SRI MUTHUKUMARAN INSTITUTE OF TECHNOLOGY

(Approved by AICTE, Accredited by NBA and Affiliated to Anna University, Chennai)

Chikkarayapuram (Near Mangadu), Chennai- 600 069.

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

YEAR/SEM: III / V
SUBJECT CODE &NAME: CEC 345- OPTICAL COMMUNICATION NETWORKS

TWO MARKS QUESTIONS AND ANSWERS

UNIT II- Transmission Characteristics of Optical Fibers

1. **Differentiate linear scattering from non-linear scattering.**

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode. Non-linear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same or other modes at different frequencies.

2. **What are the types of material absorption losses in silica glass fibers?**

The types of material absorption losses in the glass composition are

- Absorption by impurity atoms in the glass material.
- Intrinsic absorption by the basic constituent atoms in the glass material.

3. **How do we minimize optical losses at the interface?**

Optical losses at the interface can be minimized if

- Jointed fiber ends are smooth
- Perpendicular to fiber axis
- Two fiber axes are perfectly aligned

4. **What is meant by attenuation coefficient of a fiber?**

If P(0) is the optical power in a fiber at the origin (at Z = 0), then the power P(Z) at a distance z further down the fiber is

$P (z) = P (0) e^{-\alpha_p z}$

The above equation can be rewritten as

$\alpha_p = (1 / z) \{ P(0) / P(z)\}$. Where α_p is the fiber attenuation coefficient given in units of km^{-1}

5. **What is meant by dispersion in optical fiber?**

Dispersion of the transmitted optical signal causes distortion in both analog and digital signals along optical fibers. Dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel.

6. **What are the ways to reduce macrobending losses?**

Ways to reduce macrobending losses are

- Designing fibers with large relative refractive index differences.
- Operating at the shortest wavelength possible.

7. **Define – Group Velocity Dispersion (GVD) .**

Intra-modal dispersion is pulse spreading that occurs within a single mode. The spreading arises from the finite spectral emission width of an optical source. This phenomenon is known as Group Velocity Dispersion.

8. What is meant by linear scattering?

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode.

9. What is intra Modal dispersion?

Intra Modal Dispersion is pulse spreading that occurs within a single mode. The spreading arises from finite spectral emission width of an optical source. This phenomenon is also called as group velocity dispersion.

10. Why intra modal dispersion occurs?

Intra modal dispersion occurs because colours of light travel through different materials and different waveguide structures at different speeds.

11. What are the causes of intra modal dispersion?

There are two main causes of intra modal dispersion.
They are

- Material Dispersion
- Waveguide Dispersion.

12. What is wave guide dispersion?

Wave guide dispersion occurs because of a single mode fiber confines only about 80% of optical power to the core. Dispersion arises since 20% of light propagates in cladding travels faster than the light confined to the core.

Amount of wave-guide dispersion depends on fiber design. Other factor for pulse spreading is inter modal delay.

13. Compare splices and connectors.

Splices	**Connectors**
Permanent or semipermanent joints	Temporary joints
Splice loss is low	Connector loss is high

14. Define- Polarization Maintaining Fiber? (PMF)

PMF is an optical fiber in which the polarization of linearly polarized light waves launched into the fiber is maintained during propagation, with less or no cross coupling of optical power between the polarizations modes. Such fiber is used in special application where processing the polarization is essential.

15. What is material dispersion?

Material dispersion arises from the variation of the refractive index of the core material as a function of wavelength. Material dispersion is also referred to as chromatic dispersion. This causes a wavelength dependence of group velocity of given mode.So it occurs because the index of refraction varies as a function of optical wavelength. Material dispersion is an intra modal dispersion effect and is for particular importance for single mode wave guide.

16. What is group velocity?

If L is the distance travelled by the pulse, β is the propagation constant along axis then ,the group velocity is the velocity at which energy is a pulse travels along the fiber.

$$V_g = C^* (d \beta / dk)$$

17. What is polarization?

Polarization is a fundamental property of an optical signal. It refers to the electric field orientation of a light signal which can vary significantly along the length of a fiber.

18. What is pulse broadening?

Dispersion induced signal distortion is that, a light pulse will broaden as it travels along the fiber. This pulse broadening causes a pulse to overlap with neighbouring pulses. After a time 't', the adjacent pulses can no longer be individually distinguished at the receiver and error will occur.

19. What is polarization mode dispersion (PMD)?

The difference in propagation times between the two orthogonal polarization modes will result pulse spreading. This is called as polarization mode dispersion. (PMD)

20. What is fiber birefringence?

Imperfections in the fiber are common such as symmetrical lateral stress, non circular imperfect variations of refractive index profile. These imperfections break the circular symmetry of ideal fiber and mode propagate with different phase velocity and the difference between their refractive index is called fiber birefringence.

21. What is mode coupling?

Mode coupling is another type of pulse distortion which is common in optical links. The pulse distortion will increase less rapidly after a certain initial length of fiber due to this mode coupling and differential mode losses. In initial length coupling of energy from one mode to another arises because of structural irregularities, fiber diameter etc.

and material dispersion can then be shifted to zero dispersion point to long wavelength. The resulting optical fiber are called as dispersion Shifted Fiber.

22. Define - Cut-off Wavelength of the fiber

The cut-off wavelength is defined as the minimum value of wavelength that can be transmitted through the fiber. The wavelengths greater than the cut-off wavelength can be transmitted.

23. Write a note on scattering losses.

Scattering losses in glass arise from microscopic variation in the material density from compositional fluctuation and from structural in-homogeneities or defects occurring during fiber manufacture.

24. What is intramodal delay?

The factor which gives rise to pulse spreading is called as intra-modal delay. It is a result of each mode having a different value of group velocity at a single frequency.

25. Mention the losses responsible for attenuation in optical fibers.

The losses which are responsible for attenuation in optical fibers are as follows

- Absorption losses
- Scattering losses
- Bending losses

26. What is the function of coupler? What are the different types of optical couplers?

A coupler is a device which is used to combine and split signals in an optical network..
Different types of couplers are

- Directional coupler
- Star coupler
- Fused fiber coupler
- 2 x 2 coupler

27. What are the requirements of good couplers?

The requirements of good couplers are

- Good optical couplers should have low insertion losses.
- Insensitive to temperature
- Good optical couplers should have low polarization-dependent loss.
- Reliability

28. What is intermodal dispersion?

Intermodal dispersion is a pulse spreading that occurs within a single mode. The spreading arises from finite spectral emission width of an optical source. It is called as group velocity dispersion or intermodal dispersion.

29. Define - Microscopic Bending

Fiber losses occur due to small bending arise while the fiber is inserted into a cable is known as Microscopic Bending.

30. Write Short notes on Scattering losses.

Scattering losses caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas light is then partially scattered in all directions.

31. What is Rayleigh scattering?

The index variation causes a Rayleigh type of scattering of light.

Rayleigh scattering in glass in the same phenomenon that scatters light from sun in the atmosphere, giving rise to blue sky.

32. Write the expression for Rayleigh Scattering Loss. The
expression for Rayleigh Scattering loss is given by $\alpha_{scat} = (8\pi^3/3\lambda^2)$
$(n^2 - 1)^2 k_B\, T_f\, \beta_T$
where n= refractive index k_B =
Boltzman constant T_f = fictive
temperature
β_T = isothermal compressibility
λ = operative wavelength

33. When will Rayleigh Scattering Occurs?

Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions. Rayleigh scattering occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light.

34. What do you mean by fiber optic coupler?

A **fiber optic coupler** is a device used in optical fiber systems with one or more input fibers and one or several output fibers. Light entering an input fiber can appear at one or more outputs and its power distribution potentially depending on the wavelength and polarization.

35. What do you mean by fiber optic connectors?

An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass. Better connectors lose very little light due to reflection or misalignment of the fibers. In all, about 100 fiber optic connectors have been introduced to the market.

36. List the features of optical connectors. The

features of good connector are:

- Low insertion loss
- Low cost and low environmental sensitivity
- Reliability
- High return loss (*low* amounts of reflection at the interface)
- Ease of use
- Ease of installation

37. What is the need for fiber alignment?

Fiber optic sensors constitute the core of telecommunication markets as well as being important part of automotive and industrial applications. With the recent renewed growth and technology advances in fiber optics, there is an increasing need for automating photonics alignment.

38. What do you mean by micro-bend Losses?

Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled.Microbend losses are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase micro-bend loss. External forces are also a source of micro- bends.

39. List the two major categories of fiber joints.

The two major categories of fiber joints are

- Fiber splices
- Fiber connectors

40. What are splices?

The splices are generally permanent fiber joints, whereas connectors are temporary fiber joints. Splicing is a sort of soldering.

41. What are the requirements of splices?

The requirements of splices are

- Should be easy to install
- Should have minimum power loss
- Should be strong and light in weight
- Should cause low attenuation.

42. What are the methods of fiber splicing?

There are three methods of fiber splicing. They are :

- Electric arc fusion splicing or fusion splicing
- Mechanical splicing
- V-groove splicing or loose tube splicing.

PART – B

1. Clearly bring out the differences between intra and intermodal dispersion.

Chromatic or intramodal dispersion : It may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

1. Material dispersion :

Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is saidto exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

2. Waveguide dispersion :

The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times forthe rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when d2β/d🍃2!=0. Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns/ km).However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

Intermodal dispersion :

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes. This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber.

Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening.

However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers.

Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of100). Thus graded index fibers used with a multimode source give a tremendous bandwidth advantage over multimode step index fibers. Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion mechanisms. In theory, this is the case with single-mode step index fibers where only a single mode is allowed to propagate. Hence they exhibit the least pulse broadening and have the greatest possible bandwidths, but in general are only usefully operated with single-mode sources.

In order to obtain a simple comparison for intermodal pulse broadening between multimode step index and multimode graded index fibers, it is useful to consider the geometric optics picture for the two types of fiber.

2. **Compare linear and non-linear scattering losses in optical fibers.**

a) **Linear scattering** : This mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes, there is no change of frequency on scattering.

Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the nonideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at present.

1.Rayleigh scattering :

Rayleigh scattering is the dominant intrinsic loss mechanism in the low-absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with wavelength.

These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing-in of density inhomogeneities are fundamental and cannot be avoided.

The subsequent scattering due to the density fluctuations, which is in almost all directions, produces an attenuation proportional to 1/λ4 following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \qquad (2.4)$$

where γR is the Rayleigh scattering coefficient, λ is the optical wavelength, n is the refractive index of the medium, p is the average photoelastic coefficient, βc is the isothermal compressibility at a fictive temperature TF, and K is Boltzmann’s constant. The fictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature. Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber following the relation:

where L is the length of the fiber. It is apparent from Eq. (2.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

$$\mathscr{L} = \exp(-\gamma_R L) \qquad (2.5)$$

2.Mie scattering :

Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength. These result from the nonperfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core– cladding interface, core–cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than λ/10, the scattered intensity which has an angular dependence can be very large.

The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses. The inhomogeneities may be reduced by:

✓removing imperfections due to the glass manufacturing process;

✓carefully controlled extrusion and coating of the fiber;

✓increasing the fiber guidance by increasing the relative refractive index difference.

b) Nonlinear scattering losses :

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several onlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels.

This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels.

The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers. These scattering mechanisms in fact give optical gain but with a shift in frequency, thus contributing to attenuation for light transmission at a specific wavelength. However, it may be noted that such nonlinear phenomena can also be used to give optical amplification in the context of integrated optical techniques

1. **Stimulated Brillouin Scattering :**

Stimulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber. The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon* of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength.

The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, making SBS a mainly backward process. As indicated previously, Brillouin scattering is only significant above a threshold power density. Assuming that the polarization state of the transmitted light is not maintained, it may be shown that the threshold power PB is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts} \qquad (2.6)$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, αdB is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in Eq. (2.6) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.

2. **Stimulated Raman scattering :**

Stimulated Raman scattering (SRS) is similar to SBS except that a high-frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also, SRS can occur in both the forward and backward directions in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber.

Using the same criteria as those specified for the Brillouin scattering threshold given in Eq. (2.6), it may be shown that the threshold optical power for SRS PR in a long single- mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts} \qquad (2.7)$$

3. Explain the various types of dispersion mechanisms and factors contributing to signal distortion.

Dispersion :

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. When considering the major implementation of optical fiber transmission which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. The phenomenon is illustrated in Figure, where it may be observed that each pulse broadens and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. The effect is known as intersymbol interference (ISI). Thus an increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced. The error rate is also a function of the signal attenuation on the link and the subsequent signal-to-noise ratio (SNR) at the receiver.

For no overlapping of light pulses down on an optical fiber link the digital bit rate *B*T must be less than the reciprocal of the broadened (through dispersion) pulse duration .

Hence:

$$B_T \leq \frac{1}{2\tau} \qquad (2.10)$$

The conversion of bit rate to bandwidth in hertz depends on the digital coding format used. For metallic conductors when a nonreturn-to-zero code is employed, the binary 1 level is held for the whole bit period τ. In this case there are two bit periods in one

wavelength (i.e. 2 bits per second per hertz), as illustrated in Figure 2.8(a). Hence the maximum bandwidth *B* is one-half the maximum data rate or:

$$B_T(\text{max}) = 2B \qquad (2.12)$$

However, when a return-to-zero code is considered, as shown in Figure 2.8(b), the binary 1 level

is held for only part (usually half) of the bit period. For this signaling scheme the data rate is

equal to the bandwidth in hertz (i.e. 1 bit per second per hertz) and thus *B*T = *B*.

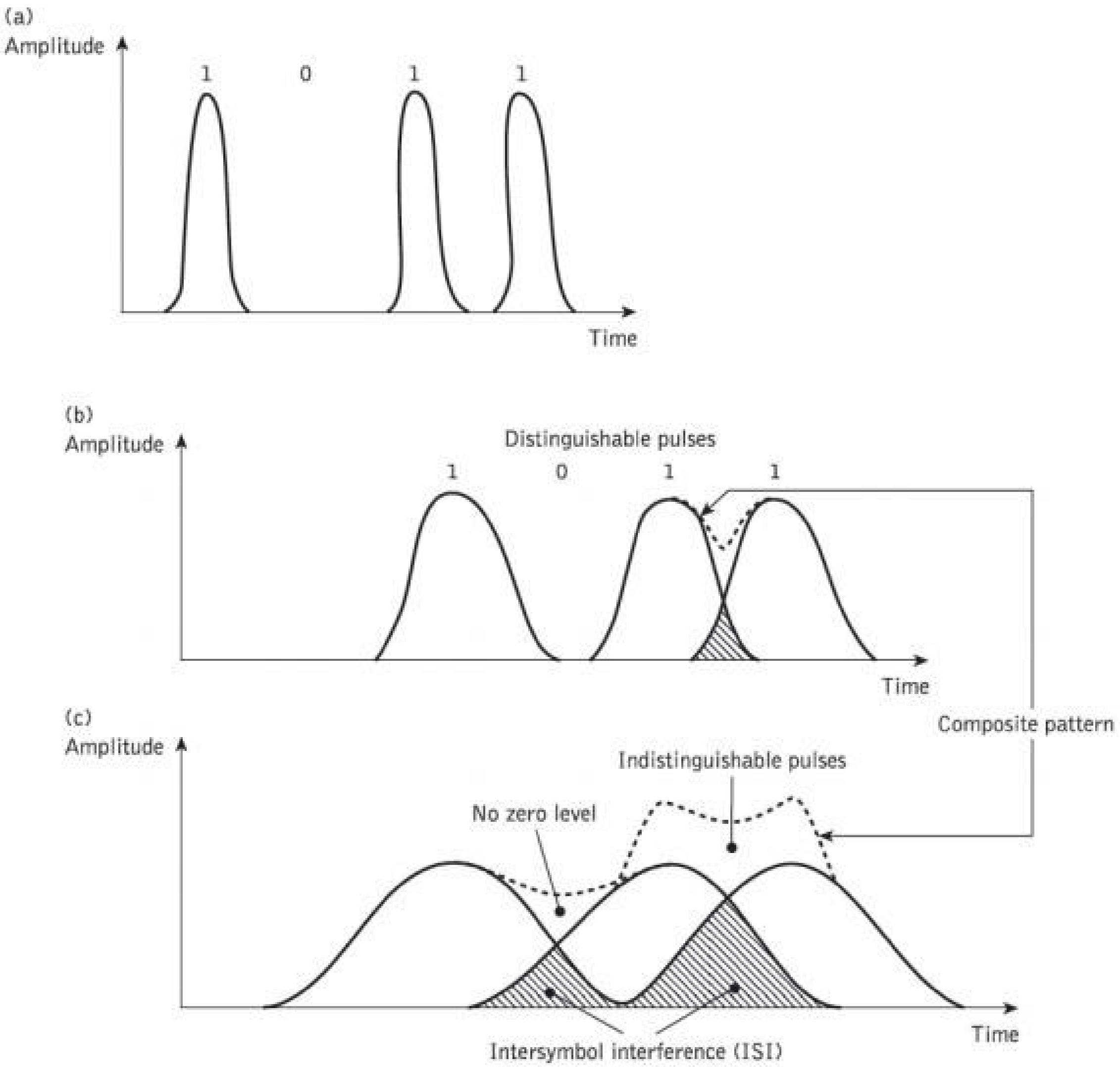

Figure 2.7 An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance $L1$; (c) fiber output at a distance $L2 > L1$

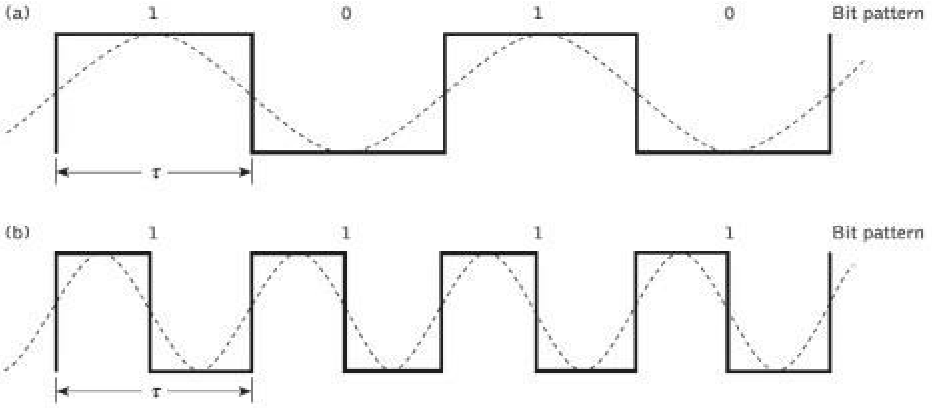

Figure 2.8 Schematic illustration of the relationships of the bit rate to wavelength for digital codes: (a) nonreturn-to-zero (NRZ); (b) return-to-zero (RZ)

The bandwidth *B* for metallic conductors is also usually defined by the electrical 3 Db points (i.e.

the frequencies at which the electric power has dropped to one-half of its constant maximum value). However, when the 3 dB optical bandwidth of a fiber is considered it is significantly larger than the corresponding 3 dB electrical bandwidth. Hence, when the limitations in the bandwidth of a fiber due to dispersion are stated (i.e. optical bandwidth *B*opt), it is usually with regard to a return to zero code where the bandwidth in hertz is considered equal to the digital bit rate. Within the context of dispersion the bandwidths expressed in this chapter will follow this general criterion unless otherwise stated.

When electro-optic devices and optical fiber systems are considered it is more usual to statethe electrical 3 dB bandwidth, this being the more useful measurement when interfacing an optical fiber link to electrical terminal equipment.

a)Intramodal Dispersion :

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure.

1.Material dispersion :

Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

Hence the group delay is given by:

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \tag{2.13}$$

$$\tau_m = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \tag{2.14}$$

Where *n*1 is the refractive index of the core material. The pulse delay 🔀m due to material dispersion in a fiber of length *L* is therefore:

For a source with rms spectral width and a mean wavelength, the rms pulse broadening due to material dispersion 📅m may be obtained from the expansion of Eq. (2.14) in a

Taylor series about where:

$$\sigma_m \simeq \sigma_\lambda \frac{d\tau_m}{d\lambda} \qquad (2.16)$$

As the first term in Eq. (2.15) usually dominates, especially for sources operating over the 0.8 to 0.9 μm wavelength range, then:

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c}\left[\frac{dn_1}{d\lambda} - \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right]$$

$$= \frac{-L\lambda}{c}\frac{d^2n_1}{d\lambda^2} \qquad (2.17)$$

Hence the pulse spread may be evaluated by considering the dependence of m on , where from Eq. (2.14):

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2n_1}{d\lambda^2}\right| \qquad (2.18)$$

The material dispersion for optical fibers is sometimes quoted as a value for $|\lambda^2(d^2n_1/d\lambda^2)|$ or simply $|d^2n_1/d\lambda^2|$.

However, it may be given in terms of a material dispersion parameter M which is defined as:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| \qquad (2.19)$$

and which is often expressed in units of ps nm−1 km−1.

Therefore, substituting the expression obtained in Eq. (2.17) into Eq. (2.16), the rms pulse broadening due to material dispersion is given by:

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{2d^2\tau_m}{d\lambda^2} + \dots \qquad (2.15)$$

2.Waveguide dispersion :

The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when d2β/d❧2!=0 . Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns/ km).

However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

b) Intermodal dispersion :

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes.

This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber. Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers.

Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of 100). Thus graded index fibers used with a multimode source give a tremendous bandwidth advantage over multimode step index fibers. Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion mechanisms. In theory, this is the case with single-mode step index fibers where only a single mode is allowed to propagate. Hence they exhibit the least pulse broadening and have the greatest possible bandwidths, but in general are only usefully operated with single-mode sources.

In order to obtain a simple comparison for intermodal pulse broadening between multimode step index and multimode graded index fibers, it is useful to consider the geometric optics picture for the two types of fiber.

4. Describe the attenuation mechanisms in optical fiber.

Attenuation :

The attenuation or transmission loss of optical fibers has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determined the maximum transmission distance prior to signal restoration, optical fiber communications became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5 dB km−1).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the decibel. The decibel, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power *P*i into a fiber to the output (received) optical power *P*o from the fiber as:

$$\text{Number of decibels (dB)} = 10 \log_{10} \frac{P_i}{P_o} \tag{2.1}$$

This logarithmic unit has the advantage that the operations of multiplication and division reduce to addition and subtraction, while powers and roots reduce to multiplication and division. However, addition and subtraction require a conversion to numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(\text{dB}/10)} \tag{2.2}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB km−1) following:

$$\alpha_{\text{dB}} L = 10 \log_{10} \frac{P_i}{P_o} \tag{2.3}$$

where αdB is the signal attenuation per unit length in decibels which is also referred to as the fiber loss parameter and L is the fiber length. A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are influenced by the material composition, the preparation and purification technique, and the waveguide structure. They may be categorized within several major areas which include material absorption, material scattering (linear and nonlinear scattering), curve and microbending losses, mode coupling radiation losses and losses due to leaky modes.

Material absorption losses in silica glass fibers

Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

1. **Intrinsic absorption**

An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region. However, it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 μm wavelength range, as illustrated in Figure 2.1, which shows a possible optical attenuation against wavelength characteristic for absolutely pure glass.

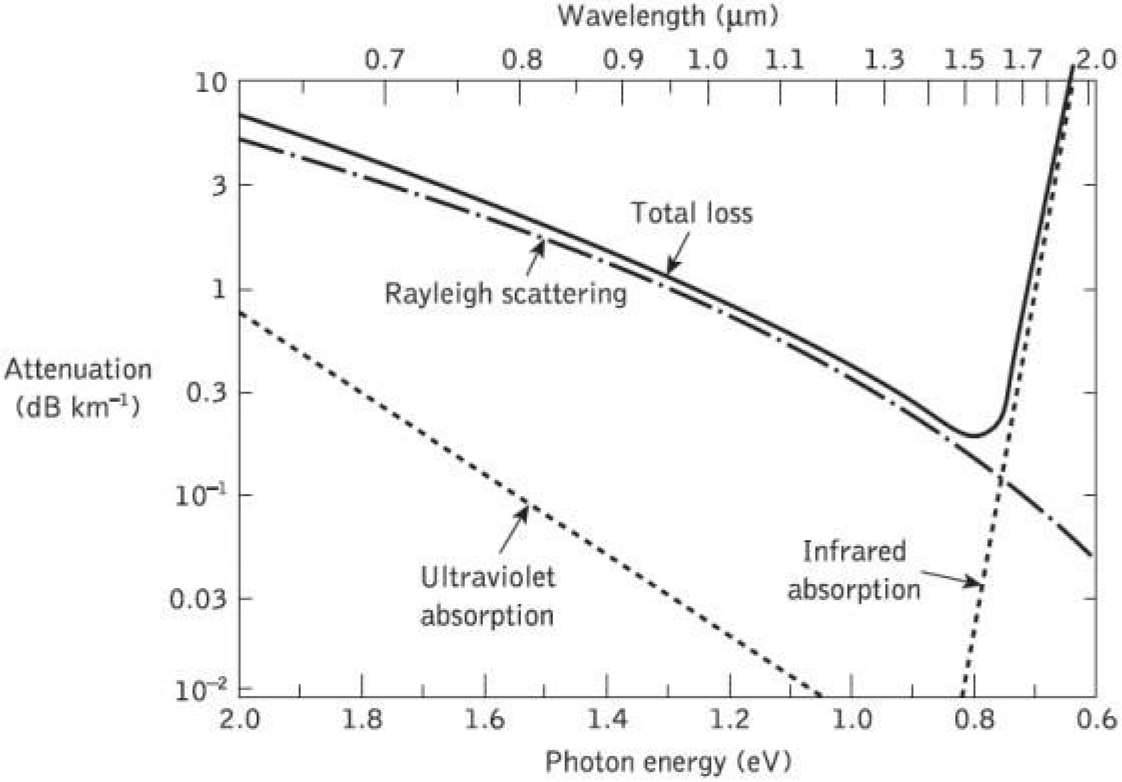

Figure 2.1 The attenuation spectra for the intrinsic loss mechanisms in pure GeO2–SiO2 glass

It may be observed that there is a fundamental absorption edge, the peaks of which are centered in the ultraviolet wavelength region. This is due to the stimulation of electron transitions within the glass by higher energy excitations.

The tail of this peak may extend into the window region at the shorter wavelengths, as illustrated in Figure 2.1. Also in the infrared and far infrared, normally at wavelengths above 7 μm, fundamentals of absorption bands from the interaction of photons with molecular vibrations within the glass occur.

These give absorption peaks which again extend into the window region. The strong absorption bands occur due to oscillations of structural units such as Si–O (9.2 µm), P– O (8.1 µm), B–O (7.2 µm) and Ge–O (11.0µm) within the glass. Hence, above 1.5 µm the tails of these largely far-infrared absorption peaks tend to cause most of the pure glass losses.

However, the effects of both these processes may be minimized by suitable choice of both core and cladding compositions. For instance, in some non oxide glasses such as fluorides and chlorides, the infrared absorption peaks occur at much longer wavelengths which are well into the far infrared (up to 50 µm), giving less attenuation to longer wavelength transmission compared with oxide glasses.

2. **Extrinsic absorption**

In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption from transition metal element impurities.

Some of the more common metallic impurities found in glasses are shown in the Table 2.1, together with the absorption losses caused by one part in 109

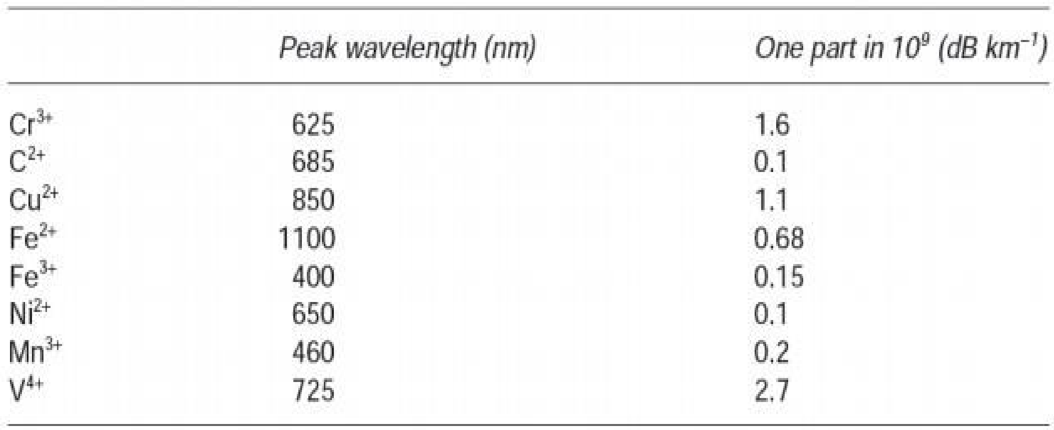

Table 2.1 Absorption losses caused by some of the more common metallic ionimpurities in glasses, together with the absorption peak wavelength

	Peak wavelength (nm)	*One part in 10^9 (dB km^{-1})*
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

It may be noted that certain of these impurities, namely chromium and copper, in their worst valence state can cause attenuation in excess of 1 dB km−1 in the near-infrared region. Transition element contamination may be reduced to acceptable levels (i.e. one part in 1010) by glass refining techniques such as vapor-phase oxidation, which largely eliminates the effects of these metallic impurities.

However, another major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH ion) dissolved in the glass. These hydroxyl groups are bonded into the glass structure and have fundamental stretching vibrations which occur at wavelengths between 2.7 and 4.2μm depending on group position in the glass network. The fundamental vibrations give rise to overtones appearing almost harmonically at 1.38, 0.95 and 0.72 μm, as illustrated in Figure 2.2. This shows the absorption spectrum for the hydroxyl group in silica.

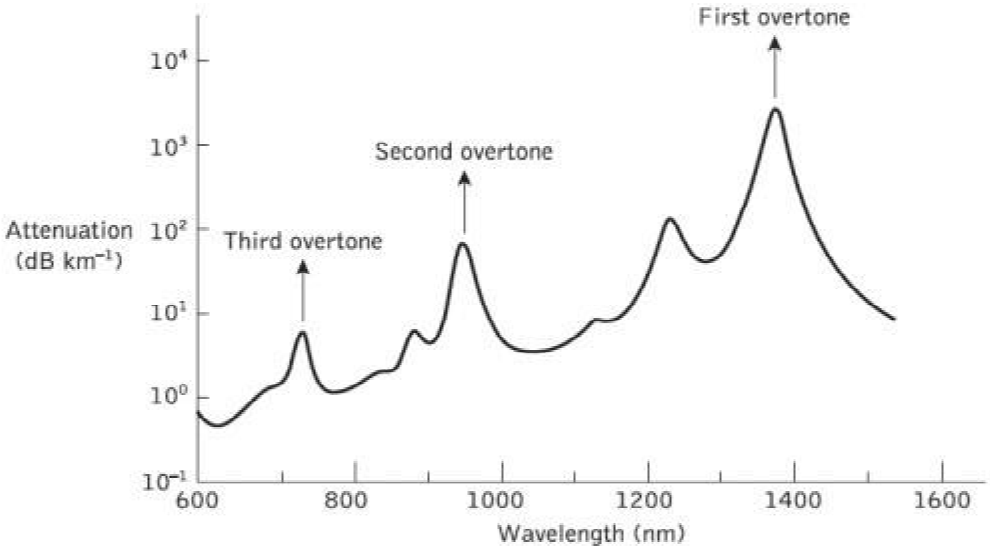

Figure 2.2 The absorption spectrum for the hydroxyl (OH) group in silica.

Furthermore, combinations between the overtones and the fundamental SiO2 vibration occur at 1.24, 1.13 and 0.88 μm, completing the absorption spectrum shown in Figure 2.2.It may also be observed in Figure 3.2 that the only significant absorption band in the region below a wavelength of

1 μm is the second overtone at 0.95 μm which causes attenuation of about 1 dB km−1 for one part per million (ppm) of hydroxyl.

5. Explain Multimode Stepindex fiber with all its diagrams and equations.

Multimode step index fiber :

Using the ray theory model, the fastest and slowest modes propagating in the step index fiber may be represented by the axial ray and the extreme meridional ray (which is incident at the core–cladding interface at the critical angle φc) respectively. The paths taken by these two rays in a perfectly structured step index fiber are shown in Figure 2.9. The delay difference between these two rays when traveling in the fiber core allows estimation of the pulse broadening resulting from intermodal dispersion within the fiber. As both rays are traveling at the same velocity within the constant refractive index fiber core, then the delay difference is directly related to their respective path lengths within the fiber. Hence the time taken for the axial ray to travel along a fiber of length L gives the minimum delay time TMin and:

$$T_{\mathrm{Min}} = \frac{\text{distance}}{\text{velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c} \tag{2.20}$$

where *n*1 is the refractive index of the core and *c* is the velocity of light in a vacuum. The extreme meridional ray exhibits the maximum delay time *T*Max where:

$$T_{\mathrm{Max}} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta} \tag{2.21}$$

Using Snell’s law of refraction at the core–cladding interface following Eq. (2.2):

$$\sin\phi_c = \frac{n_2}{n_1} = \cos\theta \tag{2.22}$$

where *n*2 is the refractive index of the cladding. Furthermore, substituting into Eq. (2.21) for cos⚠ gives:

$$T_{\mathrm{Max}} = \frac{Ln_1^2}{cn_2} \tag{2.23}$$

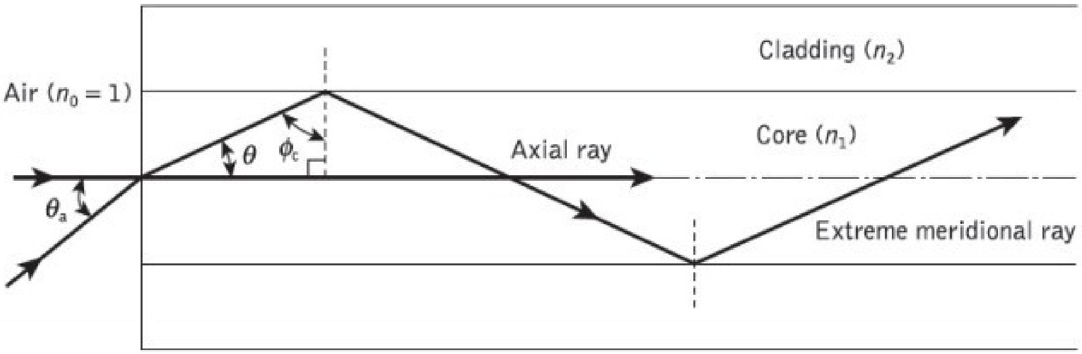

Figure 2.9 The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber

The delay difference ➦*T*s between the extreme meridional ray and the axial ray may be obtained by:

$$\begin{aligned}\delta T_s = T_{\mathrm{Max}} - T_{\mathrm{Min}} &= \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} \\ &= \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right) \end{aligned} \tag{2.24}$$

$$\simeq \frac{Ln_1^2\Delta}{cn_2} \quad \text{when } \Delta \ll 1 \tag{2.25}$$

where ° is the relative refractive index difference. However, when °<< 1, then from the definition given by Eq. (2.9), the relative refractive index difference may also be given approximately by:

$$\Delta \simeq \frac{n_1 - n_2}{n_2} \tag{2.26}$$

Hence rearranging Eq. (3.24):

$$\delta T_s = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{Ln_1\Delta}{c} \tag{2.27}$$

Also substituting for Δ from Eq. (2.10) gives:

$$\delta T_s \simeq \frac{L(NA)^2}{2n_1 c} \tag{2.28}$$

where *NA* is the numerical aperture for the fiber. The approximate expressions for the delay difference given in Eqs (2.27) and (2.28) are usually employed to estimate the maximum pulse broadening in time due to intermodal dispersion in multimode step index fibers. Again considering the perfect step index fiber, another useful quantity with regard to intermodal dispersion on an optical fiber link is the rms pulse broadening resulting from this dispersion mechanism along the fiber. When the optical input to the fiber is a pulse *p*i(*t*) of unit area, as illustrated in Figure 2.10, then

It may be noted that *p*i(*t*) has a constant amplitude of 1/➦*T*s over the range:

$$\int_{-\infty}^{\infty} p_i(t)\,\mathrm{d}t = 1 \tag{2.29}$$

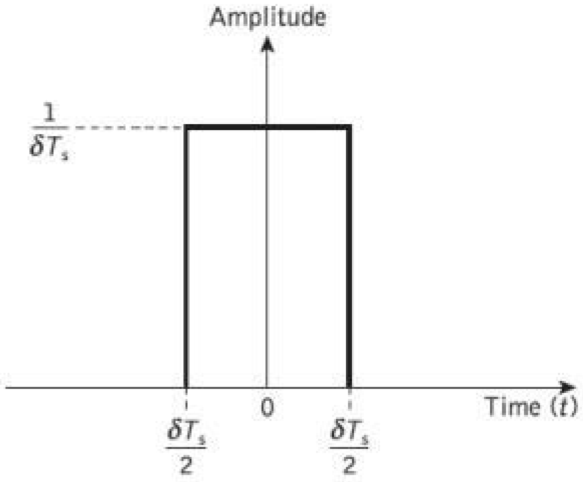

Figure 2.10 An illustration of the light input to the multimode step index fiber consisting of an ideal pulse or rectangular function with unit area

$$\frac{-\delta T_s}{2} \le p(t) \le \frac{\delta T_s}{2}$$

The rms pulse broadening at the fiber output due to intermodal dispersion for the multimode step index fiber 📅s (i.e. the standard deviation) may be given in terms of the variance 📅s2:

$$\sigma_s^2 = M_2 - M_1^2 \tag{2.30}$$

Where *M*1 is the first temporal moment which is equivalent to the mean value of the pulse and *M*2, the second temporal moment, is equivalent to the mean square value of the pulse.

Hence:

$$M_1 = \int_{-\infty}^{\infty} t p_i(t)\, \mathrm{d}t \tag{2.31}$$

And:

$$M_2 = \int_{-\infty}^{\infty} t^2 p_i(t)\, \mathrm{d}t \tag{2.32}$$

The mean value *M*1 for the unit input pulse of Figure 2.10 is zero, and assuming this is maintained for the output pulse, then from Eqs (2.30) and (2.32):

$$\sigma_s^2 = M_2 = \int_{-\infty}^{\infty} t^2 p_i(t)\, \mathrm{d}t \tag{2.33}$$

Integrating over the limits of the input pulse (Figure 3.12) and substituting for *p*i(*t*) in Eq. (2.33) over this range gives:

$$\sigma_s^2 = \int_{-\delta T_s/2}^{\delta T_s/2} \frac{1}{\delta T_s} t^2 \, \mathrm{d}t$$

$$= \frac{1}{\delta T_s}\left[\frac{t^3}{3}\right]_{-\delta T_s/2}^{\delta T_s/2} = \frac{1}{3}\left(\frac{\delta T_s}{2}\right)^2 \qquad (2.34)$$

Hence substituting from Eq. (2.27) for δ*T*s gives:

$$\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3}c} \simeq \frac{L(NA)^2}{4\sqrt{3}n_1 c} \qquad (2.35)$$

Equation (2.35) allows estimation of the rms impulse response of a multimode step index fiber if it is assumed that intermodal dispersion dominates and there is a uniform distribution of light rays over the range 0≤⚠≤⚠a The pulse broadening is directly proportional to the relative refractive index difference ° and the length of the fiber *L*. The latter emphasizes the bandwidth–length trade-off that exists, especially with multimode step index fibers, and which inhibits their use for wideband long-haul (between repeaters) systems. Furthermore, the pulse broadening is reduced by reduction of the relative refractive index difference ° for the fiber.

Intermodal dispersion may be reduced by propagation mechanisms within practical fibers. For instance, there is differential attenuation of the various modes in a step index fiber. This is due to the greater field penetration of the higher order modes into the cladding of the waveguide. These slower modes therefore exhibit larger losses at any core–cladding irregularities, which tends to concentrate the transmitted optical power into the faster lower order modes. Thus the differential attenuation of modes reduces intermodal pulse broadening on a multimode optical link.

Another mechanism which reduces intermodal pulse broadening in nonperfect (i.e. practical) multimode fibers is the mode coupling or mixing. The coupling between guided modes transfers optical power from the slower to the faster modes, and vice versa. Hence, with strong coupling the optical power tends to be transmitted at an average speed, which is the mean of the various propagating modes. This reduces the intermodal dispersion on the link and makes it advantageous to encourage mode coupling within multimode fibers.

The expression for delay difference given in Eq. (2.27) for a perfect step index fiber may be modified for the fiber with mode coupling among all guided modes to:

$$\delta T_{sc} \simeq \frac{n_1 \Delta}{c} (L L_c)^{\frac{1}{2}} \qquad (2.36)$$