

FUNDAMENTALS OF OPTICAL FIBER TRANSMISSION-2

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1. Optical cables

The optical fibres have numerous applications in

- telecommunication
- computer nets
- sensors
- medical devices (for example, endoscopes)

Taking into account the ability to transmit the signal we can distinguish:

- passive mode (signals or data transmission without any modification)
- active mode (employed in optical amplifiers)

The optical filament of the fiber which consists of core and cladding has to be surrounded with several external layers to protect from mechanical damages, and also from environmental factors such as moisture or temperature. In telecommunication and in computer nets the optical fibers are arranged into clusters of filaments, surrounded by common or separate protection layers, forming the optical cable. The first optotelecommunication cables contained 4, 8, 24, and 48 fibers. The present cables contain up to 400 fibers in one cable, enabling the digital transmission on the order of petabits. This means 10^{15} bits of digital information per second (see Table 1).

Table 1. The typical parameters of copper cables and optical cables

	Copper cable	Optical fibre
diameter (inches)	2.8	0.5
weight (lb/1000-ft length)	4800	80
capacity (megabits/sec)	3.15	417

We distinguish two ways of optical filaments packing in the cable:

- tight buffer
- loose buffer

In the tight buffer packing, the external radius of optical fiber with primary cladding is equal to the internal radius of the secondary coating (See Fig. 2.1). The cables of a tight buffer type are used in construction designed for short distance connections inside buildings.

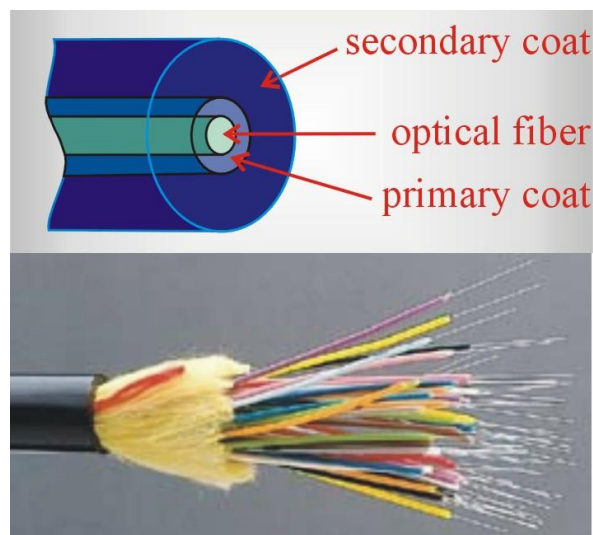


Fig. 2.1. Scheme of tight buffer

In the loose buffer packing, the external radius of the primary cladding is smaller than the internal radius of secondary layer. Optical fibers are placed in the loose buffer freely. The loose buffer is frequently produced in a two-ply buffer. The internal layer of the buffer is filled in with plastic material (e.g. aramid yarn) or gel characterized by the small friction index. This protects from local macro - and microbends. The external buffer protects from external

environment (see Fig.2.2). The cables of loose buffer packing type are used in constructions designed for long distance connections inside the buildings.

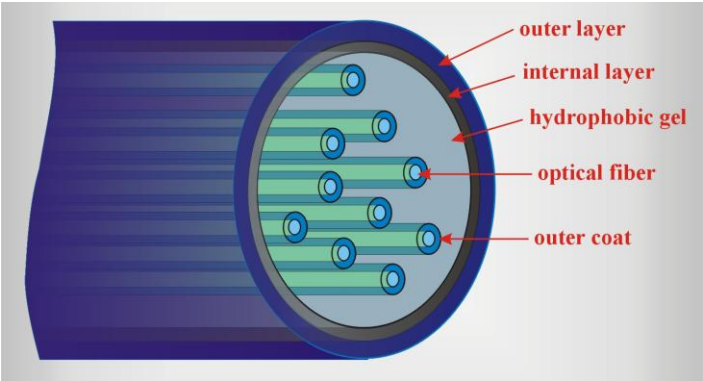


Fig. 2.2. Scheme of loose buffer

Because the optical fibers are placed freely inside the loose buffer, the length of the optical fiber is larger than the length of the buffer (Fig. 2.3)

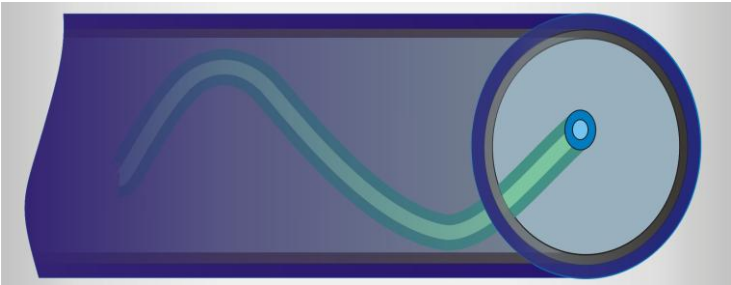


Fig. 2.3. Arrangement of the optical fiber in the loose buffer.

The gel filling in the buffer has hydrophobic properties to block the access of water to its interior

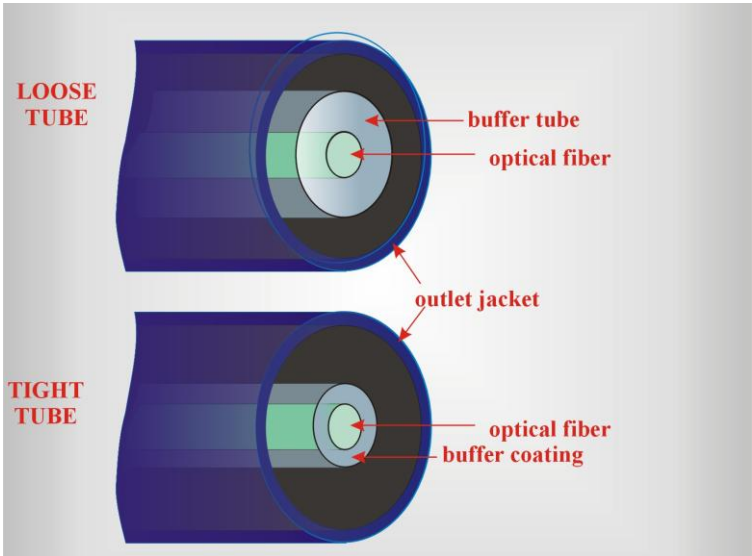


Fig. 2.4. Cross section of the loose and tight buffers

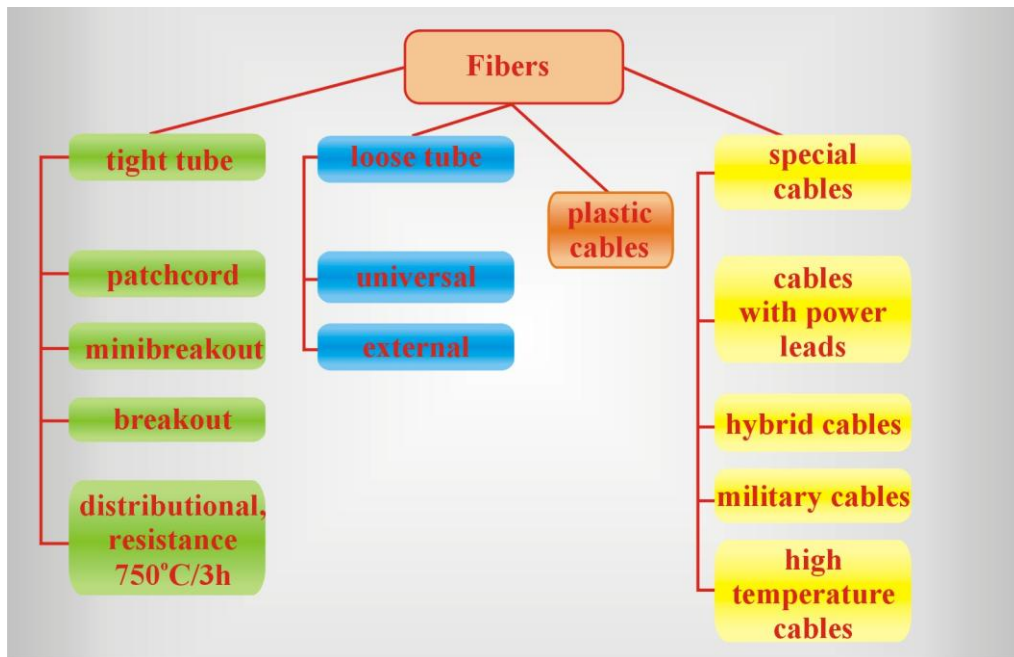


Fig. 2.5. Types of cables.

There are many types of tight buffer cables (Fig.2.5):

- **Patchcord cables** - used to crossing of optical tracks in telecommunicational junction-lines and the commutation nodes. They consists of short optical segments ended with suitable connectors. The simplest construction is the one or two filaments in tight cladding, surrounded with aramid or glass filaments and then covered with an external layer,
- **Breakout cables** – 2 to 24 filaments in similar cladding as in patchcord cables, and then commonly covered with an external layer (Fig.2.4) ,
- **Minibreakout cables** - optical filaments gathered together, protected by cladding made of aramid or glass and covered with an external layer.
- **Pigtail** – designed to finishing of optical cable filaments with welding or with mechanical connectors. It is a short section, at about 2 m in tight buffer one-sidely optical connector ended (Fig.2.6). In the fig. 2.6 it is shown the SC junction- ending

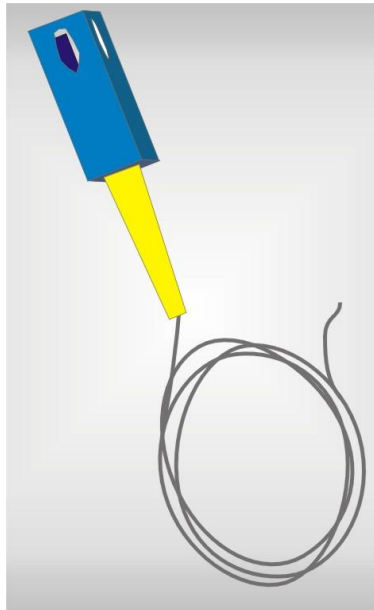


Fig. 2.6. Pigtail with SC junction ending

There are several variants of cables with filaments in loose buffer:

- **One- buffer construction** – 4 to 12 filaments are placed inside buffer,
- **Multi-buffer construction** – 4 to 14 buffers twisted around dielectric central unit(Fig. 2.7). Every buffer has from 4 to 14 filaments



Fig. 2.7. Breakout cable

Figure 2.8. shows a cross section of a buffer with a central element.

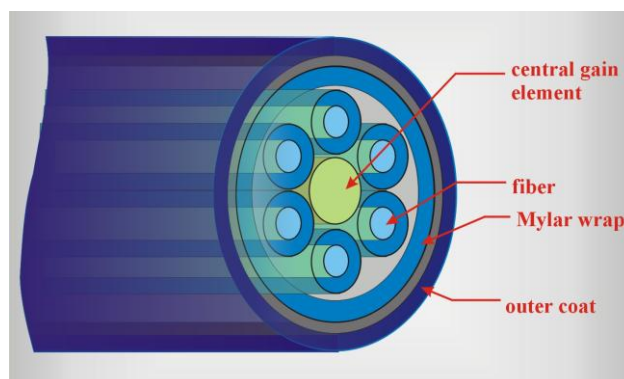


Fig. 2.8. Cross section of buffer with central gain element

Apart from the tight and loose buffers, there is a semitight buffer. Fig. 2.9 shows a cross section of the fiber of the *simplex and duplex* type in a semi-tight version.

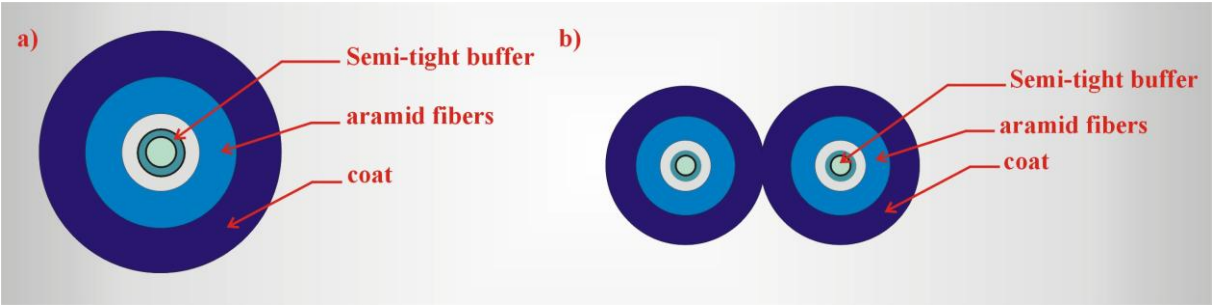


Fig. 2.9 Cross section of the fiber of type (a) *simplex*, (b) *duplex*.

Figures 2.10 and 2.11 show a crossing cable of duplex type; multimode MMF, with SC-ST tips and single mode SMF with SC-SC tips.



Fig 2.10. Crossing cable of duplex type; multimode MMF, with SC-ST tips



Fig 2.11. Crossing cable of duplex type; single mode SMF, SC-SC end

2. Parameters of optical fibres

The optical net will operate properly, when we first select the proper optical fiber, apply the proper light transmitter that emits the light which is directed into the fiber, as well as the proper receiver that detects the light at the end of the fiber. We will talk about the transmitters in chapter 5, and about the receivers in chapter 6. In this chapter we will discuss the most

important parameters of the optical fiber, which should be taken under consideration while building an optical net.

We distinguish the wide range of parameters for optical fibers:

1. Optical

- operating wavelength, nm
- attenuation, dB
- attenuation per km, dB/km
- dispersion
- refraction index (value and profile)
- numerical aperture NA
- cut-off frequency and cut-off wavelength
- mode field diameter (type of mode, core radius)
- polarization properties (polarization mode dispersion PMD, beat length)
- temperature stability of parameters

2. Geometrical

- Transverse dimension, geometry

3. Mechanical

- Break damage threshold, bend radius

4. Additional parameters (for special filaments)

- Kind of active doping material
- Kind of environment in which the cable is installed

In this chapter we will concentrate on the optical parameters. Some of them, such as: mode properties, polarization properties, influence of refraction index, cut-off frequency, have already been discussed in chapter 1. Other, such as dispersion, will be discussed in detail in chapters 3 and 4.

Table 2. Comparison of typical parameters of optical fibers

Fibre type					
Operating wavelength (nm)	400	633	800	1300	1550
Attenuation per km (dB/km)	350	<12	<5	<2	<2
Cut-off length (nm)	<380	<600	<800	<1250	<1400
Radius (µm)	3	3.5	5	9	10
Beat length	<2	<3	<5	<7	<8
Numerical aperture (NA)	0.14	0.14	0.14	0.14	0.14

2.1. Losses (dB) and attenuation [dB/km]

For the description of power losses in an optical fiber one can use the term of losses A , which is expressed in decibels (dB)

$$A = \frac{10}{L} \log \left[\frac{P(l_2)}{P_0(l_1)} \right] \tag{2.1}$$

or, the term losses per km α called attenuation and expressed in [dB/km]

$$\alpha = \frac{10}{L} \log\left[\frac{P(l_2)}{P_0(l_1)}\right] \quad (2.2)$$

where $P(l_2)$ and $P_0(l_1)$ denote optical powers at the end (point l_2) and at the beginning (l_1) of optical fiber, L denotes the optical length. The minus sign is omitted. Therefore, 10 decibels correspond decrease of signal 10 times, 20 dB - 100 times and so on. Consequently, in case when at distance of 1 km the signal intensity decreases to:

50 % of the primary value, the attenuation per km is 3dB/km,
 1% - 20dB/km
 0.1% -30dB/km
 0.01% -40 dB/km

Example: Optical fiber losses	
Data:	Signal of 10 mW is introduced to optical fibre at the length of 5-km. Signal of 1 μ W gets the receiver
Find:	Optical fiber losses
Solution:	<p>Losses in <i>dB</i>, are given by formula:</p> $10 \log_{10} (P_0/P) = 10 \log_{10} (10 \text{ mW}/10^{-3} \text{ mW})$ $P_0/P = 10 \log_{10} 10^4 = 40 \text{ dB.}$ <p>So, attenuation that means the losses per 1 km of optical fiber are the following</p> $40 \text{ dB}/5\text{km} = 8 \text{ dB}/\text{km}.$

Let's compare attenuation for the single mode and multimode fibers:

Single mode fiber

1310 nm 0.33- 0.42 dB/km

1550 nm 0.18-0.25 dB/km

Multimode fiber (gradient profile of refraction index in the core)

850 nm 2.4-2.7 (50/125) 2.7-3.2 (62.5/125) dB/km

1300 nm 0.5-0.8 0.6-0.9 dB/km

Losses and attenuation per km are measured with a device called reflectometer. We will discuss those at the end of this chapter. Fig. 2.12. shows the typical optical reflectometer.



Fig.2.12. Typical reflectometer for optical attenuation measurements
 FLT4 products.molexpn.com.pl

Fig. 2.13. and Table 3 present attenuation in three optical windows which were discussed in chapter 1.

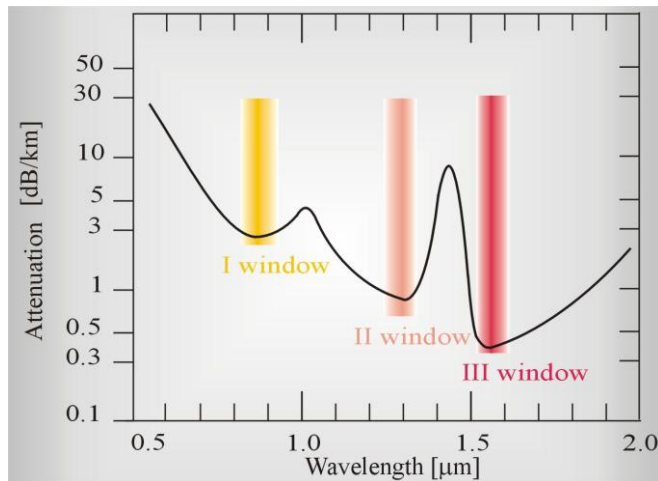


Fig. 2.13. Attenuation in the three optical windows

Table 3 Attenuation in three optical windows

Transmission window	Wavelength [nm]	Attenuation [dB/km]
I	850	~3
II	1310	0.3 – 0.5
III	1550	0.18 – 0.3

The losses and attenuation are related to many physical phenomena and mechanical factors such as:

- 1) Rayleigh scattering ($T \propto \frac{1}{\lambda^4}$) caused by fluctuations of density of optical fiber material (glass),

- 2) Absorption in ultra violet from the valence to the conduction band for wavelengths < 200 nm (0.2 μm),
- 3) absorption in far infra-red for the II and III harmonic of the vibrational mode (1.38 μm and 0.95 μm) for O-H bond (OH⁻ ion) or water,
- 4) absorption in far infa-red for the sum frequency mode of OH⁻ ion and Si-O bond (1.23 μm)
- 5) absorption in infra-red for the vibrational mode of Si-O (9 μm),
- 6) absorption of trace metal ions (Cu⁺², Cr⁺², Fe⁺²) and hydrogen H₂ (1.24 μm),
- 7) fiber irregularity (microbends, diameter fluctuation).

2.2. Numerical aperture

Numerical aperture NA defines of the maximum angle (Fig. 2.14) between the entering ray and the axis of the optical fiber, above which the phenomenon of the total internal reflection does not occur any more and the ray cannot be propagated in the optical fiber. The angle is called the acceptance angle.

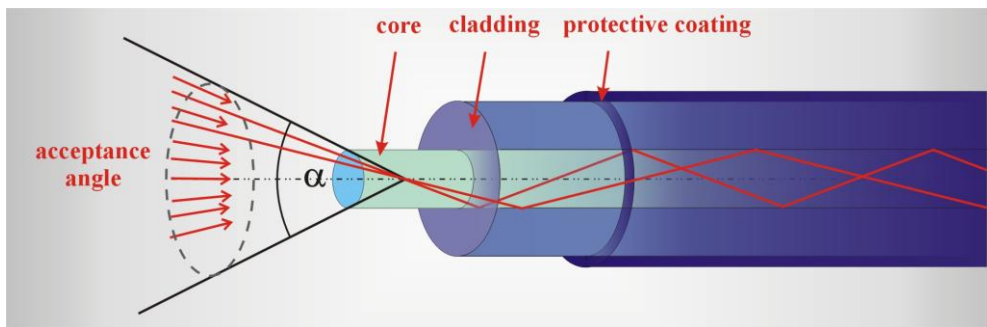


Fig. 2.14. Illustration of acceptance angle characterizing the numerical aperture NA

Numerical aperture NA is defined as the sinus of a half of the acceptance angle. The typical values are 0.1-0.4 which correspond to acceptance angle 11°- 46°. Optical fiber transmits only the light entering the optical fiber under the angle equal or smaller than the acceptance angle. We will show, that the numerical aperture NA depends on the refraction index of the core and the cladding and it is expressed by formula

$$NA = \sin \alpha = \sqrt{n_{co}^2 - n_{cl}^2} \quad (2.3)$$

Let's derive the formula for the numerical aperture NA.

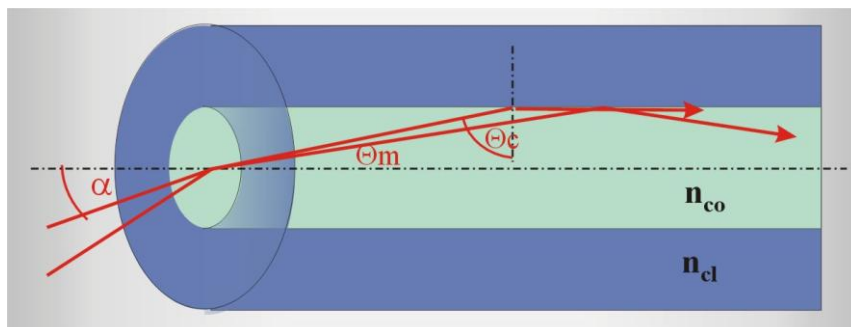


Fig. 2.15. Auxiliary figure for the derivation of formula for numerical aperture NA

From Snellius law we know that at the critical angle Θ_c for the total internal reflection is expressed by the formula

$$n_{co} \sin \Theta_c = n_{cl} \sin 90^0 = n_{cl} \quad (2.4)$$

From the relationship of sum of angles in a triangle one gets

$$n_{co} \sin(90^0 - \Theta_m) = n_{cl} \quad (2.5)$$

and

$$n_{co} \cos \Theta_m = n_{cl} \quad (2.6)$$

From the reduction formulas one receives

$$n_{co} \sqrt{1 - \sin^2 \Theta_m} = n_{cl} \quad (2.7)$$

After squaring both sides of the equation we obtain:

$$n_{co}^2 (1 - \sin^2 \Theta_m) = n_{cl}^2 \quad (2.8)$$

and from this

$$n_{co}^2 - n_{co}^2 \sin^2 \Theta_m = n_{cl}^2 \quad (2.9)$$

Using the Snellius law once again for the core – air refraction for the light ray entering the optical fiber one gets

$$n_{co}^2 \sin^2 \Theta_m = 1 \sin^2 \alpha \quad (2.10)$$

and substituting (2.10) to (2.9) one gets

$$n_{co}^2 - \sin^2 \alpha = n_{cl}^2 \quad (2.11)$$

Finally we obtain the formula for the numerical aperture NA

$$NA = \sin \alpha = \sqrt{n_{co}^2 - n_{cl}^2} \quad (2.12)$$

Table 4. presents the numerical aperture NA for different types of optical fibers as well as the another parameters, such as core radius, attenuation per km and the product of distance and bandwidth.

Table 4. Types of optical fibers

Type	Radius of core/ cladding (μm)	NA	Attenuation per km (dB/km)	Product distance*width (MHz-km)
Multimode, small distances	100/200	0.3	5 - 10	20 - 200
Single mode	6/125	0.03	0.1	1000
Multimode, gradient, large distances	50/125	0.2	1 - 5	500 - 1500

2.3. Cut-off frequency

The effective thickness of the optical fiber is defined by the formula

$$V = \frac{2\pi a}{\lambda_0} (n_1^2 - n_2^2)^{1/2} \quad (2.13)$$

where n_1, n_2 – refraction index of the core and the cladding, a – core radius, λ_0 – wavelength of the light propagating through the fiber. Let's remind that the effective thickness of the optical fiber given by (2.13) is expressed by the same formula as the parameter called the normalized frequency which allow to define a cut-off frequency.

The number of the modes depends on the normalized frequency $v = \frac{2\pi a}{\lambda_0} \sqrt{n_1^2 - n_2^2}$, which has been introduced earlier (1.56, chapter 1). The given mode can propagate in optical fiber only, when the value of the normalized frequency v exceeds the characteristic for every mode value, called the **cut-off frequency**. When $v < 2.405$, the characteristic equations described in chapter 1 do not have a solution which means that no mode of TE_{op} as well as of TM_{op} type propagate through the fiber. The only mode propagating without any limitations is the hybrid mode HE_{11} for which the cut-off frequency equals zero. This is the case of the single mode fiber. For the normalized frequency higher than 2.405 the fiber propagates more than one mode and operates as a multimode fiber.

2.4. Dispersion coefficient D

The next important parameter is related to the dispersion phenomena occurring in optical fibers. Generally, dispersion in optical fibers leads to signal degradation. Fig. 2.16. illustrates the different phenomena leading to signal degradation. The first type of degradation is related to attenuation. However, the attenuation reduces the intensity of signal, but it does not change the time duration of a pulse propagating through the fiber. The pulse remains in its temporal interval.

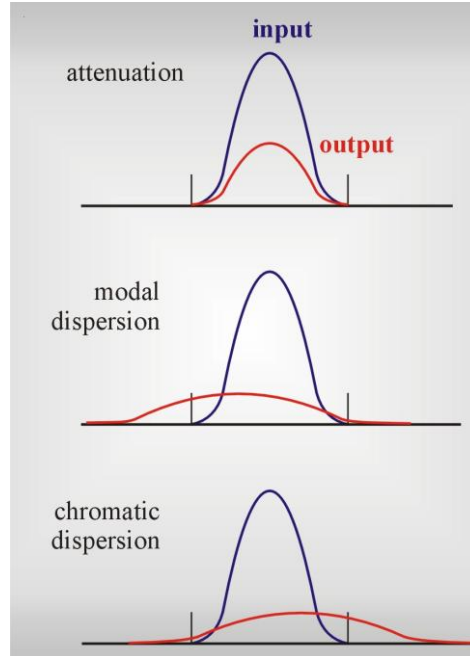


Fig. 2.16. The main reasons of signal degradation

The next factors that cause the signal degradation are the mode dispersion, the chromatic dispersion as well as the polarization mode dispersion. We will discuss the phenomena related to dispersion in details in chapter 3. Here, we will stress only that all kinds of dispersion cause the signal broadening.

The mode dispersion results from the fact that the light in the optical fiber can propagate along different optical paths, so the initial pulse reaches the detector at various time intervals leading to the temporal pulse broadening.

The chromatic dispersion results from the fact, that the refraction index depends on wavelength. The short pulses are significantly non-monochromatic, so the different components propagate at different velocities v_g .

To describe the dispersion one uses the **dispersion coefficient D** defined as

$$D = \frac{dt_g}{d\lambda} \left[\frac{ps}{nm \bullet km} \right], \text{ where } t_g = \frac{1}{v_g} = \frac{d\beta}{d\omega} \quad (2.14)$$

The dispersion coefficient D is a measure of the temporal broadening of the pulse in ps (picoseconds) after passing 1 km in the optical fiber, when the width of spectral line of light source is 1 nm. The term v_g is called the group velocity, and will be discussed in details in chapter 3.

2.5. Polarization mode dispersion (PMD)

In optical fibers a phenomenon of birefringence can occur. The birefringence in fibers is described by a parameter called the mode birefringence B_m (do not confuse this symbol with the normalized propagation constant B defined by the equation (1.81))

$$B_m = \frac{|\beta_y - \beta_x|}{k_0} = n_{ef}^x - n_{ef}^y, \quad (2.15)$$

where β_y and β_x are the propagation constants of the orthogonal modes, and n_{ef}^x and n_{ef}^y are the effective refraction index in x and y direction, k_0 is the wave vector. The effective refraction indices are defined by the equation (1.82)

Another parameter which defines a fiber birefringence is a **beat length**

$$L_B = \frac{2\pi}{|\beta_y - \beta_x|} = \frac{\lambda}{B_m}, \quad (2.16)$$

where L_B is optical the path, on which the phase difference of the orthogonal modes increases by $\frac{\pi}{2}$. The phase difference $\frac{\pi}{2}$ means that the power between the orthogonal modes is exchanged. This phenomenon repeats periodically.

The birefringence results in the mode dispersion related to polarization. The parameter characterizing the polarization-mode dispersion (PMD) is the time delay ΔT between the two orthogonal components. This parameter is a measure of the pulse deformation (the temporal pulse broadening) on the path L for the optical fiber characterized by the mode birefringence B_m and it is expressed by the formula

$$\Delta T = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| = L|\beta_{1x} - \beta_{1y}| = L\delta\beta_1 \quad (2.17)$$

where

$$\delta\beta_1 = k_0(dB_m / d\omega) \quad (2.18)$$

Now, we are able to understand the parameters mentioned in the typical catalogues of optical fibers (see Table 5). In chapter 3 we will deepen our knowledge about the phenomena of dispersion.

Table 5 Parameters of optical fibres

Typical parameters of optical fibres						
SINGLE MODE FIBRES						
	Wavelength [nm]	G.652.B	G.652.C / D	G.653	G.655	G.656
Attenuation constant [dB/km]	1310	≤ 0.38	≤ 0.34	≤ 0.50	≤ 0.40	≤ 0.40
	1285-1330	≤ 0.40	-	-	-	-
	1385	-	≤ 0.31	-	≤ 0.40	≤ 0.40
	1460	-	-	-	-	≤ 0.40
	1550	≤ 0.23	≤ 0.21	≤ 0.25	≤ 0.22	≤ 0.35
	1525-1575	-	-	≤ 0.27	-	-
	1625	-	≤ 0.24	-	≤ 0.25	≤ 0.40
Mode field diameter [μm]	1310	9.1 ± 0.3	9.2 ± 0.4	8.4 ± 0.6	-	-
	1550	10.2 ± 0.4	10.4 ± 0.5	-	8.4 ± 0.6	8.6 ± 0.4
Chromatic dispersion [ps/nm·km]	1285-1330	≤ 3	≤ 3	-	-	-
	1550	≤ 18	≤ 18	-	-	-
	1525-1575	-	-	≤ 3.5	-	-
	1460-1625	-	-	-	-	2.0-12.0
	1530-1565	-	-	-	2.6 – 6.0	-
	1565-1625	-	-	-	4.0 – 8.9	-
Neutral dispersion wavelength [nm]		≥ 1302 ≤ 1322	≥ 1302 ≤ 1322	1550 ± 25	< 1450	< 1405
Cut-off wavelength [nm]		≤ 1260	≤ 1260	≤ 1350	≤ 1260	≤ 1325
PMD [ps/√km]	1550	< 0.5	< 0.1	0.5	< 0.1	< 0.1

Basic parameters of optical fibres								
MULTIMODE FIBRES 50/125								
	Wavelength [nm]	OM1	OM2	OM3 SL	OM3	OM3 XL	GIGA	GIGA XL
Attenuation constant [dB/km]	850	≤ 2.5	≤ 2,5	≤ 2,5	≤ 2.5	≤ 2,5	≤ 2,5	--
	1300	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	--
	1240-1550	--	--	--	--	--	--	≤ 0.7
Transfer bandwidth [MHz·km]	850	≥ 200	≥ 500	≥ 700	≥ 1500	≥ 3500	≥ 600	--
	1300	≥ 500	≥ 500	≥ 500	≥ 500	≥ 500	≥ 1200	--
	1240-1550	--	--	--	--	--	--	≥ 500
Gigabit Ethernet Link Distance [m]	850	--	--	≤ 150 (10 Gb/s)	≤ 300 (10 Gb/s)	≤ 550 (10 Gb/s)	≤ 750 (1 Gb/s)	--
	1300	--	--	--	--	--	≤ 2000 (1 Gb/s)	--
	1240-1550	--	--	--	--	--	--	≤ 550 (1 Gb/s)
Numerical aperture NA		0.200 ± 0.015						
Group Index of Refraction	850	1.482						--

	1300	1.477
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Basic parameters of optical fibres		MULTIMODE FIBRES 62.5/125				
	Wavelength [nm]	OM1	OM2	OM2XL	GIGA	GIGA XL
Attenuation constant [dB/km]	850	≤ 3.0	≤ 3.0	≤ 3.0	≤ 3.0	--
	1300	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	--
	1240-1550	--	--	--	--	≤ 0.7
Transfer bandwidth [MHz·km]	850	≥ 200	≥ 500	≥ 600	≥ 200	--
	1300	≥ 500	≥ 500	≥ 1200	≥ 600	--
	1240-1550	--	--	--	--	≥ 500
Gigabit Ethernet Link Distans [m]	850	--	--	--	≤ 500 (1 Gb/s)	--
	1300	--	--	--	≤ 1000 (1 Gb/s)	--
	1140-1550	--	--	--	--	≤ 550 (1 Gb/s)
Numerical aperture NA		0.275 ± 0.015				
Group Index of Refraction	850	1.496				--
	1300					

3. Balance of optical power in optical system

When the optical system of fibers is projected, one should consider many factors in order the system to work correctly. Figure 2.17 defines some of them.

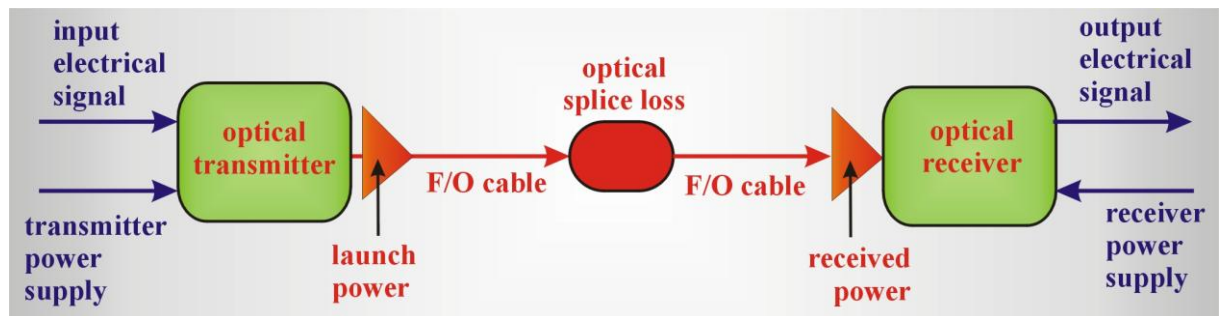


Fig. 2.17. Parameters which should be taken under account while building the optical net.

The list of factors, which should be considered is shown in Table.6

Table.6 Parameters which should be taken under account while building the optical net (www.fiber-optics.info)

Parameter	Factors to consider
Transmission distance	The complexity of arrangement grows when distance grows
Operating wavelength	Typical: 780, 850, 1310, 1550, and 1625 nm
Kind of fiber	Single mode fiber, multimode fiber, dispersion shifted, and so on, bandwidth
Dispersion	How large dispersion system tolerates, or if the compensation of dispersion is needed
Fiber nonlinearity	Whether the signal quality is influenced by the signal degradation caused by the stimulated scattering of Raman, Brillouin, phase automodulation, etc.,
Transmittance optical power	Connected with previous considerations, optical power expressed in dBm
Light source	LED diode or laser, if laser, what type: FP, DFB, DBR
Detector sensitivity	Expressed in dBm
Detector type	Photodiode PIN, avalanche APD or <u>IDP</u> , taking into account sensitivity and response time
Gain type	Electronic, optical, amplifier type
Modulation code	<u>AM</u> , <u>FM</u> , <u>PCM</u> , or <u>Digital</u>
Bit Error Rate	Typical 10^{-9} , 10^{-12}
Signal/noise rate	Expressed in dB
Type of connection	Types and number of connectors
Environment influence	Moisture, temperature, sunny exposure
Mechanical parameters and fire protection	Internal, external use, flammability

The procedure presented below allows determining step by step the importance of the factors presented above.

- Distance and losses per km (attenuation) involved are the most important factors. One should choose the proper kind of fiber, taking into account the above-mentioned parameters, as well as choose the kind of connectors,
- Choose suitable combination of transmitter and receiver set, depending on type of transmitted signal (analog, digital, audio, video, RS -232, etc.),
- Count the total losses of optical power, taking into account the fiber attenuation, weld losses, connectors losses, etc. These parameters are given by a manufacturer,
- Compare the losses with detector sensitivity. Consider if detector is able to measure the level of optical powers reaching receiver set,
- Apply a margin of error, at least 3dB for a whole system,
- Check whether the bandwidth of the optical fiber is adequate to signal which you want to send. If not – choose another combinations of transmitter/receiver set (wavelength) or consider the lower loss of fiber.

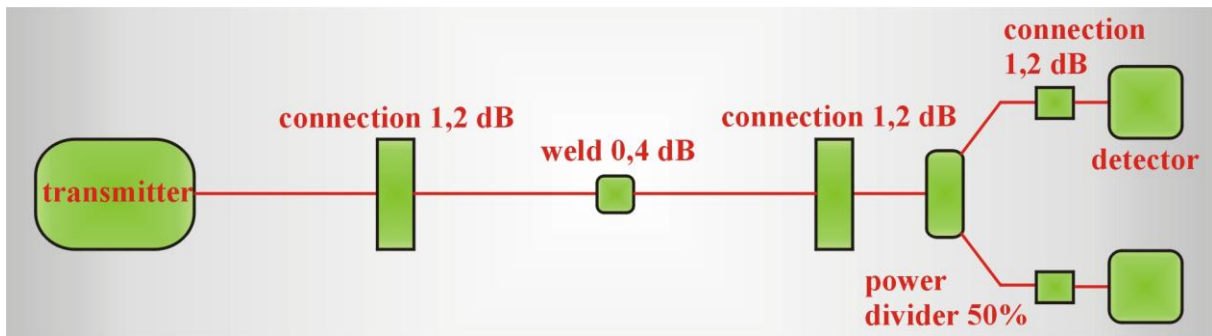


Fig.2.18. Illustration of losses of the optical fiber system for which the balance of power has been counted below

Let's apply the above mentioned instructions to calculate the balance of power for a system presented in Figure 2.18. To calculate the power balance we must compare the input power and calculate all the losses. The input power must be higher than the losses. The balance of power serves as a tool to choose the proper optical power of the source to assure sufficient quantity of input light, which has to be higher than the detector sensitivity. Let the project margin be -5dB and consider the losses difficult to estimate, e.g. bends losses. The calculation is expressed in decibels (dB), the unit of dBm is used for light. The losses of optical power in dB is described by the formula

$$X [dB] = 10 \log \left(\frac{P_1}{P_0} \right) \quad (2.19)$$

where P_0 is the initial optical power, P_1 is the power after passing the optical path L . While preparing the power balance it is convenient to present the absolute values of the source power and the detector sensitivity in decibels (which are denoted as dBm in contrast to the attenuation unit expressed in dB). To operate with the absolute units, we have to establish the reference. If we establish arbitrarily that 1mW corresponds to the value of 0 dBm, the signal at power of +10 dBm is equal to the optical power of 10 mW, and -10 dBm corresponds to 0.1 mW. Applying the dBm units facilitates calculation. When the total losses in optical fiber are 20 dB, it means that the power of -20dBm reaches detector, and this corresponds to optical power of 0.01 mW.

In order to design the project properly, first we have to be aware of attenuation during the coupling of the optical fiber with the light sources and the receiver sets. The light source and the fiber are coupled with lenses, usually the GRIN (gradient index) type or SELFOC (self – focusing) lenses (Fig. 2.19)

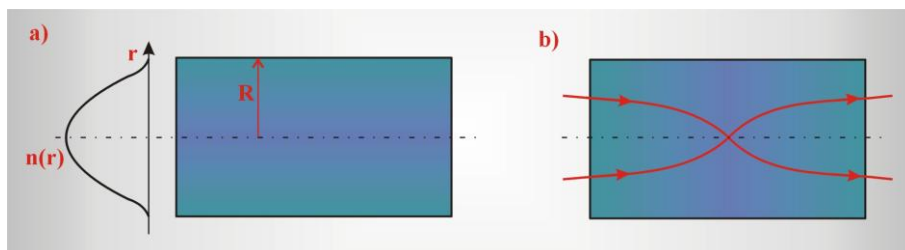


Fig. 2.19. Lenses of GRIN (gradient index) or SELFOC (self –focusing) type

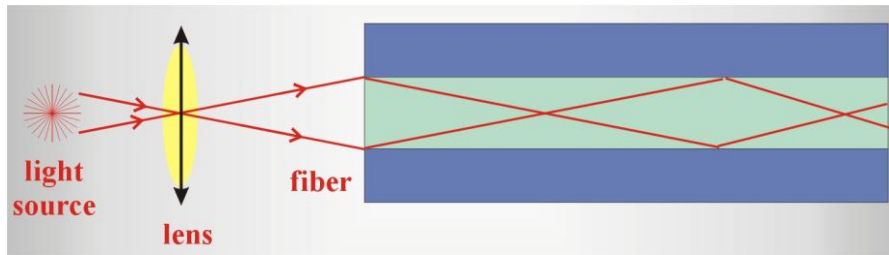


Fig.2.20. Illustration of coupling of light source with the optical fiber

The coupling efficiency η of the light source with the fiber is expressed by formula

$$\eta = \left(\frac{NA_f}{NA_s} \right)^2 F \min \left(1, \left(\frac{a}{r_s} \right)^2 \right) \quad (2.20)$$

where

NA_f – numerical aperture of optical fiber

NA_s - numerical aperture of the source

a – fiber core radius

r_s - source emission surface radius

F – coefficient describing losses caused by the Fresnel reflection at the fiber entrance, caused by the different core and air refraction indices, typically $F=0.95$

This formula expresses a simple observation, resulting from Fig. 2.20, that the coupling reaches maximum when the source emission surface is smaller /equal to the fiber core surface. Otherwise, part of the light is lost. This lost part is equal to

$$1 - \left(\frac{a}{r_s} \right)^2. \quad (2.21)$$

Having the knowledge of the coupling efficiency η of the light source and the optical fiber, we can start to count the power balance for the system presented in Fig. 2.18.

Example: One should design the optical system using the diode LED at $\lambda = 820\text{nm}$. The diode emission surface diameter is $40\mu\text{m}$. The numerical aperture of diode $NA_s = 1$ is coupled with the fiber of the numerical aperture $NA_f=0.45$ and the core diameter of $50\mu\text{m}$. The system is made of the optical fiber characterized by the attenuation of 5dB/km at 820nm wavelength. The length of the fiber is 5km . Calculate the minimum optical power of the light must be sent by the LED diode, if the PIN photodiode at sensitivity of -20dBm ($10\mu\text{W}$) is applied as the detector. The optical system configuration is shown in Figure 2.18.

Solution:

$$\text{Loss of source coupling} = (NA_f / NA_s)^2 F = (0.45/1)^2 \cdot 0.95 = 0.192 = 7.2 \text{ dB}$$

(because $\eta = (NA_f/NA_s)^2 F \min [1, (a/r_s)^2]$; $\min [1, (50/40)^2] = 1$)

Connector losses	$= 3 \cdot 1.2\text{dB} = 3.6\text{dB}$	3.6 dB
Weld losses	$= 0.4\text{dB}$	0.4 dB
Fiber losses	$= 5\text{km} \cdot 5\text{dB/km} = 25\text{dB}$	25.0 dB
Power divider losses	$= 50\%$	3.0 dB
Project margin	$= 5\text{dB}$	5.0 dB
	SUM OF LOSSES	46.2 dB

The required optical power of the source can be calculated from the balance:

$$P_o = P_{RX} + P_L \quad (2.22)$$

where P_o – required optical power, P_{RX} – detector sensitivity, P_L – total optical system losses so: $P_o = -20 \text{ dBm} + 46.2 \text{ dBm} = 26.2 \text{ dBm}$ (417 mW), as 0 dBm corresponds to 1 mW.

3. Optical reflectometer

The reflectometer OTDR (optical time domain reflectometer) is the basic device for controlling the optical line, both before the operation starts and during the operation for periodical checking. The reflectometer measures the losses A, expressed in decibels (dB)

$$A = 10 \log \left[\frac{P(l_1)}{P(l_2)} \right] \quad (2.23)$$

and the losses per km (attenuation) α expressed in [dB/km]

$$\alpha = \frac{10}{L} \log \left[\frac{P(l_1)}{P(l_2)} \right] \quad (2.24)$$

where $P(l_2)$ and $P_0(l_1)$ denote optical powers at the end (point l_2) and at the beginning (l_1) of the optical fiber, L is the length of the fiber. The reflectometer is based on the phenomenon of light scattering called the Rayleigh scattering. Fig.2.21 shows the various types of scattering and it illustrates the mechanism of Rayleigh scattering.

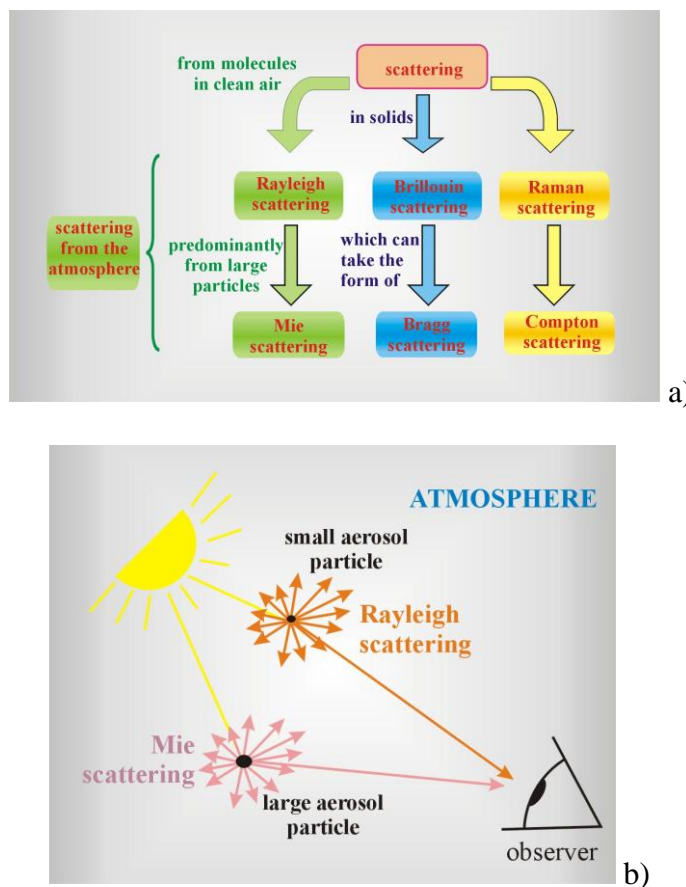


Fig. 2.21. Types of scattering (a) and illustration of the Rayleigh scattering mechanism (b)

The principle of reflectometer operation is presented in Figure 2.22. The light pulses are sent by a laser or a diode to the optical fiber by the optical coupler. The pulses of light propagating in the optical fiber undergo scattering in the glass core. Let assume that at some point of the fiber there is any micro-inhomogeneity due to bend, damage or connection to the other part of the fiber. This point shows a little bit different Rayleigh scattering than the rest of the fiber. The Rayleigh scattering occurs in all directions, but for the measurements we use only a small part of the backward scattered light. The scattered optical signal is monitored by the receiving device (photodiode, most often the avalanche diode APD) and provide information that some places in the fiber show abnormal scattering.

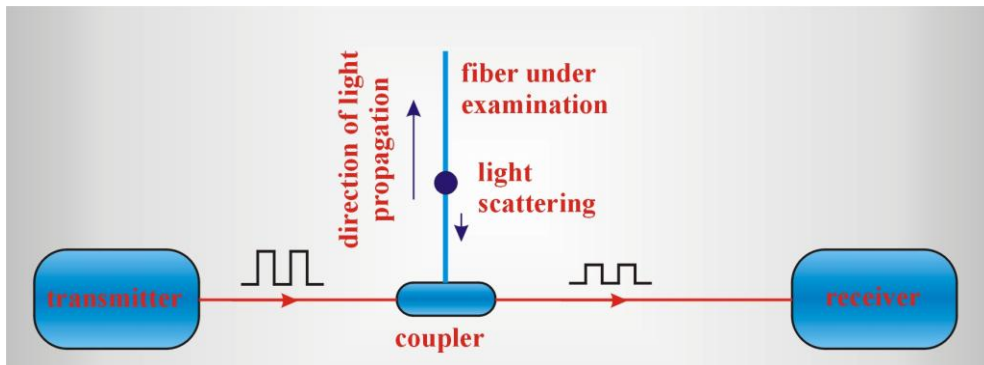


Fig.2.22. The physical principle of reflectometer based on the Rayleigh scattering

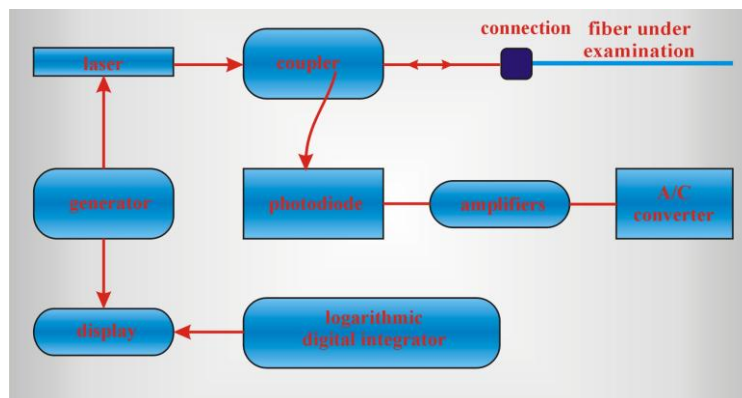


Fig.2.23. Scheme of the reflectometer [1]

The reflectometer consists of the transmission part with a laser, pulse modulating device (pulse generator). The optical pulse is directed to the coupler and it enters the fiber under the examination through the fiber connector. The light scattered backward return back and is directed by the same coupler to the receiving system with the photodiode which converts the optical signal into the electrical signal. Because the received signal is very weak, it is gained in the amplifier, then converted onto the digital signal in the A/C converter, from which it gets to the digital integrator, which increases the signal/noise ratio. The digital integrator is the high-speed box, in which the consecutive pulses are added and averaged afterwards. The reflectometer measures the time delay between the forward initial pulse and the backward scattered pulse. Dividing this time delay by two (because the light passes to a given point of optical fiber and then returns) and multiplying by the velocity of the light in the optical fiber

($v = \frac{c}{n}$), we obtain the information about the distance between the entrance to the optical fiber and the point of the signal scattering. The reflectometer measurements can deliver many important information: optical power loss (dB), attenuation (dB/km) caused by welds, connectors, damages, breaking. In the echogram presented below one can clearly see some events occurring in the optical fiber, such as damaged connecting, weld, bending, stressing or tearing of the fiber.

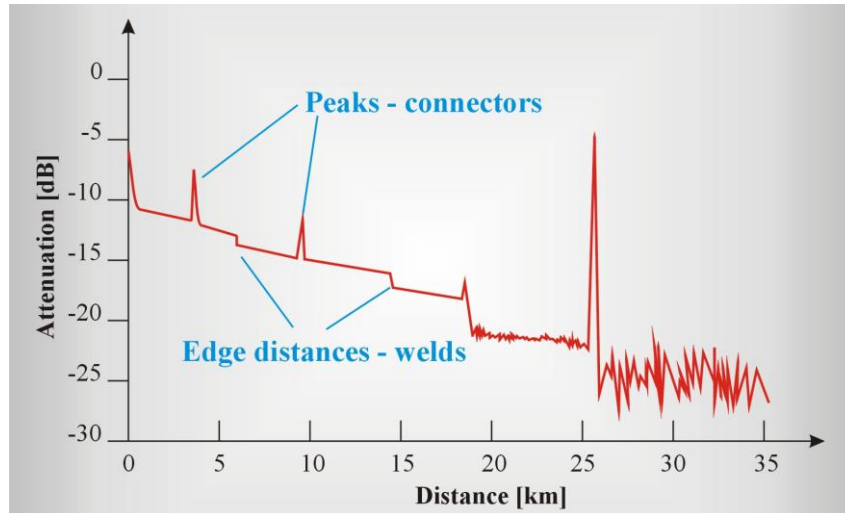


Fig.2.24 The typical echogram of signals observed in the reflectometer [1]

The main parameters characterizing the optical reflectometer are the following:

- Working wavelength of the reflectometer (850nm, 1310 nm, 1550 nm),
- Duration of the transmitted pulses (from 10 ns to 20000 ns) – the measurement dynamics increases with the pulse duration, but the resolution decreases at the same time, which denotes lower measurement quality and the loss of details in the echogram,
- Length of the measured optical line. The good reflectometer should be able to measure distances exceeding 200 km,
- Resolution (in terms of attenuation or a distance)
- The measurement dynamics (the difference between the largest and the smallest value of pulse which can be measured by the reflectometer). Usually, the dynamics of the reflectometer is about 20-45dB,
- The linearity of the device: e.g. if the linearity is +/- 0.05 dB and the measured attenuation is 10 dB, the error resulting from nonlinearity ranges from -0.5dB to +0.5dB.

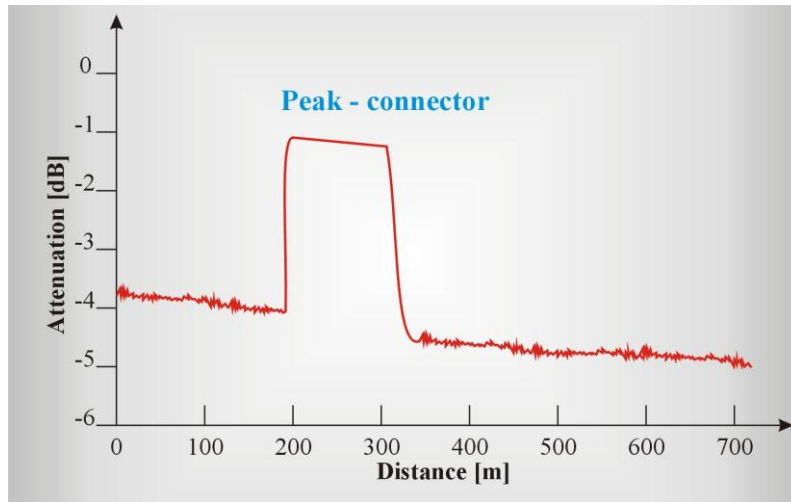


Fig.2.25. The signal from the connector between the two separated parts of a fiber [1]

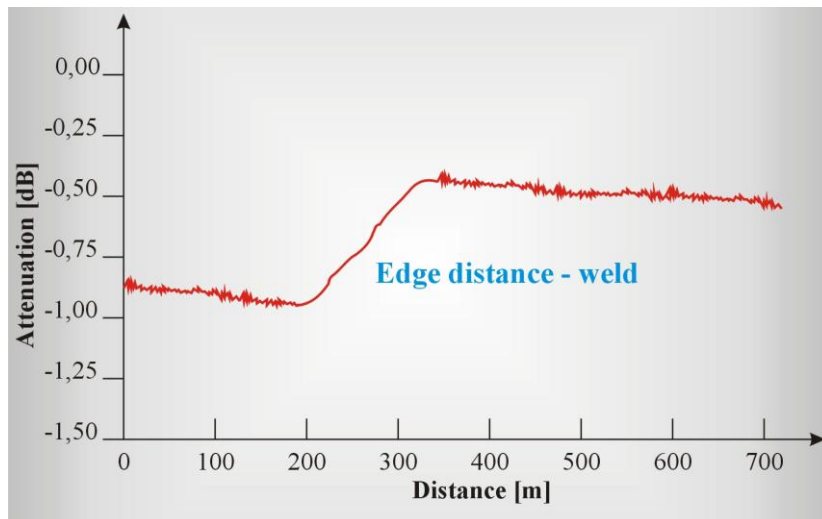


Fig.2.26. The signal from the weld between the two separated parts of a fiber [1], edge distance – with "instep" or "lowering", caused by the different light scattering properties of the connected sections of the optical fiber.

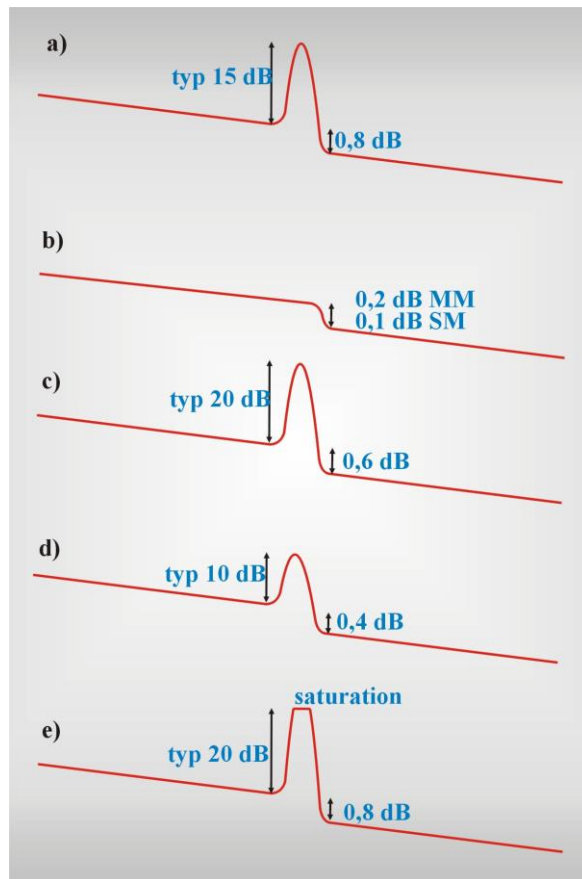


Fig.2.27. Various kind of signals from the reflectometer [1], MM-multimode fiber, SM-single mode fiber,

- a) Mechanical connector
- b) Weld connector
- a) PC connector
- b) Super PC connector
- c) Connector with the air distance

4.1. Brillouin reflectometer BOTDR (Brillouin optical time domain reflectometer)

Another kind of reflectometers is based on the Brillouin scattering. In the typical reflectometers the Rayleigh scattering is employed for analysis. The BOTDR reflectometer utilizes the phenomenon of the inelastic Brillouin scattering, related to generation of acoustic wave at frequency f_B . The signal resulting from the Brillouin scattering, with a frequency red-shifted by f_B , propagates backward along the examined optical fiber. The frequency value depends on the optical fiber properties, stresses in the core, temperature. Typical values are of the order of 13 GHz for 1310 nm and 11 GHz for 1550 nm.

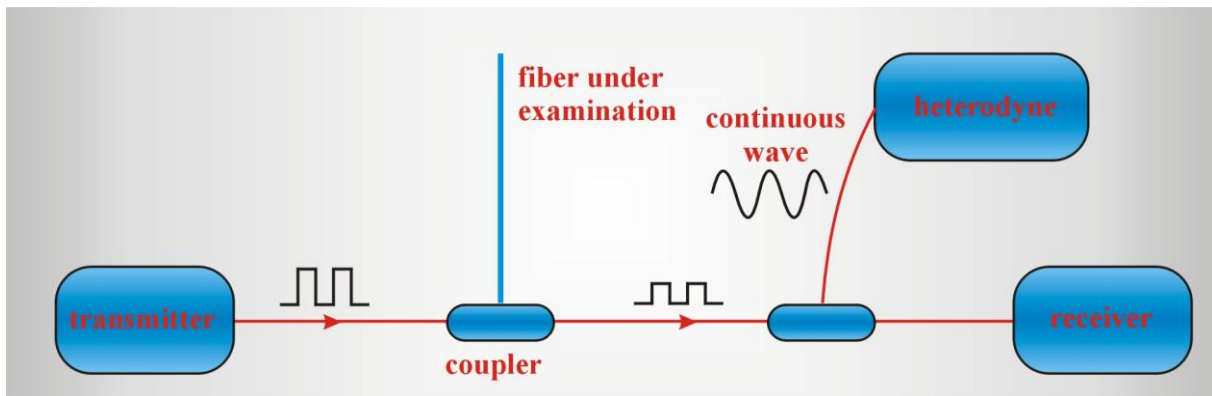


Fig.2.28 The physical principle of reflectometer based on the Brillouin scattering (BOTDR)

The scattered light gets back to receiver via the coupler like in the OTDR based on the Rayleigh scattering. The receiver set in BOTDR is of the coherent type, with the heterodyne detection. The continuous laser acts as the heterodyne. The heterodyne light is mixed with the scattered light. Its frequency is lower than the transmitted frequency by a value smaller than the frequency f_B . The received modulation of the signal is at about 100 MHz.

The advantages of BOTDR in comparison with OTDR are the following:

- larger measurement dynamics,
- larger sensitivity of attenuation changes measurement, which enables the detection of mechanical stresses existing in the optical fiber that can result in fiber breaking.