

### 7.21 Optical filters

Filters change the spectral distribution of the energy of emitted radiation or they almost evenly weaken the radiation in a certain, relatively broad region of the spectrum. The effect of filters is characterized by the coefficient of spectral transmissivity \( \tau(\lambda) \) as a function of the wavelength of emitted radiation according to the relation

\[
\tau(\lambda) = 1 - \rho(\lambda) - \alpha(\lambda),
\]

where

\[
\rho(\lambda) = \frac{\Phi_{\lambda r}}{\Phi_{\lambda e}}
\]

is the spectral coefficient of reflectance, and

\[
\alpha(\lambda) = \frac{\Phi_{\lambda a}}{\Phi_{\lambda e}}
\]

is the spectral coefficient of absorption.
By the law of energy conservation the sum of reflected, absorption and passed radiation must be equal to incident energy. It must therefore hold
\[
\rho(\lambda) + \alpha(\lambda) + \tau(i) = 1.
\] (7.44)

Let us finally define the coefficient of spectral transmissivity \(\tau(\lambda)\) by the relation
\[
\tau(\lambda) = \frac{(\Phi_{\text{el}})_{\text{OUT}}}{(\Phi_{\text{el}})_{\text{IN}}},
\] (7.45)

which describes the filter transmissivity for radiation: for example, the value \(\tau(500 \text{ nm}) = 0.7\) means that radiation of wavelength 500 nm is absorption- and reflection-weakened by 30% during throughput. The spectral coefficient of own transmissivity is
\[
\tau_i(\lambda) = \frac{(\Phi_{\text{el}})_{\text{OUT}}}{(\Phi_{\text{el}})_{\text{IN}}},
\] (7.46)

and the coefficient of own absorption \(\alpha_i(\lambda)\)
\[
\alpha_i(\lambda) = \frac{(\Phi_{\text{el}})_{\text{val}} - (\Phi_{\text{el}})_{\text{vyl}}}{(\Phi_{\text{el}})_{\text{val}}},
\] (7.47)

where we relate the output or absorbed radiant flux to the input flux and not to the total incident radiation.

In view of the above, the function \(\tau(\lambda)\) can be determined either using \(\alpha(\lambda)\) (so-called absorption filters) or using \(\rho(\lambda)\) (so-called interference filters). Using low-absorption interference filters the so-called colour dividers can be designed.

The region of wavelength of incident radiation is divided into a part through which radiation has passed and a part with reflected radiation. From the viewpoint of radiation receiver it is most important that at the output of optical radiation receiver the ratio of radiator signal to the signal of noisy background should be as large as possible.

The need for filtering was mentioned in connection with information transmissions inside closed spaces, where the matter in question was to filter the undesirable disturbance components of daylight and lighting. This problem is relatively easy to solve using an optical high-pass filter (the above disturbance components are in lower wavelengths). The application in multiplex systems requires a more challenging solution using interference filters.

Undesirable disturbing light can today be filtered directly, using commercial photodiodes with embedded optical filters. Optical filters made of coloured glass achieve a high degree of throughput, e.g. filter RG 700: 1% at \(\lambda = 750\) nm, 80% at \(\lambda = 800\) nm, and 97% at \(\lambda = 860\) nm; filter RG 850: 1% at \(\lambda = 820\) nm, 80% at \(\lambda = 870\) nm, and 97% at \(\lambda = 920\) nm.

Optical filters can be used to implement filters of the type of low-pass, high-pass, band-pass, and notch filter, just like in electrical technology.

It is even possible to make use of the favourable properties of optoelectronic elements when, for example, a combination of optical high-pass filter and a photodiode behaves as an optical pass-band filter with cut-off frequencies \(\lambda_{\text{mez1}}\) and \(\lambda_{\text{mez2}}\).

In some simple applications it has been found of advantage (also because of availability) to use a non-exposed but developed reversal film (Agfa CT 18, Fomachrom D 18). Using such films, the interference caused by fluorescent lamp can be limited and the effect of daylight strongly reduced.
In practical implementations using high-quality filters (coloured glass) the signal-to-noise ratio is often reduced by more than 15 dB.

There are also filters on the basis of phototropic glass, in which the throughput coefficient is reduced via short-time radiation. They begin to find application as optical memories in data processing. They are also frequently used as adaptive grey filters in sunglasses.

Dispersion filters can also be used for the purpose of filtering, when the decomposition is performed by prism or optical grating. When the prism is used, optical losses are 5 – 7 dB (but the cost is high and mass production difficult).

Optical gratings are of much promise; their optical losses are ca. 2 – 4 dB, the cost is low and mass production relatively easy.

Absorption filters

Material used for absorption filters is, above all, suitable coloured glass. While the effect of a specific filter on radiation is described by the coefficient \( \tau(\lambda) \), to calculate the transmissivity for various filter thicknesses we need the coefficient \( \tau_i(\lambda) \). It holds \( \tau_i(\lambda) > \tau(\lambda) \) since the coefficient \( \tau_i(\lambda) \) does not include reflection losses. In the filter calculation the following relation is sufficient

\[
\tau(\lambda) = \tau_i(\lambda)(1 - 2 \rho_x).
\]

where \( \rho_x \) is the coefficient of surface reflectance given by the relation

\[
\rho_x = \left( \frac{n_x - n_s}{n_x + n_s} \right)^2
\]

and can thus be determined from the refractive index or as the so-called reflection factor \((1 - 2 \rho_x)\) from the catalogues of coloured glass [8.26].

The coefficients \( \tau_{i1}(\lambda) \) and \( \tau_{i2}(\lambda) \) for two filters of the same material and thicknesses \( d_1 \) and \( d_2 \) are given by the relation

\[
[\tau_{i2}(\lambda)]^{d_2} = [\tau_{i1}(\lambda)]^{d_1},
\]

so that using relation (7.49) recalculation to any arbitrary thickness of colour filter is possible. Large thicknesses narrow down the transmissivity region but, on the other hand, they reduce the transmissivity through the filter.

Combining different filters into a beam of rays, we obtain the total transmissivity coefficient as the product of the transmissivity coefficients of the individual filters

\[
\tau(\lambda) = \tau_1(\lambda) \tau_2(\lambda) \ldots
\]

Thus a filter system can be realized by transmissivity curves that cannot be realized by individual filters.

The characteristic of the filter given above is mostly bell-shaped; if rare earth oxides are used, narrow bands of absorption and transmissivity can be obtained. Typical curves of the transmissivity of glass absorption filters are given in Fig. 7.70.
Interference filters

Interference filters can realize transmissivity curves that are unattainable with the aid of absorption filters. This mainly concerns the possibility of implementing line and narrow-band filters, in which for optional wavelengths $\lambda_0$ the maximum transmissivity $\tau_{\text{max}}(\lambda_0)$ attains as much as 0.4, and which transmit in only a very narrow band of wavelengths. The filtering effect is the result of multiple reflections between semi-transmissive layers. Two semi-transmissive layers with an interlayer (interlayers) are deposited onto a glass plate, whose thickness $d$ determines the wavelength $\lambda_0$ with maximum transmissivity in a plane normal to the incidence plane. For light that is incident at an angle the transmissivity and reflectance values are different and this must be taken into account. The production of interference filters is currently on such a high level that even this problem is solved satisfactorily, as will be seen later.

Another possible application consists in vapour-deposition of a wedge interlayer, which yields a variable interference filter. The transmissivity band $\lambda_0 \pm \Delta \lambda$ gets shifted with the coordinate of the respective part of the filter. These filters are applied in the design of simple monochromator.

The theoretical design and calculation of the filters are relatively complicated in view of the existing amount of combinations of different transparent layers. We start from an analytical description as in the case of high-frequency lines. For individual filter layers the cascade matrix

$$A_i = \begin{bmatrix} \cos \frac{2\pi nd}{\lambda} & j \frac{1}{n} \sin \frac{2\pi nd}{\lambda} \\ j n \sin \frac{2\pi nd}{\lambda} & \cos \frac{2\pi nd}{\lambda} \end{bmatrix},$$

holds, where $n$ is the refractive index of the layer,

$\lambda$ is the wavelength,

$d$ is the layer thickness.
For the structure of an interference filter made up of \( n \) layers, the resultant cascade matrix is determined

\[
A_v = \sum_{i=1}^{n} A_i. \tag{7.53}
\]

Let matrix \( A_v \) have the form

\[
A_v = \begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}, \tag{7.54}
\]

then by [8.28] the relation between reflected and transmitted light is given by

\[
\frac{R_0}{A_0} = \frac{am_{11} + bm_{12} - cm_{21} - m_{22}}{am_{11} + bm_{12} + cm_{21} + m_{22}}, \tag{7.55}
\]

where \( R_0 \) is the amplitude of reflected light in input medium,
\( A_0 \) is the amplitude of incident light in input medium,
\( a, b, c \) are coefficients dependent on refractive index and propagation angle in input and output mediums,
\( m_{11}, m_{12}, m_{21}, m_{22} \) are the elements of a matrix that is the product of \( k \) matrices.

\[
\begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix} = \begin{bmatrix}
m_{11}^i & m_{12}^i \\
m_{21}^i & m_{22}^i
\end{bmatrix} \cdots \begin{bmatrix}
m_{11}^k & m_{12}^k \\
m_{21}^k & m_{22}^k
\end{bmatrix} \tag{7.56}
\]

Elements of the \( i \)-th matrix only depend on optical properties (i.e. refractive index and thickness of the layer) and the propagation angle in the \( i \)-th layer. The schematic diagram of the filter is given in Fig. 7.71.

![Principle of interference filter](image)

The following denotation is used in the figure:

- \( k \) is the number of layers,
- \( d_1 - d_k \) is the thickness of layers,
- \( n_1 - n_k \) is the refraction angle of layers,
- \( n_0 \) is the refraction angle of input medium,
- \( n_{k+1} \) is the refraction angle of output medium,
- \( \phi_0 \) is the incidence angle of light,
\( \varphi_{k+1} \) is the angle at which light leaves the filter,

\( \varphi_1 - \varphi_k \) is the angle at which light propagates in individual layers.

For the theoretical and general cases when the filter does not absorb any light, it will hold for the transmissivity

\[
T = 1 - R. 
\tag{7.57}
\]

All the considerations have up to now concerned polarized light. If we consider (non-polarized) light, we can perform a replacement of filter solution by two components, one of which, \( P \), lies in the incidence plane, and the other component, \( S \), is normal to the incidence plane.

For the intensity of natural light \( I \) it holds

\[
I = \frac{I_p}{2} + \frac{I_s}{2},
\tag{7.58}
\]

where \( I_p \) is the intensity of light polarized in incidence plane, \( I_s \) is the intensity of light polarized perpendicularly to incidence plane.

For the ratio of reflected to incident light intensities it thus holds

\[
\frac{I_r}{I} = \frac{I_{rp} + I_{rs}}{I_{dp} + I_{ds}},
\tag{7.59}
\]

and for the ratio of refracted to incident light it holds

\[
\frac{I_1}{I_d} = \frac{I_{dl} + I_{ls}}{I_{dp} + I_{ds}}.
\tag{7.60}
\]

For the determination of \( R \) for perpendicular incidence it will hold (\( I_p = I_s \))

\[
R = \left( \frac{R_0}{A_0} \right)^2,
\tag{7.61}
\]

for oblique incidence

\[
R = \left( \frac{R_{op}}{A_{op}} \right)^2 + \left( \frac{R_{os}}{A_{os}} \right)^2.
\tag{7.62}
\]

On the assumption that the thicknesses of individual filter layers can be chosen arbitrarily, a number of various filter combinations can be obtained. It has been found that for practical realization two kinds of filter have significant properties.

a) filters with the structure \( HLHL \ldots LHLH \)

where \( H \) is a layer of high refractive index, and \( L \) is a layer of low refractive index. For the layer thickness it holds

\[
d_H = \frac{Z}{4n_H \cos \varphi_H},
\tag{7.63}
\]

and

\[
d_L = \frac{Z}{4n_L \cos \varphi_L}.
\tag{7.64}\]
The reflectance increases with increasing number of layers, and for a certain wavelength $Z$ almost 100% reflectance can be attained. The waveform for this type of filter is shown in Fig. 7.72a.

b) filters with the structure $HLHL \ldots HLLH \ldots HLH$ feature a twofold layer $LL$, with theoretical zero reflectance being attained. The waveform of this type of filter is shown in Fig. 7.72b.

![Waveform of interference filter variants](image)

**Fig. 7.72:** Interference filter variants: a) structure $HLHL \ldots LHLH$, b) structure $HLHL \ldots HLLH \ldots HLH$.

The theoretical design for the following practical realization is very demanding. Programs for the calculation of filters have been written. They enable choosing the following filter structures

- $HLHL \ldots LHLH$,
- $HLH \ldots HLLH \ldots HLH$,
- an arbitrary combination of 3 types of layer ($H$, $L$, $M$),
- different structures.

Designation $M$ is used for a layer with medium refractive index.

Seven filter parameters are further defined:

- number of layers,
- refractive index of input medium,
- refractive index of output medium,
- refractive index of layers,
- layer thickness,
- range of wavelengths of incident light, i.e. the range in which we want to establish the spectral characteristics of filter.

Thus the filter characteristic can mainly be influenced by an appropriate refractive index of the respective medium (e.g. SiO\textsubscript{2} with a refractive index of 1.49, TiO\textsubscript{2} with a refractive index of 2.3, ZnS with a refractive index of 2.35), by a change in the number of layers, and by a change in layer thickness. With increasing number of layers the reflectance at basic wavelength and in its neighbourhood increases up to 100%, and simultaneously the steepness of characteristic increases. With increasing thickness, the maximum reflectance gets shifted towards higher wavelengths.

It has turned out in filter analysis that minor deviations in thickness and refractive index from the set values are of no substantial effect on the nature of dependence. Concrete values change, for example, such that for a change in layer thickness within (-5: +5) and in refractive index within (-0.02: +0.02) from the set values they are less than 1 dB. Refractive index deviations of individual layers within (-0.02: +0.02) shift the transmissivity band within 1-2 nm. Thickness deviations are of greater effect: for example, deviations within (-5: +5 nm) shift the transmissivity band by as much as 8 nm, deviations within (-10: +10 nm) by as much as 15 nm, and deviations within (-15: +15 nm) by as much as 40 nm.

A changing incidence angle affects the filter waveform according to relations (7.63) and (7.64). By Snell’s law, with increasing incidence angle there is also an increase in the angles at which light propagates in individual layers. It is obvious that under constant thicknesses and refractive indices increasing angle of propagation reduces the fundamental wavelength. It can be said that with increasing incidence angle the filter characteristics get shifted towards lower wavelengths. However, for small incidence angles (smaller than 10\(^\circ\)) the difference in comparison with perpendicular incidence is negligible.

So far we have only considered the appearance of the 1\(^{\text{st}}\) maximum of reflectance in cases when the phase difference in layers is equal to \(\pi\), and the appearance of the 1\(^{\text{st}}\) minimum of reflectance when the phase difference is equal to \(2\pi\). From the theoretical viewpoint the phase differences \(\pi, 3\pi, 5\pi \ldots\) (for which reflectance maxima appear) are equivalent and similarly for \(2\pi, 4\pi, 6\pi \ldots\) when reflectance minima appear.

If the fundamental wavelength \(Z\) is chosen, on which the 1\(^{\text{st}}\) reflectance maximum appears, we can write that the \(k\)-th maximum appears for the wavelength
\[
\lambda_k = \frac{Z}{2k - 1}
\]
and the \(k\)-th minimum appears for the wavelength
\[
\lambda_k = \frac{Z}{2k}.
\]

If, for example, we choose the 850 nm wavelength (the region of 1\(^{\text{st}}\) maximum), then 2\(^{\text{nd}}\) and 3\(^{\text{rd}}\) maxima will be on the 283 nm and 170 nm wavelengths, respectively. Similarly with the minima: the first lies on the wavelength 425 nm, the second and third minima on the wavelengths 212.5 nm and 142 nm, respectively. Mutual spacing of wavelengths is very suitable for practical applications.

Two filter variants are given in Fig. 7.73.
Individual manufacturers give the characteristics of filters most frequently in graphic form or in tables. Some firms (e.g. Schott) will make filters to customers’ requirements. Filters are mostly subdivided by bandwidth, their application, and material base; parameters and, of course, dimensions are also given. Standard diameter values are 12, 15, 25, and 50 nm; thickness 3 – 9 nm. With the gradual deployment of DWDM systems the problematic of optical filters gains in topicality. Important world companies offer these products in compliance with ITU-T recommendations. For example, the firm AocTel offers filters with 50 GHz and 100 GHz frequency spacing, numerous couplers, and muxdemux modules. An example of the 50 GHz filter is given in Fig. 7.74.
7.22 Experience of building Czechoslovak optical routes

The first experience was gained in the construction of the first optical route between AE Prague Centre and AE Dejvice (1984). The results confirmed the high-quality parameters of the route, which offered favourable conditions for planning further routes. After some delay, another construction was undertaken by the Alcatel Company (1989). The year 1989 saw the beginning of the construction of first optical routes.
The first optical cables in this country were laid as communication cables in large cities (Prague, Brno), between exchanges in order to increase the throughput of circuits necessary for extending the telephone network at that time.

With the beginning of digitization it turned out to be necessary to deploy fibre-optics also in transport networks. The first optical cable was laid in the central reservation of the motorway Prague – Brno – Bratislava, with extensions to Germany and Hungary. The so-called northern fibre-optic branch went from Vienna via Znojmo, Brno, Olomouc, Ostrava, and Warsaw to Scandinavia. The networks belonged to the then monopoly operator SPT TELEKOM. This firm gradually built a digital overlay network and made the whole country “optical”. This project terminated in the year 2000. Only the ring topology was applied and the technologies were supplied by AT & T, later also by Siemens and Alcatel. This process was greatly accelerated by the huge damage to metallic networks during floods in Moravia and East Bohemia; moreover, optical cables in HDPE pipes that were already in operation at that time exhibited extremely higher resistance.

Power engineering and railways incorporated optical fibres in their networks and in the 1990s other operators – GTS, NEXTRA, ETEL, TISCALI, CESNET, SITEL, etc. – did the same.

Around the year 2000 the market got oversaturated with optical fibres, the hoped-for increase in operation did not materialize, and telecommunication companies suffered the notorious stock-market crash.

Currently in this country, only sporadic construction of optical routes takes place; routes are being moved (in connection with motorway construction) and wavelength multiplexers are being connected in operationally overloaded fibres.

The construction of FTTH networks currently attracts much attention. In 2007 a pilot network of the type of FTTH was launched in Bohuňovice. The project was realized with EU support funding. In addition to the conventional potentials of this network, automated reading of water consumption is envisaged (and consequently also the supervision of the water-supply pipeline).

Optical cables are in most cases installed by specialized firms, which are properly equipped for this work. Equipment and devices for “fibre-optic” are costly. The basic outfit includes blowing equipment, air compressor, fibre cleaver, splicing machine, optical power source and meter, and reflectometer (OTDR). Tools, cleaning facilities, etc. are indispensable. After installation the final measurements are performed, by the direct method and OTDR (from both ends A and B) and the route is then handed over to the operator.

**7.23 Experience of building metropolitan optical network in Brno**

After graduating from the Technical University of Brno (TUB) in 1968 the author of the present book was with the firm Czechoslovak Telecommunications, trunk transmission division. After transferring to TUB, he participated, among other things, in building the TUB data network, which was formed by interconnecting individual localities by coaxial (mostly self-supporting) cables and radio links.

After the arrival of “optics” the author (together with Ing. O. Dostal, CSc. – The Masaryk University) took part in the first pilot project of optical interconnection of the computer centres of MU and TUB, using an optical cable (ca. 4 km long).
In the first stage, MU and TUB discussed with SPT TELECOM the possibility of the network being built by the latter. After lengthy and unsuccessful negotiations, MU and TUB decided in 1993 to build their own private optical computer network under the name Brno Academic Computer Network (BACN). Because of limited funding and the high cost (in terms of money and time) of buried cables, the network was built using self-supporting optical cable installed on Brno roofs. The terminal devices for the network are also very expensive and therefore, with regard to the price, self-supporting gradient fibre 62.5/125 μm without metallic element was chosen. The cable contained a total of 8 MM optical fibres. Cables for indoor lines had 4 fibres. Outdoor and indoor fibres were fused and housed in cable joints. These cable joints are placed in lockable cabinets to prevent access to them. At each point where a router is mounted, the indoor fibres are brought to a distribution box. The whole network was operated on ETHERNET at 10 Mbit\cdot s^{-1}.

The second stage of building the BACN network was started at the turn of 1996 by the implementation of the “Project of the development of Brno Academic Computer Network” and by upgrading the network. The aim of the project was to extend the network to further localities and enable further institutions to connect to the backbone optical network. The project was funded from the Dynamic Development fund. For the interconnection of localities 8 single-mode fibres (SI) and 4 gradient fibres (GI) were used.

In subsequent years, buried routes were mainly built and this was done either by building new routes to university localities (in view of their importance) or by additionally laying cables in trenches dug out by other firms building private cable networks. Because of the shift in the requirements of the network technologies used the currently laid cables have only single-mode fibres, mostly 48 or 96 fibres (SI). The firms NETPROSYS and AVENET participated significantly in the development of the network.

When the network began to be built, much emphasis was placed on the maximum possible extension of it. In the course of time, requirements for increased network quality and bandwidth came to be raised. At that time it was considered convenient to build a new backbone network (ATM), which, in addition to high-speed transmissions brings a number of further services. Among them is the possibility of creating virtual networks, which are absolutely necessary in medical applications. Changes were made in the localities Botanická (UVT MU), Obilní trh (Faculty of Medicine, MU) and Kotlářská (Faculty of Science, MU). These changes and the efforts to make maximum use of network potentials led to subsequent adjustments in the network distribution system in both the Metropolitan network and some localities. The most dramatic change concerned the Kotlářská locality (the most important locality as regards network operation), where the whole network topology was changed. The changes that were made increased the speed of ETHERNET from 10 Mbit\cdot s^{-1} to 155 Mbit\cdot s^{-1}.

Exploiting the changes made gave rise to new applications in the field of medicine and initiated the realization of larger systems that provided students and lecturers with access to databases containing, for example, X-ray photographs of patients from various periods of treatment, results of tomographic examinations, angio-examinations, etc. Implementing the Obilní trh node enabled deploying this technology straight at the data source.

A further stage in building the BACN network began only in 2001 because thanks to the preceding highly positive changes made in the backbone network there was no urgent need to rebuild it. At that time a new advanced alternative appeared, namely to build a new backbone network based on the gigabit Ethernet technology. The new gigabit backbone network was built in the year 2002. While building this network, there was a radical change: until the end of last century a network was built by the method of successive steps, i.e. as new requirements for communication appeared and financial resources became available, the network topology
was gradually defined. The new gigabit backbone network was built by “the big bang” method, i.e. the network structure and topology were defined at the very beginning and the building process was then affected by allocation of funds. Today the network contains over 90 important and basic nodes. Currently, the total length of optical fibres and cables amounts to more than 150 km. Through the Masaryk University node the network is connected with Prague via a 2.5 Gbit s\(^{-1}\) link. From Prague the connection is worldwide.

An ever increasing network with growing numbers of users thus came into being. The network (BACN) currently interconnects universities, Academy-of-Science sites, courts of justice, tax offices, governmental offices, hospitals and other facilities with access to the network. The building of BACN falls into several stages. A new stage of building the BACN network mostly starts when upgrading the power and extent of the network is possible or when new funding is allocated. The users of this network include Vodafone, O2, and other organizations. The schematic diagram of the current network is shown in Fig. 7.75.
The Brno Academic Computer Network, which interconnects various institutions all over Brno, is connected to other localities in the Czech Republic via CESNET or rather CESNET 2 because the CESNET project has entered a new generation of its development.

**Fig. 7.75:** Schematic diagram of metropolitan academic optical-cable network in Brno.
This network is a national high-speed computer network designed for science, research, development, and education. Its backbone interconnects the largest university towns in the Czech Republic, which are circuits with high transmission speeds. The users are mostly universities, the Academy of Science of the Czech Republic, but also some secondary schools, hospitals, and libraries. The CESNET project is now part of several other projects such as TERENA, GEANT, DANTE, CEENet, and GLIF. The CESNET project itself participates in the development of medical applications with other EU countries (e.g. the university in Bologna) in an effort to design pilot projects for the European Union.

Fig. 7.76: Schematic diagram of high-speed computer network for science, research and education – CESNET 2.

The CESNET 2 network is connected to the European network GEANT, which is an association of 30 operators of national academic networks in Europe. In mid 2004 the GEANT project concentrated on further developing the European academic backbone network called GEANT 2. The project is scheduled for 4 years. At present, the speed of GEANT network is up to 10 Gbit·s⁻¹ (see Fig. 7.77).
**Examples of network exploitation**

Apart from the standard application of the Internet, the network is utilized for editing journals, E-learning, and voice and video transmission; current interest is focused on the transmission of medical data, pictures, and videoconferencing.

The interdisciplinary project MeDiMed (Metropolitan Digital Imaging System in Medicine) solves problems of medical applicability, legal aspects, and problems of the technical assurance itself.

It is concerned with building a metropolitan archive, so-called PACS (Picture Archiving and Communication System), and with interconnecting hospital modalities (diagnostic facilities) such as ultrasound (US), digital mammography (DMG), computer tomography (CT), magnetic resonance (MR), etc.
The aim is to exploit medical informatics for increasing the quality of medical operativeness and medical care, and for improving the conditions of medical research and teaching of graduates in medicine.

Solving these problems involves archiving image data, transmission of high-quality pictorial information between individual sites (hospitals) with which the patient came into contact during treatment, holding remote consultations with specialists or preparing a plan and simulation of future treatment.

The result is easier and quicker formulation of correct diagnosis, avoidance of repeated examinations, savings in patient’s and doctor’s time and thus also financial means.

This system, which is part of the MeDiMed project, was set up for processing, transmitting and archiving medical information and data in 1999. In that same year the first modalities were connected to the system. One of the primary tasks of the system was the conversion of data into the DICOM (Digital Imaging Communications in Medicine) format. In the year 2000, after the basic trial period, the research workers obtained much specific information concerning the potentials and limitations of the installed PACS system.

DICOM is a format for archiving medical data that has gained worldwide acknowledgement. This format is also used by the MeDiMed project and its PACS central archive for data archiving and transmission. The format must contain all the data necessary for the archived studies to have a trustworthy informative value such as the key words of the study for easy retrieval, description of the study and possibly the procedure adopted in the treatment, and visual documentation.

Information transmitted for the MeDiMed project represents a very sensitive matter since patient’s personal data are involves, which no unauthorized person must get hold of. Hospitals make heavy demands on the security of transmitted data. Researchers therefore concentrate on two important facts:

- **Securing the BACN network against physical damage or getting hold of important information.** For the sake of sufficient security of sensitive data on servers and archiving devices the main servers were placed in a separate, physically partitioned and locked section. The arrangement is similar in the stand-by centre of the Faculty of Medicine of the Masaryk University in Brno.

- **Getting hold of information about patients via the network.** This method of endangering patient’s information is in optical fibre transmission of data protected by a secret method of data ciphering. The archived data are protected by a number of access and protection passwords. The archiving system is divided into several levels, which protect the whole system. Authenticated access provides a further protection of the data and system. The application of firewalls is an important form of protecting data against abuse. Before the input into the transmission network the central PACS servers terminate in a firewall, which ensures the filtering of operation. At the hospital side there is a compiler firewall (administered by the PACS system), which is connected to the hospital boundary router. In this way the security of the PACS system is protected.

A range of diverse hospital workplaces are currently connected to the metropolitan PACS server. Decisive in the identification of individual workplaces is today the IP address of the workstations of the respective workplace. This solution is fully satisfactory only for sources of image data or viewing stations used only by a single user. An alternative to authenticated access is a logical requirement on the part of doctors (on duty in other hospitals, mobile surgeries, doctors working at home, ...). This problem was solved by assigning private
unique IP addresses to individual users. Another step in this direction consisted in determining the device that would determine one’s private IP address using the PKI (Private Key Infrastructure). The solution chosen here was the application of USB keys.

A very important advantage of the project consists in that it is supported by the technology of an instruction and research subsystem, which is expected to enhance greatly the level of teaching undergraduate and postgraduate students of medicine. The solution is conceived such that it fully meet the requirements of compatibility with systems working in real operation; the aim is to create for the user an environment that basically does not differ from real operational systems.

This is closely related to the problem of providing and securing pictorial studies that are suitable for research and instruction purposes as part of the instruction system. All information is removed (or modified) that might reveal patient’s identity but with a maximum informative value of the study being preserved. In 2004 the development of an anonymization module was completed that enabled transmitting selected anonymized studies to the database of the instruction and research system.

A pictorial study that has been included in the instruction system must be provided with a standard description of patient’s problem, with the treatment procedure attached. A set of key words must also be provided to enable simple retrieval of study materials.

Tremendous advances in the development of medicine and diverse technical devices and instruments, together with the great potentials of diagnostics and medical examination, offer new possibilities of exploiting the PACS picture system. Until recently the situation was such that the application of this information remained on the level of doctor’s subjective evaluation. Today, performing a number of examinations (most frequently CT and MR because these methods can provide 3D information on patient’s internal structures) and their mutual evaluation offers the possibility of creating 3D models (modelling of bones and tissues based on the above CT and MR examinations), planning surgical and reconstruction operations, simulations of operation procedures, tool navigation and aiming, and, last but not least, a realistic training of the operation using a simulator. This new possibility began to be developed beyond the initial frame of the MeDiMed project by 3D modelling of tissues on the basis of CT/MR data. Starting from a design of clinically utilisable system of processing CT and MR data for creating 3D computer models of human tissues, so-called “Virtual development and application centre” was established. Virtual only because it involves highly interdisciplinary cooperation in the fields of state-of-the-art medicine, mechanical engineering, and information technology. To build a unified centre embracing all the necessary fields would be very demanding in terms of funding, personnel and technology. Thus workers engaged in this programme remain in their current position and communicate via the CESNET 2 network. This solution in the form of virtual centre is of great advantage because it saves time (of doctors and technicians) and capacities of very special and costly equipment (CT, MR, 3D printers, software, etc.) necessary for the creation of 3D computer models. Since a future extension of the exploitation of pictorial information is envisaged, the establishment of “only” a virtual centre has the added advantage of easy connection of further localities to the project.

For example, doctors of Thomayer Faculty Hospital (TFH) have shown much interest in this area because they need neurosurgical consultations with the Central Military Hospital (CMH) in Střešovice when treating complicated polytraumata (mostly victims of road accidents) and do not have their own neurosurgical team. They are often challenged to decide whether to continue a treatment within accident surgery or to send the patient to the neurosurgery ward for immediate operation. A strict requirement on the part of the CMH
specialist is that the consultation for TFH must not tax them too much. Therefore they insist on processing the picture under consultation in their standard environment. In practice this means including the TFH pictures under consultation in the CMH system as if pictures from their specialized centre were concerned.

In addition to increased quality of treatment, the impeccably working MeDiMed system also brings savings in cost and storage room. Information archived today by PACS needed formerly a great amount of paper, rolls of film and other material, the purchase price of which was not exactly cheap. With the MeDiMed system, which operates without much financial demand, there are savings both in cost and in the storage room that was formerly necessary for such an amount of materials.

### 7.24 Selected examples of optical networks of various operators

As mentioned earlier, the year 2000 witnessed a boom in the construction of optical cable networks. Czech firms competed in laying cables, which eventually led to the current glut of fibre capacities, which are not in operation. Some examples of the construction of networks for various operators will be given below.

The Czechoslovak Communications, later Czech Telecom, now Telefónica O2 is one of the big (if not monopolistic) operators, above all thanks to the huge access (subscriber) networks. It was one of the first pioneers in the construction of an optical link, 4 km long, between the Automatic Exchange (AE) in Prague-Centre and the AE in Prague-Dejvice, where the installation of 8-fibre gradient cable (manufactured by the Japanese firm SUMITOMO) was tested.

Subsequently, further junction cables were installed between exchanges all over the Czech Republic with the aim of increasing the channel capacities in large cities.

Around the year 1985 numerous local optical networks were built, as well as optical networks in HV switching stations, in engineering plants, etc.

The first long-distance optical cable using SI fibres connected Prague, Brno, and Bratislava (it is buried in the motorway central reservation), later it was extended to cover Germany and Hungary. Another, northern branch was later built from Vienna via Brno, Olomouc, Ostrava, and Warsaw to Scandinavia.

After the 1990s the Czech Telecom network started to be digitalized. Construction by the method of “digital overlay network” (DON) was chosen; the construction was finished towards the end of 2000. The optical circuits built assure failure-free operation. The O2 network is shown schematically in Fig. 7.78. Basically, the network has been completed, and currently wave multiplexers are being deployed along the backbone route. The network is based on optical cables made by the firms OFS (Lucent Technologies AT&T) and Samsung. It has some 30000 km of optical cables, which roughly corresponds to 800 000 km of fibres. The cables have 24, 48 or 96 fibres. From the competitors’ viewpoint, O2 has most fibres and uniform coverage with termination in the centres of cities.
Fig. 7.78: Simplified survey of backbone optical network of Telefónica O2.

ČD – Telematika

The company has been on the market since 1994 but its activities have been more pronounced only since 2004. It was in an ideal position to build new networks because most railway stations are in the centre of a town so that new cables are easy to be laid in the railway roadbed or suspended from power line poles. The network used the SDH technology and most of the cables comply with the ITU-T G.652 standard; the network is being enhanced by the deployment of the DWDM technology. The schematic representation of the network corresponds to the network of railway lines and is shown in Fig. 7.79.

Fig. 7.79: Topology of ČD – Telematika network.
The services offered include: voice services, Internet connection, IP protocol services, hire-out of fibres (SM 9/125 μm), hire-out of circuits (from 2 Mbit s⁻¹ to 2.5 Gbit s⁻¹). Security supervision and monitoring of the network.

ČEZ ICT Services network

The company ČEZ ICT Services, a.s., ranks with advanced providers of fully convergent ICT services. Through its own huge infrastructure it provides attractive ICT services in interesting groupings and with a varied range of applications. The special position of the company is based on the contractual association with its owner, the parent company ČEZ, a.s.

Many years’ experience in the area of providing services for power engineering is a tested means to complex and highly professional services of guaranteed high quality.

In connection with the expansionist policy of the parent company ČEZ, the ČEZ ICT Services Company participates in consultation and integration solutions both at home and abroad, from proposing the design through to its practical implementation.

The company is a member of the international association of power engineering operators 4cE (For Connecting Europe), a member of RIPE (Reseaux IP Europeens), APVTS (Association of operators of public telecommunications networks), and NIX.CZ (Neutral Internet eXchange).

The total length of the company’s backbone optical network exceeds 7 000 km. The nodes, which are mainly located in power engineering facilities (power plants, switching stations, etc.) and in regional and former district capitals as well as in other locations all over the Czech Republic, are equipped with transmission technologies allowing digital transmission in 64 kbit s⁻¹ to 2.5 Gbit s⁻¹ capacities. The backbone network utilizes the wavelength division multiplex (DWDM), synchronous digital hierarchy (SDH), and

Fig. 7.80: Topology of ČEZ ICT Services.
plesynchronous digital hierarchy (PDH) technologies. **Fig. 7.80** gives the network layout with outputs to neighbouring countries.

The services offered include: customized connection to the network, hire-out of circuits and fibres, solutions with the Fibre Channel protocol, radio-network and wireless access services.

The company has at its disposal a network of optical fibres and metallic cables, using part of them for its own network and offering the rest to customers for their use.

**GTS Novera network**

This is another of the many networks now in operation in this country. Most of the operators are interested in interconnecting towns and localities with heavy operation such as Prague, Brno, Olomouc, and Ostrava, and with output to foreign countries. Services are provided by private persons, companies, banks, mobile operators, etc. From among the companies we may give, for example, Aliatel, Nextra, Etel, Tiscali, Sitel, T-Systems, OptoNet, and others.

Let us now take as an example the already mentioned GTS Novera network (**Fig. 7.81**). It had as its base the Prague network Dattel (mostly laid in the Prague Metro), which was gradually extended and united with, for example, the network INEC (an Internet operator). It was later extended to Slovakia and other countries. The company also operates radio and satellite networks. The services offered are again the above mentioned standard services.

![Fig. 7.81: Topology of GTS Novera network.](image)

### 7.25 Further possibilities and methods in optoelectronics

The application potential of optoelectronics is very broad and affects various professions and activities. Let us give some of them in brief:

- sensors, a range of optical fibre applications in the measurement of deformations (of girders) in building industry, in the measurement of the level of liquids, in security technology,
- optical memories, optical recording (CD, DVD, etc.),
- laser printers,
- holography (3D recording),
- medicine (diagnostics, ophthalmology, surgery),
- spectral analysis,
- displays,
- broad application in industries,
- measurement technology.

A more detailed description would be beyond the scope of the present publication.

To conclude this sub-chapter, let us stress in brief two areas that are connected with our topics.

Security technology - this concerns the problems of using optical fibres (cables) in the protection of objects (airports and similar). These systems are based on microbends in fibres caused by the fibres being trod on or by touching a fence in which the fibres are built in. They are referred to as perimetric security systems. Changes in the fibre are detected and evaluated and subsequently alarm may be raised. These systems are very reliable. For details the reader is referred to the technical manual of the firm Security technologies.

From the viewpoint of the optoelectronic systems described above it is necessary to draw up a design of the system, calculate the technical parameters and propose the project. Using a software solution can in many cases make this work easier. In network design it is possible to use, for example, the OPTSIM program or the MATLAB & Simulink program kit (HUMUSOFT). Leading design firms include INTAR, SUDOP, etc.

### 7.26 Health protection during work with optical links

When laying and installing optical cables it is necessary to observe the respective safety-at-work regulations, in particular those concerning work in cable cellars, work with inflammable materials, and work in public communications places.

When working with optical cables, workers will get in touch with organic solvents, substances that form the filler material, and the glass material of the optical fibres themselves. In all these situations, increased standards of personal hygiene must be observed. Special attention must be paid to optical glass fibres, which must be cleaved, cleaned and otherwise handled during installation. Glass splinters are particularly dangerous since they can cause injuries to the skin and eyes. It is therefore imperative to handle the fibre with utmost care and gather all glass splinters in a special case (box) with some oil in it.

During the work with optical cables, human health can be at risk also due to light radiation, which in telecommunications systems is between 780 and 1650 nm (visible light region 400-700 nm). With these wavelengths living tissues can at this excessive intensity be damaged. Considering the powers of sources of optical radiation, which range from several mW up to 1 or 2 W during pulsed mode, the human eye is at risk of burnt retina, inflammation or cataract of the lens of the eye.

Even higher powers occur in free-space communication, where the LD transmission elements are combined into high-power radiators.
In the course of building, maintaining and repairing optical telecommunication cables light sources are being disconnected from the optical fibre, fibre ends containing radiation the being handled, optical connectors are being disconnected, etc. It is therefore necessary to respect the following principles:

- The distance from which the active area of an optical element (fibre, connector, etc.) is being observed, and from which radiation is emitted must not be less than 25 cm.

- Places from which optical radiation is emitted can be viewed through optical devices (magnifying glass, microscope) only with the radiation source turned off.
8 Measuring methods in optical communications

The development of optoelectronic telecommunication systems has entailed the development of new measuring methods and instruments for the measurement of the parameters of fibres, cables and other optoelectronic elements. At first glance it might seem that the measuring methods are analogous to the methods used for metallic lines but in fact they are markedly different. Take, for example, the measurement of attenuation: the name is the same in both cases, the theoretical foundation is the same but the approach is completely different. The difference in measuring methods is given by the specific properties and behaviour of light.

Leading manufacturers of optoelectronics currently offer a whole range of measuring devices that feature simple operation and rapid measurement. The instruments are in most cases provided with standardized connectors for optical radiation input and output.

For the area of optical measurement numerous recommendations have been worked out in IEC, ITU-T and DIN, others are in the stage of preparation and a lot has still to be done, in metrology in particular.

Optical measuring methods can be divided from various points of view; in the following we will stick to this division:

- Measurement on optical fibres;
  - optical measurement,
  - mechanical measurement.
- Transmission measurement on optical fibres:
  - measurement of attenuation,
  - measurement of dispersion,
  - measurement of polarization mode dispersion,
  - measurement of backscatter;
  - measurement of bandwidth.
- Measurement of optoelectronic components.
- Special measuring methods.
- Measuring instruments.

Another division can be from the viewpoint of application: for example, measuring methods for the manufacture of optical fibres, measuring methods for the manufacture of optical cables, measuring methods for the installation of cables, and measuring methods for operational measurement.

From the viewpoint of building an optical track the following measurement must be taken into account:

- preparatory measurement (prior to acceptance inspection and prior to installation),
- measurement during cable installation,
- measurement on an installed route,
- final measurement (acceptance inspection after installation),
- measurement during device installation,
- regular check measurement of operation,
- localization of possible failures on optical track,
- check measurement of time stability of devices,
- permanent check of the working of the whole optical system,
- experimental measurement.

Most of the measurement consists in establishing the parameters of optical fibre and the properties of optoelectronic modules of the system. The measurement set includes a permanent check of the working of the system, which consists in electrical measurement of error rate and its evaluation.

8.1 Methods of optical fibre excitation for measuring purposes

Since the lightguide is never ideally straight and cylindrical but exhibits random bends and cross-section ellipticity, rays propagating in it are also liable to random changes. New modes can be formed on fibre inhomogeneities that were not present in the mode distribution before this inhomogeneity and, on the contrary, modes can disappear (by emission into the jacket or by absorption) that till then participated in the transmission. This event is known as mode overflow, the so-called mode conversion.

After a certain passage through optical fibre (of several units to hundreds of metres) there is a certain balance in the distribution of power into individual modes, so-called stable mode distribution. This state is highly desirable for the conditions of correct measurement of optical fibre parameters.

When this requirement is not respected the measurement can, due to the existence of differential attenuation, carry an error that completely distorts the results. When measuring close to the source in particular, the mode distribution changes and does not guarantee measurement reproducibility.

Conditions of stable mode distribution also for verification on short sections can be approximated by using special devices inserted between the source and the fibre being measured. It is possible to use:

- couplers,
- mode scramblers,
- mode filters.

Couplers are used for specific coupling of optical power to the fibre being measured, i.e. with exactly determined numerical aperture and with the required size of beam trace. The couplers can be of the classical type, i.e. made up of lenses and diaphragms or of the fibre type, with a fibre of suitable parameters.

In the mode scrambler heavy decoupling (mixing) of modes takes place, which leads to a homogeneous distribution of power on its output [9-41].

The mode filter is used to remove undesirable higher modes before the input to the unit being measured.
Coupler realizations for a fibre of 50 μm in diameter and theoretical numerical aperture NA = 0.2, inclusive of the coupling condition, are standardized in IEC. According to this recommendation, the mode distribution can be considered stable when after the passage of radiation through a fibre 2 m long the beam half-width measured in the near region is $26 \pm 2$ μm and the numerical half-aperture measured in the far region is $NA = 0.11 \pm 0.02$.

According to the American association EIA, excitation approximates well the stable mode distribution when the diameter of excitation beam is $70\% \pm 5\%$ of the core diameter of the fibre being measured, and the numerical aperture is $70\% \pm 5\%$ of its numerical aperture. For the fibre under consideration, the diameter of the beam trace should be 35 μm and its numerical aperture 0.14. The above examples of coupler are illustrated in Fig. 8.1.

Another approach consists in overexciting the measured fibre by an optical beam, which means that the fibre is being excited by a beam whose diameter and numerical aperture are larger than the diameter and numerical aperture of the fibre being measured. For the telecommunication gradient fibre 50/125 μm the excitation beam should (according to IEC) have a diameter larger than 140 μm and a numerical aperture larger than 0.3. The excitation beam axis must be identical to the fibre axis. To remove the higher modes and to approximate stable mode distribution a mode filter is connected to the input of the fibre being measured. The filter can be obtained by winding the fibre onto a smooth cylinder (mandrel wrap filter). For the 50/125 μm fibres a filter is recommended that consists of 5 fibre turns on a smooth cylinder of 18 to 22 mm in diameter (see Fig. 8.2). Using such a mode filter a measuring accuracy of $\pm 0.05$ dB·km$^{-1}$ can be obtained.
Perfect stable mode distribution can be obtained in such a way that a 1000 m section of so-called dummy fibre (pre-fibre) is inserted between the transmitter and the fibre being measured, as shown in Fig. 8.3.

![Mode filter diagram](image)

**Fig. 8.2**: Mode filter.

The filter quality can be assessed using the filter efficiency criterion $\Delta \Theta$ according to the relation

$$\Delta \Theta = \frac{\Theta_2 - \Theta_1}{\Theta_2} \times 100\%,$$

(9.1)

where $\Theta_1$ is the angle of a beam exiting a fibre element 1 km long, $\Theta_2$ is the angle of a beam exiting a fibre 2 m long, coupled to a mode filter (see Fig. 8.3).

Mode scramblers can also act as mode filters: because of the coupling of higher modes in mode scramblers, they act as filters. Examples of a mechanical scrambler and a serpentine scrambler (the fibre is intertwined with seven cylinders of 1 cm in diameter, their centres are spaced 1.3 cm) are given in Fig. 8.4. Mode scramblers made from different types of fibre are
shown in Fig. 8.5. The first of them, made up of different bits of fibre, is frequently used in practice. The assembly is usually composed of ca. 1 m of SI fibre, a GI fibre of the same length, and a third, SI fibre of 1 m in length. After the mode scrambler in the above composition a certain fibre section (ca. 500 m) is connected to stimulate stable mode distribution. Only an output prepared in this way can be connected to the fibre being measured. In the other case given in Fig. 8.5, a section (ca. 2 m) of poor-quality fibre of different dimensions and inhomogeneities is used for mode scrambling.

![Mechanical mode scramblers](image)

**Fig. 8.4**: Mechanical mode scramblers.

![Fibre-type mode scramblers](image)

**Fig. 8.5**: Fibre-type mode scramblers.

The results of attenuation measurement depend, to a considerable extent, on excitation conditions of the fibres being measured. With the development of optoelectronics, its specific parts, instruments, and measuring methods this dependence gradually decreases.

Couplers that need to be adjusted are of no use for practical purposes; they are better suited to laboratory measurement. On the other hand, however, instruments designed for field measurement require much attention and great care in repeated measurement. The reason lies in the special effect of losses in the splices (connectors) of the measuring apparatus on the fibre being measured. While in electrical measurement the possibility of losses in connectors and splices can usually be neglected, in optical measurement these losses play an important role. Because of the difficulty of setting accurately the same measuring conditions, the
definition and measurement of the input (output) power are very difficult. Losses in optical connectors are comparable with the losses in tens to hundreds of metres of optical fibre. Moreover, even in types of the highest quality there are certain fluctuations in losses in repeated installation, which are difficult to define generally.

In the first place, they are losses due to connector design tolerances, in particular axial misalignment, imperfect contact of fibre edges, and faulty fibre cleavage. In practice this means the impossibility to measure with a greater accuracy than these uncertain losses in connectors. Since connectors are deployed on the transmitting as well as the receiving side, we are faced here with a fundamental limitation of the potential measuring accuracy (above all the measurement of optical powers). For these reasons the measurement of optical fibres is conducted at both ends and the average value is then established.

**Formation of optical flux**

Laser diodes (LD) or light-emitting diodes (LED) are used as stabilized sources. The output level of LD depends on temperature and reflected light. To remove changes caused by this dependence the output level is monitored and, using the feedback loop, the output level is stabilized.

A stabilized source operating on the 1.3 μm wavelength requires the surrounding temperature to be strictly stabilized. This stabilization is provided using a feedback circuit and the Peltier cooling element, see Fig. 8.6.

![Fig. 8.6: Stabilized optical source circuit.](image)

The temperature characteristic of the output level of stabilized optical source with LD has in the temperature range 5 - 50 °C a deviation of less than 0.05 dB.

At a constant temperature, LEDs have a stable output level for a long time and with extremely high reliability. But output level is very sensitive to effects of surrounding temperature. If a surrounding temperature sensor with a diode for temperature compensation is used, adequate stability can be obtained. The temperature characteristic of the output level of stabilized optical source with LED has in the temperature range 5 – 50 °C a deviation of less than 0.5 dB for the 0.85 μm and 1.3 μm bands.

The wavelength of the spectral width of light emitted by stabilized source must also be stabilized. For the sake of measurement accuracy the emitted average wavelength must be around 5 nm.
Some instruments are equipped with temperature control, which eliminates changes in wavelength oscillation caused by changes in surrounding temperature. The light-emitting elements used are LED. Due to their high temperature stability they are also suitable for the measurement of transmission bandwidth.

The source of visible light consists of a He-Ne laser and an optical fibre connector. The connector is designed such that it forms a clearly visible optical flux in optical fibre. The mutual position of the He-Ne laser tube and the connector is stable, and to couple the optical flux to the optical fibre a lens is used most frequently.

The radiation emitted from the optical fibre connector into space is immediately diffused in order to protect workers against any health risk. For increased safety a protective device is provided, which interrupts the emission of light when the optical fibre connector is removed.

Sources of visible light are used in testing the optical fibre from the viewpoint of damage and for the identification of individual fibres.

**Optical detectors**

The optical receiver detector is usually formed by the avalanche photodiode or the PIN photodiode. The choice of sensor material (Si or Ge) depends on the required region of the measurement wavelength:

- Si material 0.5-1.1 μm
- Ge material 1.1-1.6 μm

PIN diodes are used for highly sensitive detectors:

- PIN Si, input power -90 dBm,
- PIN Ge, input power -75 dBm.

APD for current measurement of higher levels:

- APD Si, input power -60 dBm,
- APD Ge, input power -40 dBm.

The range of levels measured is up to +10 dBm.

### 8.2 Measurement on optical fibres

**Optical measurement**

The test of fibre continuity or possibly fibre identification is conducted in the visible light region. Visual inspection of individual fibres is performed using the He-Ne laser or another suitable source of (white) light with the possibility of coupling to the fibre. This method serves as a first quick check and identification of fibres.

**Measurement of numerical aperture**

Numerical aperture NA is an important parameter in the assessment of the efficiency of the coupling between the optical source and the fibre or between two fibres or between the fibre and the optical detector. It is given by the relation:

\[
NA = \sin \Theta_{\text{max}} = \sqrt{n_1^2 - n_2^2}.
\]

In view of the fact that refractive indices of the core, \(n_1\), and the jacket, \(n_2\), are often difficult to establish, numerical aperture NA is determined from the wavelength of radiation
characteristic at the output of a short section of uniformly excited fibre, namely from the width of radiation characteristic in 5% of maximum intensity. Effective numerical aperture is established in the same way on a sufficiently long section of fibre with stabilized mode distribution; it is approximately 50 – 70% of the value of theoretical numerical aperture. The method is illustrated in Fig. 8.7.

![Fibre being measured](image)

**Fig. 8.7:** Measurement of numerical aperture.

The fibre is coupled to the optical transmitter via a suitable coupler. At the fibre output, the optical receiver (detector) is mounted on a swing arm; it detects radiant intensity in dependence on the size of angle Θ measured from the fibre axis.

The dependence of the level of emitted optical power $P_{opt}$ on angle Θ from the end of GI fibre of 2 m in length is given in Fig. 8.8.

![Radiation characteristic](image)

**Fig. 8.8:** Radiation characteristic of GI fibre of 2 m in length.

*Interference method for measuring refractive index profile.* We distinguish two methods, destructive and non-destructive. In the destructive method, a thin slice is separated from the optical fibre and, irradiated by laser, it is examined under interference microscope. The precise value of refractive index is calculated from interference lines. In the non-
destructive method the fibre, irradiated by laser and immersed in inert liquid, is examined also under interference microscope.

**Measurement of refractive index profile by the near-field method.** A lens is placed at the fibre output and a photodiode on the swing arm performs the detection; the recording can be displayed on a screen. In this way the waveform of surface density of radiant intensity is obtained, see Fig. 8.9.

![Fig. 8.9: Measurement of refractive index profile.](image)

The drop in the refractive index value in the fibre axis is typical of the gradient fibre and is due to the manufacturing technology (collapse of the tube during the manufacture of preform).

In gradient fibres various overshoots sometimes appear on the curve measured and therefore it is difficult to establish the actual diameter of the optical fibre core. The core diameter is thus determined from the refractive index waveform for the value of refractive index \( n_3 \) given by the equation

\[
\left( n_1^2 - n_2^2 \right) = n_3^2 + k \left( n_1 - n_2 \right)
\]

(9.3)

where

\( n_1 \) is the maximum refractive index value of the core

\( n_2 \) is the refractive index of the jacket

\( n_3 \) is the refractive index of the core at the core/jacket interface

The parameter \( k = 0.05 \) is defined by IEC.

This method can also be used to perform a geometrical check of fibre dimensions, for which very strict requirements have been laid down. The maximum admissible non-circularity of the core cross-section is 6\% (which means that the difference between the largest and the smallest core diameter must not exceed 3 \( \mu m \)), and the maximum admissible non-circularity of the fibre jacket cross-section is 2\% (hence the maximum difference of the cross-sections is 2 \( \mu m \)).

### 8.3 Mechanical measurement

This group of measurement includes a whole range of measuring methods for establishing the quality of the manufactured cable. The methods thus mostly concern laboratory measurement and operational measurement.

**Measurement of tension** is one of the most followed types of measurement. Force is applied to the cable on special tensile test machines and measurement is conducted on each fibre separately. Generally, attenuation grows with tension and up to certain values it is reversible. Establishing these values is very important for ensuring safe installation of cables.
Measurement of temperature dependence is very important for operational reasons. In most cases, increased attenuation appears at low temperatures. From long-term measurement of the temperature dependence of cables judgment can be formed as to the process of aging.

From among other frequently conducted tests and measurements we can at least mention: measurement of bending, measurement of impact, resistance to loading, etc.

8.4 Transmission measurement on optical fibres

Most of this measurement came to be used to establish the quality of optoelectronic transmission systems.

Measurement of optical power

The measurement of optical power is one of the basic types in the area of optical measurement. This measurement is performed via converting the power of optical beam, which is emitted directly by different optical sources or emanates from optical fibre, to electric signal by means of an optoelectronic (O/E) converter.

An optical power meter consists of three parts: indicator, sensor, and adaptor, see Fig. 8.10. The adaptor adapts the light flux from a source or fibre such that it is best adapted to the sensor dimension, and thus maximum optical power can be delivered to the sensor. The sensor converts optical power to electric power. The indicator serves to display the electric signal on a screen.

![Fig. 8.10: Measurement of optical power.](image)

These parts of the optical power meter can be exchangeable so that the device can be used for measuring the required wavelength range of the power being measured, and for various types of signal reception.

The measurement enables establishing
- operation of opto/electronic converters and modules (or transmitter and receiver),
- losses in fibres (fibre attenuation),
- losses in the splices of parts of optical route,
- function of passive optical elements (attenuation networks, connectors, optical switching arrays).

The measurement is conducted on the respective wavelength, which can be set in advance. The choice depends on the electro/optical and opto/electronic converters used, which are fundamental elements of sources and receivers.

The block diagram of an optical power meter is given in Fig. 8.11. To increase the receiver sensitivity, an optical signal chopper with subsequent synchronous detection is used in addition to the generally known blocks (CU stand for control unit). The sensitivity is thus increased by ca. 20 dB.
Measurement of attenuation

Attenuation represents the basic and most important transmission parameter and is an overall measure of optical power losses in the optical signal propagation through the fibre. Using the well-known definition, the attenuation of optical fibre between two points (1, 2 – input, output) is determined from the relation

$$A(\lambda) = 10 \log \frac{P_1}{P_2} \text{ (dB)},$$  \hspace{1cm} (9.4)

where $P_1, P_2$ are the optical powers (W) for wavelength $\lambda$.

In the case of stable mode distribution in the fibre, specific fibre attenuation can be defined for wavelength $\lambda$

$$\alpha(\lambda) = \frac{A(\lambda)}{\ell} \text{ [dB.km$^{-1}$]},$$  \hspace{1cm} (9.5)

where $\ell$ (km) is the distance between point 1 and point 2.

The measurement of attenuation is mostly performed only for discrete wavelengths of 850 nm, 1300 nm, 1310 nm or 1550 nm. The spectral characteristic of attenuation is mainly important to fibre manufacturers.

IEC recommends three methods for the measurement of fibre attenuation:

- cut-back method,
- insertion loss method,
- backscattering method.

Because of its high sensitivity, the cut-back method is recommended as a reference method (although it is a destructive method). After coupling the optical power from a stabilized optical source (with connected internal or external transmit unit T.J. – coupler, filter) to the measured fibre (Fig. 8.12) of length $l$, the power is measured at point 2 at the end of the fibre (power meter). With the coupling conditions unchanged, the fibre is cleaved ca. 2 m from the beginning (at point $l$) and output $P_1$ is measured. Attenuation and specific attenuation of the fibre are calculated using relations (9.4) and (9.6). An accuracy of 0.01 dB . km$^{-1}$ can be achieved by this method.
The *insertion loss method* also requires measuring in two steps. This is an operational method and is particularly suitable in the case of connected fibres and cables. In the first place, the measuring equipment must be calibrated via interconnecting the source and the detector (see Fig. 8.13). After measuring we obtain the value of power $P_1$. The fibre being measured is then connected between the optical transmitter and the power meter, and the value of power $P_2$ is obtained. Attenuation and specific attenuation of the fibre are again determined using relations (9.4) and (9.5). In this case, the attenuation measured consists of fibre attenuation and attenuation of the splice of the fibre being measured. In the measurement of connected cables, the measurement precision is a function of the connector used and is usually worse than 0.2 dB.
The method is used in practice also in such a way that on each side of the route (A, B) both the source (transmitter) and the power meter (receiver) are located. The method proceeds in four steps: two measurements are first made on each side via connecting the power meters to sources (calibration), and two measurements with the fibre connected in both directions. A simplified fundamental schematic is given in Fig. 8.14. The four values of optical power obtained, $P_{11}$, $P_{12}$, $P_{21}$, $P_{22}$, are used to calculate the operational attenuation of fibre according to the relation

$$ A = \frac{P_{12} P_{21}}{P_{11} P_{22}}. \quad (9.6) $$

The specific attenuation can be calculated by substituting into (9.7) and (9.6).

If in the above method we want to establish losses in the splices, we use for calibration fibres of 2 to 3 m in length and of the same kind as the fibre being measured. On the assumption that the coupling losses of connecting the reference cable and the cable being measured are the same and the attenuation of reference cable can be neglected, then the attenuation obtained in this way corresponds to losses in the cable alone.

The backscattering method (the principle is described below) for the measurement of fibre attenuation is based on a completely different principle. In the two preceding methods optical power was measured after passage through the fibre while in this method the time dependence of backscattered optical power $P$ (or the level) during pulse propagation in the fibre is evaluated, which yields information on the quality of the whole fibre in dependence on its length (see Fig. 8.15). From this dependence we can establish the attenuation of a homogeneous section of fibre according to the relation

$$ A(\lambda) = 5 \log \frac{P_1}{P_2} \quad (dB) \quad (9.7) $$

Fig. 8.15: Measurement of attenuation in a splice (fibre values are known).
and the specific attenuation by substituting relation (9.8) into relation (9.6). The meter, an optical reflectometer, is much more complicated than the power meter and, consequently, also more expensive. However, using a display and recorder, the method provides information not only about fibre attenuation but also about the fibre quality (failures, defects) along the whole of its length.

The measurement of attenuation in a splice belongs to important measurements in the construction of optical routes. Immediately after fusing (or otherwise joining) sections of optical fibre it is absolutely necessary to measure and check the quality of the splice made. If the splice is found to be of poor quality, the splice must be made again.

The measurement of attenuation in a splice is laborious and time-consuming, and requires much care. There are two ways how to proceed in practice:

- using the manufacturer’s parameters of the fibres being joined,
- without knowing the attenuation of the fibres being joined.

In the first case, the sections of the two fibres to be joined by splice S are from the viewpoint of attenuation known from the measurement protocols provided by the manufacturer. Prior to making the splice S, the level $P_1$ is measured on the side of the first fibre section (see Fig. 8.15). Subsequent to making the splice S, the level $P_2$ is measured on the output of the section being joined. The splice attenuation is determined from the relation

$$A_S = P_1 - P_2 - a_2 \text{ (dB)},$$

where $a_2$ dB is the attenuation from factory protocols for a specific length and transmission wavelength.

In the second case, when the attenuation of the sections being joined is not known, the procedure is as follows. Prior to fusing, the level $P_1$ is measured on the output of the first section. A provisional splice PS is made (see Fig. 8.16) and the level is measured on the output of the spliced section $P_2$. After the provisional splice, in the direction from the input, the fibre is interrupted and the level $P_3$ is measured. The definite splice DS is made and the value of power level $P_4$ is found. Attenuation $V_2$ of the section being joined is then

$$A_2 = P_3 - P_2 \text{ (dB)}.$$ 

Attenuation in the definite splice is

$$A_{DS} = P_1 - P_4 - A_2 \text{ (dB)}.$$
Fig. 8.16: Measurement of attenuation in a splice (fibre values are not known).

In the measurement of connector attenuation a special reference fibre of 2-3 m in length is used. It is connected between the transmitter and the receiver, and the level of optical power $P_1$ is measured. The reference fibre is replaced with a fibre obtained by joining two short sections by a connector (the fibre must be of the same length and type as the reference fibre). The level $P_2$ is measured and the connector attenuation is established from the relation

$$A_K = 10 \log_{10} \left( \frac{P_1}{P_2} \right) \text{ (dB)}.$$  \hspace{1cm} (9.11)

**Measurement of backscatter**

The backscattering method is an effective means of diagnosing optical fibres. The method provides a detailed picture of the attenuation and possible fluctuations in geometrical and physical parameters along the fibre, inclusive of failure localization.

The method is based on evaluating the time dependence of backscattered power of a narrow optical pulse coupled to the fibre. Backscattered light detected at its input comes from the Fresnel reflections from refractive index discontinuity and from Rayleigh’s scattering on microscopic fluctuations of glass refractive index. The amount of backscattered light is directly proportional to the passing optical power. Changing the intensity of backscattered light enables measuring the fibre attenuation.

The fibre length can be established from the time delay of the reflection from the rear end of fiber with respect to the reflection from the input end.

An analysis of backscattered light provides a picture of the fibre homogeneity (inhomogeneity), and allows monitoring whether the mode distribution has become stable.

Great advantages of the method are its non-destructive nature and the possibility of measuring from one fibre end.
To get a mathematical representation of backscatter signal it is necessary to perform an analysis of light energy on an element of optical fibre, then to consider light scattering on a length, then to determine the power returning back to the fibre, and finally to define the relation for backscatter as a function of time.

Consider an optical pulse of energy $E_0$ sent at time $t = 0$ from the fibre beginning $x = 0$. At a distance $x$ from fibre beginning the radiant energy of pulse $E_i(x)$ will be

$$E_i(x) = E_o \exp \left[ -\int_0^w \alpha'(\ell) \, d(\ell) \right], \quad (9.12)$$

where $\alpha'(\ell)$ is the attenuation. For a certain constant value it will hold

$$E_i(x) = E_o \, e^{(-a'x)}. \quad (9.13)$$

Now consider scattering in $x, x + dx$, then

$$dE_a(x) = E_o \, \alpha_a(x) \exp \left[ -\int_0^w \alpha'(\ell) \, d(\ell) \right] \, dx, \quad (9.14)$$

where $\alpha_a(x)$ is the scattering coefficient at point $x$. Only part of this energy can propagate in opposite direction in the fibre ($S(x)$). Thus

$$dE_p(x) = E_o \, S(x) \, \alpha_a(x) \exp \left[ -\int_0^w \alpha'(\ell) \, d(\ell) \right] \, dx. \quad (9.15)$$

When viewed from the input side, it holds

$$dE(x) = E_o \, S(x) \, \alpha_a(x) \exp \left[ -\int_0^w \alpha'(\ell) \, d(\ell) - \int_0^x \alpha'^*(\ell) \, d(\ell) \right] \, dx, \quad (9.16)$$

where $\alpha'^*(\ell)$ is the attenuation of reverse direction. In the case that $\alpha'(\ell) = \alpha'^*(\ell) = \alpha$, then

$$dE(x) = E_o \, S \, \alpha_a \, e^{(-2a x)} \, dx. \quad (9.17)$$

Symbols for the calculation are given in Fig. 8.17.

![Fig. 8.17: Element of optical fibre.](image)

By interchanging the variables $E$ and $x$ we obtain the dependence of power on time

$$E_o = P_o \, \Delta t. \quad (9.18)$$

It holds

$$2x = v_{sk} \cdot t, \quad (9.19)$$
\[
d x = \frac{v_{sk}}{2} \, \text{dt},
\]

where \( \Delta t \) is the pulse width, and \( v_{sk} \) is the group velocity.

Then we get

\[
P(t) = 0.5 \, P_0 \, \Delta t \, S \, \alpha_d \, v_{sk} \, e^{-\alpha \, v \, t}.
\]

(9.21)

It is clear from the result that backscatter power is dependent on input power \( P_0 \), pulse width \( \Delta t \) and on the fibre parameters \( S \) and \( \alpha_d \) (\( \alpha_d \) are losses due to Raileigh’s scattering per unit of length).

The coefficient of backscattering \( S \) for a fibre with step refractive index is calculated according to the relation

\[
S = \frac{3 \, \Delta^2}{8 \, n_i^2},
\]

(9.22)

for a fibre with parabolic refractive index

\[
S = \frac{\Delta^2}{4 \, n_i^2},
\]

(9.23)

where

\[
\Delta = \sqrt{n_i^2 - n_2^2}.
\]

(9.24)

The resultant exponential curvature depends on the size of attenuation and on group velocity.

When choosing the pulse width it is necessary to accept a compromise between the requirement for photodiode sensitivity and the resolution power. With increasing pulse length the maximum measurable total attenuation increases but the accuracy of length measurement decreases. The power of reflected radiation is ca. 50 to 60 dB lower than a passing optical pulse and this makes heavy demands on the device sensitivity.

For reasons given above, the design of optical reflectometer is continuously being perfected. Principles known from information theory (problems of signal and noise reception) are applied such as correlation methods and frequency synthesis methods. Also, memories are employed, in which certain values of attenuation of reflected pulses are stored and their average values are evaluated (this reduces measurement errors caused by receiver noise). A more detailed discussion of these methods would be beyond the scope of this publication; this is rather a matter for specialists in the area of measurement in telecommunications.

The fundamental principle and method of backscatter measurement are obvious from the block diagram shown in Fig. 8.18. For the measurement itself it is sufficient to connect the fibre being measured to the input connector of the reflectometer.
The reflectometer is composed of a source of optical pulses, an optical system for splitting the optical beam, and an optical receiver with evaluation of the time interval between the sent pulse and the reflected pulse.

The source is a semiconductor laser with a minimum power of 5-15 mW at 10 ns pulse width. The optical system with lenses and semi-transmissive mirror serves to couple optical power to the fibre and deliver reflected light back to the detector so that the ratio is 1:1; 50% of optical power flowing through the optical splitter is lost for the measurement.

The relations between direct and reflected radiation in the fibre have already been defined by a derived relation (9.21). To make the method clear, let us assume that the fibre exhibits a serious failure or is interrupted; the power of light $P_R$ reflected from the failure at a distance $\ell$ from the fibre beginning will be

$$P_R(t) = \frac{Rk}{2\alpha(\ell)} P_0, \quad (9.25)$$

where $t$ is the time interval between the sent pulse and the reflected pulse, $P_0$ is the power of transmitter pulse, $R$ is the surface reflectance, $k$ are losses due to the optical system inclusive of beam splitting, $2\alpha(\ell)$ is the average of losses in forward and reverse direction.

For the accuracy of localizing the failure the reflectance of the surface under examination, which is very different for different damages, is of great significance. It follows from the Fresnel relations that the maximum reflection is for perpendicular light incidence, and it holds

$$\left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2, \quad (9.26)$$

where $n_1$ is the effective refractive index, and $n_2$ is the refractive index of the surroundings.
For the typical core refractive index $n_1 = 1.5$ and $n_2 = 0$ (the case of air), which is a situation occurring in the ideal case, the result is 0.04, which corresponds to a back reflection of 4% of energy. In practice, however, the fibre fracture surface may be rough, cracked and surrounded with water ($n_2 = 1.33$) so that a reflection of 0.1 to 1% of energy can mostly be reckoned with.

During the return passage the pulse is directed by the divider to the photodetector, where it is converted to electric pulse. The input and the output pulse are displayed simultaneously on the screen and the time interval between them is subtracted. Distance to failure $ℓ$ is determined from the relation [9-2]

$$ℓ = \frac{tc}{2n_1} \pm \frac{Δtc}{2n_1}, \quad (9.27)$$

where $t$ is the time difference between the sent pulse and the returned pulse, $Δt$ is the widening of reflected pulse due to fibre dispersion, $c$ is the velocity of light in vacuum, and $n_1$ is the core refractive index.

Finally, to express the total dependence of detected power of backscatter $P(t)$ on time delay $t$ or on the corresponding distance $ℓ$ from the fibre end we calculate fibre attenuation from two points. The total fibre attenuation with the boundaries $ℓ_1$ and $ℓ_2$ is established from the relation

$$a = \frac{ℓn}{n_1} \frac{P_2 - ℓn P_1}{t_2 - t_1} = \frac{ℓn}{n_1} \frac{P_2 - ℓn P_1}{2(ℓ_2 - ℓ_1)}, \quad (9.28)$$

The meter is usually equipped with an amplifier with logarithmic characteristic, which enables displaying sections with constant optical power losses as straight lines, whose gradient of line is a quality indicator of these losses. Any discontinuity (e.g. attenuation in splices and connectors) shows as a sudden drop in the characteristic being measured.

An example of the waveform of received power of backscatter from optical route is shown schematically in Fig. 8.19. In the example, the reflection of light on fibre input and on fibre interruption is evident. From the decreases in (losses of) attenuation on splices, attenuation can be read directly in dB if a calibrated scale is used. The line gradients give directly a picture of the size of attenuation in the fibre.
Fig. 8.19: Waveform of received backscatter power shown on a display.

An illustration of the result on the display and the on the print-out of a fully automated reflectometer is shown in Fig. 8.20.

Fig. 8.20: Measurement protocol of OTDR reflectometer.

The reflectometer used was EXFO FTB300. A ballast fibre (L = 500 m) was connected between points 2 and 3. Points 4, 5 and 6 are splices along the route, where cable transfer was carried out. Mark 7 terminates the cable in RSU. Part of the meter is a table giving the attenuation values at the route points given above. The measurement was conducted on the 1310 nm wavelength.

The speed of measuring by this method is evident; the print-out gives immediately the values of splice attenuation, specific attenuation and operational attenuation of individual
lengths, and, last but not least, some important values of the measurement protocol such as refractive index, length of measured fibres, time of measurement, etc.

The accuracy of the measurement itself is also noteworthy when compared with similar measurements known for metallic lines. The high accuracy is due to the fact that pulses modulated to the carrier frequency of optical radiation are used in the measurement. The pulse frequency bandwidth is much smaller than the carrier frequency. The optical pulse is then deformed to a lesser degree and this enable higher measurement accuracy. For example, for a length of 70 km and a pulse width of 10 ns the accuracy of localizing the fibre fracture is better than ±10 m.

The above backscatter method of measurement is a precise method frequently used in practice. Using this method the following measurements can be conducted:

- measurement of optical power losses of the route (i.e. in the fibre, splices and connectors),
- measurement (localization) of failures and damage in fibres (currently the only method for this kind of measurement),
- measurement of the lengths of individual route sections.

*Measurement of bandwidth*

The optical signal being transmitted is not only attenuated in the optical fibre but it is also being deformed due to the dispersion properties of fibre. Dispersion is responsible for the undesirable widening of pulses, which limits the length of repeater (amplifying) section and the transmission capacity.

Bandwidth measurement can be implemented in the time domain and in the frequency domain.

*Measurement in the time domain*

It is the most frequently used method for measuring dispersion by the pulse method. The pulses used in the measurement are shorter than 1 ns (e.g. 200 ps), they have the character of the unity Dirac pulse. The pulses are generated by a suitable laser source and coupled to the fibre being measured. At the fibre output they are detected by the avalanche photodiode and processed by the sampling oscilloscope; their sampled waveform $P_2(t)$ is then stored in the computer memory. The fibre being measured is then shortened to a length $x$ (ca. 2 m) while observing the input conditions. At the fibre output the waveform $P_1(t)$ is then measured. Using the fast Fourier transform the Fourier images of the waveforms $P_1(t)$ and $P_2(t)$ are calculated and from these the transmission function of the fibre being measured is calculated according to the relation

$$H(f) = P_2(f) \cdot P_1(f)^{-1}.$$  \hspace{1cm} (9.29)

An analogy to this method that uses the optical splitter is shown in Fig. 8.21. The waveforms of input and output pulses are plotted in the figure. The symbols used in the figure correspond to relation (9.30) ($2\tau_1$ is the width at half the pulse height at fibre input, $2\tau_2$ is the width at half the pulse height at fibre output, $\Delta t_{vid}$ is the intermodal dispersion, and $\Delta t_{chr}$ is the chromatic dispersion).
The method is suitable rather for laboratory applications, where the measurement can be adjusted in a corresponding manner.

When measuring in the *frequency domain*, the connection according to Fig. 8.22 is used. Sinusoidally modulated optical signal with tunable frequency is coupled to the fibre being measured. Both the transmitter and the receiver must have a large bandwidth, up to 1 GHz (top-class measuring instruments up to 3 GHz) with attenuation that can span 15 to 35 dB, depending on the type and quality of the instrument. The decrease in amplitude is measured for each frequency; narrow-band detection, where the detected signal is evaluated selectively, is of advantage. The spectral analyzer can be used as the measuring instrument; the bandwidth can be read from Fig. 8.21. The maximum modulation frequency $f_{\text{mod max}}$ corresponds to 50% of the maximum amplitude of electric signal, which corresponds to a level decrease by 6 dB (electric) or 3 dB (optical).
The mutual relation between dispersion $\Delta t$ and bandwidth $S = f_{\text{mod max}}$ is given by the relation

$$\Delta t = \frac{0.44}{f_{\text{mod max}}} \text{ (ns km$^{-1}$)}.$$  \hspace{1cm} (9.30)

**Measurement of chromatic dispersion**

**Method of phase shift and differential phase shift**

By the ITU-T G.650 recommendation, the method of phase shift is given as the reference method for measuring the chromatic dispersion of optical fibres. A modulated radiation source of several wavelengths is used for the measurement. At the receiver side the instrument used for the detection of the test signal being received is an instrument for phase measurement such as the vector-voltmeter. The output phase measured is compared with the input phase of the signal and their difference is used to determine the change in the signal phase after the passage through the optical cable route being measured. A disadvantage of this method can be seen in the necessity to use a different fibre in the cable as the reference route in Fig. 8.24, via which information about the input phase is transmitted from the transmitter to the receiver.

**Fig. 8.24:** Method of phase shift.
Method of delayed pulses in the time domain

This method consists in transmitting optical pulses in/on different wavelengths but with a precisely determined pulse magnitude and spacing. A comparison of the spacing of input pulses with that of the pulses received on the output is used to determine the delay due to chromatic dispersion. The connection which is similar to that in the preceding methods but without reference fibre is in Fig. 8.25.

![Method of delayed pulses](image)

**Fig. 8.25**: Method of delayed pulses.

Fig. 8.26 gives an example of the connection of generator of optical pulses with given time spacing. A cascade of Bragg gratings serves as the monochromator. The pulse generator modulates the radiation of a wide-spectrum source such as LED diode. From the coming pulse the diode reflects components of selected wavelengths with certain time spacing back into the route being measured. The base is a cascade of Bragg gratings, which is formed by different gratings with sections of optical fibre between the gratings. Each of these gratings reflects radiation of different wavelength. The result of this connection is that a sequence of pulses of different wavelengths with given time spacing comes into the measured fibre of the route. After the passage through the route the time spacing of pulses changes due to the effect of chromatic dispersion. By comparing the spacing on the input with that on the output of the route being measured the values of delay due to chromatic dispersion are established.

![Method of delayed pulse, with a cascade of Bragg gratings](image)

**Fig. 8.26**: Method of delayed pulse, with a cascade of Bragg gratings.

An example of the resultant measurement of optical route using a chromatic dispersion meter is given in Fig. 8.27.
Measurement of polarization mode dispersion (PMD)

The interferometric method of measuring PMD is based on the interference (wave addition) of low-coherence (coherence – spectral purity) of optical radiation. The block representation of the method is shown in Fig. 8.28. An interferometer is placed on the output of the optical route being measured, which separates the radiation into two branches. A fixed mirror is in one branch and a movable mirror in the other branch. The movable mirror changes the phase shift between received signals of the two branches and, with the aid of interference, the delay due to PMD is shown on the detector.

A typical example of the plot obtained by this method is given in Fig. 8.29.
Fig. 8.29: Example of PMD plot of optical fibre, obtained by interferometric method.

In the bottom of the figure the interferogram shows the correlation functions of two mutually perpendicular polarization planes. The pronounced peak is the autocorrelation function of the measuring signal itself, which depends on the shape of its spectrum.

This method is sometimes referred to as TINTY (Traditional Interferometry Analysis); the more recent method GINTY (General Interferometric Analysis) suppresses the effect of autocorrelation peak. In this method the resultant signal, which contains optical radiation from both branches of the interferometer, is again divided by polarization light into two mutually perpendicularly polarized components, with each of them incident on a separate detector. Interference occurs on the detectors and the two correlation components are expressed. By subtracting the interferogram we obtain the mutual correlation, and by adding up we obtain the pure autocorrelation. This method enables measuring also routes with EDFA amplifiers. It is a quick method, it is not necessary to measure individual route sections separately.

Method of scanning the wavelength

The measurement of PMD by the method of scanning the wavelength is based on the principle of measuring the optical power passing along the measured optical route in dependence on the wavelength. The block representation is given in Fig. 8.30. The radiation source can be a tunable laser or a wide-spectrum LED diode.

Fig. 8.30: Method of scanning the wavelength.

Compared with the preceding method, this one is slower and the fibre is susceptible to vibration.
**Method of POTDR**

This method of measuring combines the measurement of PMD with the method of optical reflectometry. This means that it enables measuring the whole route and determining a possible critical section with increased PMD value, which can be subsequently replaced and thus the prescribed values of PMD are achieved (POTDR – Polarization Optical Time Domain Reflectometry).

The POTDR method makes partial use of the classical OTDR method of backscatter measurement. It operates on a similar principle but the POTDR method differs in that the reflectogram is evaluated via polarization. The principle of the method: we try to transmit into the route fibre a measuring signal in the form of a train of pulses and from the backscattered radiation (effect of Rayleigh’s backscatter) we read information about the PMD of individual sites on the route fibre. The dependence of the PMD of route fibre can be expressed by the relation

\[
\text{PMD} \approx \beta \sqrt{l \cdot h},
\]

where \(\beta\) is the double refraction in the fibre (ps . km\(^{-1}\)), i.e. the difference in the propagation speed of the two polarization modes mentioned, \(l\) is the fibre length, and \(h\) gives the coupling length at which there is a significant change in the axis (shape) of the double refraction in the fibre, which leads to a marked exchange of energy between the polarization modes. PMD increases with the magnitude of double refraction in the fibre, with the fibre length and with the coupling length. With increasing length of the fibre and thus a smaller energy exchange between the two modes, which propagate at different speeds, PMD will play a greater role. For the longitudinal analysis of PMD we need to obtain from the backscattered radiation from the fibre also information about its local double refraction and coupling length. To establish this information we send short pulses of polarized optical radiation into the fibre. This purpose is served by the DOP (Degree of Polarization) method, which establishes the results from backscattered radiation. We monitor the degree of polarization. The schematic of this connection is shown in Fig. 8.31. The radiation source is a DFB laser of a very narrow spectrum, which is different from the current OTDR meters. It is used here in order to prevent signal depolarization in the fibre because the signal might propagate via several wavelengths. In this case, double refraction of the fibre would cause for different wavelengths different changes in the state of polarization SOP and thus depolarize the signal. Such a (undesirable) mechanism of depolarization must be suppressed by narrow-spectrum radiation source. Polarized output radiation from the DFB laser is coupled to the fibre being measured. For backscattered radiation from individual sites of the route fibre the DOP is analyzed using a polarimeter and an OTDR detector.

![Fig. 8.31: Measurement of PMD by the method of DOP analysis.](image)
A strong double refraction in fibre $\beta$ brings about a quick rotation of polarization state, which leads to the depolarization of radiation within the measuring pulse, thus contributing to a reduction of the degree of polarization. A weak double refraction of fibre $\beta$ will result in a high DOP measured, and vice versa. But the DOP will also depend on intermodal coupling (coupling length $h$). With some simplification, the situation can thus be divided into three groups:

1. fibres with weak double refraction (small $\beta$) – the DOP will be high (up to 1), irrespective of intermodal coupling. In practice, these are optical fibres with a small PMD value,
2. fibres with a strong double refraction and strong intermodal coupling (large $\beta$ and short coupling length $h$) – the DOP will be low due to the strong double refraction (for a backscattered signal it will approximate the value $1/3$) and will change rapidly due to the strong intermodal coupling. In practice, these are optical fibres with average PMD values,
3. fibres with a strong double refraction and weak intermodal coupling (large $\beta$ and long coupling length $h$) – here, in addition to $\beta$ and $h$, it also depends on the mutual position of SOP of polarization and on the shape of double refraction in the fibre. The DOP can then fluctuate between low and high values but it will change only slowly. In practice these are optical fibres with high PMD values.

It follows from the above that not only the DOP value itself but also the speed of DOP change is important. The measuring instrument then performs an analysis of the results measured. Because of the considerable speed of DOP change it is first necessary to determine the average DOP value from several tens of samples. The measuring instrument then performs measurement for two states of input polarization, which yields two measurement results: DOP and $\text{DOP}_C$ (complementary), from which the $\text{DOP}_{\text{GEO}}$ parameter is calculated using the relation

$$\text{DOP}_{\text{GEO}} = \sqrt{\text{DOP}^2 + \text{DOP}_C^2},$$

(9.32)

which provides information about the real DOP value of radiation backscattered from a given section of route fibre. The measuring instrument has a parameter $h\text{DOP}$ for monitoring the speed of DOP changes. This parameter is equal to the fibre length along which the DOP changes markedly – the quicker the DOP changes, the smaller the $h\text{DOP}$ parameter. From an analysis of the DOP parameter of individual sections of optical fibre of route the following can be concluded:

- on sections with high $\text{DOP}_{\text{GEO}}$ value the PMD value will be low because there is a small double refraction of fibre here,
- on sections with varying or low $\text{DOP}_{\text{GEO}}$ value and thus with a possible larger double refraction of fibre, and on the assumption that the $h\text{DOP}$ parameter is small, then the PMD value will be low because there is a strong intermodal coupling in the fibre,
- average, then the PMD value will be average,
- large, then the PMD value will be high because there is a weak intermodal coupling in the fibre.

After the evaluation of the values measured, the polarization reflectogram (POTDR) will display several measurement results and graphs, above all the POTDR reflectogram,
where individual cable sections and route sites can be followed. The longitudinal resolution power of this method is of the order of hundreds of metres; routes of tens of km in length can be measured. In the POTDR reflectogram display, sites with low, increased and high PMD values are presented in colour.

The second graphical representation that can be displayed is the waveform of the hDOP function, which is yet another important curve of the overall evaluation of PMD. In addition to the hDOP function, horizontal straight lines are also displayed, which mark the limit values of PMD. These limit values can be set by the users themselves.

The third (and most important) graphical representation is the DOP curve. In one graphical display several parameters can be seen in different colours – the DOP, DOP\(_C\) and DOP\(_\text{GEO}\) curves. The DOP\(_\text{GEO}\) curve has the greatest informative value regarding the actual state of PMD.

The last possibility is the graphical representation of the curves (for both input states of POTDR polarization) of normalized Stokes parameters S1 to S3.

On top of all this, information about splice and connector sites can, of course, also be read from the final measurement protocol.

It is necessary to stress that the measurement of POTDR does not replace the total absolute values of PMD delay, which are measured using one of the interferometric methods, it only complements them.

### 8.5 Measurement of optoelectronic components

In our treatment so far we have had a source of radiation (LD or LED) on the input, photodiodes (PIN or APD) on the output, we have considered various passive elements, etc. and we have always assumed their failure-free operation with their intrinsic parameters. In many cases, however, it is necessary to establish the true parameters of these components, be it in connection with the manufacture or test measurement, etc.

One of the most important parameters of radiation sources is emitted power and its spectral characteristic. Optical power meters and optical spectrum analyzers are used to measure these parameters.

For measuring and checking detectors a corresponding radiation source is used together with a power meter or a selective meter.

The basic parameters of passive components (attenuation members, couplers, etc.) are insertion attenuation, directivity or division ratio. To measure these quantities, the same measuring facilities are necessary as for the measurement of attenuation of optical fibres, i.e. a stabilized radiation source and a meter of optical power.

### 8.6 Special measurement methods

Included in this measurement category can be special laboratory measurements, research measurements, measurements with special measuring instruments, and single-purpose measurements.

Measurement with the application of spectral analyzer enables:

- measuring in a wide range of wavelengths from 0.6 \(\mu\)m to 1.7 \(\mu\)m, depending on the structure of the elements used in the optical communication system,
- a wide dynamic range for the measurement of wavelength attenuation characteristics and of the emitted spectrum of LED with a lens,
- very accurate wavelength measurement with an accuracy of ± 1 nm,
- measurement with high resolution power for LD, spectral measurement with an accuracy of ± 0.1 nm.

The measurement of optoelectronic telecommunication systems, in particular from the viewpoint of their development, concerns the measurement of optical power of transmission modules, the system reserve and the error rate. These measurements are performed using an optical power meter, which should be provided with probes of the measurement of the power of arbitrarily modulated optical signals and also the d.c. component.

In the measurement of the system reserve and system error rate a measuring optical attenuator is used, whose function is to simulate the optical route. It can be used with advantage to measure the linearity and sensitivity of detectors and receiver modules.

The measuring equipment for the installation and maintenance of optical track requires three basic measuring instruments: the backscatter meter (optical reflectometer) for the checking of the whole route, the optical power meter for the checking of the transmitting part, and the measuring optical attenuator for the checking of the receiving part.

Measurement of optical cable. In the course of cable installation the attenuation of individual fibres and attenuation of splices are measured using the backscatter meter. The meter is connected in the station where installation work starts. Attenuation is measured for all the fibres of each cable run before joining them to another run.

In the next step, attenuation of the splice of optical fibres of two manufacturing runs is measured. In this measurement the splice quality is the measure and if the attenuation is not low enough, the fibre splice must be made anew.

Attenuation and sometimes also dispersion are measured on an installed elementary section. Attenuation of splices is performed from the opposite end than in the case of splicing.

With an installed section, the fibre measurement is performed using an optical transmitter and receiver. At the beginning of the section the optical signal with already measured level $P_1$ is introduced into the fibre. The input and output sides of the fibre are connected to the measuring instruments with connectors. Using a power meter the received level $P_2$ is measured on the output. Optical attenuation of the fibre is given by the relation

$$ A_L = P_2 - P_1. $$

(9.33)

Each fibre is measured twice and the average of the two measurements is entered as value $A_L$ in the protocols. When the measurement is repeated, the transmitter is disconnected, its level is measured, and the receiver is also disconnected and then re-connected.

Measurement of splice attenuation in backward direction. This measurement is carried out after the installation of an elementary section from opposite direction to that in which the cable joint installation proceeded. With this measurement performed, the average attenuation value of each splice is determined

$$ a_s = \frac{a_1 + a_2}{2}. $$

(9.34)

The average attenuation value of the splice $a_p$ of a section is established by adding up all the values $a_s$ and dividing this sum by the number of splices $n$
The value $a_p$ should not exceed 0.05 dB. The frequency of splice attenuation in the cable joint is shown in Fig. 8.32.

![Frequency of splice attenuation](image)

**Fig. 8.32:** Frequency of splice attenuation.

For high-speed transmissions and for the deployment of DWDM systems the measurement of chromatic dispersion and polarization mode dispersion (PMD) is required. The necessary meters are very costly and the measurement is carried out via outsourcing to specialized firms.

### 8.7 Supervision (monitoring) of optical networks

The development of optical networks has led to the problem of checking individual fibres and the whole network. Operation outage can be monitored in the electrical layer of transmission. Important customers (banks, etc.) that possess “their rented” fibres are interested in their fibre being constantly monitored and they insist on being immediately informed of any failure (type, site, etc.).

This optical supervision is run on the 1625 nm wavelength, which is above the wavelengths used for the strictly informative transmissions. The principle may be based on the direct transmission method or on the application of OTDR. The drop (interruption of transmission) is detected and this failure state can be transmitted to the dispatching centre or by cell phone to the responsible worker.

The above methods can be combined. One of the registered and most elaborate systems on the market is the MLS (Monitoring Line System) system [9-7]. Details of this system, its characteristic, configuration, technical parameters, etc. are described in the literature.
9 Example of optical networks of various operators:

9.1 Sloane fiber optic network

A good quality backbone network is fundamental for conducting telecommunications business. Our company owns the optical cables used by leading Czech and foreign operators in their backbone networks (see Fig. 9.1). The optical cables that we operate are built into protected areas in the Družba and IKL oil pipelines, and along railway line belonging to České dráhy.

Fig. 9.1: Sloane optical backbone.

The telecommunications business is our long-term focus. Since 2000, when the company was founded by a strategic investor who bought the optical cables in the oil pipelines from the MERO a.s. company, we have continuously invested into the expansion of our network and into mobile technologies. Our company's stability, innovation and activity provide a solid foundation for our partners' business activities. Our clear strategy, with its purely wholesale focus, makes us an ideal partner for companies in the telecommunications sector.

Sloane's optical backbone network has been constructed with maximum regard to safety and robustness. The high quality and accessible services are ensured by winding the optical cables so that reserve links for DWDM, GE and SDH are included. The entire network is monitored by a supervisory centre operating 24x7x365.
9.2  **OptoNet Communication, spol. s r. o.**

A new dynamic company operating optical line with lengths of 240 km since foundation. Due to the key backbone optical line, which passes through the center of the Vysočina region before heading towards the Austria border (Havlíčkův Brod - Jihlava-Znojmo-Hate) the company has obtained a professional partner which belongs among the most significant national and international operators. The basic Dark Fiber service is now used by companies such as GTS, CD-Telematika, CRA, Sloane Park Property Trust among others. New services offered by OptoNet include professional Internet connectivity, IP telephony (VoIP), IP TV and hosted applications.

The basic concept of this new operator is not to focus on the acquisition and operation of high volumes of domestic end users, but to address the development of the services portfolio aimed at company and corporate customers, services for regional government and the public sector according to their concept.

Due to the high skill level and qualifications of the company specialists, OptoNet provides (see Fig. 9.2) solutions based on real customer needs. All services are split into specific brand groups, each focused on the end user target group.

![OptoNet Regional optical network](image_url)

**Fig. 9.2:** OptoNet Regional optical network.
OptoNet Communication services:

Multimedia services platform
- Videoconferencing, IP TV, On-line sessions and streaming, multimedia portals,
- Webcasting and EDUcasting, Webinars, ...

Optical backbone services offered using a WHOLESALE model
- Rent of optical fibers, IP transit, L2 and L3 VPN networks, Internet, VoIP, IPTV, ASP, Billing and Provisioning...

Services of the professional telecommunication center in the Vysočina region
- Complete arranged telehouse, geographically suitable position, connectivity to all significant operators, remote service and monitoring, server hosting

Connectivity services for optical infrastructure designed for corporate customers.
Highspeed Internet, VoIP services, PBX interconnection, monitoring IP systems and smart building implementation, etc.
10 FTTH Znojmo network

10.1 Project Location

Znojmo - a Czech town, located in Southern Moravia close to the nearby Czech - Austrian border has approximately 36,000 inhabitants. The region is interesting from a historical point of view as well as renowned for its picturesque scenery.

10.1.1 Project Goal

The prime goal of the entire Optical FTTH networks iWebs - Znojmo project is to maintain the competitive environment in the already acquired customer base via the transparent and modular topology of the FTTH network. The customers are the end-users from the residential and commercial sector in addition to clients from various institutions and statutory subjects. A further task is to expand this customer base in order to develop the company business which is the provision of quality communication services with high added value and liability.

The current infrastructure, owned by iWebs s.r.o. is primarily based on the distribution of services via wireless communication. A big feature of wireless transmission is the use of air as a carrying medium for communication among the points of such a network. Except for external natural effects such as rain, snow, frost and fog, a considerable influence is also presented by the existence of technological limits without the currently available product portfolio. This is meant from both a technical and economical point of view. The aforementioned aspects mean the impossibility of deploying and distributing modern Triple-Play services and data-voice-video to end-users. At the same time these aspects do not prevent the use of services utilizable for example, for supervisory security systems, parking systems, use of public transport terminals, services for IZS towns, infochannel etc.

The company is aware of the competitive advantage of network providers which fulfill the new requirements for unified communication infrastructures therefore the key target is to build-up and operate such an infrastructure in order to compete in the competitive environment of Znojmo.

10.1.2 Scope of project

The target area of the offer of communication services is the entire area of Znojmo. The whole concept of the project study enables modular extensibility on any future expansion within a defined region independent to the type of topology and infrastructure that will eventually be used in this region. This is especially related to particular areas of optical access infrastructure in concrete objects and entrances to housing estates. Particularly the following:

- Bolzánova housing estate,
- Přimětice housing estate.
10.1.3 NGN/NGA Networks

To ensure that the entire infrastructure fulfills the above mentioned objectives, it is more appropriate to use the global design of the project within the concept and architecture of a modern NGN (Next Generation Networks) network.

The main decision is whether we design the network with centralized or distributed services architecture.

Both versions enable to offer the same portfolio of services for corporate and residential subscribers. Recently, the centralized model of services distribution has been almost the only one. However, the dynamic growth of the service portfolio and the demands on the capacity of the transmission network places ever greater demands on central technology to ensure the operation of Security SW, Deep Packet Inspection, Anti-X services, Intrusion Prevention Systems etc.

The centralized model is close to its limitation, despite the market continuing to offer more powerful devices that can raise the upper limit; although only for a short time and with high financial costs.

From the point of view of the above mentioned information, the whole concept is based on a modern NGN architecture network, where all services will be offered in the infrastructure of the defined area of the town of Znojmo distributed in a decentralized manner, using a distributed PoP (Point of Presence) model. This global view of the metropolitan network is ensured by the AON (Active Optical Network) architecture backbone, based on circle topology. The technologies belonging to the core functions (the kernel of the whole infrastructure), such as the connection to other transit lines, connection to multimedia service providers, the switching and routing functions and network administration - are located outside the project itself, in the Telehouse, data and telecommunication center of OptoNet Communication, spol. s r. o. in Jihlava. The Telehouse is also one of the sites located on the
backbone circle. The Telehouse provides connection to all key national and multinational operators and service providers. This ensures the delivery of service infrastructure to optical networks with high quality and with unmatched levels of availability, the potential for dual purchases of services and their redundancy. The proposed global model provides a highly flexible choice of access infrastructure.

The schematical diagram is shown in Fig. 10.2.

Fig. 10.2: FTTH network in Znojmo schematical diagram.
11 References


