Chapter 3

Transmission Characteristics of Optical Fibers

3.1 Introduction

- Most optical fibers are used for transmitting information over long distances.
- Two main advantages of fiber: (1) wide bandwidth and (2) low loss.
- Attenuation caused mainly by absorption and scattering

- Bandwidth is limited by an effect called dispersion.
- Transmission of light along the fiber in different modes causes modal dispersion while chromatic dispersion is caused by the light entering the fiber at different wavelength.

3.2 Attenuation

- The low 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 determines 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}).

- Attenuation mainly due to material absorption, material scattering.
- Others include bending losses, mode coupling losses and losses due to leaky modes
- There are also losses at connectors and splices.

3.3 Material Absorption Losses

- 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 or extrinsic.

3.3.1 Intrinsic Absorption

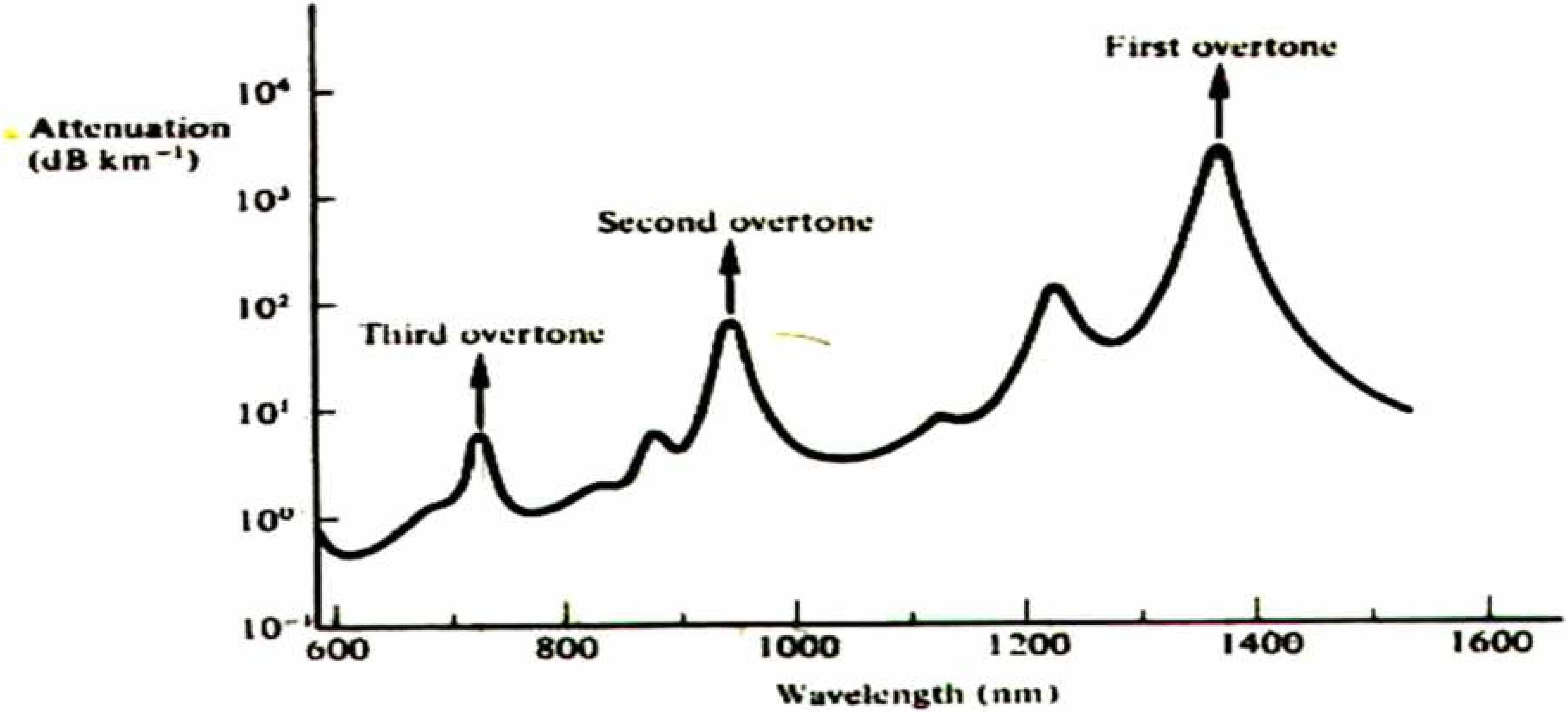
- Intrinsic absorption is a natural property of glass. It is strong in the ultraviolet (UV) region and in the infrared (IR) region of the electromagnetic spectrum.
- However both these considered insignificant since optical communication systems are normally operated outside this region.

3.3.2 Extrinsic Absorption

- In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption from metal element impurities.
- Some of these impurities namely chromium and copper can cause attenuation in excess of 1dB/km in near infrared region.
- Metal element contamination may be reduced to acceptable levels (i.e. one part in 10^{10}) by glass refilling techniques such as vapor phase oxidation which largely eliminates the effects of these metallic impurities.

- Another major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH ion) dissolved in the glass.
- The absorption occurs almost harmonically at 1.38 µm, 0.95 µm and 0.72 µm as illustrated in figure 3.1

Figure 3.1



The absorption spectrum for the hydroxyl (OH) group in silica. Reproduced with permission from D. B. Keck, K. D. Maurer and P. C. Schultz, *Appl. Phys. Lett.*, **22**, p. 307, 1973.

Conclusions:

1. Intrinsic absorption is mostly insignificant in a wide region where fiber systems operate. However, these losses prohibit the extension of fiber system below UV and longer wavelength.

2. Extrinsic losses minimised by reducing impurities and by avoiding wavelength corresponding to water absorption.

3.4 Linear Scattering Losses

Linear scattering may be categorized into two major types:

1.Rayleigh

2.Mie scattering.

Both result from the non-ideal physical properties of the manufactured fiber which are difficult and in certain cases, impossible to eradicate at present.

3.4.1 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 the wavelength of the light.
- 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 l/λ^4 following the Rayleigh scattering formula.

The loss (dB/km) can be approximated by the formula below with λ in μm;

$$\sim \; = 1.7\left(0.85 / a\right)^{4}$$

3.4.2 Mie Scattering

- Linear scattering may also occur at inhomogeneities which are comparable in size to the guided wavelength.
- These result from the non-perfect 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.

3.5 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 nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels.
- This 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 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.

3.5.1 Stimulated Brillouin Scattering

- It occurs when signal power reaches a level sufficient to generate tiny acoustic vibrations in the glass.
- Acoustic waves change the density of a material and thus alter its refractive index.
- The resulting refractive index fluctuations can scatter light.

- This can occur at powers as low as 3mW in single mode fibers.

- The treshold power P_B is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 v \alpha_{dB} \text{ watts}$$

where d and λ are the fiber core diameter and the operating wavelength respectively, both measured in micrometers, α_{dB} is the fiber attenuation in decibels per kilometer and v is the source bandwidth (i.e. injection laser) in GHz.

- The equation allows the determination of the threshold optical power which must be launched into a single mode optical fiber before Brillouin scattering occurs

- This can occur at powers as low as 3mW in single mode fibers.
- The treshold power P_{thBR} is given by:

$$P_{thBR} \approx 21 \frac{A_{eff}}{g_B L_{eff}}$$

A_{eff} = Effective core area
L_{eff} = Effective interaction length
$g_{\mathbf{B}}$ = elasto-optic coefficient

Example: $g_{\mathbf{B}} = 5 \text{ X } 10^{-11}$ m/W, $A_{eff} = \pi w^2$, $L_{eff} = 10/\alpha$

0.2 dB/km, $\pi w^2 = 50\ \mu m^2$

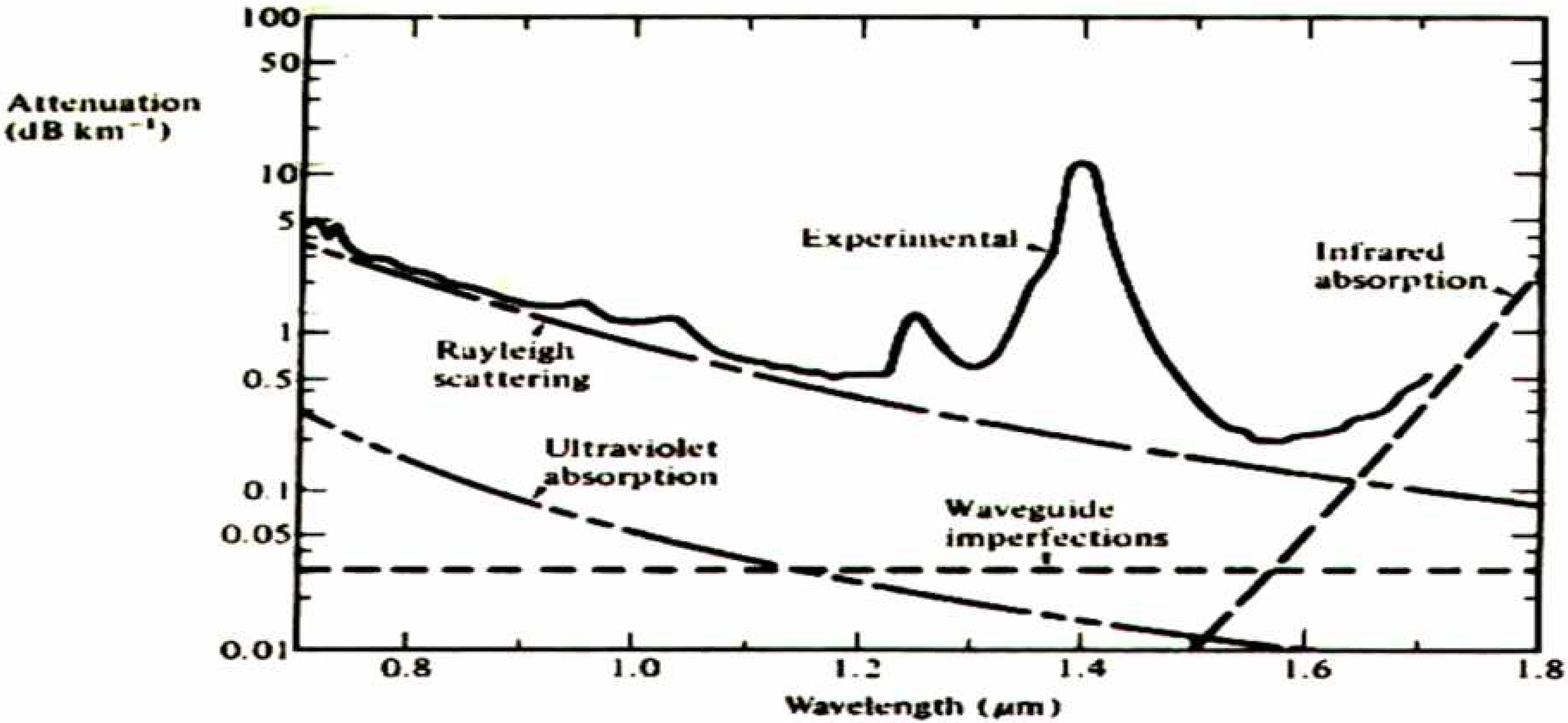
3.5.2 Stimulated Raman Scattering

- Stimulated Raman scattering is similar to stimulated Brillouin scattering except that Raman scattering occurs in the forward direction 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, the threshold optical power for stimulated Raman scattering P_R in a long single mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \alpha_{dB} \text{ watts}$$

Figure 3.2



The measured attenuation spectrum for an ultra low loss single mode fiber (solid line) with the calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation (dashed and dotted lines)

3.6 Fiber Bend Loss

- Optical fibers suffer radiation losses at bends or curves on their paths.

- This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes tight energy to be radiated from the fiber.

- An illustration of this situation is shown in Fig. 3.3

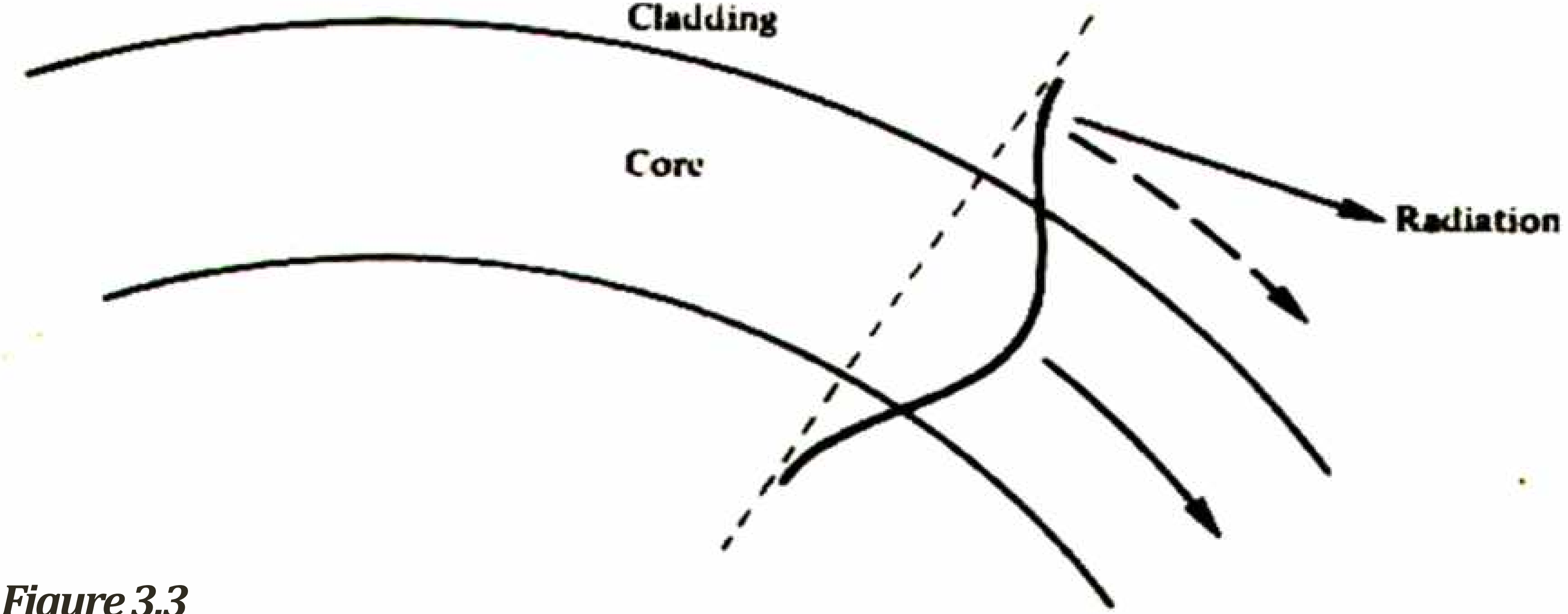


Figure 3.3

An illustration of the radiation loss at a fiber bend. The part of the mode in the cladding outside the dashed arrowed line may be required to travel faster than the velocity of light in order to maintain a plane wavefront. Since it cannot do this, the energy contained in this part of the mode is radiated away.

Large bending losses tend to occur at a critical radius of curvature R_c, which may be estimated from:

$$R_c \cong \frac{3n_1^2\,\text{a}}{4\text{®}\left(n_1^2 - n_2^2\right)^{\frac{3}{2}}}$$

- It may be observed from the expression given that possible bending losses may be reduced by:

- Designing fibers with large relative refractive index differences

- Operating at the shortest wavelength possible.

3.7 Dispersion

- Fiber bandwidth is determined by an effect called dispersion.
- Dispersion causes distortion of digital and analog signals.
- Dispersion can be divided into modal dispersion or also known as intermodal dispersion and chromatic dispersion or also known as intramodal dispersion.

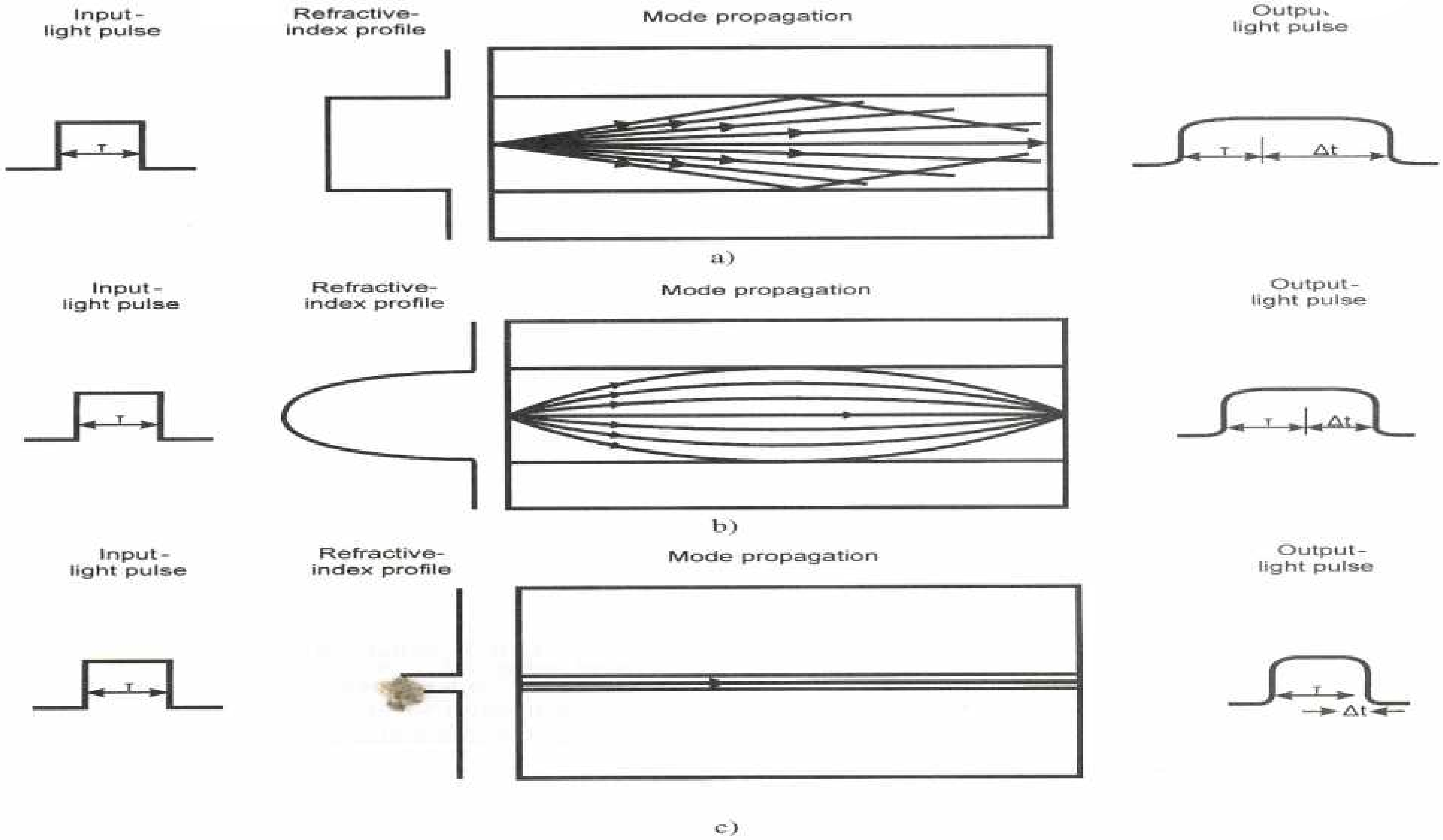
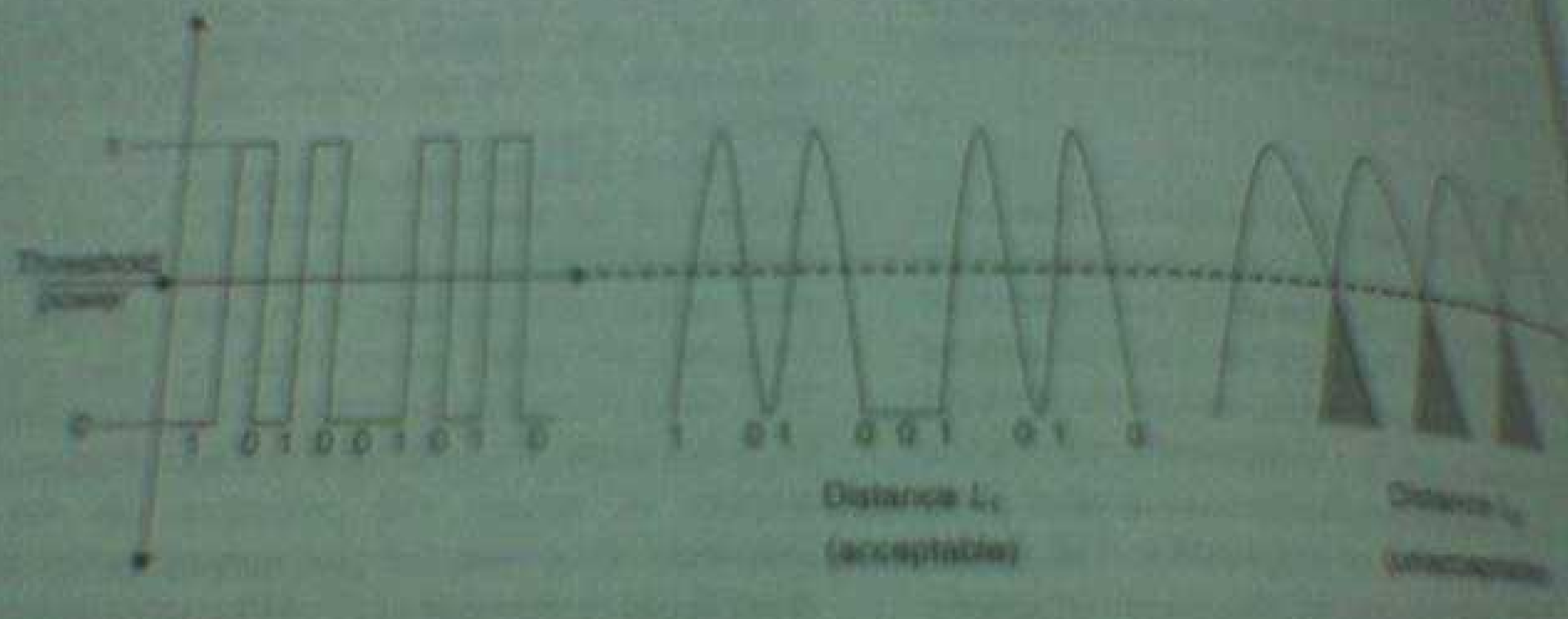


Figure 3.15 Dispersion in three types of optical fiber: (a) Step-index multimode fiber; (b) graded-index multimode fiber; (c) step-index singlemode fiber.

At distance L_2, spreading has caused pulse overlap, the optical detector cannot successfully recover the data, resulting in a significant increase of ISI.



Pulse dispersion.

3.7.1 Intramodal or Chromatic Dispersion

- This dispersion is due to the finite spectral linewidth($\Delta\lambda$) of the optical source.
- Since the propagation velocity depends on the wavelength, different wavelength will have different propagation times causing pulse dispersion to occur.
- Dispersion can be seen as velocity variation with λ. This maybe caused by dispersive properties of the material or guidance effects within the fiber structure known as waveguide dispersion. These are known as material dispersion and waveguide dispersion, respectively.

3.7.1.1 Material dispersion

- Material dispersion is caused by the natural property of glass, the material used in manufacturing fiber.
- Pulse broadening due to material dispersion happens because pulses at different wavelengths have different group velocities are 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 that is $d^2n/d\lambda^2 \neq 0$ (LARGER λ LOWER n)

- Cause of Material dispersion, D_M -- refractive index of silica varies with the wavelength.
- Can be approximated by:

$$D_M = 122(l - \lambda_{ZD}/\lambda)\ ps/nmkm$$

[λ_{ZD} = zero dispersion wavelength (λ_{ZD} = 1276 nm for pure silica or can be approximated as 1300 nm)]

Manufacturers also specify the chromatic dispersion parameter by

$$D_M = D(\lambda) = \frac{S_0}{4}\left[\lambda - \frac{\lambda_{ZD}^4}{\lambda^3}\right]$$

S_o is the zero-dispersion slope in ps/(nm^{2}km). Typical value is 0.097 ps/(nm^{2}km).

The unit for material dispersion, D_M is read as picosecond of pulse spreading per nanometer of source spectral width per km of path length. D_M is negative for wavelengths below λ_{ZD} and becomes positive above that.

3.7.1.2 Waveguide dispersion, D_W

- Caused by the fact that light is guided by a STRUCTURE within CORE and CLADDING.
- Pulses of same mode but different wavelengths need to travel at different angle or different group velocities.

- For a particular mode whose propagation constant is β the fiber exhibits waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$.
- 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.

- However, with single mode fibers waveguide dispersion may be significant due to the fact that due to small value of V, the spot size will be small causing quite a large portion of the light to propagate through the cladding. The cladding portion of the wave will travel faster since $n_2 < n_1$. This causes waveguide dispersion.

3.7.1.3 Total chromatic dispersion, D

- The total chromatic dispersion can be obtained by adding D_M and D_W i.e. **$(D_M + D_W)\Delta\lambda$**

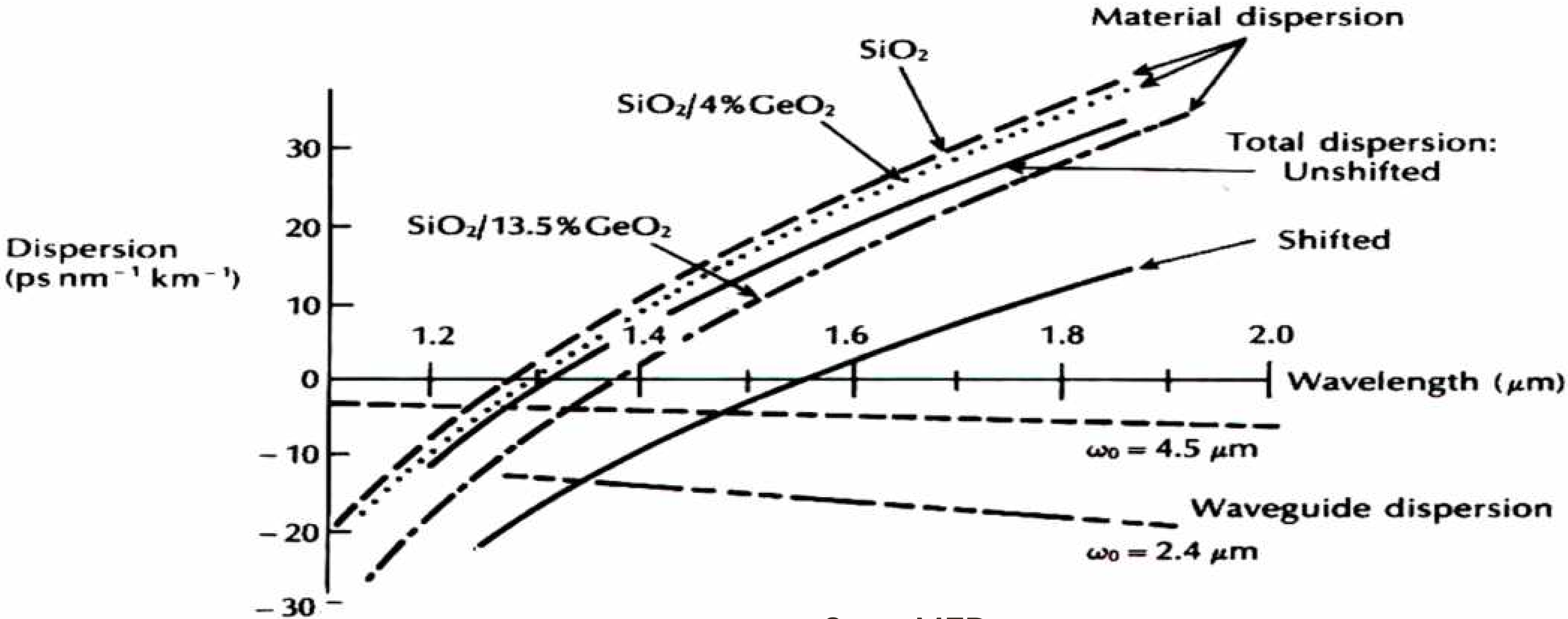
- Normally $D_M > D_W$ in the range of wavelengths 800 - 900 nm.

- Therefore, waveguide dispersion can be neglected except for systems operating in the region 1200 nm - 1600 nm.

- The main effect of D_W is to shift λ_{ZD} by an amount 30 - 40 nm so that the total dispersion is zero near 1.31 μm.

- It also reduces the total dispersion from its material value D_M in the wavelength range 1.3-1.6 μm.

- Pulse spreading reduces BW and data capacity of a fiber communication link.
- Therefore, we must reduce dispersion by operating at zero dispersion wavelength or choosing a very coherent light sources (i.e. with small $\Delta\lambda$).
- It was found earlier that, lowest attenuation is achieved at 1550 nm.
- If the dispersion curve could be made to have zero dispersion at this λ we can have an optimum system.
- This is achieved by dispersion shifted fiber achieved by modifying the fiber so that D_M and D_W cancel each other at the lowest attenuation (i.e. at λ=1.55μm)



$2w_0 = MFD$

Figure 3.5 Material, waveguide and total dispersion characteristics for conventional and dispersion shifted step index single-mode fibers showing variation with composition and spot size (ω_0).

- Other methods are by using dispersion flattened fiber, dispersion shifted fiber and depressed cladding fiber. All these methods modify the refractive index profile of the fiber:

  a) Dispersion shifted fiber.

  The waveguide dispersion is exploited to interact with the material dispersion to shift the zero dispersion wavelength to a value which will have the lowest attenuation. That is, the zero dispersion wavelength is shifted from 1.276 µm to 1.55 µm. This is made possible due to the fact that D_W depends on fiber parameters and can be modified to interact with D_M

b) Dispersion flattened fiber.

The fiber is modified to achieve low dispersion window over the low loss wavelength region between 1.3 μm and 1.6 μm.

c) Depressed cladding fiber

The fiber is made so that the core is surrounded by a thin inner cladding whose index is low and an outer cladding whose index is slightly higher.

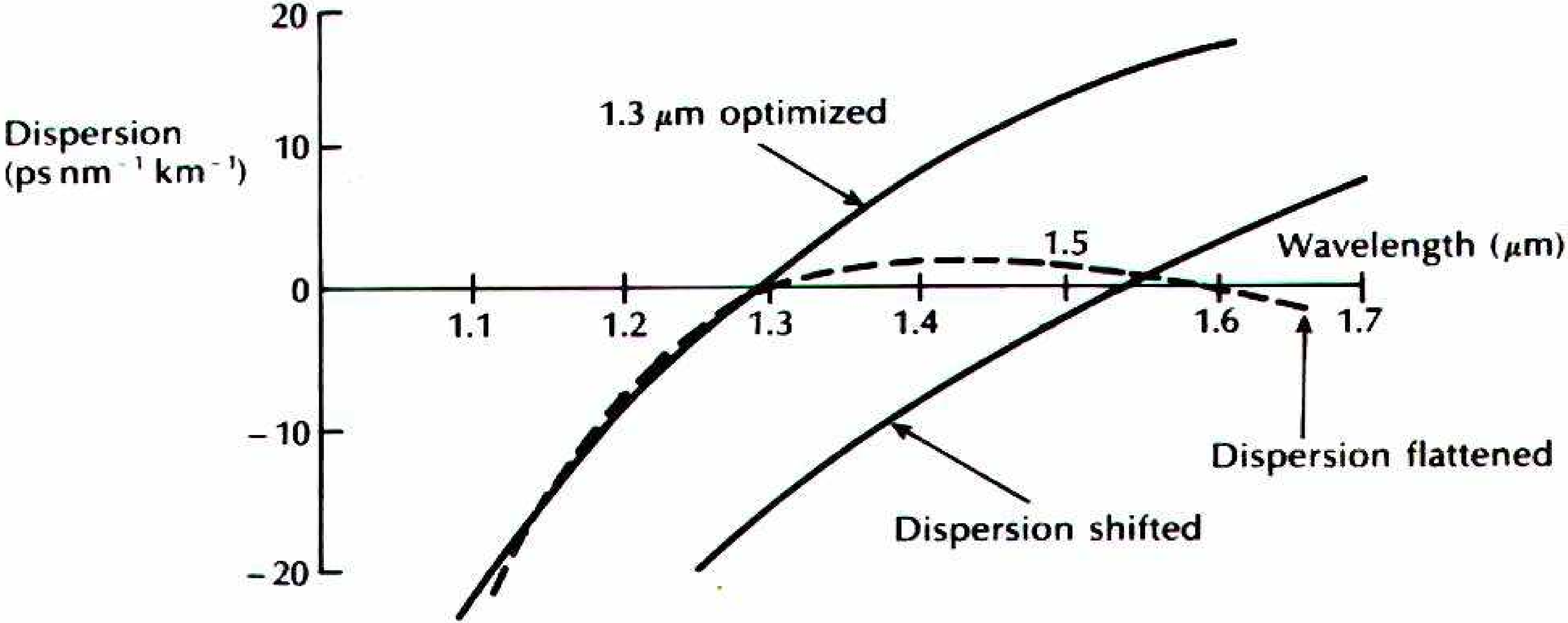
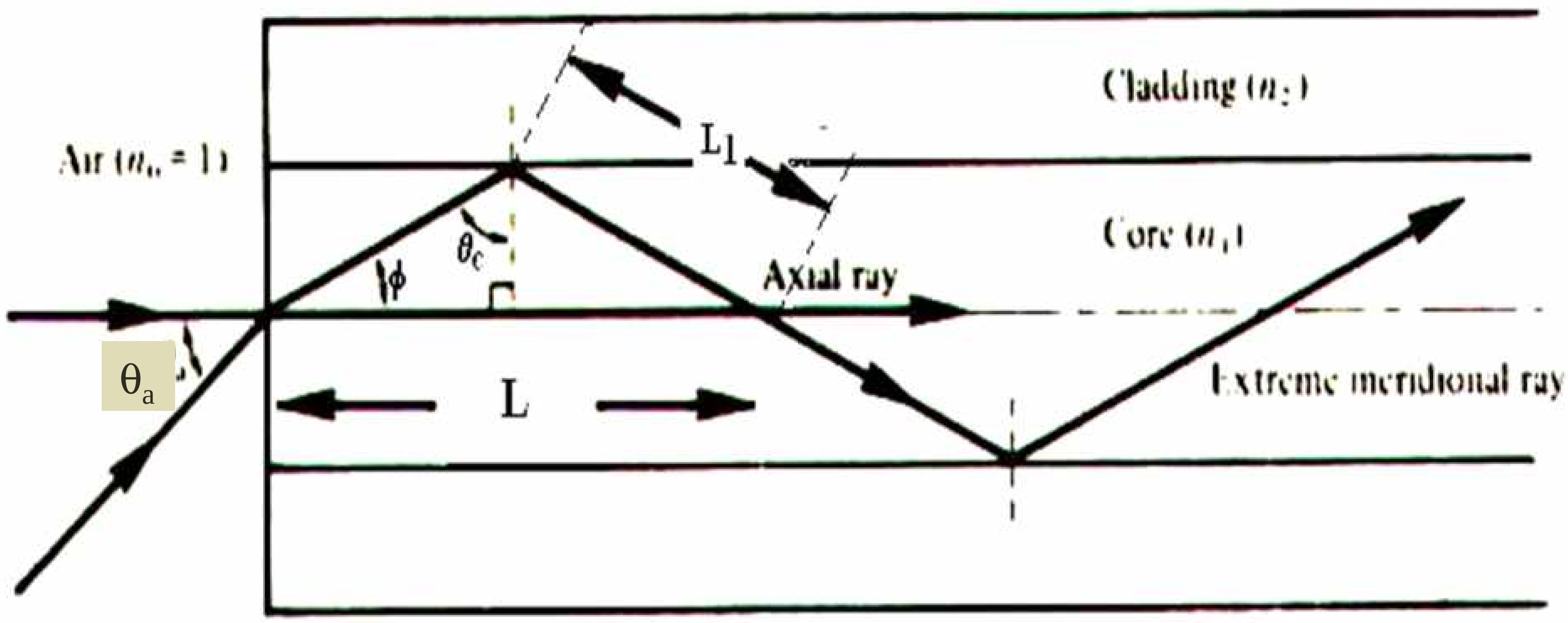


Figure 3.6 Total dispersion characteristics for the various types of single-mode fiber.

3.7.2 Intermodal Dispersion

- Different modes propagating through the fiber will have different net velocities and will arrive at different time at the output This causes the waveform to spread.
- This is called multimode or modal dispersion.
- Multimode dispersion does not depend on $\Delta\lambda$.
- Therefore even if the source has $\Delta\lambda = 0$, then D_M and D_W will be zero, but it will still suffer multimode dispersion.

- The amount of modal dispersion or spreading is easily developed by the difference in travel time between mode propagating at the steepest angle with respect to the axis.
- Using the ray theory model, the fastest and slowest modes propagating in 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 θ_c, respectively.



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

- Axial ray travel time,

$$t_{\min} = \frac{L}{c / n_1}$$

- The critical angle ray or the extreme ray will arrive last among the many rays (or modes), because it travel the farthest.

- The travel time is,

$$t_{max} = \frac{L / \cos \text{¤}}{c / n_1} = \frac{L / \frac{n_2}{n_1}}{c / n_1}$$

$$\cos \text{¤} = \frac{L / 2}{L_1}$$

$$t_{max} = \frac{L n_1^2}{c n_2}$$

Distance = $2L_1$

= L/cos q

sin q_c = n_2/n_1 = cos q

- Therefore pulse spread per unit length is,

$$(t_{max}-t_{min})/L = \Delta(t/L)_s$$
$$= n_1^2/cn_2 - n_1/c$$
$$= n_1 (n_1 - n_2)/cn_2$$
$$= (n_1/c)\Delta ;[(n_1 - n_2)/ n_2 = \Delta]$$
$$= (NA)^2/2cn_1 \quad ;[NA = n_1(2\Delta)^{1/2}]$$

- This expression gives the pulse spread per unit length that can be used to estimate maximum pulse broadening due to intennodal dispersion in MMF.
- Therefore, in MMF all three dispersion mechanism exist simultaneously that is material dispersion, waveguide dispersion, and multimode dispersion.

3.7.2.1 Bandwidth calculations

- The maximum bit rate (B_T) can be estimated from the total dispersion. There are two approach in estimating the bandwidth namely assuming non-overlapping of the digital pulses and certain degree of overlapping of the pulses.

- Assuming the non-overlapping case,
  $B_T = 1/2\tau$ bits/sec.

- In the case of the overlapping pulses, the pulses are assumed to have a Gaussian distribution with standard deviation or r.m.s width σ. The bit rate will then be given by,
  $B_T = 0.2/\sigma$ bits/sec

The table below shows the types of fiber and the kinds dispersion present in each of them respectively:

Fiber Type	Dispersion Present
Multimode Fiber Step Index	D_M, D_W, Modal
Multimode Graded Index	D_M, D_W, Modal
Single Mode Fiber	D_M, D_W

The formulas for modal dispersion for the various type of fibers according to overlapping and non-overlapping approximations are:

Fiber	Non Overlapping	Overlapping (Gaussian)
SI- MMF(sec)	$2_s = \frac{L(NA)^2}{2cn_1} = \frac{Ln_1\Delta}{c}$	$\pm_s = \frac{L(NA)^2}{4\sqrt{3}cn_1} = \frac{2_s}{2\sqrt{3}}$
GRIN-MMF(sec)	$2_g = \frac{n_1\Delta^2}{8c}L$	$\pm_g = \frac{n_1\Delta^2 L}{20c\sqrt{3}}$
Max bit rate(bit/sec)	$B_T = \frac{1}{2\tau}$	$B_T = \frac{0.2}{\sigma}$

3.8 Overall Fiber Dispersion

- The overall dispersion in fibers comprise both intramodal and intermodal terms.
- The total rms broadening σ_T is given by:
  $\sigma_T = (\sigma_C^2 + \sigma_n^2)^{1/2}$ where σ_C is the intramodal or chromatic broadening and σ_n is the intermodal broadening caused by delay differences between the modes (i.e. σ_s for multimode step index fiber and σ_g for multimode graded index fiber.
- The intramodal term σ_c consist of pulse broadening due to both material and waveguide dispersion.
- However, since waveguide dispersion is generally negligible compared with material dispersion in multimode fibers, then $\sigma_c = \sigma_m$

Birefringence (B): dependence of refractive index on wave polarization. Can cause polarization-mode dispersion (PMD) or birefringence dispersion. Only serious at very high bit rate (above 10 Gb/s).

To reduce this the fiber must have ideal symmetric cross-sectional properties, i.e. the refractive indices along the x-axis (n_x) and y-axis (n_y)must be equal.

$B = n_x - n_y$

Polarization: when the signal comprises of waves having different polarization, polarization dependent loss (PDL) occurs.