COURSE: *OPTICAL COMMUNICATION* (EC317)
UNIT-II

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Distortion in Optical Fibers

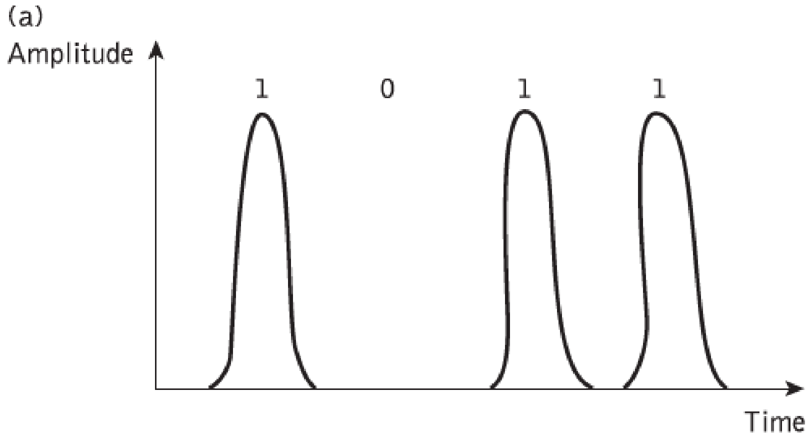
- When an optical signal is transmitted on an optical fiber, the signal is distorted due to two phenomena: dispersion and attenuation.

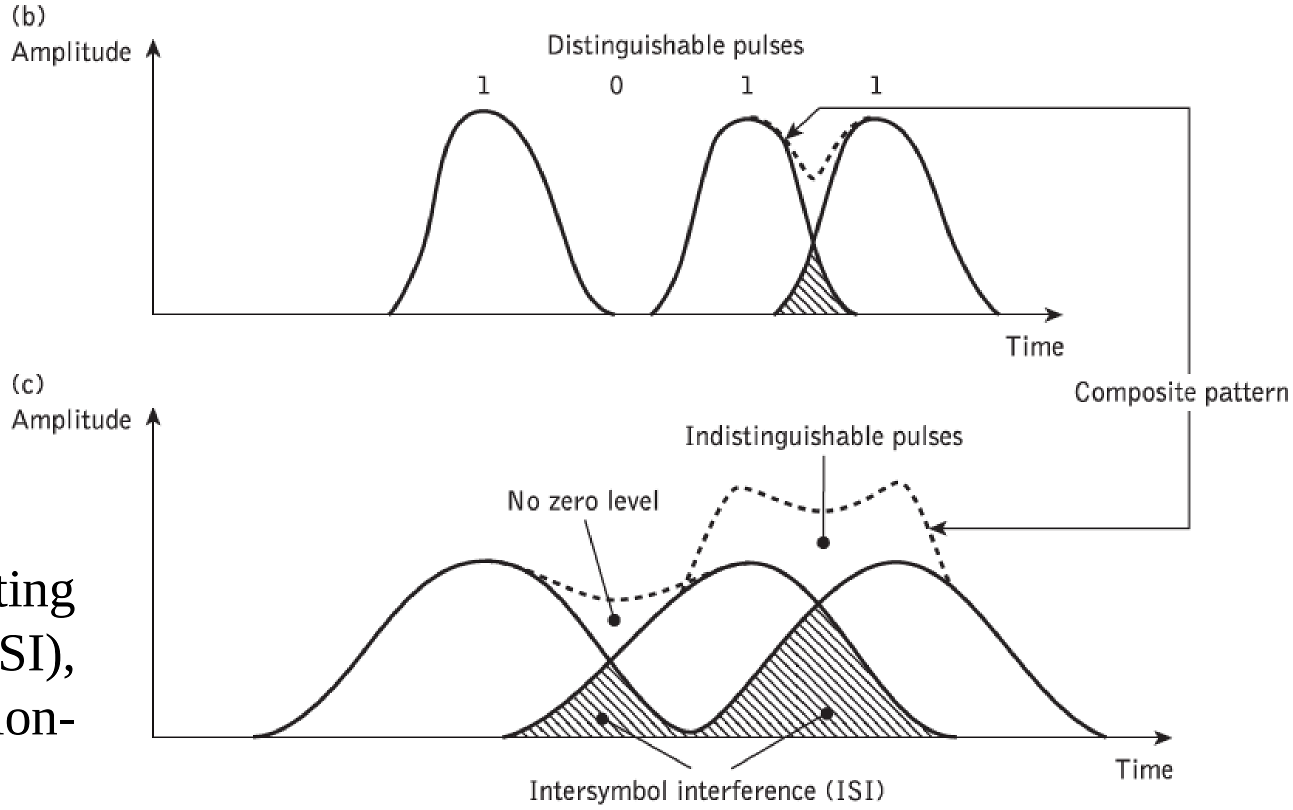
Distortion in optical fiber

- **Attenuation**
  - Material attenuation
    - Absorption
    - Scattering
  - Bending loss
  - Radiation
- **Dispersion**
  - Intramodal dispersion
    - Material dispersion
    - Waveguide dispersion
  - Inter modal dispersion

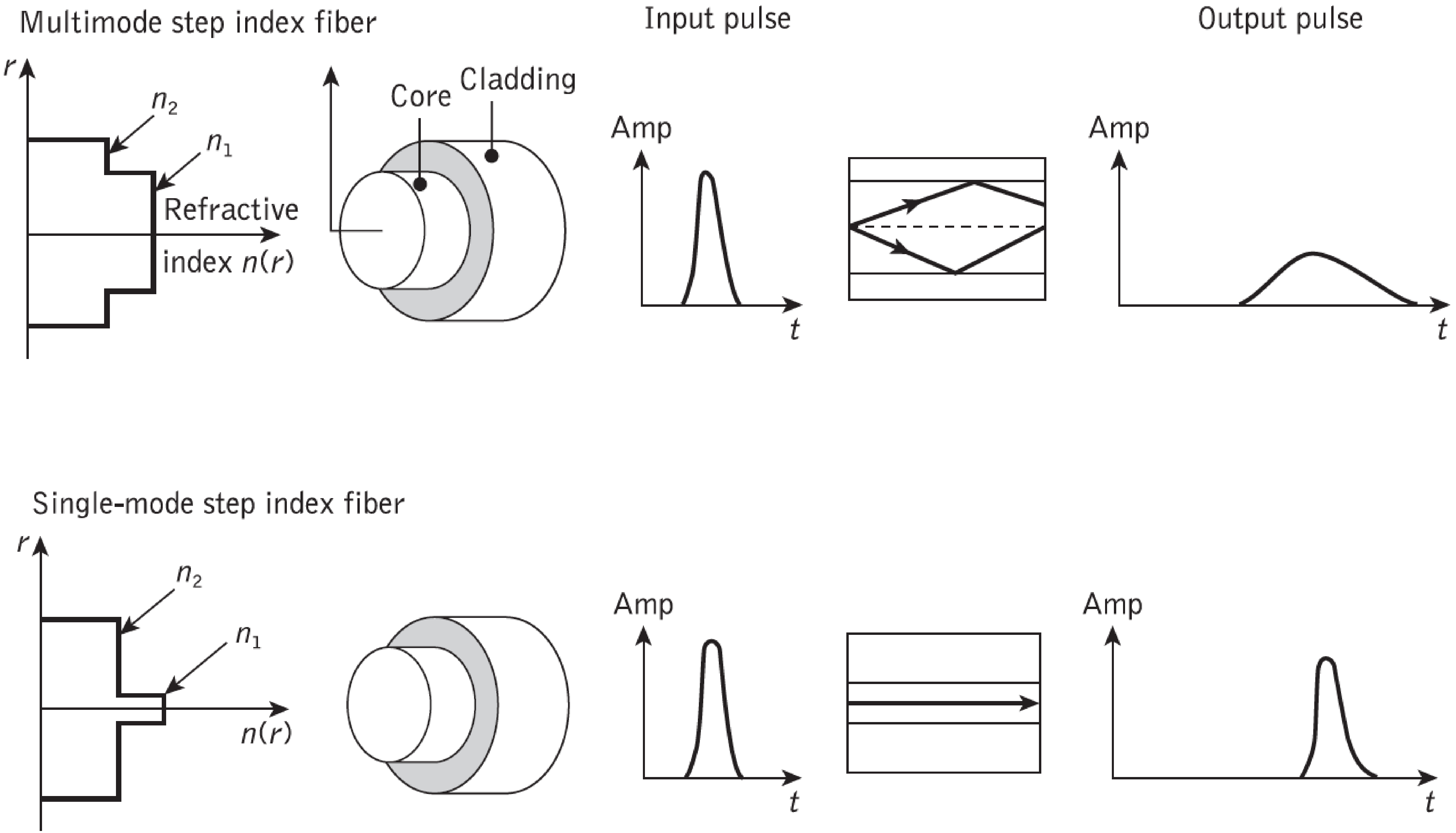
DISPERSION

- When light is launched into an optical fiber in the form of a light pulse to transmit the information
- The broadening of the transmitted light pulses as they travel along the fiber is known as dispersion.





- the overlap between adjacent pulses, creating errors in the receiver output (i.e., ISI), resulting in the limitation of information-carrying capacity of a fiber.


Multimode step index fiber
Input pulse
Output pulse
r
n_2
n_1
Refractive index $n(r)$
Core
Cladding
Amp
t
Amp
t
Single-mode step index fiber
r
n_2
n_1
$n(r)$
Amp
t
Amp
t

CHROMATIC OR INTRAMODAL DISPERSION

- This type of dispersion 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
- 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 (group velocity 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)**.

MATERIAL DISPERSION

- This arises due to the variations of the refractive index of the core material as a function of wavelength.
- This refractive index property causes a wavelength dependence of the group velocity of a given mode; that is, pulse spreading occurs when different wavelengths follow the same path.
- The group velocity is given by $v_g = \frac{d\omega}{d\beta}$; where the propagation constant $\beta = \frac{2\pi n_1(\lambda)}{\lambda}$ and $\omega = \frac{2\pi c}{\lambda}$
- A time delay or group delay in the direction of the propagation $t_g = \frac{L}{v_g}$

$$t_g = \frac{L}{v_g} = L\frac{d\beta}{d\omega} \ or \ \frac{L}{c}\frac{d\beta}{dk}$$

MATERIAL DISPERSION

$$\frac{d\beta}{d\lambda} = -\frac{2\pi}{\lambda^2}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad and \qquad \frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2}$$

- Therefore

$$t_g = L\frac{d\beta/d\lambda}{d\omega/d\lambda} = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$

- If the spectral width of the optical source is not too wide, then the delay difference per unit wavelength along the propagation path is approximately $\frac{dt_g}{d\lambda}$.
- For spectral components which are $\delta\lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta\tau$ over a distance L is:

$$\delta\tau = \left|\frac{dt_g}{d\lambda}\right|\delta\lambda = \frac{L}{c}\lambda\left|\frac{d^2n_1}{d\lambda^2}\right|\delta\lambda$$

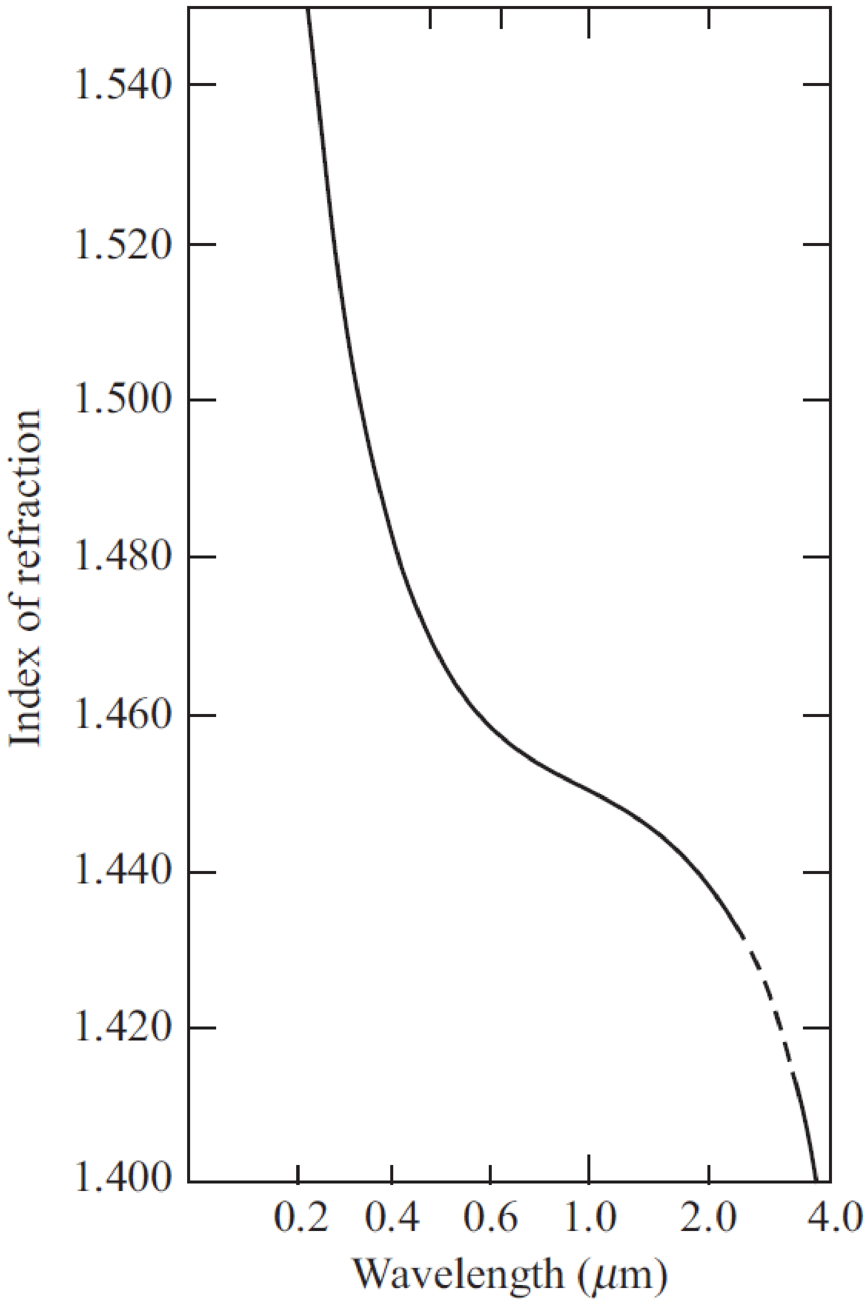
- The material dispersion of optical fibers is quoted in terms of the material dispersion parameter D_{mat} given by

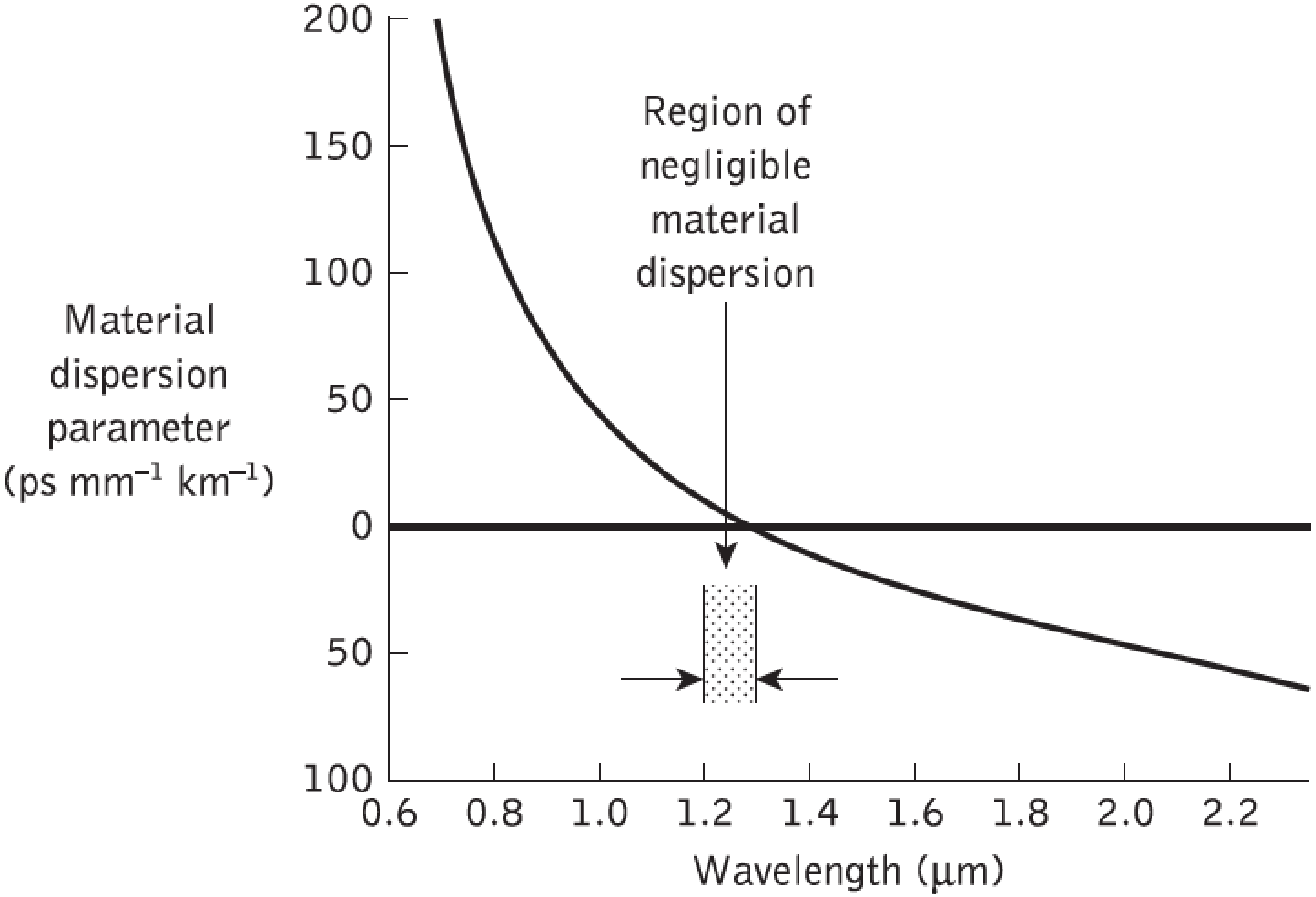
$$D_{mat} = \frac{1}{L}\frac{\delta\tau}{\delta\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right|$$

D_{mat} has the units of ps nm^{-1} km^{-1}.

- In the case of optical pulse, if the spectral width of the optical source is characterized by its rms value of the Gaussian pulse σ_λ, the pulse spreading over the length of L, σ_m can be well approximated by:

$$\sigma_{mat} = \left|\frac{dt_g}{d\lambda}\right| \sigma_\lambda = L D_{mat} \sigma_\lambda$$


1.540
1.520
1.500
1.480
1.460
1.440
1.420
1.400
Index of refraction
0.2
0.4
0.6
1.0
2.0
4.0
Wavelength (μm)


Material
dispersion
parameter
(ps mm⁻¹ km⁻¹)
200
150
100
50
0
50
100
Region of
negligible
material
dispersion
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Wavelength (μm)

Waveguide dispersion

- The degree of waveguide dispersion depends on the fiber design.
- Waveguide dispersion usually can be ignored in multimode fibers, but its effect is significant in single-mode fibers.
- This dispersion arises because the difference in core-cladding spatial power distributions, together with the speed variations of the various wavelengths, causes a change in propagation velocity for each spectral component.
- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number.
- In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

$$b = \frac{\left(\frac{\beta}{k}\right)^2 - {n_2}^2}{{n_1}^2 - {n_2}^2}$$

WAVEGUIDE DISPERSION

For small values of the index difference $\Delta = (n_1 - n_2)/n_1$, can be approximated by

$$b \approx \frac{\frac{\beta}{k} - n_2}{n_1 - n_2} \quad \Rightarrow \beta \approx kn_2(b\Delta + 1)$$

the group delay t_{wg} arising from waveguide dispersion is $t_g = \frac{L}{v_g} = \frac{L}{c}\frac{d\beta}{dk}$

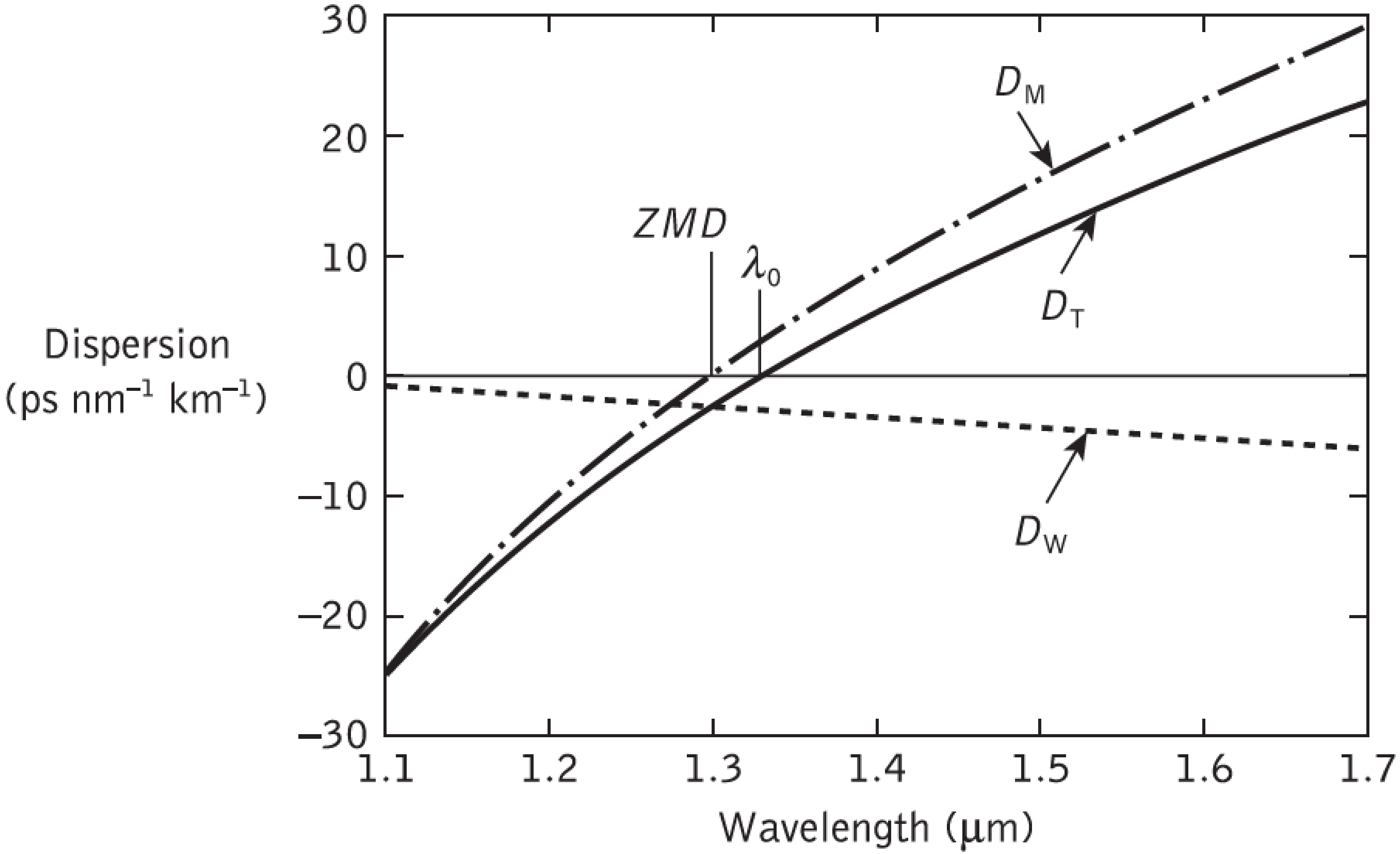
$$t_g = \frac{L}{c}n_2\left(1 + \Delta\frac{d(kb)}{dk}\right) = \frac{L}{c}n_2\left(1 + \Delta\left(b + k\frac{db}{dk}\right)\right) = \frac{L}{c}n_2\left(1 + \Delta\left(b + k\frac{db}{dV}\frac{dV}{dk}\right)\right)$$

$$V = kan_1\sqrt{2\Delta} \quad \Rightarrow \frac{dV}{dk} = an_1\sqrt{2\Delta} = \frac{V}{k}$$

$$t_g = \frac{L}{c}n_2\left(1 + \Delta\frac{d(bV)}{dV}\right)$$

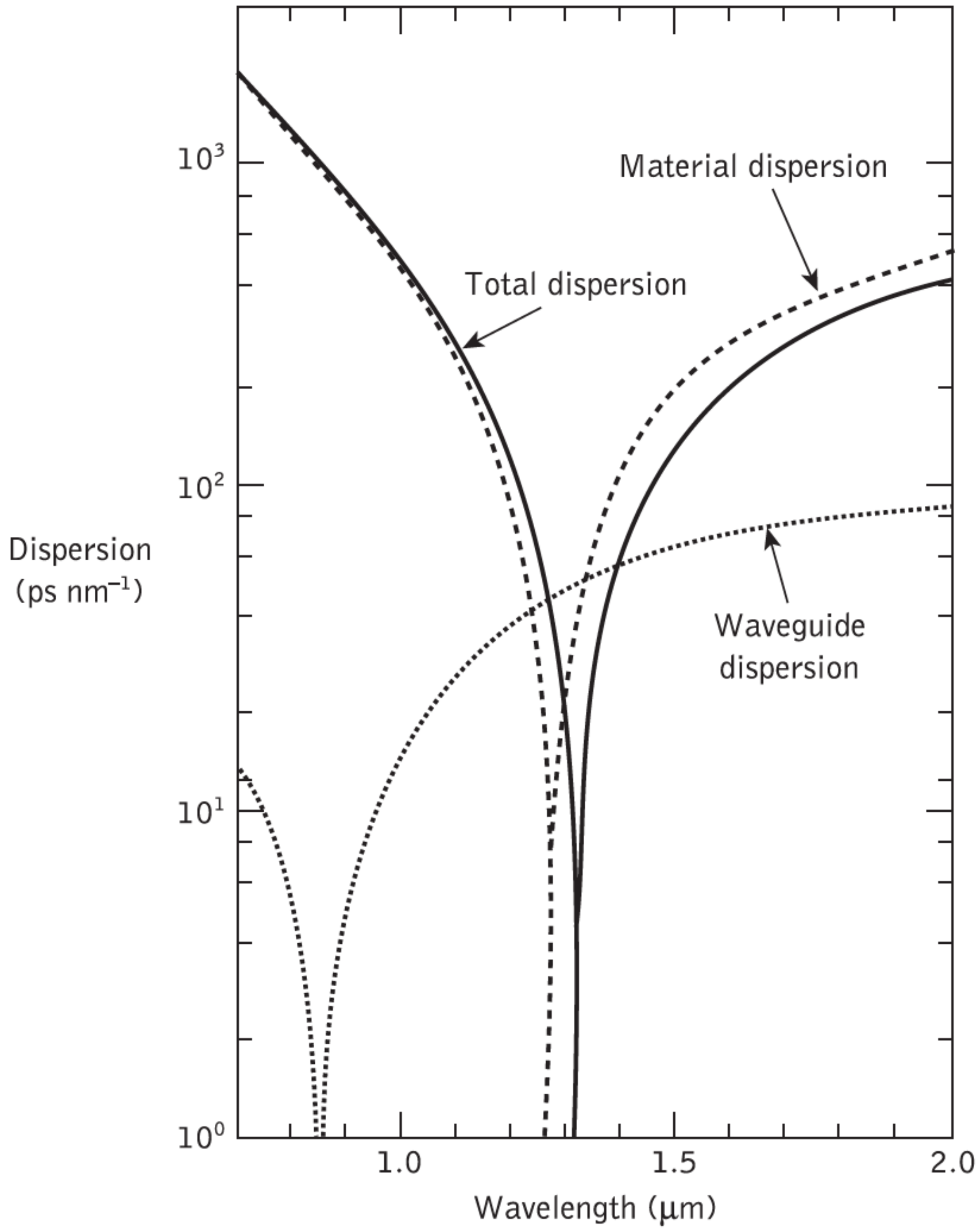
The waveguide dispersion is

$$D_{wg} = \frac{1}{L}\left|\frac{dt_g}{d\lambda}\right| = \frac{n_2\Delta}{c}\frac{d}{d\lambda}\left(\frac{d(bV)}{dV}\right)\frac{dV}{dV} = \frac{n_2\Delta}{c}\frac{V}{\lambda}\left(\frac{d^2(bV)}{dV^2}\right)$$



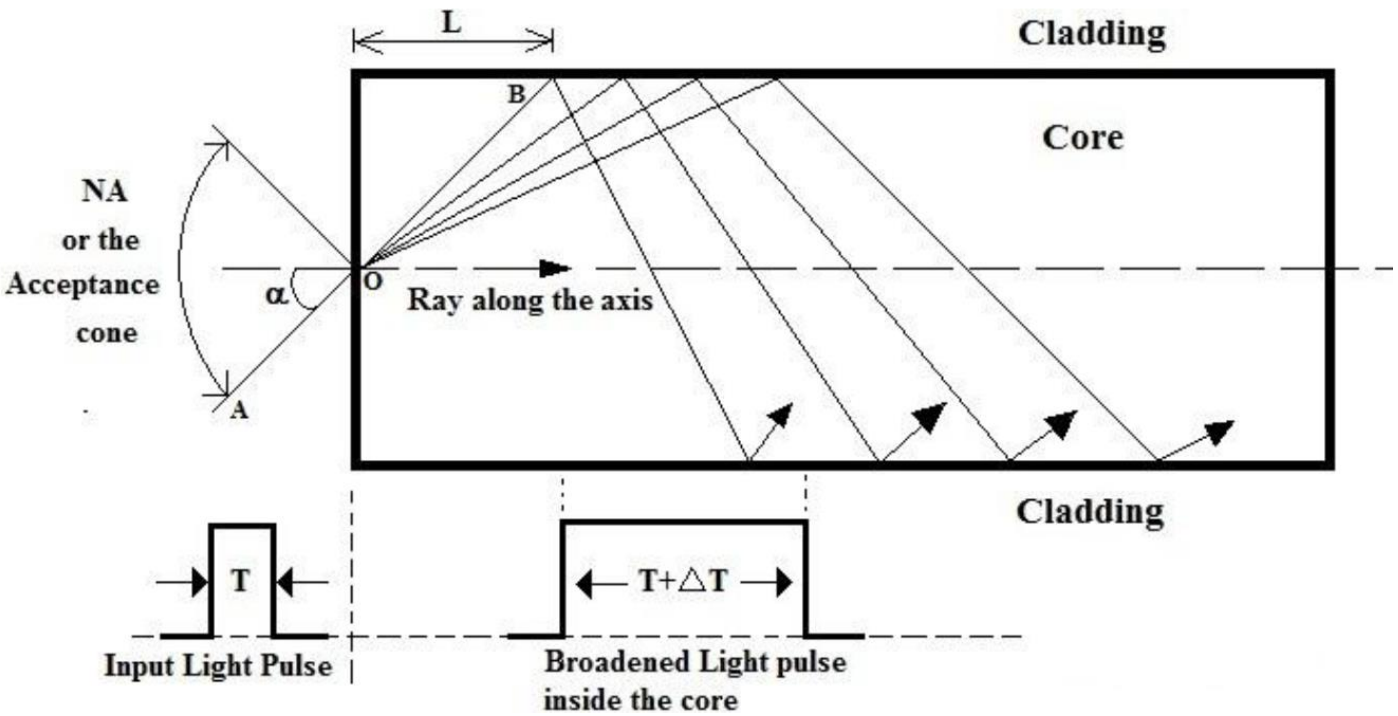
Dispersion (ps nm⁻¹ km⁻¹)
30
20
10
0
−10
−20
−30
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
ZMD
λ_0
D_M
D_T
D_W

- The wavelength at which the first-order dispersion is zero λ_0 may be extended to wavelengths of 1.55 μm and beyond by a combination of three techniques. These are:
  - lowering the normalized frequency (V) for the fiber;
  - increasing the relative refractive index difference Δ for the fiber;
  - suitable doping of the silica with germanium.



INTER-MODAL DISPERSION

- The light rays travel different paths inside the core of an optical fiber because different light rays are incident on the tip of the optical fiber at different angles within the acceptance cone and lead to the broadening of the actual time-width of the pulse. This phenomenon is called as inter-modal dispersion
- Intermodal dispersion or modal delay appears only in multimode fibers.



INTER-MODAL DISPERSION

- This broadening is simply obtained from ray tracing and for a fiber of length L is given by

$$\Delta T = T_{max} - T_{min}$$

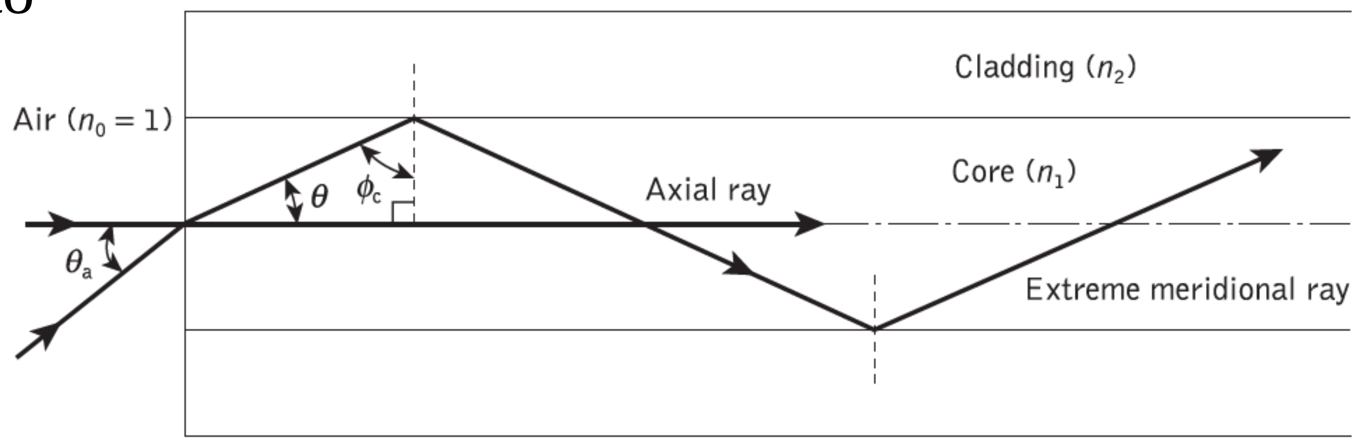
$$T_{min} = \frac{L}{c} n_1 \qquad and \qquad T_{max} = \frac{L}{c\cos\theta} n_1$$

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

$$\Delta T = \frac{L}{c} n_1 \left(\frac{n_1}{n_2} - 1 \right) \approx \frac{L}{c} n_1 \Delta$$

The rms pulse broadening due to intermodal dispersion

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



PROBLEMS

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

(a) the delay difference between the slowest and fastest modes at the fiber output;

(b) the rms pulse broadening due to intermodal dispersion on the link;

(c) the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion

Sol:

(a) The delay difference

$$\Delta T = \frac{L}{c} n_1 \Delta = 6 \times 1.5 \times \frac{0.01}{3 \times 10^5} = 300\ ns$$

(b) The rms pulse broadening due to intermodal dispersion

$$\sigma_s = \frac{L}{2\sqrt{3}c} n_1 \Delta = 86.7\ ns$$

(c) The maximum bit rate may be estimated in two ways:

$B_{T,max} = \frac{1}{2\Delta T} = 1.7\ Mbps$ or $B_{T,max} = \frac{0.2}{\sigma_s} = 2.3\ Mbps$

PROBLEMS

- A glass fiber exhibits material dispersion given by $|\lambda^2(d^2n_1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per km for a good LED source with an rms spectral width of 20 nm at this wavelength.

Sol:

Given that $\left|\lambda^2 \frac{d^2n_1}{d\lambda^2}\right| = 0.025$

Operating wavelength $\lambda = 850$ nm

RMS spectral width $\sigma_\lambda = 20\ nm$

The material dispersion

$$D_{mat} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2\frac{d^2n_1}{d\lambda^2}\right| = \frac{0.025}{3\times 10^5\times 850} = 98.04 \text{ ps nm}^{-1}\text{ km}^{-1}$$

The rms pulse broadening per km

$$\frac{\sigma_{mat}}{L} = D_{mat}\sigma_\lambda = 1.96\ ns/km$$

PROBLEMS

- A manufacturer's data sheet lists the material dispersion D_{mat} of a GeO_2-doped fiber to be 110 ps/(nm-km) at a wavelength of 860 nm. Find the rms pulse broadening per km due to material dispersion if the optical source is a GaAlAs LED that has a spectral width of 40 nm at an output wavelength of 860 nm.

ATTENUATION

- Signal attenuation (fiber loss) largely determines the maximum repeaterless separation between optical transmitter & receiver (i.e., maximum transmission distance between a transmitter and a receiver)
- Signal attenuation is usually expressed in the logarithmic unit of the decibel.
- The decibel, which is used for comparing two power levels, may be defined 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

$$Power\ ration\ in\ dBs = -10\log_{10}\left(\frac{P_o}{P_i}\right) = 10\log_{10}\left(\frac{P_i}{P_o}\right)$$

- In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB/km)

$$\alpha = \frac{1}{L}10\log_{10}\left(\frac{P_i}{P_o}\right) \qquad in\ dB/km$$

EXAMPLE

When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. *Determine:*

(a) the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices;

(b) the signal attenuation per km for the fiber.

(c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB;

Sol:

(a) The overall signal loss/attenuation

$$\alpha(dB) = 10\log_{10}\left(\frac{P_i}{P_o}\right) = 16\ dB$$

(b) The signal attenuation per km

$$\alpha(dB/km) = \frac{16}{8} = 2\ dB/km$$

(c) the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 9 dB. Hence, the overall signal attenuation for the link is: 29 dB

Attenuation in fibers

- 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**.
- The basic attenuation mechanisms in a fiber are **material absorption, material scattering (linear and nonlinear scattering), curve and micro-bending losses**, mode coupling radiation losses and losses due to leaky modes. There are also losses at connectors and splices

MATERIAL ABSORPTION LOSS

- Material absorption is 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.
- Absorption by **atomic defects** in the glass composition (i.e., imperfections in the atomic structure of the fiber material).
    - these defects include missing molecules, high-density clusters of atom groups, or oxygen defects in the glass structure
- Absorption is caused by the following mechanisms:
    - Intrinsic absorption
    - Extrinsic absorption

Intrinsic and Extrinsic absorption loss

- **Intrinsic absorption** caused by the interaction with one or more of the major components of the glass or fiber material.
  - electronic absorption bands (associated with the band gaps of the amorphous glass materials) in the ultra violet (UV) region and from atomic vibration bands in the near-infrared (IR) region
- The UV loss contribution in dB/km at any wave length (given in µm) can be expressed empirically (derived from observation or experiment) as a function of the mole fraction x

$$\alpha_{uv} = \frac{154.2x}{46.6x + 60} \times 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)$$

- In the near-infrared region above 1.2 µm,

$$\alpha_{IR} = 7.81 \times 10^{11} \exp\left(\frac{-48.48}{\lambda}\right)$$

- **Extrinsic absorption** by impurity atoms in the glass material.

Impurity	*Loss due to 1 ppm of impurity (dB/km)*	*Absorption peak (nm)*
Iron: Fe^{2+}	0.68	1100
Iron: Fe^{3+}	0.15	400
Copper: Cu^{2+}	1.1	850
Chromium: Cr^{2+}	1.6	625
Vanadium: V^{4+}	2.7	725
Water: OH^{-}	1.0	950
Water: OH^{-}	2.0	1240
Water: OH^{-}	4.0	1380

SCATTERING LOSS

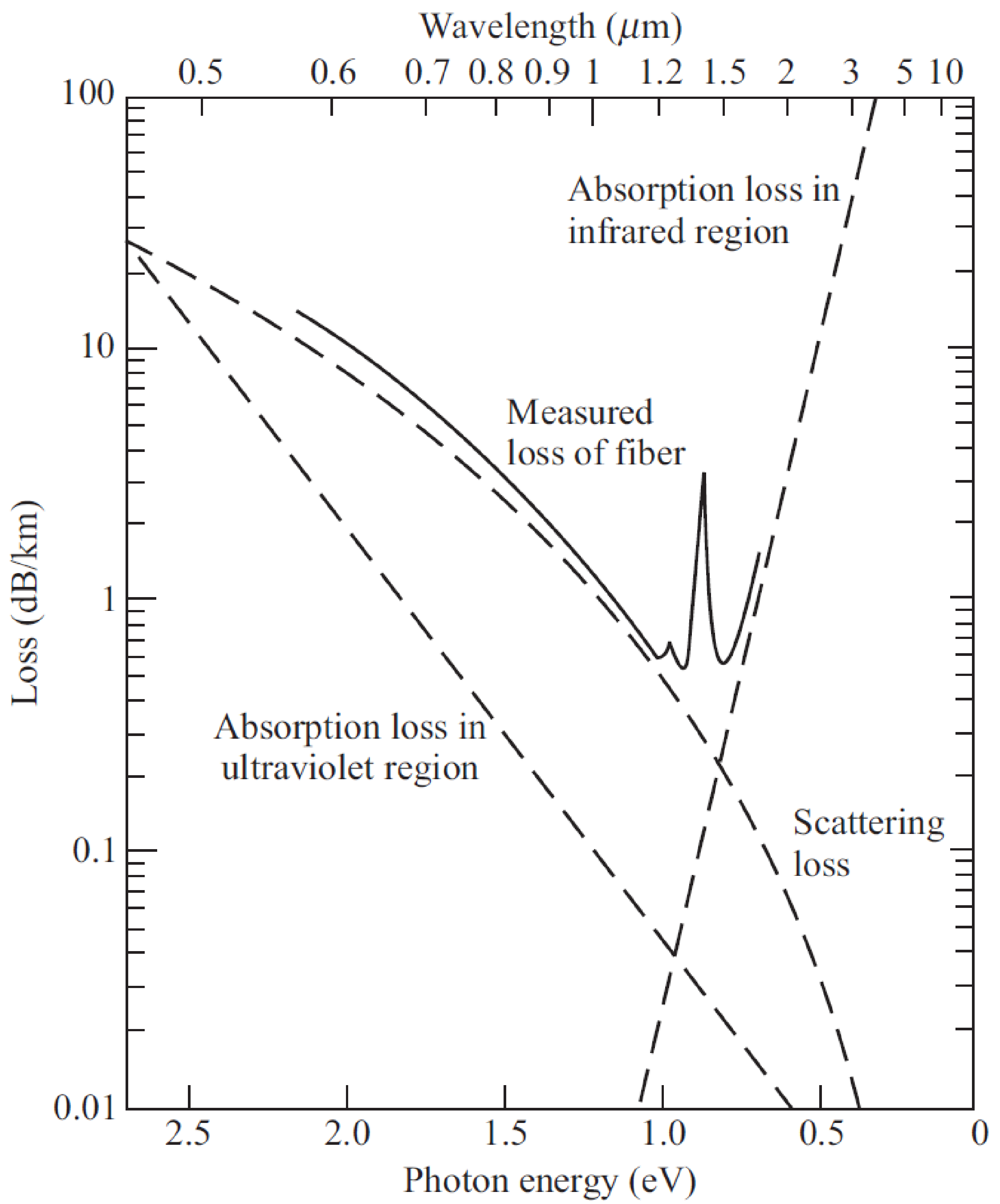
- Small (compared to wavelength) variation in material density, chemical composition, and structural inhomogeneity scatter light in other directions and absorb energy from guided optical wave.
- The essential mechanism is the Rayleigh scattering. Since the black body radiation classically is proportional to λ^{-4}, the attenuation coefficient due to Rayleigh scattering is approximately proportional to λ^{-4}.

$$\alpha_{\text{scat}} = \frac{8\pi^3}{3\lambda^4}(n^2 - 1)^2 \, k_B T_f \beta_T \qquad \alpha_{\text{scat}} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T$$

$$h = 6.626 \times 10^{-34} \text{ Js}, \quad k_B = 1.3806 \times 10^{-23} \text{ JK}^{-1}, \; T: \text{Temperature}$$

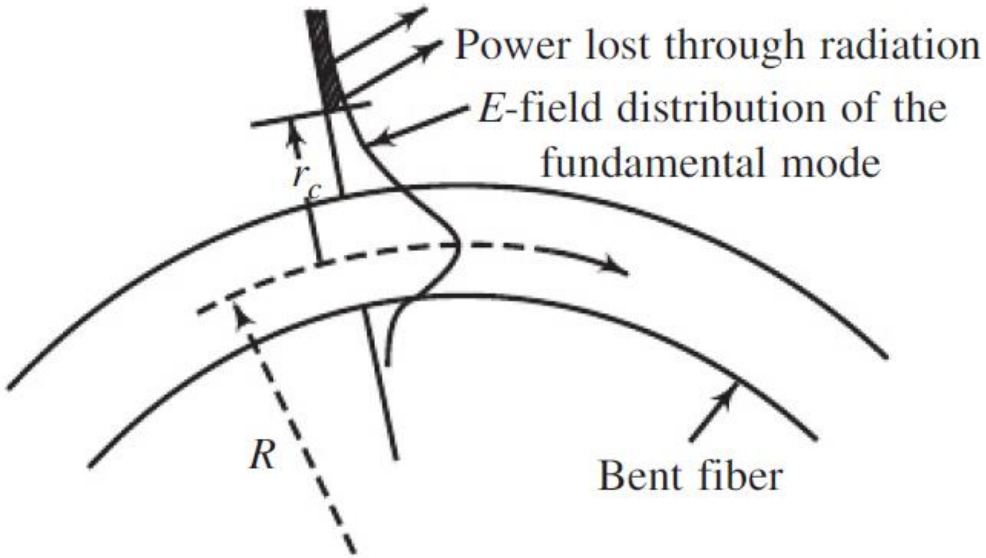
where p is the photo-elastic coefficient

β_T is the isothermal compressibility of the material


Wavelength (μm)
0.5
0.6
0.7
0.8
0.9
1
1.2
1.5
2
3
5
10
100
10
1
0.1
0.01
Loss (dB/km)
Absorption loss in infrared region
Measured loss of fiber
Absorption loss in ultraviolet region
Scattering loss
2.5
2.0
1.5
1.0
0.5
0
Photon energy (eV)

Bending loss

- An optical fiber tends to radiate propagating power whenever it is bent. Two types of bends
  - macro-bends with radii much larger than the fiber diameter and
  - random micro-bends of the fiber axis that may arise because of faulty cabling.
- Every guided core mode has a modal electric-field distribution that has a tail extending into the cladding. This evanescent field decays exponentially with distance from the core.
- the optical energy in the tail beyond r_c is lost through radiation



$$M_{\text{eff}} = M_\infty \left\{ 1 - \frac{\alpha+2}{2\alpha\Delta} \left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR} \right)^{2/3} \right] \right\}$$

- The amount of optical radiation from a bent fiber depends on the field strength at r_c and on the radius of curvature R.
- Since higher-order modes are bound less tightly to the fiber core than lower order modes, the higher-order modes will radiate out of the fiber first.

EXAMPLE PROBLEM

- Consider a graded-index multimode fiber for which the index profile α = 2.0, the core index n_1= 1.480, the core-cladding index difference Δ = 0.01, and the core radius a = 25 μm. If the radius of curvature of the fiber is R = 1.0 cm, what percentage of the modes remain in the fiber at a 1300-nm wavelength?

$$\frac{M_{\text{eff}}}{M_\infty} = 1 - \frac{\alpha + 2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR}\right)^{2/3}\right]$$

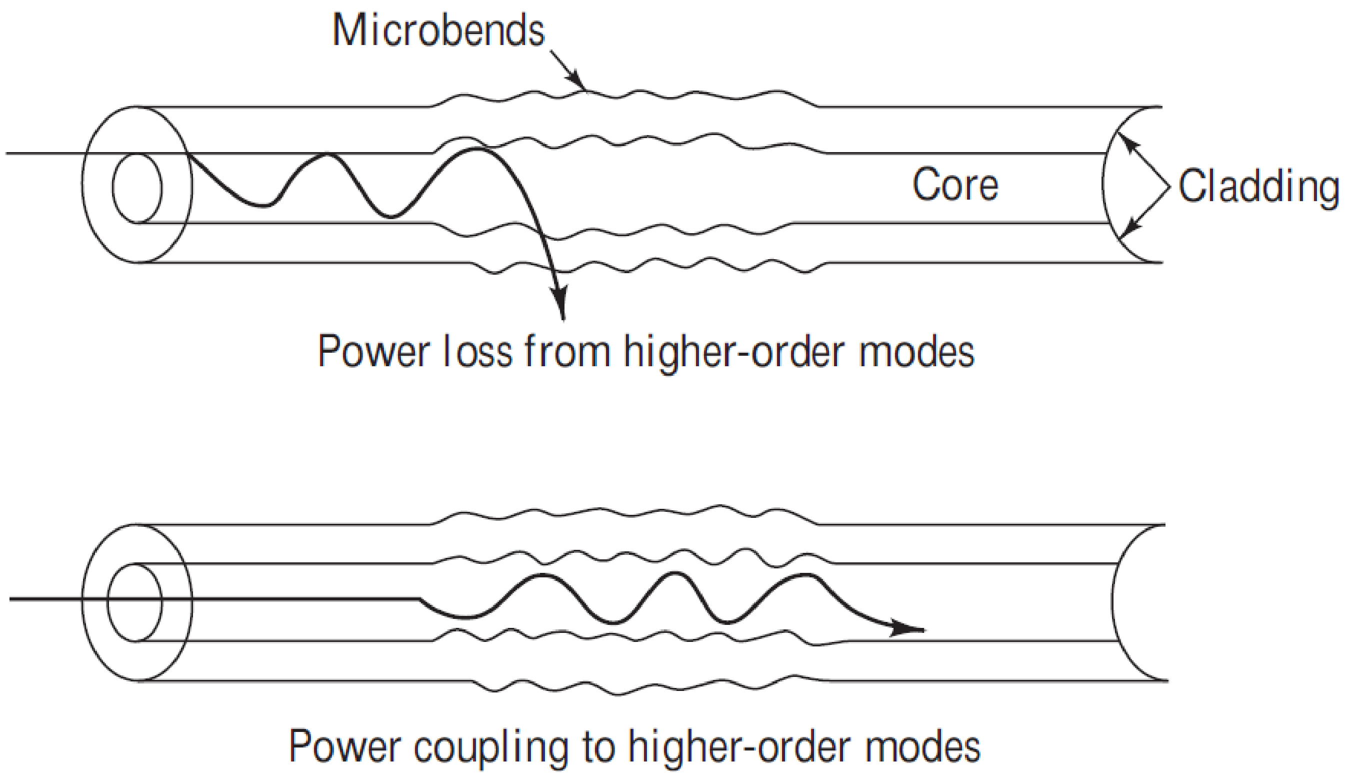
$$= 1 - \frac{1}{.01}\left[\frac{2(25)}{10000} + \left(\frac{3(1.3)}{2(1.465)2\pi(10000)}\right)^{2/3}\right]$$

$$= 0.42$$

Thus 42 percent of the modes remain in this fiber at a 1.0-cm bend radius.

MICRO-BENDING LOSS

- The micro-bends are caused by manufacturing defects which are in the form of non-uniformities in the core radius or in the lateral pressure created by the cabling of the fiber. The effect of mode coupling in multimode fibers on pulse broadening can be significant for long fibers.
- Micro-bend losses in single-mode fibers can also be excessive if proper care is not taken to minimize them. One way to reduce such losses in single-mode fibers is to choose the V -value near the cut-off value of Vc (e.g., 2.405 for the step-index profile), so that the mode energy is confined mainly to the core.



EXAMPLE

- A certain optical fiber has an attenuation of 0.6 dB/km at 1310 nm and 0.3 dB/km at 1550 nm. Suppose the following two optical signals are launched simultaneously into the fi ber: an optical power of 150 mW at 1310 nm and an optical power of 100 mW at 1550 nm. What are the power levels in mW of these two signals at (a) 8 km and (b) 20 km?

Sol:

Example

A continuous 40-km-long optical fiber link has a loss of 0.4 dB/km.

(a) What is the minimum optical power level that must be launched into the fiber to maintain an optical power level of 2.0 mW at the receiving end?

(b) What is the required input power if the fiber has a loss of 0.6 dB/km?

Sol:

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, Fiber optics and optoelectronics, Oxford University Press 2004