8. GUIDED WAVE CHANNELS

Since wireless transmissions allow to use the radio channels for telephone communications in reasonable cases only (mobile telephones are such an exception), the telephone communication is carried mostly by guided waves i.e. cable connections. The whole world is covered by telecommunication network. Technical product of such a great complexity can operate only under uniform technical specifications. Such a set of specifications is defined and regularly updated by the CCITT. The goal of the present chapter is to give insight to the wave propagation modes used for the wirebound connections and to present some of the requirements and procedures specified by the CCITT recommendations. For more detailed studies, the reader is referred to the information given in the References.

8.1. Specification of the Signal Transmission

The method used for the transmission depends to a great extent on the properties of the signal to be transmitted. In today's communication a great variety of signals (speech, music, steady picture, moving picture, text, data, communication software), signals necessary for the control of the telephone exchanges (e.g. dialling) and feeding current of remote power supplies (e.g. for microphones) are transmitted. At the beginning, separated telecommunication networks were developed for the transmission of the different signals. In the last decades, these services are undergoing integration on different levels.

Besides the above signals, transmission techniques includes also the transmission of multiplexed signals created for the more efficient (multiple) usage of the line. Multiplexing procedures are discussed in Chapter 13. The essential consequence of the multiplexing is the increase of the bandwidth of the transmitted signals, proportionally to the extent of the multiplexing.

The telephone service as the means of speech transmission is of greatest importance. When a speech transmission is specified, it has to be kept in mind that the communication is being performed between two human brains and that the microphone and the receiver are positioned a few centimeters apart from the mouse and from the ear. The essential aim of the speech transmission is to maintain speech intelligibility at a 95...97 per cent level while other signal parameters are of minor importance, e.g. the recognition of the speaker is not necessary. Requirements for the signal transmission have been derived from the results of the subjective tests carried out for this purpose (see Table 8.1.).

Table 8.1 Main Parameters of Speech Transmission

Equivalent acoustic attenuation	30-40 dB
Signal-to-noise ratio	10-20 dB
Signal-to-crosstalk or echo	25-35 dB
Frequency range	300-3400Hz
Attenuation ripples in the range	2-15dB
Delay (for duplex connection)	250ms
Time-dependent ripple of the delay	±30ms
Envelope delay as a function of frequency	±30-60 ms
Phase shift	indifferent

8.2. Transmission by TEM Waveguides

8.2.1. Duplex Telephone Connection

The block diagram of a bidirectional duplex audio frequency telephone connection is shown in Fig. 8.1. The connection is terminated by 2-wire sections with repeaters while the middle part consists of 4-wire sections with repeaters. The reason of this arrangement is a complex technical and economical problem which will be explained in this chapter.

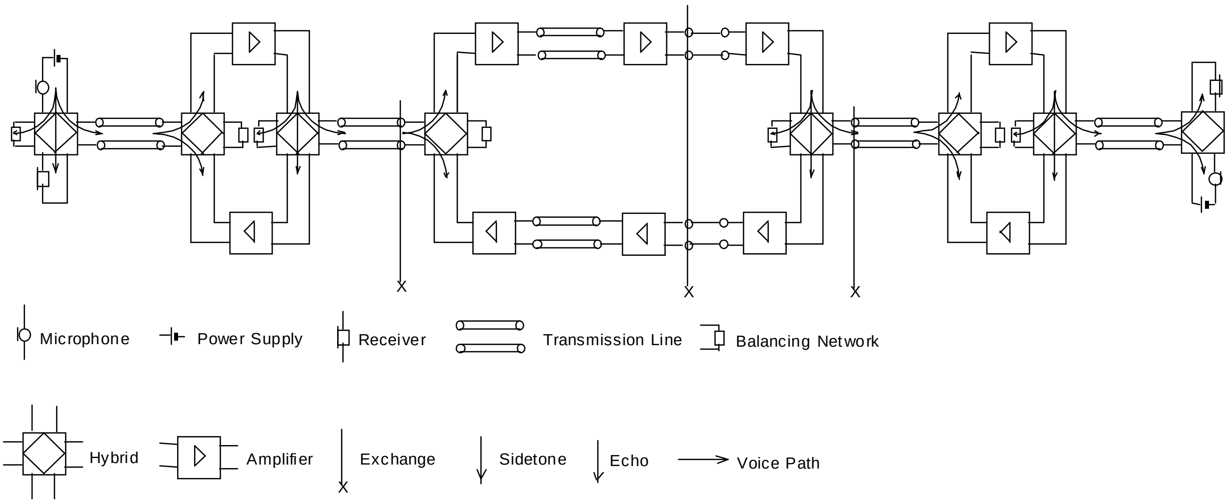


Figure 8.1. Duplex Audio Frequency Connection with Hybrids

The 2-wire sections are transformed to 4-wire sections by means of the so-called hybrid. A hybrid is a circuit with four ports. The input signal put at one of the ports is passed to the two neighbouring ports in such a way that the signal power is halved while there is no output at the port opposite to the input, provided the neighbour ports are terminated by the same impedance (see Fig. 8.2.a). Following each transformation, the signal is attenuated theoretically by 3 dB. Since the elements of the hybrid are not ideal, the total attenuation is about 3.5 dB as shown in Fig. 8.2.b.

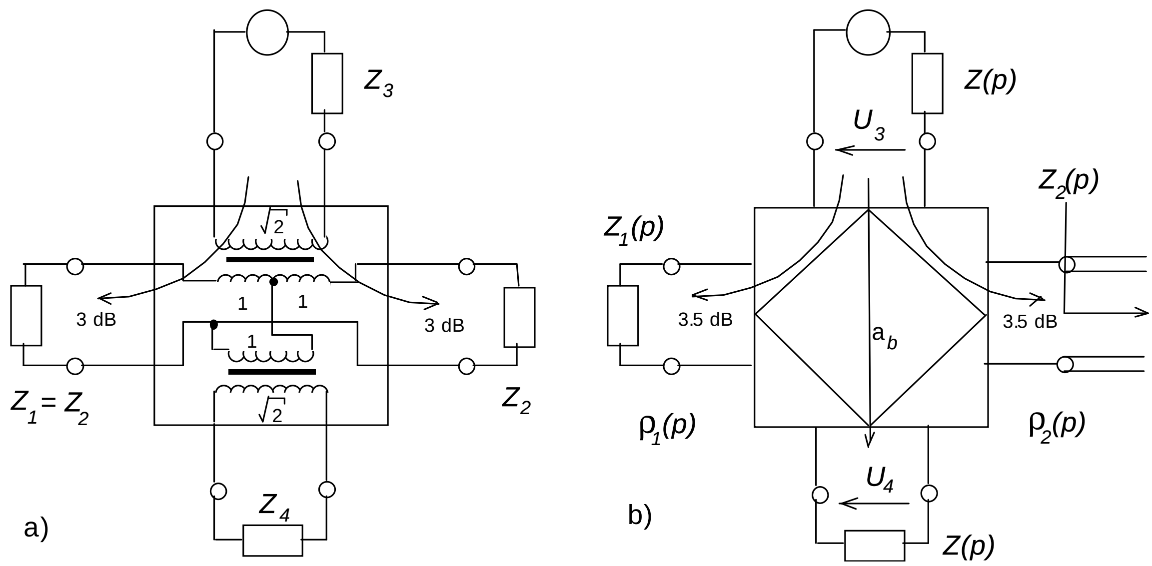


Figure 8.2 Power Distribution of an Ideal (a) and a Real (b) Hybrid

In the actual circuit the hybrid is terminated by a pair of amplifiers, input and output impedance of which being of the same value $Z(p)$. The transmission line has a frequency dependent wave impedance $Z_2(p)$ which is approximated by the balancing impedance $Z_1(p)$. As the consequence of the mismatch, the insertion loss undergoes a change but this is so small that we may still calculate with the 3.5 dB value. A certain amount of the signal, however, reaches also the opposite port producing thus an echo. The relative magnitude of this signal can be characterized by the backward attenuation a_b:

$$a_b(\omega) = 20\lg|U_3(j\omega)/U_4(j\omega)| = 7\text{dB} - 20\lg|r_2(j\omega) - r_1(j\omega)| \qquad (8.1)$$

where r_1 and r_2 are the reflection coefficients of the two-ports:

$$\rho_i(p) = [Z_i(p) - Z(p)][Z_i(p) + Z(p)]^{-1},\ i = 1, 2,\ |\rho_i(p)| \le 1 \qquad (8.2)$$

The practical value of a_b is about 20-25 dB.

8.2.2. Structure of the TEM Waveguides

TEM waveguides consist of two metal conductors and a dielectric insulator between them. The distance of the conductors is small compared to the signal wavelength. In such waveguides only the TEM (transversal electromagnetic) base mode is present. Three different constructions are used as TEM waveguides:

1.) The so called *aerial line* is a pair of bronze wires mounted on telegraph poles. Due to the open structure, crosstalk with radio broadcasting limits the maximum usable frequency at 150 kHz (see Fig. 8.3.). The crosstalk between the aerial lines is reduced by regular swap of the two wires and by symmetrical line transformers.

2.) The symmetrical cable consists of two or four copper wires separated by an insulator. Flat cables, as well as aerial lines are used especially in the subscriber circuits. Twisted pair and star-quad cables are used in the 2-wire and 4-wire audio frequency circuits and in multiplex sections. The electromagnetic field of the symmetrical cable is more closed but crosstalk between such cables may occur by electromagnetic coupling if the cables are near to each other. This crosstalk can be compensated up to 600 kHz. In the case of a *single* symmetrical cable, the crosstalk is negligible and the maximum usable frequency is limited by the attenuation at 5 MHz (see Fig. 8.3.).

3.) The coaxial cable consists of two concentric conductors. The central wire is separated from the cylindrical outer shielding conductor by a cylindrical spacing layer of insulation. Coaxial cables cannot be used at frequencies lower than 60 kHz since the penetration depth of the electromagnetic waves propagating inside the cable reaches the thickness of the shielding tube which can be economically manufactured. The upper frequency is limited by the attenuation at 60 MHz (see Fig. 8.3.). Coaxial cables are used in multiplex connections.

In practice, common cables are made of the symmetrical and the coaxial cable, sheath of which consists of a metal-plastic-bitumen composition. The factory length of the air, terrestrial, river and undersea cables is about 1 km. The cables are wound on a drum.

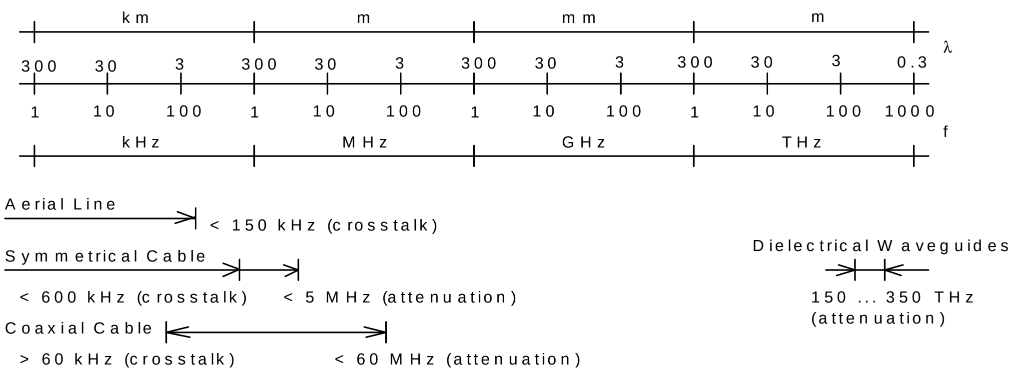


Figure 8.3. Frequency Range of the Waveguides Used in Telecommunication

8.2.3. Transmission Model of TEM Waveguides

TEM waveguides can be modelled by the transmission line. A section of such a line is characterized by the wave impedance $Z_0(p)$ and the propagation constant $\gamma(p)$. At the input the line is terminated by the generator impedance $Z_1(p)$ and at the output by the loading impedance $Z_2(p)$. Substituting $Z(p)=Z_0(p)$ into equation (8.2), $\rho_i(p)$ can be computed. If $Z_i(p)=Z_0(p)$ then $\rho_i(p) = 0$ so that voltages $U_i(p)$ are transmitted without reflection:

$$U_2(jw) = U_1(jw)\, e^{-g(jw)l} = U_1(jw)\, e^{-[a(w)+jb(w)]l} \qquad (8.3)$$

where $a(\omega)$ is the wave attenuation constant and $\beta(\omega)$ is the phase shift constant:

$$a(w) = l \cdot a(w) \ \ and \ \ b(w) = l \cdot b(w) \qquad (8.4)$$

Another essential transmission parameter is the delay. Suppose that a modulated signal (see chapter 11) is transmitted with carrier frequency w_O so that $b(w)$ is constant within the passband range $w_1...w_2$. The modulation content (e.g. the envelope) will therefore be delayed by T_c, remains, however, undistorted while the carrier will be phase-shifted by T:

$$T_g = t_g(w_o),\ \ t_g(w) = db(w)/dw = l\ db(w)/dw = l/v_g(w) \qquad (8.5)$$

$$T_p = t_p(w_o),\ \ t_p(w) = b(w)/dw = l\ b(w)/dw = l/v_p(w) \qquad (8.6)$$

where $\tau_g(\omega)$ and $\tau_p(\omega)$ are the group and the phase delays, respectively, while $v_g(w)$ and $v_p(\omega)$ are the group and the phase velocities. It follows from Table 8.1. that the above $b(w)$ is suitable for speech transmission if $w_1 \leq 300$ Hz and $w_2 \geq 3400$ Hz.

$Z_0(p)$ and $\gamma(p)$ can be derived from R [Ω/km], G [S/km], L [H/km] and C [F/km] parameters of the TEM waveguides which are given for the unity of the length. At extreme frequencies the following approximate relations are valid:

$$a(w)\big|_{w\to 0} \approx \sqrt{RG}, \qquad a(w)\big|_{w\to\infty} \approx Q\sqrt{RG}, \qquad (8.7)$$

$$b(w)\big|_{w\to 0} \approx wQ\sqrt{LC}, \quad b(w)\big|_{w\to\infty} \approx w\sqrt{LC}, \qquad (8.8)$$

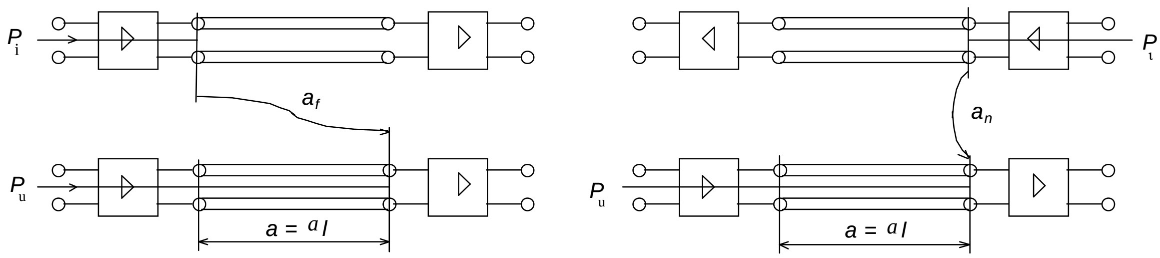
$$Q = \frac{1}{2}\left(\sqrt{\frac{RC}{GL}} + \sqrt{\frac{GL}{RC}}\right) \geq 1, \quad Z_0(w)\big|_{w\to\infty} \approx \sqrt{\frac{L}{C}} \qquad (8.9)$$

In the whole frequency range (0...∞) the attenuation is directly proportional while the delay is inversely proportional to the value of Q, typical value of which is about 8 to 30 for TEM waveguides. In accordance with Table 8.1., this is favourable since the specification for the delay should be fulfilled for long-haul connections as well, while the attenuation can be compensated by amplifiers. For the different TEM waveguides the value of α is in the range from 0.03 to 4 dB/km.

8.2.4. Amplification of Audio Signals

The distance which has to be bridged over by wire connection is divided into amplified sections. The length of such sections is limited essentially by the near-end crosstalk. The near and the far-end crosstalks are defined by the direction of the signals (same or opposite) propagating on the two neighbouring wires as shown in Fig. 8.4. The useful power is denoted here as P_u and the power of the interfering signal as P_i, a_n and a_f are the near and the far-end crosstalk attenuations, K denotes the crosstalk protection factor. If a_k, α and K are given, l can be calculated.

Far End Crosstalk: Near End Crosstalk:



$K = a_f - al$, dB $K = a_n - al$, dB

Figure 8.4. Crosstalk Between Amplified Sections

Attenuations a_1 and a_2 of the 4-wire circuits shown in Fig. 8.1. are measured from left to right and from right to left, respectively, at the 2-wire terminals of the two hybrids. The attenuation of two 4-wire circuits is then a_1-7 and a_2-7 dB. If, however, during the operation of the exchanges the hybrids are temporarily terminated by open circuits then their attenuation will be 7 dB in accordance with equation 8.1. and 8.2. Let a_l denote the loop attenuation of the 4-wire circuit terminated by open circuits. The sufficient condition of stability is $a_l > 0$ dB. This condition can be interpreted also as $a_l/2 > 0$ dB resulting in value being close to attenuations a_1 and a_2:

$$\frac{a_l}{2} = \frac{a_1 - 7 + 7 + a_2 - 7 + 7}{2} = \frac{a_1 + a_2}{2} \quad [\mathrm{dB}] \tag{8.10}$$

i.e. if $a_1 = a_2 = a$ then $a_l/2 = a$. New circuits are designed with $a_l/2 = 7$ dB. The attenuation of the branches are 0 dB in this case, just compensating the attenuation of the cables thus arbitrary long distance can be bridged by the 4-wire amplified circuit.

Although 4-wire circuits are more expensive than the 2-wire ones, they are reasonable anyway since being used as trunk lines between two exchanges they serve many users. This feature is less effective at the ends of the connection therefore amplified 2-wire circuits are used there. The distance achievable by 2-wire circuits is strongly limited, however, because 2-wire amplifiers introduce additional loops into the system which can interact and thus degrade the stability of the system. Therefore the number of the loops should not be greater than three in the whole system.

Besides feedback, the finite attenuation of the hybrid causes echo, as well. The greater the delay, the more disturbing the echo is. The echoes of the 4-wire circuits are important since they do not have attenuation even for long lengths. For this reason, certain attenuation has to be allowed in long-haul communications or another solution has to be found to reduce the echo.

8.3. Transmission by Dielectric Waveguides

8.3.1. Principle of Dielectric Waveguides

Observing the light propagation in a glass fibre with high optical purity, $\alpha = 0.2$ dB/km minimum attenuation can be found in the frequency range between the infrared and the visible light. There is a 54 THz wide range between 1.3 and 1.7 μm where the attenuation does not exceed 0.5 dB. Outside this range, the light interacts with the electrons of the glass which increases the attenuation. In the case of small contamination caused by moisture, attenuation peaks appear in the above range so that newer minima of attenuation are present at 0.85 and 1.3 μm with attenuation values 2.5 and 0.6 dB/km, respectively.

Optical fibres are of huge importance for today's telecommunication since the resources of the Earth could not cover the demand for copper in the case of further usage of TEM waveguides.

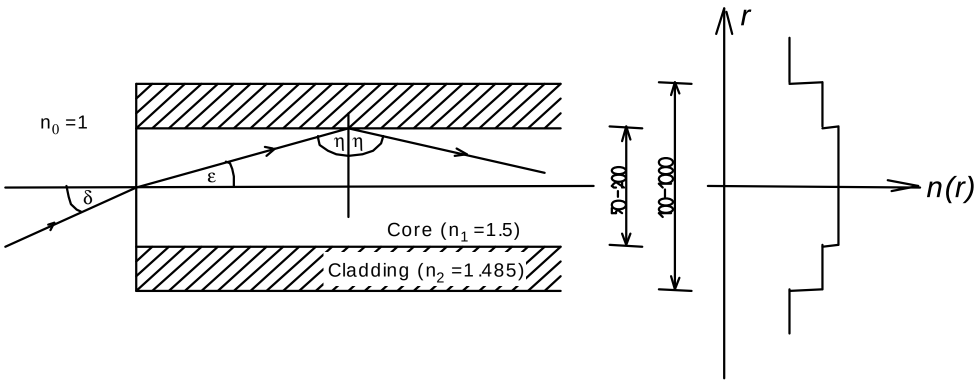


Figure 8.5. Step Index (SI) Optical Fibre

Glass fibre with homogeneous refraction index cannot be used as waveguide because of the dispersion. Surrounding, however, the glass core by a cladding with smaller refraction index as shown in Fig. 8.5., total reflection of the incoming rays can be achieved for sin $h \leq n_2/n_1$. *Numerical aperture* (*NA*) is the term used to define the maximum input angle δ_{max} for which the beam stays within the core:

$$NA = \sin \delta_{max} = n_1 \cdot \sin \varepsilon_{max} = n_1 \cdot \cos \eta_{min} = \sqrt{n_1^2 - n_2^2} \qquad (8.11)$$

8.3.2. Optical Transmitters and Receivers

The operation of light transmitters and detectors is based on the interaction of photons and electrons. For instance, semiconductor diodes are the devices operating under conditions providing such interaction. The main parameters of these devices are summarized in Tables 8.2 and 8.3. LD stands for Laser Diode, LED for Light Emitting Diode and APD for Avalanche Photo Diode.

Table 8.2 Main Parameters of Light Transmitters

Parameter	LED	LD
Emitted power	2 - 5 mW	15 - 20 mW
Incident loss	15 - 25 dB	3 dB
Middle of the band	0.8, 1.3, 1.55 μm	1.3, 1.55 μm
	350, 230, 200 THz	230, 200 THz
Unmodulated bandwidth	30 - 100 nm	0.5 - 5 nm
	10 - 30 THz	0.15 - 1.5 THz
Max. modulation freq.	50 - 100 MHz	3 - 20 GHz
Life expectancy	10^8 h	10^6 h

Table 8.3. Main Parameters of Light Detectors

Parameter	Si APD	Ge APD	In, GaAs	APD
Middle of the band $[\mu m]$	0.85	1.3	1.3	1.5
Max. modulation freq. GHz	0.15 - 1.5	0.5 - 2.5	0.5 - 4	0.5 – 2

Knowing the system specification, the proper device can be chosen. The light transmitters are strongly nonlinear, therefore impulse optical transmission (TDM) is mainly used for telecommunication.

8.3.3. Transmission Model of Dielectric Waveguides

The solution of the characteristic equation for electromagnetic field propagating in the SI optical fibre is shown in Fig. 8.6. Here *b* is the well known wave phase-shift constant, *c* is the free-space velocity of light, and the refraction indices are independent of frequency. There are only hybrid modes propagating along dielectric waveguides. The fundamental mode is propagating at all frequencies, the other modes are propagating above their own limit frequencies. If the free-space wave length is *l* then the number of modes having their limit frequency lower than $f = c/l$ is:

$$M \cong (\pi \cdot NA\ d/\lambda)^2 \ , \qquad \text{if} \quad M >> 1 \qquad (8.12)$$

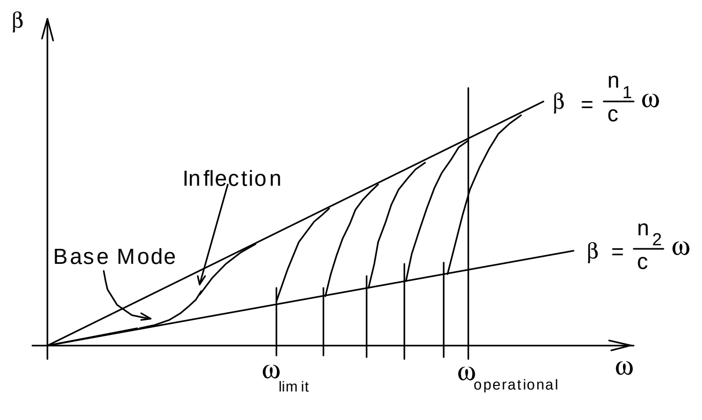


Figure 8.6. Characteristics of Propagating Modes

There are about 1000 modes propagating in SI fibres. The group delay of the individual modes at a working frequency is different (see Fig. 8.5.) which -according to equation (8.5.) results in mode dispersion of the received signal with group-delay difference $Dt_m = l\ (1/v_{gmin}$-

$1/v_{gmax}$). Supposing the received signal to be a Δt wide Gaussian impulse, at least Δt_m time should be left between two transmitted impulses. The corresponding bandwidth can be expressed as

$$B = 0.44/\Delta t \tag{8.13}$$

so that the mode dispersion can be characterized by the product $B_m \cdot l$:

$$B_m \cdot l = 0.44/(1/v_{gmin} - 1/v_{gmax}) = K, \tag{8.14}$$

where K is a constant characteristic for the fibre. Inhomogeneities of the fibre cause mode-coupling , however, which results in an experimental relation:

$$B_m \cdot l^{\zeta} = K \tag{8.15}$$

where $\zeta = 0.5...1$. The mode dispersion can be modelled by means of the geometrical optics showing that the propagation paths of the axial beam and that of the reflected beams are different.

Mode dispersion can be significantly reduced by using GI (Graded Index) fibres in which the refraction index is decreasing towards the outside of the fibre. The wave velocity in a GI fibre is increasing towards the outside so that the delay of beams with different propagation paths is balanced. The mode dispersion can be entirely eliminated if only the fundamental mode can propagate on the working frequency, i.e. if $p \cdot NA \cdot d/l < 2.4$. To achieve this mode, small d (5 to 10 µm) and small $n_1 - n_2$ (0.003 to 0.008) are needed.

Chromatic dispersion, however, is present even in the SM fibres. This is due to the values of unmodulated bandwidth Δw and wavelength Δl of the light sources (see Table 8.2) which are so large that the $b(w)$ of the fundamental mode cannot be considered flat. The $b(w)$ is curved even if $n(l)$ is constant (waveguide dispersion), in the inflexion point the curvature is zero (see Fig. 8.6.). What is more important for the curvature is that because of the influence of the light on the particles of the material of the fibre, the $n(l)$ is not constant but it has an inflexion at about 1.3 µm. In accordance with Fig. 8.5. this means that $b(w)$ would be curved even if the refraction index were of the same n_1 along the whole fibre.

As the result of the chromatic dispersion, the inflexion point of $\beta(\omega)$ can be found at about 1.3 µm. To make the analysis of the light emitting diode easier, its light is modelled by manifold of discrete carriers. The difference of the propagation delay of the maximum and the minimum carriers gives the chromatic dispersion $\Delta t = \Delta\lambda \cdot dt(l)/dl = \Delta l \cdot l \cdot D_c(l)$. Here, D_c is the chromatic dispersion

$$D_c(\lambda) = \frac{1}{l}\frac{dt(l)}{dl} = \frac{1}{l}\frac{dw}{dl}\frac{dt(w)}{dw} = -\frac{w^2}{2pc}\frac{d^2b(w)}{dw^2} \tag{8.16}$$

which becomes really zero in the inflexion point of the $\beta(\omega)$. Similarly to equation (8.14), chromatic dispersion can be characterized by the following equation:

$$B_c l = \frac{0.44}{\Delta l \left| D_c(l) \right|} \tag{8.17}$$

Finally, the total transmitted bandwidth is given by

$$B^{-2} = B_m^{-2} + B_c^{-2} + B_a^{-2} + B_v^{-2} \tag{8.18}$$

where B_a and B_v are the maximum modulation frequencies of the light transmitter and receiver, respectively. The attenuation and the dispersion determine a maximum usable length of a line section after which an impulse regenerator or the so-called repeater has to be inserted.

8.3.4. Structure of the Dielectric Waveguides

The fibre core and the cladding are made of glass compositions which are directly covered by a soft plastic sheath. The next layer is made of a hard plastic or it is a plastic tube filled with petroleum jelly. The cable consists of several such fibres, kevlar fibres (high-strength strategic plastic) and an additional plastic cover. There is also a pair of copper wire in the cable for the remote power supply of the repeaters. The factory length of the air, ground, river and marine cables is between 1 and 5 km and the cables are delivered wound on a drum. To produce longer cables, the factory-length sections are glued (a = 0.2 dB) or welded (a = 0.5 dB) to each other and protected by a muff. The fibre is connected to the transmitter and the receiver by a connector (a = 0.2 to 1 dB). The connector is mounted on some m long piece of fibre which is welded to the first section of the installed cable.

Exercises

1. What is the maximum length of a symmetrical cable without amplification if R = 54.3 Ω/km, G = 1 μs/km, L = 0.7 mH/km, C = 38.5 nF/km, K = 65 dB and a_n = 91 dB? (l = 14.9 km)
2. What is the maximum length of an optical cable between two repeaters if the data of the transmitter, cable, receiver, and channel are as follows:
   Light transmitter (LD): B_t = 1 GHz, λ = 1.3 μm, Δλ = 5 nm
   Optical cable (GI): $B_m(l$=1km) = 4.8 MHz, l = 1 km, ζ = 0.8, D_c =5 ps/(km nm), α = 0.8 dB/km, a_{conn} = 0.9 dB, a_{weld} = 0.15 dB
   Light receiver (Ge APD): B_r = 1 GHz
   Channel: B = 0.2 GHz, a = 45 dB (N = 42)

Control questions

1. What are the units of a, b and g in equation (8.3)?
2. What is the value of the attenuation determined by in the case of short and long 4-wire transmission?
3. What kind of dispersion is in an SI optical fibre?
4. Are there any metal parts in the optical cables?

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Notations

B	bandwidth	*a*	attenuation	α	attenuation constant
C	capacitance/km	*b*	phase shift	β	phase shift constant
D	dispersion factor	*c*	velocity of light	γ	propagation constant
G	reluctance/km	*e*	natural number	δ	angle
K	crosstalk immunity	*f*	frequency	ε	angle
L	inductance/km	*j*	imaginary unit	ζ	power of dispersion
M	number of modes	*l*	length of a section	η	angle
Q	quality factor	*n*	refraction index	λ	wavelength
R	resistance/km	*p*	complex frequency	Δλ	spectral width
T	delay	v	wave velocity	ρ	reflexion coefficient
U	voltage	τ	group delay	*Z*	impedance

Abbreviations

CCITT	International Telegraph and Telephone Consultative Committee
FDM	Frequency Division Multiplex
TDM	Time Division Multiplex
CDM	Code Division Multiplex
TEM	Transversal Electro-Magnetic
LW	Long Wave
MW	Medium Wave
SW	Short Wave
VHF	Very High Frequency
SI	Step Index
GI	Graded Index
SM	Laser Diode
APD	Avalanche Photo Diode