# Signal Degradation in Optical Fibers

Signal Attenuation & Distortion in Optical Fibers

- What are the loss or signal attenuation mechanism in a fiber?
- Why & to what degree do optical signals get distorted as they propagate down a fiber?

- Signal attenuation (fiber loss) largely determines the maximum repeaterless separation between optical transmitter & receiver.
- Signal distortion cause that optical pulses to broaden as they travel along a fiber, the overlap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.

Attenuation (fiber loss)

- Power loss along a fiber:

Z=0
P(0) mW

Z= l
$$P(l) = P(0)e^{-\alpha_p l} \quad \text{mw}$$
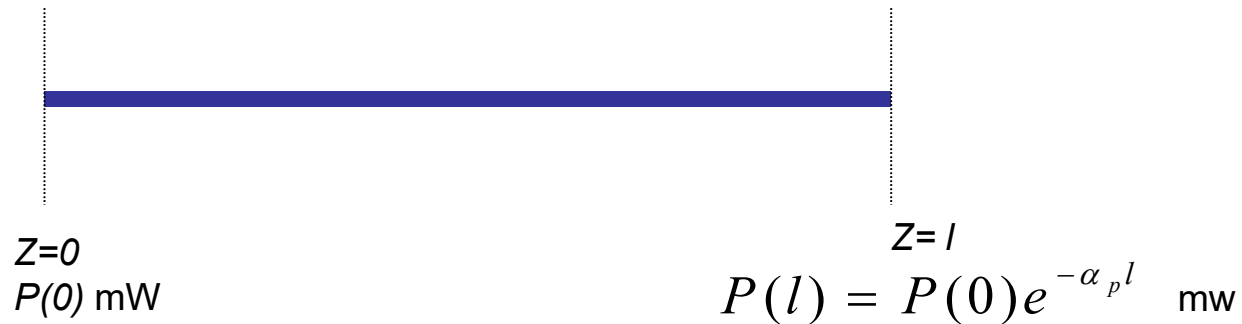
$$P(z) = P(0)e^{-\alpha_p z} \qquad \text{[3-1]}$$

- The parameter α_p is called fiber attenuation coefficient in a units of for example [1/km] or [nepers/km]. A more common unit is [dB/km] that is defined by:

$$\alpha[\text{dB/km}] = \frac{10}{l} \log\left[\frac{P(0)}{P(l)}\right] = 4.343\,\alpha_p [1/\text{km}] \qquad \text{[3-2]}$$
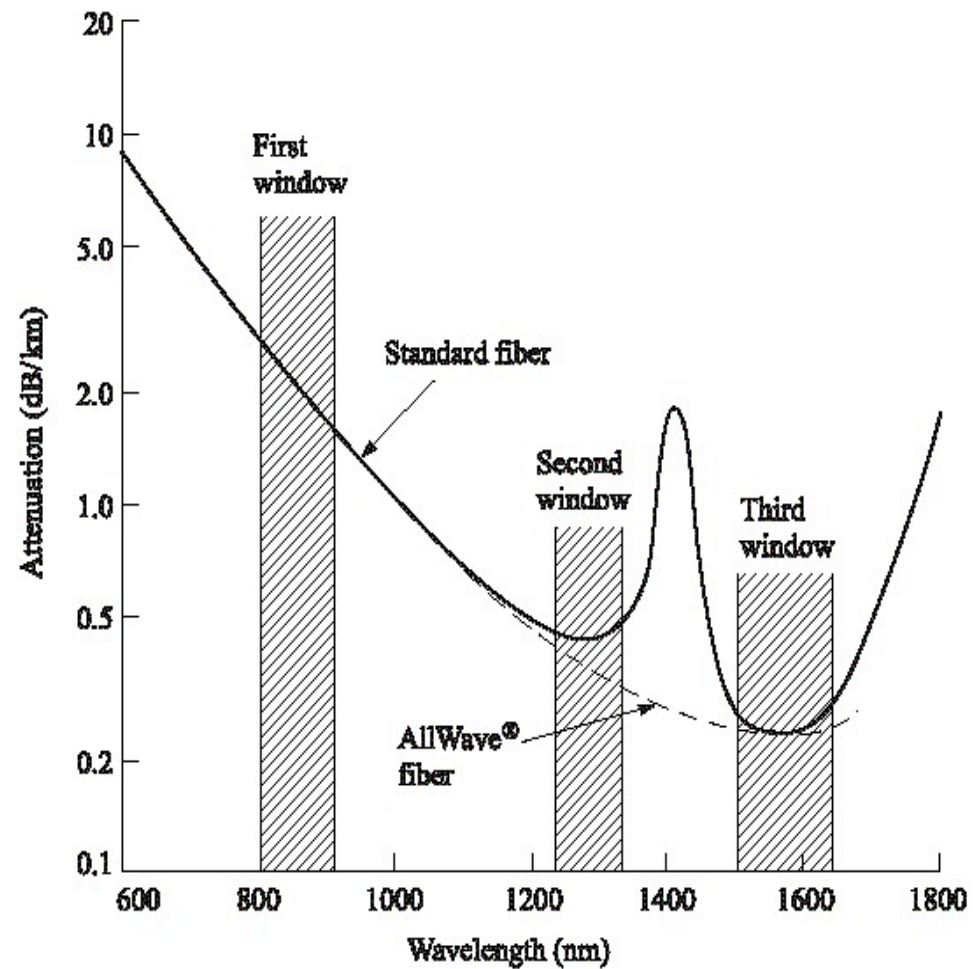
Fiber loss in dB/km

z=0

Z=l

$P(0)[\text{dBm}]$

$$P(l)[\text{dBm}] = P(0)[\text{dBm}] - \alpha[\text{dB/km}] \times l[\text{km}] \qquad \text{[3-3]}$$

- Where [dBm] or dB milliwat is $10\log(P\,[\text{mW}])$.

Optical fiber attenuation vs. wavelength

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Absorption

- Absorption is caused by three different mechanisms:

1- Impurities in fiber material: from transition metal ions (must be in order of ppb) & particularly from OH ions with absorption peaks at wavelengths 2700 nm, 400 nm, 950 nm & 725nm.

2- Intrinsic absorption (fundamental lower limit): electronic absorption band (UV region) & atomic bond vibration band (IR region) in basic SiO_2.

3- Radiation defects

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} (this is true for wavelength typically greater than 5 micrometer), the attenuation coefficient due to Rayleigh scattering is approximately proportional to λ^{-4}. This seems to me not precise, where the attenuation of fibers at 1.3 & 1.55 micrometer can be exactly predicted with Planck's formula & can not be described with Rayleigh-Jeans law. Therefore I believe that the more accurate formula for scattering loss is
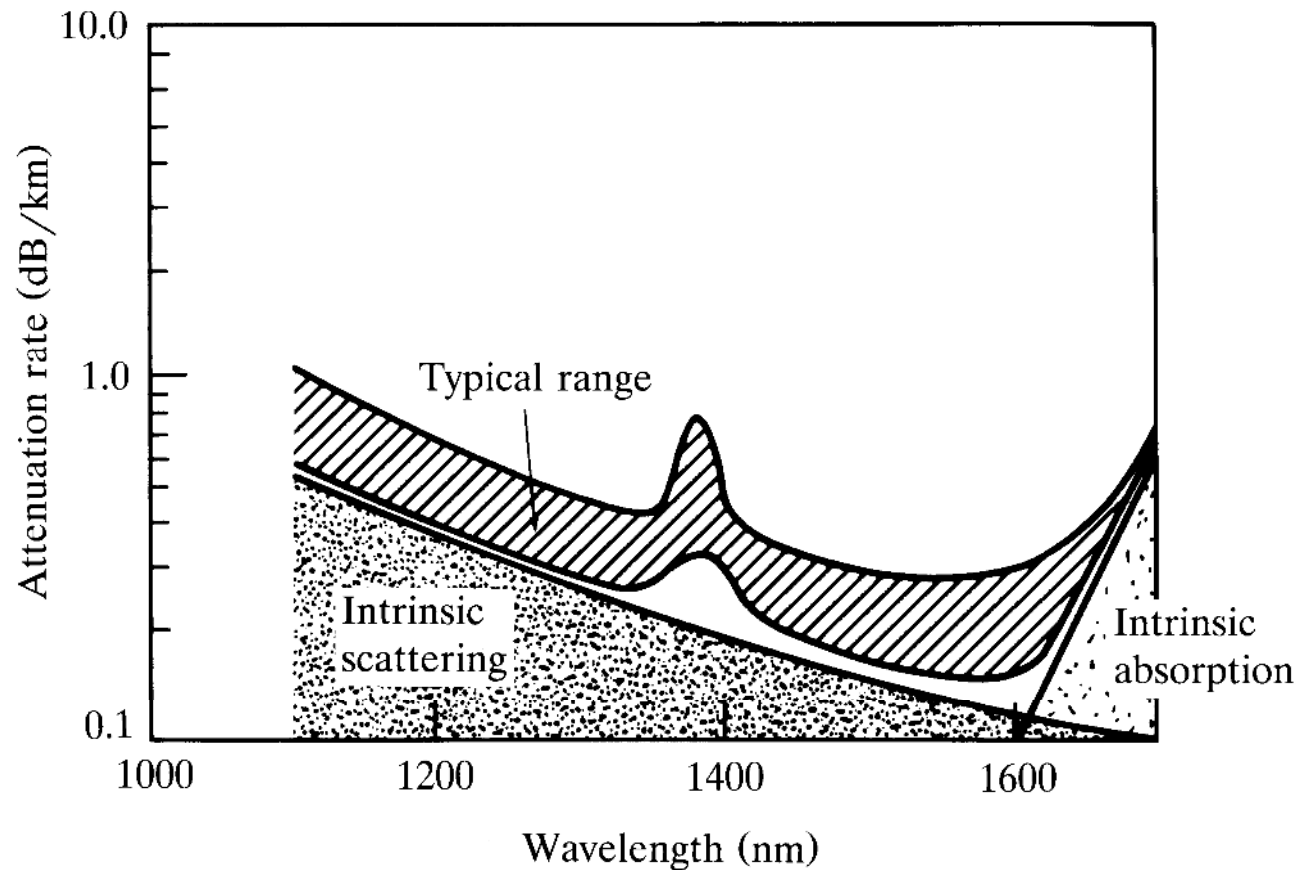
$$\alpha_{scat} \propto \lambda^{-5} \left[\exp(\frac{hc}{\lambda k_B T}) \right]^{-1}$$

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

Absorption & scattering losses in fibers
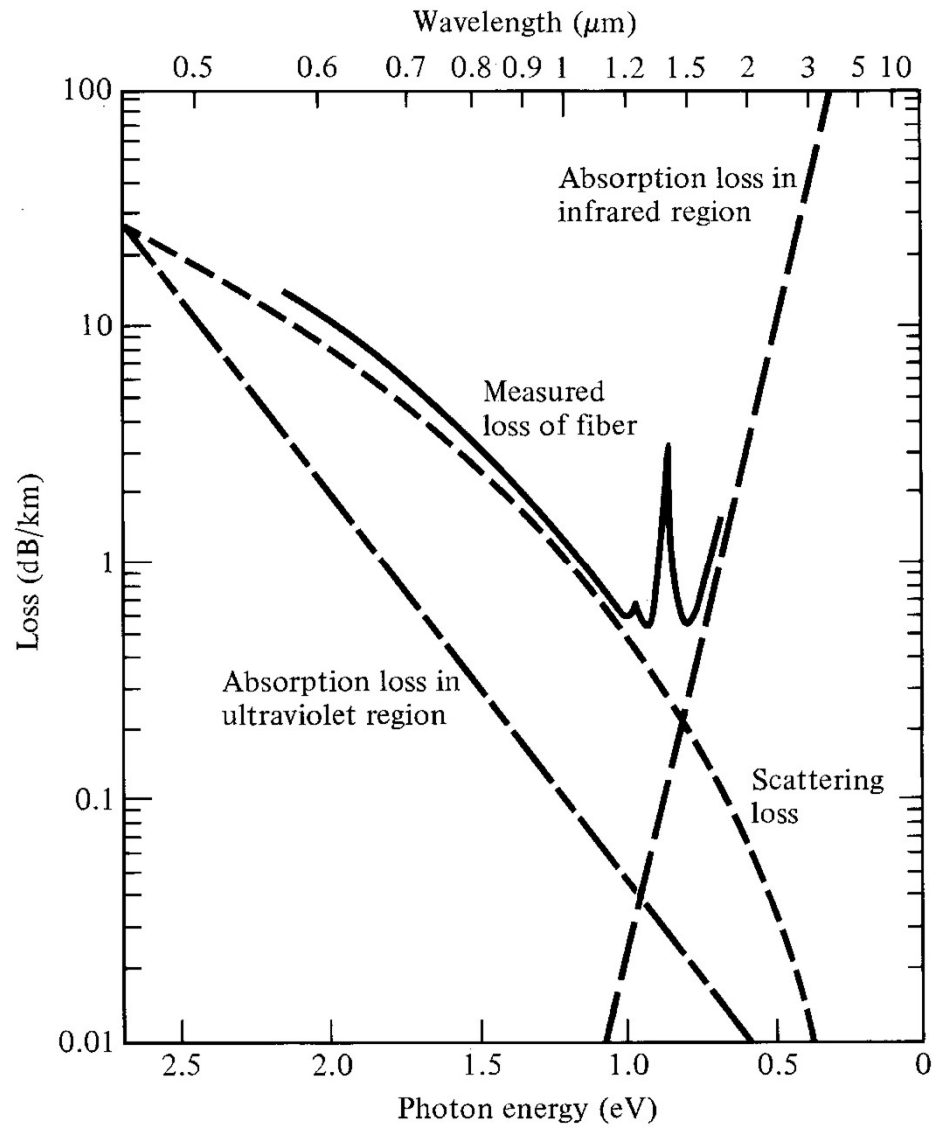
Typical spectral absorption & scattering attenuations for a single mode-fiber
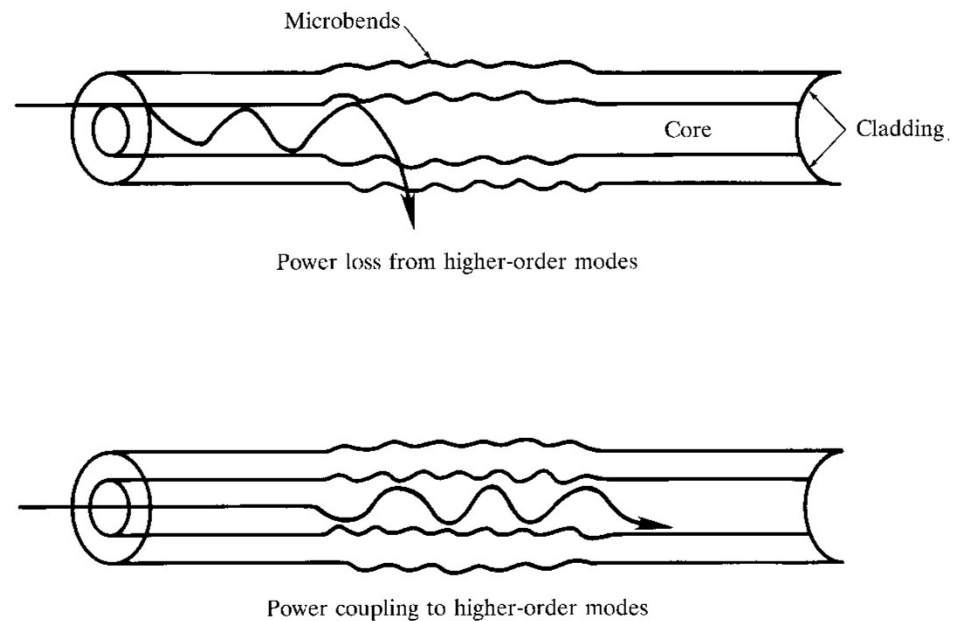
Bending Loss (Macrobending & Microbending)

- **Macrobending Loss**: The curvature of the bend is much larger than fiber diameter. Lightwave suffers sever loss due to radiation of the evanescent field in the cladding region. As the radius of the curvature decreases, the loss increases exponentially until it reaches at a certain critical radius. For any radius a bit smaller than this point, the losses suddenly becomes extremely large. Higher order modes radiate away faster than lower order modes.

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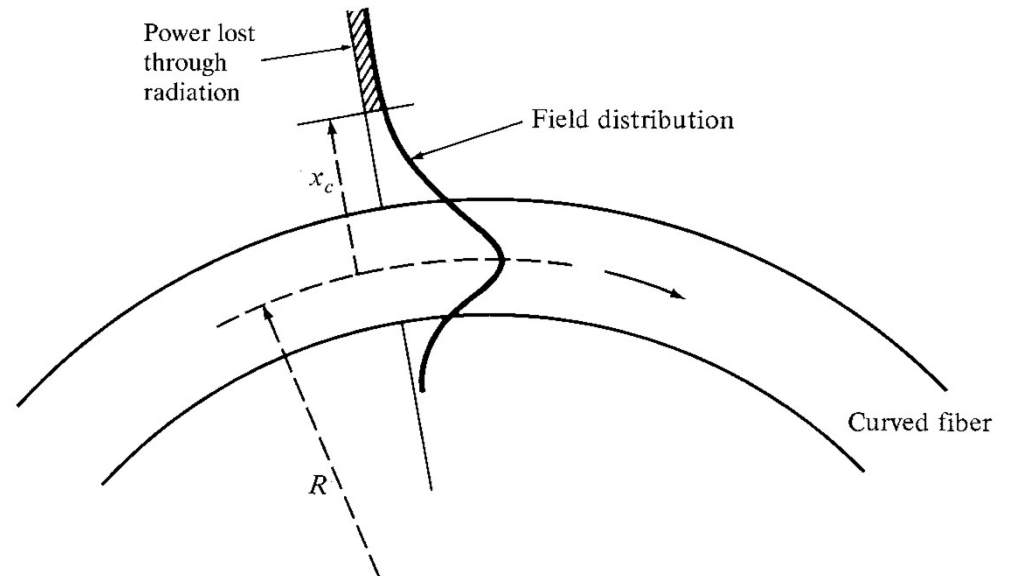
Microbending Loss

- **Microbending Loss:**
  microscopic bends of the fiber
  axis that can arise when the
  fibers are incorporated into
  cables. The power is dissipated
  through the microbended fiber,
  because of the repetitive
  coupling of energy between
  guided modes & the leaky or
  radiation modes in the fiber.

Microbends

Core

Cladding

Power loss from higher-order modes

Power coupling to higher-order modes

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Dispersion in Optical Fibers

- **Dispersion**: Any phenomenon in which the velocity of propagation of any electromagnetic wave is wavelength dependent.

- In communication, dispersion is used to describe any process by which any electromagnetic signal propagating in a physical medium is degraded because the various wave characteristics (i.e., frequencies) of the signal have different propagation velocities within the physical medium.

- There are 3 dispersion types in the optical fibers, in general:

  1- Material Dispersion
  2- Waveguide Dispersion
  3- Polarization-Mode Dispersion

  Material & waveguide dispersions are main causes of Intramodal Dispersion.

Group Velocity

- Wave Velocities:

- 1- **Plane wave velocity**: For a plane wave propagating along z-axis in an <u>unbounded homogeneous</u> region of refractive index n_1 , which is represented by $\exp(j\omega t - jk_1 z)$, the velocity of constant phase plane is:

$$v = \frac{\omega}{k_1} = \frac{c}{n_1} \qquad \text{[3-4]}$$

- 2- **Modal wave phase velocity**: For a modal wave propagating along z-axis represented by $\exp(j\omega t - j\beta z)$, the velocity of constant phase plane is:

$$v_p = \frac{\omega}{\beta} \qquad \text{[3-5]}$$

3- For transmission system operation the most important & useful type of velocity is the **group velocity,** V_g . This is the actual velocity which the signal information & energy is traveling down the fiber. It is always less than the speed of light in the medium. The observable delay experiences by the optical signal waveform & energy, when traveling a length of l along the fiber is commonly referred to as **group delay.**

Group Velocity & Group Delay

- The group velocity is given by:

$$V_g = \frac{d\omega}{d\beta} \qquad \text{[3-6]}$$

- The group delay is given by:

$$\tau_g = \frac{l}{V_g} = l\frac{d\beta}{d\omega} \qquad \text{[3-7]}$$

- It is important to note that all above quantities depend both on **frequency** & the **propagation mode**. In order to see the effect of these parameters on group velocity and delay, the following analysis would be helpful.

Input/Output signals in Fiber Transmission System

- The optical signal (complex) waveform at the input of fiber of length l is $f(t)$. The propagation constant of a particular modal wave carrying the signal is $\beta(\omega)$. Let us find the output signal waveform $g(t)$.

  $\Delta\omega$ is the optical signal bandwidth.

z-=0

Z=l

$$f(t) = \int_{\omega_c - \Delta\omega}^{\omega_c + \Delta\omega} \tilde{f}(\omega) e^{j\omega t} \, d\omega \qquad\qquad \text{[3-8]}$$

$$g(t) = \int_{\omega_c - \Delta\omega}^{\omega_c + \Delta\omega} \tilde{f}(\omega) e^{j\omega t - j\beta(\omega)l} \, d\omega \qquad\qquad \text{[3-9]}$$

If $\Delta\omega << \omega_c$

$$\beta(\omega) = \beta(\omega_c) + \frac{d\beta}{d\omega}\bigg|_{\omega=\omega_c} (\omega - \omega_c) + \frac{1}{2}\frac{d^2\beta}{d\omega^2}\bigg|_{\omega=\omega_c} (\omega - \omega_c)^2 + ... \qquad [3\text{-}10]$$

$$g(t) = \int_{\omega_c - \Delta\omega/2}^{\omega_c + \Delta\omega/2} \widetilde{f}(\omega) e^{j\omega t - j\beta(\omega)l} \, d\omega \approx \int_{\omega_c - \Delta\omega/2}^{\omega_c + \Delta\omega/2} \widetilde{f}(\omega) e^{j\omega t - j[\beta(\omega_c) + \frac{d\beta}{d\omega}|_{\omega=\omega_c}(\omega - \omega_c)]l} \, d\omega$$

$$\approx e^{-j\beta(\omega_c)l} \int_{\omega_c - \Delta\omega/2}^{\omega_c + \Delta\omega/2} \widetilde{f}(\omega) e^{j\omega(t - l\frac{d\beta}{d\omega}|_{\omega=\omega_c})} \, d\omega$$

$$= e^{-j\beta(\omega_c)l} f(t - l\frac{d\beta}{d\omega}\bigg|_{\omega=\omega_c}) = e^{-j\beta(\omega_c)l} f(t - \tau_g) \qquad [3\text{-}11]$$

$$\tau_g = l\frac{d\beta}{d\omega}\bigg|_{\omega=\omega_c} = \frac{l}{V_g} \qquad [3\text{-}14]$$
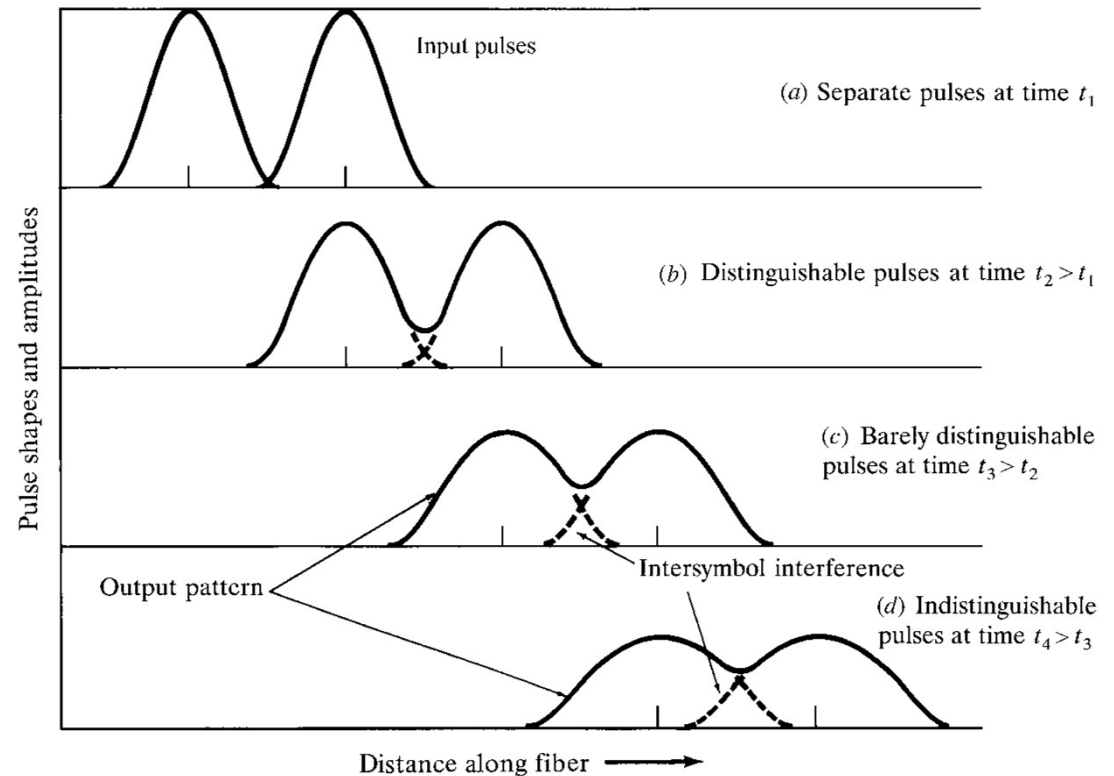
Intramodal Dispersion

- As we have seen from Input/output signal relationship in optical fiber, the output is proportional to the delayed version of the input signal, and the delay is inversely proportional to the group velocity of the wave. Since the propagation constant, $\beta(\omega)$, is frequency dependent over band width $\Delta\omega$ sitting at the center frequency ω_c, at each frequency, we have one propagation constant resulting in a specific delay time. As the output signal is collectively represented by group velocity & group delay this phenomenon is called **intramodal dispersion or Group Velocity Dispersion (GVD)**. **This phenomenon arises due to a finite bandwidth of the optical source, dependency of refractive index on the wavelength and the modal dependency of the group velocity**.

- In the case of optical pulse propagation down the fiber, GVD causes pulse broadening, leading to Inter Symbol Interference (ISI).

Dispersion & ISI

A measure of information capacity of an optical fiber for digital transmission is usually specified by the **bandwidth distance product** $BW \times L$ **in GHz.km.**

For multi-mode step index fiber this quantity is about 20 MHz.km, for graded index fiber is about 2.5 GHz.km & for single mode fibers are higher than 10 GHz.km.

Input pulses

(a) Separate pulses at time t_1

(b) Distinguishable pulses at time $t_2 > t_1$

(c) Barely distinguishable pulses at time $t_3 > t_2$

Intersymbol interference

Output pattern

(d) Indistinguishable pulses at time $t_4 > t_3$

Pulse shapes and amplitudes

Distance along fiber

How to characterize dispersion?

- Group delay per unit length can be defined as:

$$\frac{\tau_g}{L} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \qquad \text{[3-15]}$$

- 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 $\dfrac{d\tau_g}{d\lambda}$. For spectral components which are $\delta\lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta\tau$ over a distance L is:

$$\delta\tau = \left|\frac{d\tau_g}{d\lambda}\right|\delta\lambda = -\frac{L}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\delta\lambda$$

$$= \left|\frac{d\tau}{d\omega}\right|\delta\omega = \frac{d}{d\omega}\left(\frac{L}{V_g}\right)\delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega \qquad \text{[3-16]}$$

- $\beta_2 \equiv \dfrac{d^2\beta}{d\omega^2}$ is called **GVD parameter,** and shows how much a light pulse broadens as it travels along an optical fiber. The more common parameter is called **Dispersion,** and can be defined as the delay difference per unit length per unit wavelength as follows:
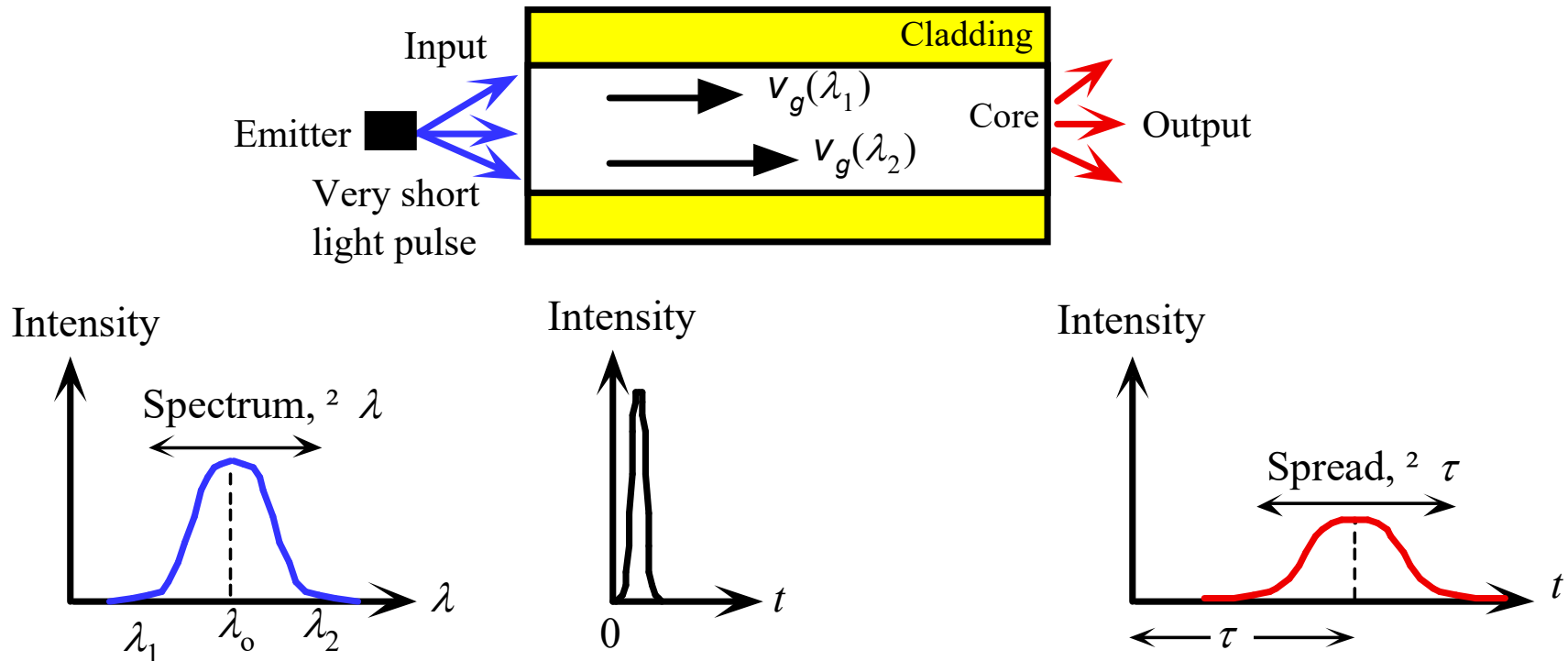
$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad \text{[3-17]}$$

- 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_g can be well approximated by:

$$\sigma_g \approx \left|\frac{d\tau_g}{d\lambda}\right|\sigma_\lambda = DL\sigma_\lambda \qquad \text{[3-18]}$$

- *D* has a typical unit of [ps/(nm.km)].

Material Dispersion

Input

Cladding

$v_g(\lambda_1)$

Core   Output

$v_g(\lambda_2)$

Emitter

Very short
light pulse

Intensity

Spectrum, $\Delta\lambda$

λ_1 λ_o λ_2 λ

Intensity

0 t

Intensity

Spread, $\Delta\tau$

$\leftarrow \tau \rightarrow$ t

All excitation sources are inherently non-monochromatic and emit within a spectrum, $\Delta\lambda$, of wavelengths. Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

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Material Dispersion

- The refractive index of the material varies as a function of wavelength, $n(\lambda)$

- Material-induced dispersion for a plane wave propagation in homogeneous medium of refractive index n:

$$\tau_{mat} = L\frac{d\beta}{d\omega} = -\frac{\lambda^2}{2\pi c}L\frac{d\beta}{d\lambda} = -\frac{\lambda^2}{2\pi c}L\frac{d}{d\lambda}\left[\frac{2\pi}{\lambda}n(\lambda)\right]$$

$$= \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \qquad\qquad \text{[3-19]}$$

- The pulse spread due to material dispersion is therefore:

$$\sigma_g \approx \left|\frac{d\tau_{mat}}{d\lambda}\right|\sigma_\lambda = \frac{L\sigma_\lambda}{c}\left|\lambda\frac{d^2 n}{d\lambda^2}\right| = L\sigma_\lambda\left|D_{mat}(\lambda)\right| \qquad\qquad \text{[3-20]}$$

$D_{mat}(\lambda)$ is material dispersion

Material Dispersion Diagrams
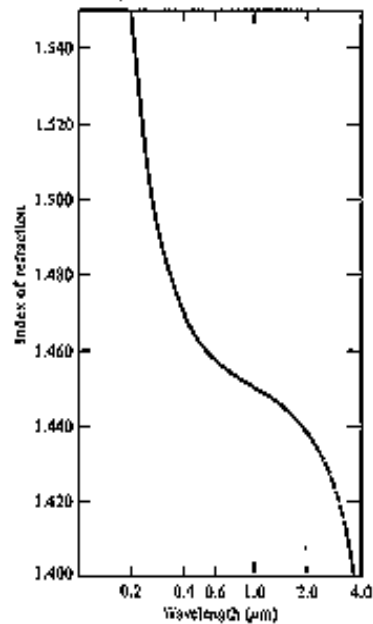
FIGURE 3-12
Variations in the index of refraction as a function of the optical wavelength for silica. (Reproduced with permission from I. H. Malitson, *J. Opt. Soc. Amer.*, vol. 55, pp. 1205–1209, Oct. 1965.)
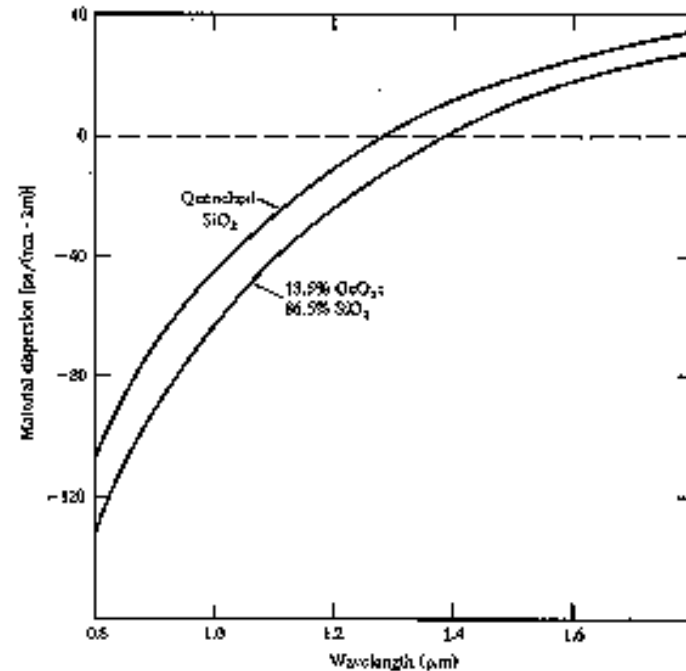

FIGURE 3-13
Material dispersion as a function of optical wavelength for pure silica and 13.5 percent GeO₂/86.5 percent SiO₂. (Reproduced with permission from J. W. Fleming, *Electron. Lett.*, vol. 14, pp. 326–328, May 1978.)

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Waveguide Dispersion

- 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:

$$b = \frac{\beta^2/k^2 - n_2^2}{n_1^2 - n_2^2} \approx \frac{\beta/k - n_2}{n_1 - n_2} \qquad \text{[3-21]}$$

- solving for propagation constant:

$$\beta \approx n_2 k(1 + b\Delta) \qquad \text{[3-22]}$$

- Using V number:

$$V = ka(n_1^2 - n_2^2)^{1/2} \approx kan_2\sqrt{2\Delta} \qquad \text{[3-23]}$$

Waveguide Dispersion

- Delay time due to waveguide dispersion can then be expressed as:

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(Vb)}{dV}\right] \qquad \text{[3-24]}$$
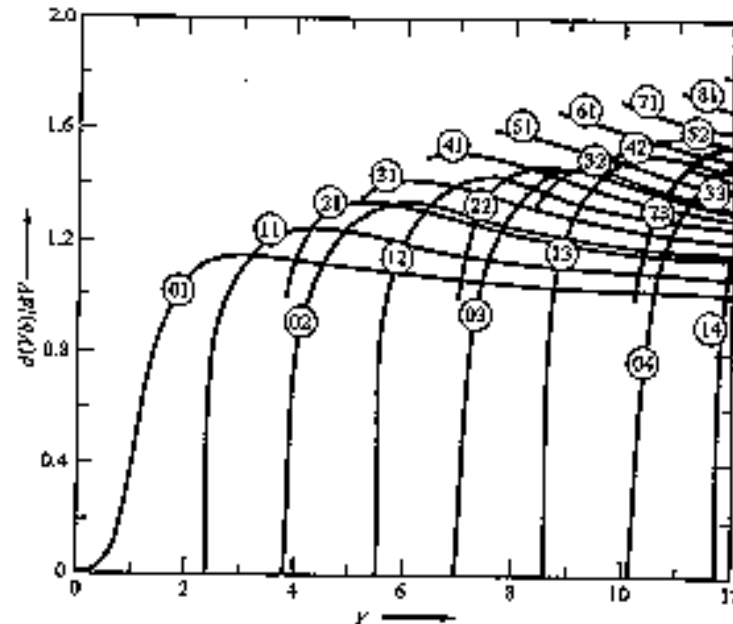
FIGURE 3-14
The group delay arising from waveguide dispersion as a function of the V number for a step-index optical fiber. The curve numbers μ designate the $LP_{\mu\nu}$ modes. (Reproduced with permission from Gloge.[37])

Waveguide dispersion in single mode fibers

- For single mode fibers, waveguide dispersion is in the same order of material dispersion. The pulse spread can be well approximated as:

$$\sigma_{wg} \approx \left| \frac{d\tau_{wg}}{d\lambda} \right| \sigma_\lambda = L\sigma_\lambda \left| D_{wg}(\lambda) \right| = \frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{dV^2} \qquad \text{[3-25]}$$
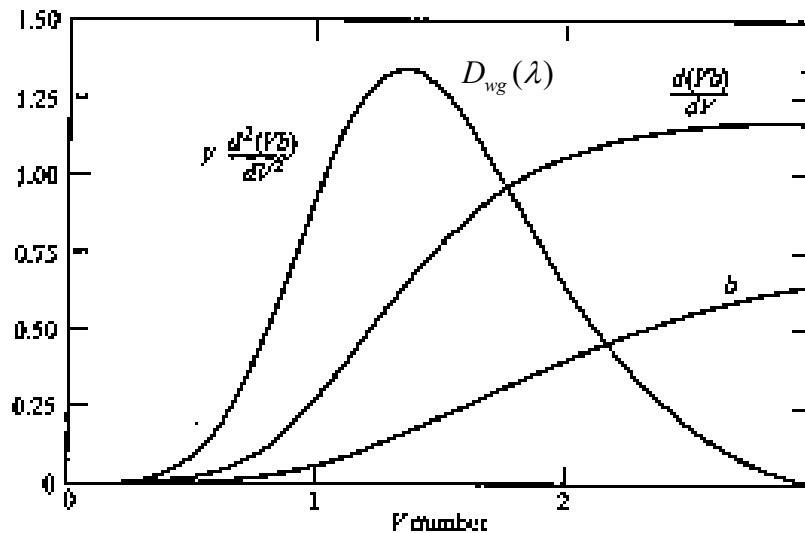
FIGURE 3-15
The waveguide parameter b and its derivatives $d(Vb)/dV$ and $V\,d^2(Vb)/dV^2$ plotted as a function of the V number for the HE_{11} mode.

Polarization Mode dispersion

Intensity

Output light pulse

$\Delta\tau$

$n_{1y} \; /\!/ \; y$

Core

E_x

$\Delta\tau$ = Pulse spread

E_y

E_x

$n_{1x} \; /\!/ \; x$

E_y

z

t

E

Input light pulse
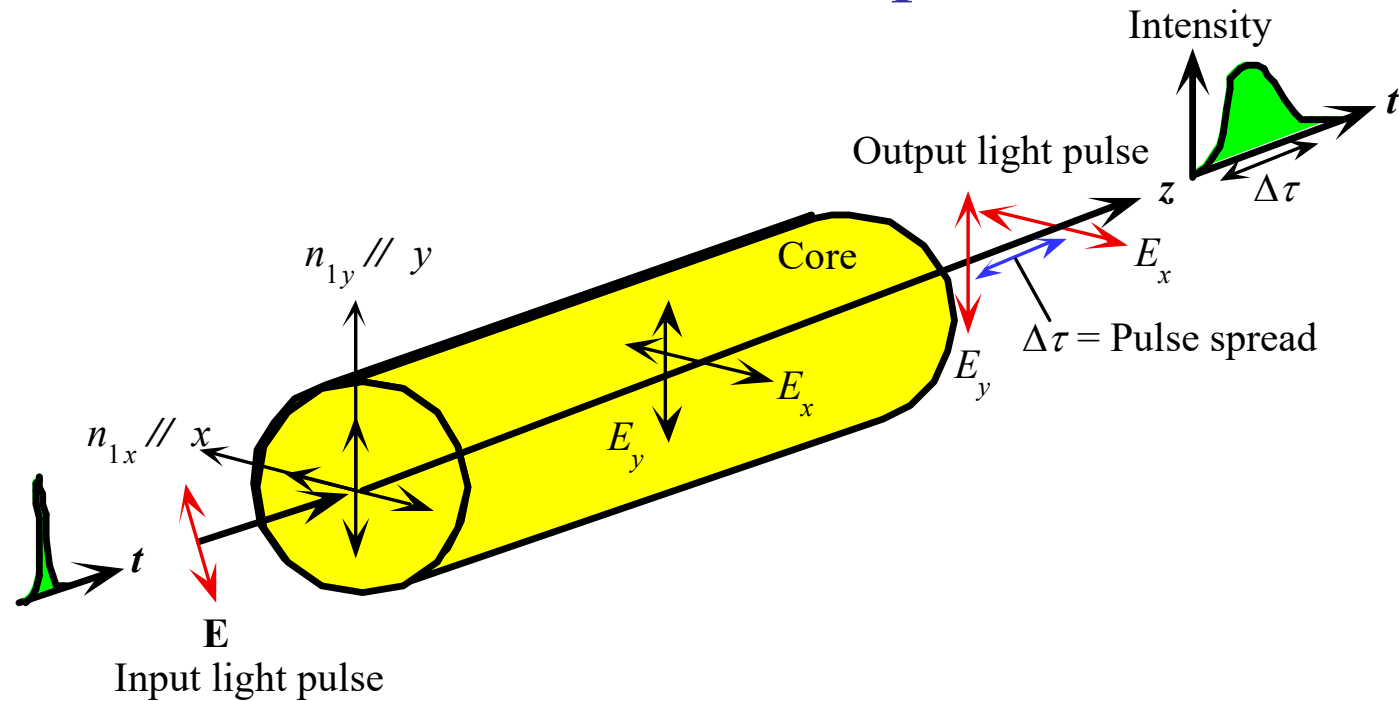
Suppose that the core refractive index has different values along two orthogonal directions corresponding to electric field oscillation direction (polarizations). We can take x and y axes along these directions. An input light will travel along the fiber with E_x and E_y polarizations having different group velocities and hence arrive at the output at different times

Polarization Mode dispersion

- The effects of fiber-birefringence on the polarization states of an optical are another source of pulse broadening. **Polarization mode dispersion** (PMD) is due to slightly different velocity for each polarization mode because of the lack of perfectly symmetric & anisotropicity of the fiber. If the group velocities of two orthogonal polarization modes are v_{gx} and v_{gy} then the differential time delay $\Delta\tau_{pol}$ between these two polarization over a distance L is

$$\Delta\tau_{pol} = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right|$$

[3-26]

- The rms value of the differential group delay can be approximated as:

$$\left\langle \Delta\tau_{pol} \right\rangle \approx D_{PMD} \sqrt{L}$$

[3-27]

Chromatic & Total Dispersion

- Chromatic dispersion includes the material & waveguide dispersions.

$$D_{ch}(\lambda) \approx \left| D_{mat} + D_{wg} \right|$$

$$\sigma_{ch} = D_{ch}(\lambda) L \sigma_\lambda$$

[3-28]

- Total dispersion is the sum of chromatic , polarization dispersion and other dispersion types and the total rms pulse spreading can be approximately written as:

$$D_{total} \approx \left| D_{ch} + D_{pol} + ... \right|$$

$$\sigma_{total} = D_{total} L \sigma_\lambda$$

[3-29]

Total Dispersion, zero Dispersion
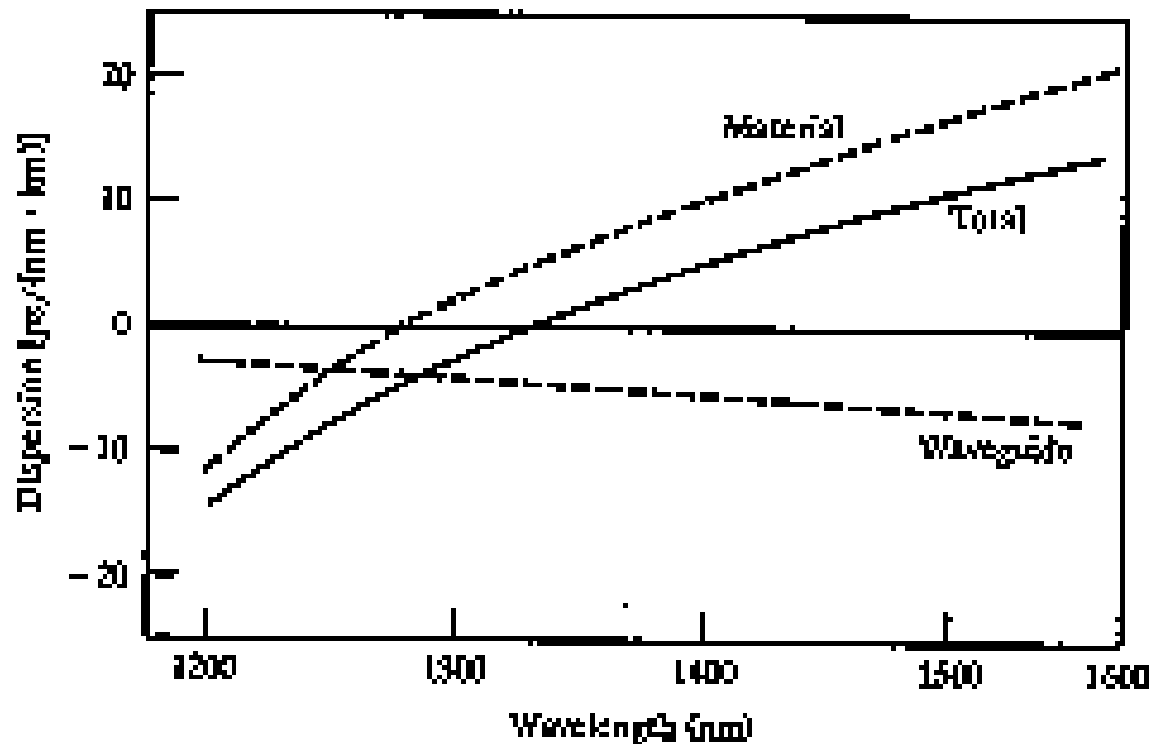
FIGURE 3-16
Examples of the magnitudes of material and waveguide dispersion as a function of optical wavelength for a single-mode fused-silica-core fiber. (Reproduced with permission from Keck,[16] © 1985, IEEE.)

Fact 1) Minimum distortion at wavelength about 1300 nm for single mode silica fiber.
Fact 2) Minimum attenuation is at 1550 nm for sinlge mode silica fiber.
Strategy: shifting the zero-dispersion to longer wavelength for minimum attenuation and dispersion.

Optimum single mode fiber & distortion/attenuation characteristics

Fact 1) Minimum distortion at wavelength about 1300 nm for single mode silica fiber.

Fact 2) Minimum attenuation is at 1550 nm for sinlge mode silica fiber.

Strategy: shifting the zero-dispersion to longer wavelength for minimum attenuation and dispersion by Modifying waveguide dispersion by changing from a simple step-index core profile to more complicated profiles. There are four major categories to do that:

1- 1300 nm optimized single mode step-fibers: matched cladding (mode diameter 9.6 micrometer) and depressed-cladding (mode diameter about 9 micrometer)

2- Dispersion shifted fibers.

3- Dispersion-flattened fibers.

4- Large-effective area (LEA) fibers (less nonlinearities for fiber optical amplifier applications, effective cross section areas are typically greater than $100 \mu \text{m}^2$).
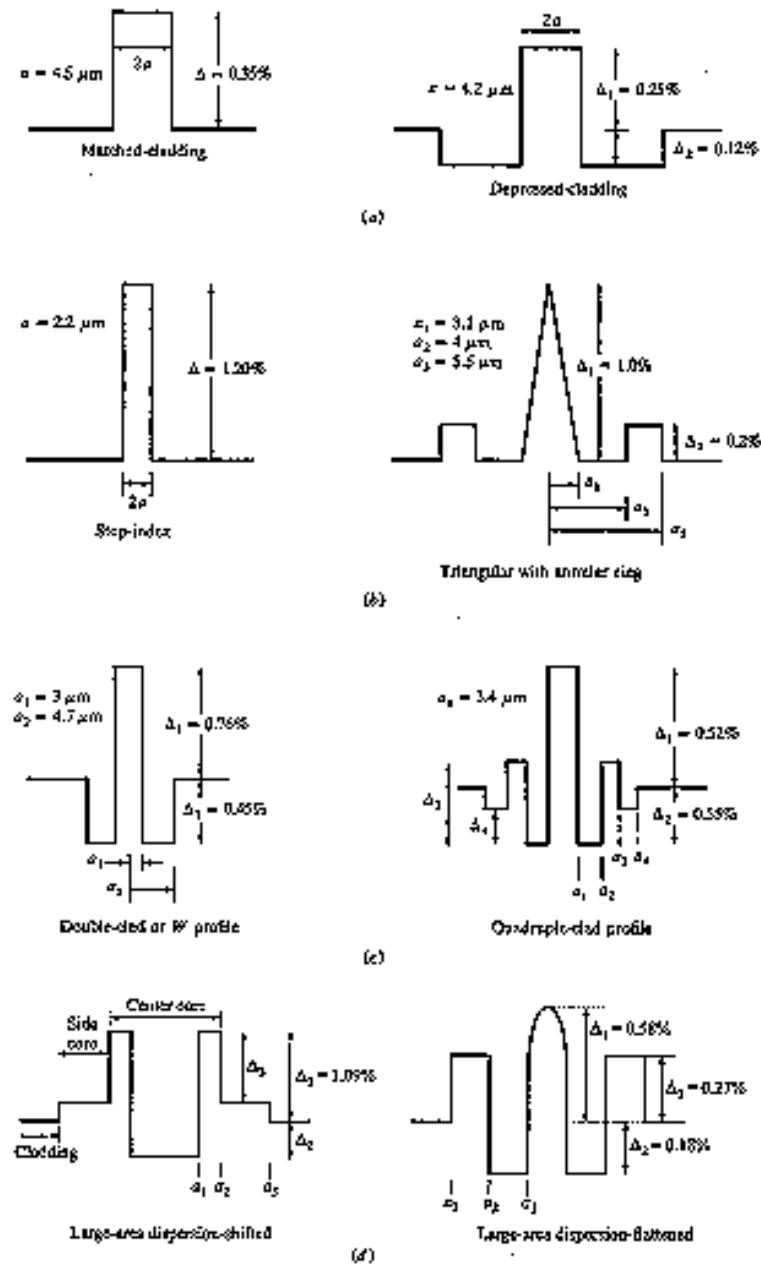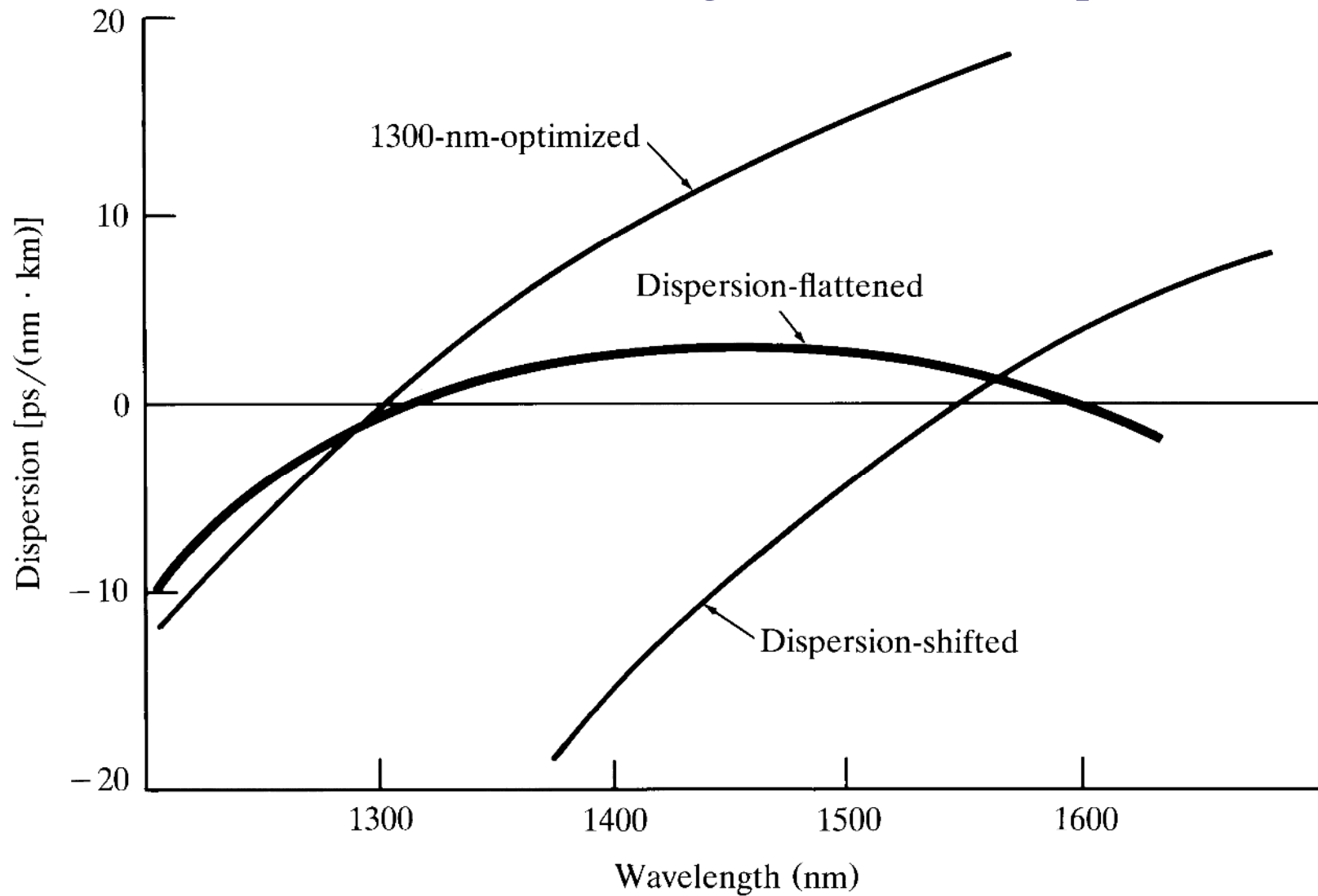
FIGURE 3-22
Representative cross sections of index profiles for (a) 1300-nm-optimized, (b) dispersion-shifted, (c) dispersion-flattened, and (d) large-effective-core-area fibers.

Single mode fiber dispersion

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Single mode fiber dispersion

Figure showing dispersion [ps/(nm · km)] versus Wavelength (nm) curves labeled: 1300-nm-optimized, Dispersion-flattened, Dispersion-shifted.
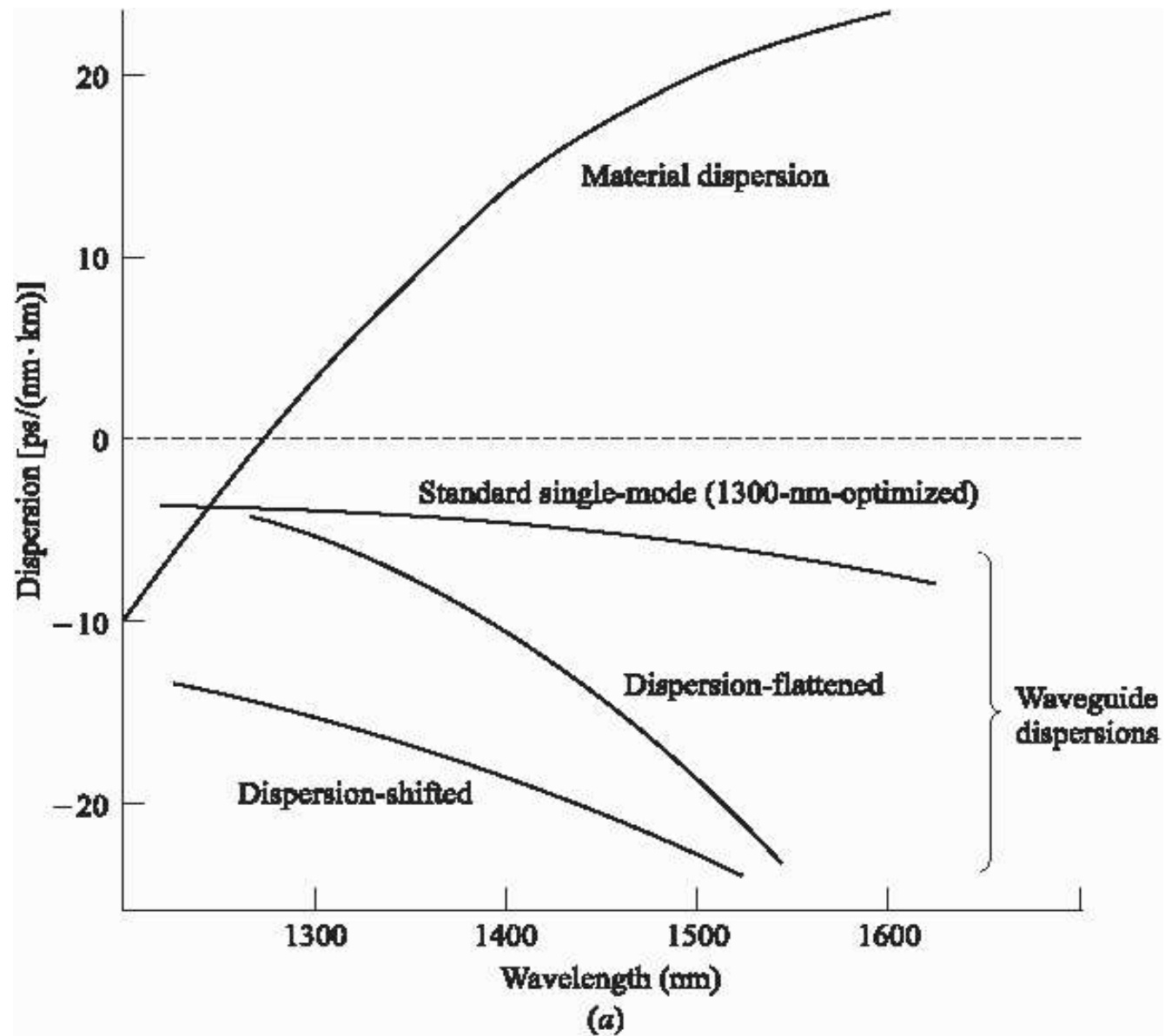
(b)

Single mode Cut-off wavelength & Dispersion

- Fundamental mode is HE_{11} or LP_{01} with V=2.405 and $\lambda_c = \dfrac{2\pi a}{V}\sqrt{n_1^{\,2} - n_2^{\,2}}$

  [3-30]

- Dispersion:

$$D(\lambda) = \frac{d\tau}{d\lambda} \approx D_{mat}(\lambda) + D_{wg}(\lambda)$$ [3-31]

$$\sigma = D(\lambda)L\sigma_\lambda$$ [3-32]

- For non-dispersion-shifted fibers (1270 nm – 1340 nm)
- For dispersion shifted fibers (1500 nm- 1600 nm)

Dispersion for non-dispersion-shifted fibers (1270 nm – 1340 nm)

$$\tau(\lambda) = \tau_0 + \frac{S_0}{8}(\lambda - \frac{\lambda_0^2}{\lambda})^2 \qquad \text{[3-33]}$$

- τ_0 is relative delay minimum at the zero-dispersion wavelength λ_0 , and S_0 is the value of the dispersion slope in $ps/(nm^2.km)$

$$S_0 = S(\lambda_0) = \frac{dD}{d\lambda}\bigg|_{\lambda=\lambda_0} \qquad \text{[3-34]}$$

$$D(\lambda) = \frac{\lambda S_0}{4}\left[1 - (\frac{\lambda_0}{\lambda})^4\right] \qquad \text{[3-35]}$$

Dispersion for dispersion shifted fibers (1500 nm- 1600 nm)

$$\tau(\lambda) = \tau_0 + \frac{S_0}{2}(\lambda - \lambda_0)^2 \qquad \text{[3-36]}$$

$$D(\lambda) = (\lambda - \lambda_0)S_0 \qquad \text{[3-37]}$$
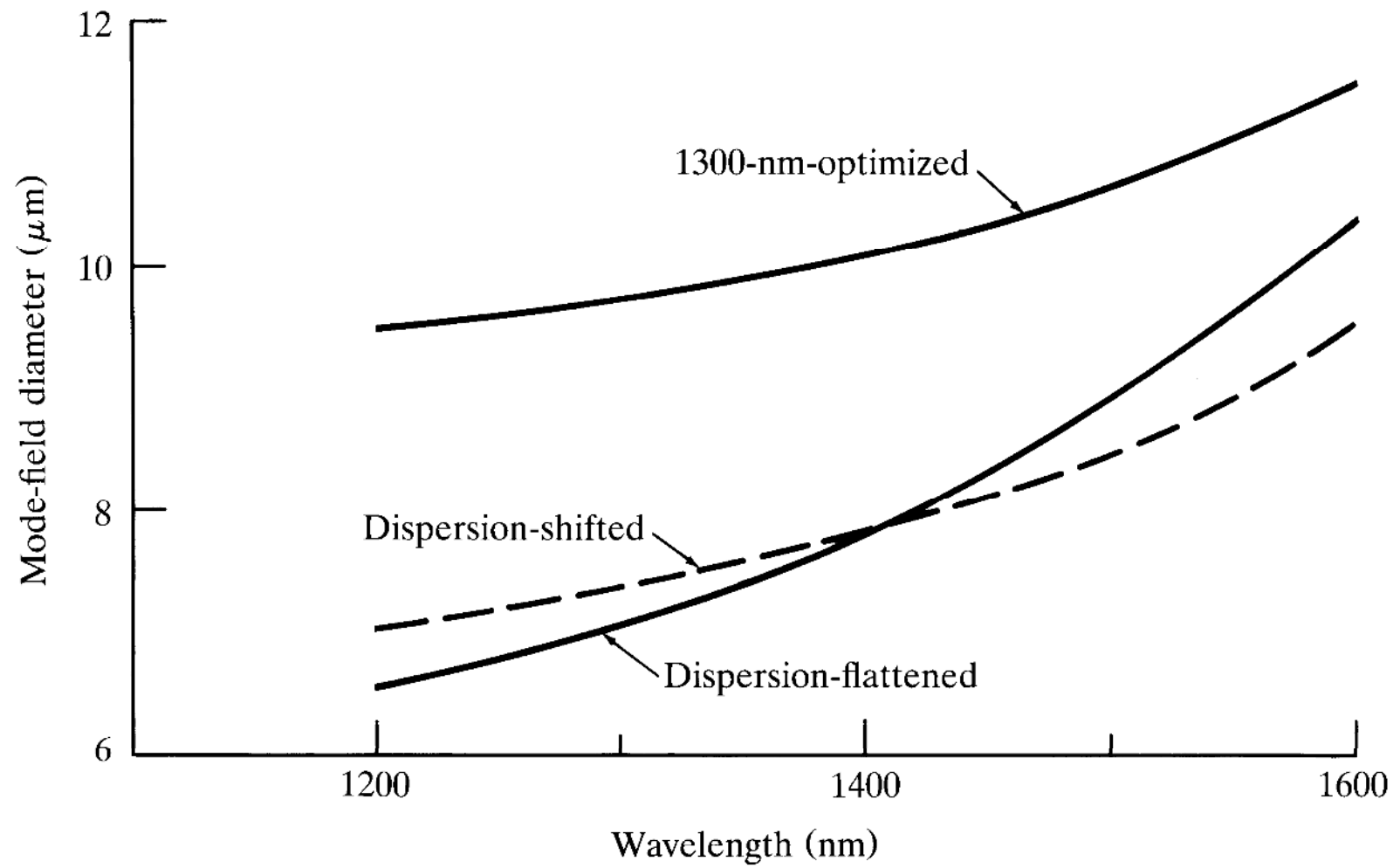
Example of dispersion
Performance curve for
Set of SM-fiber
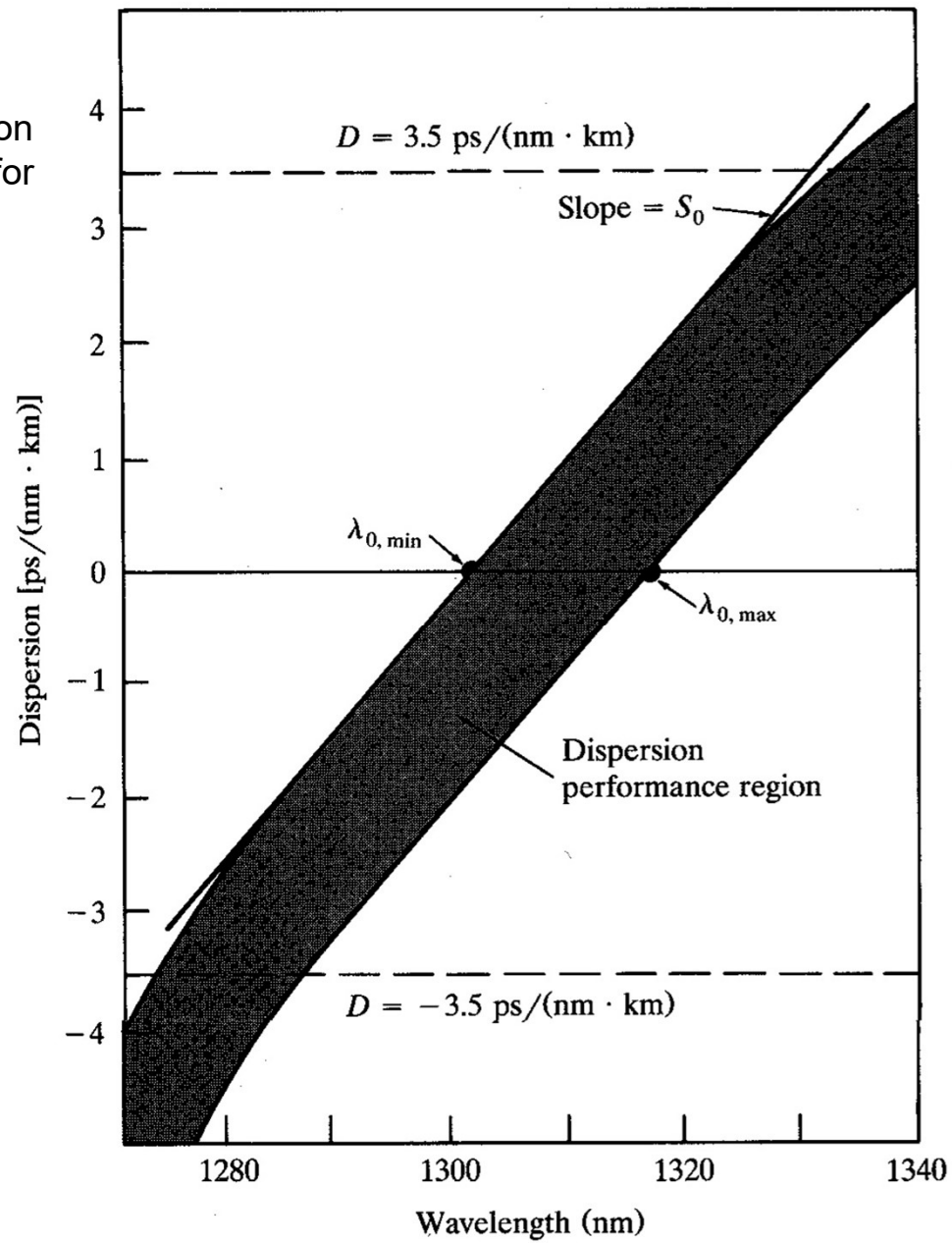
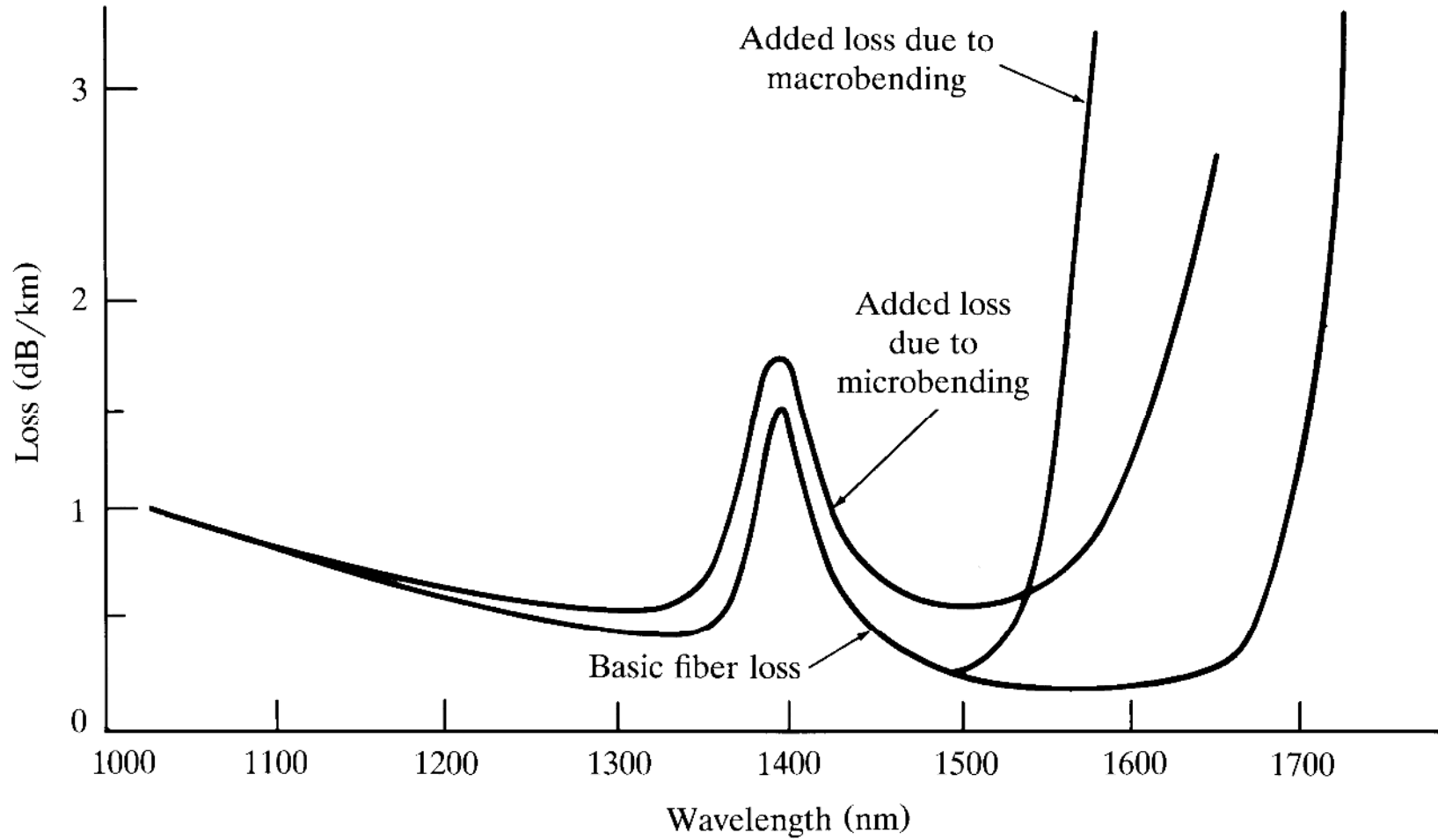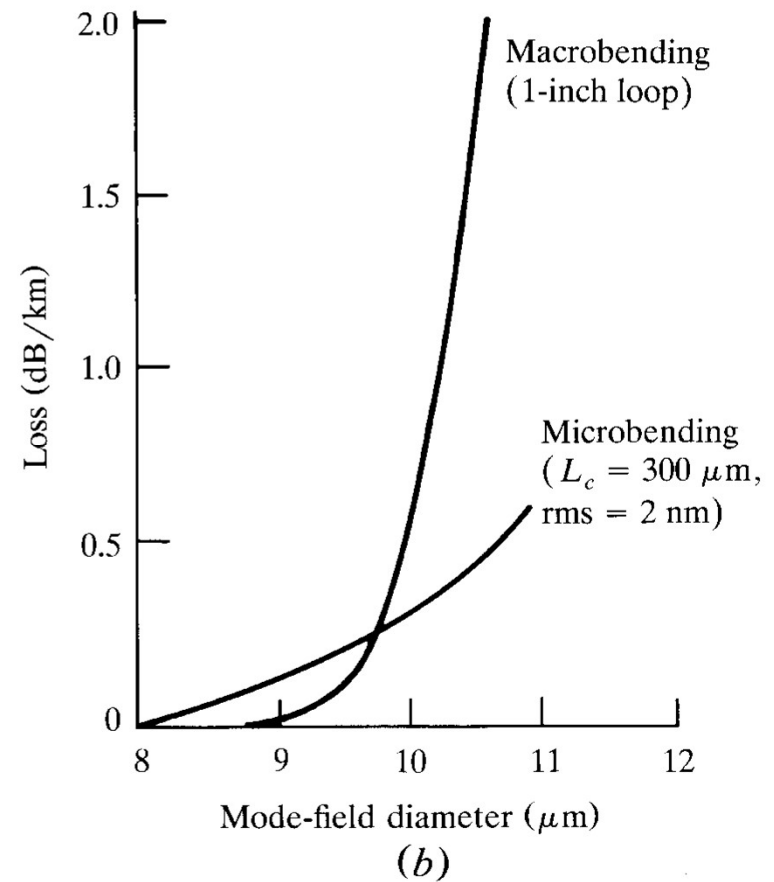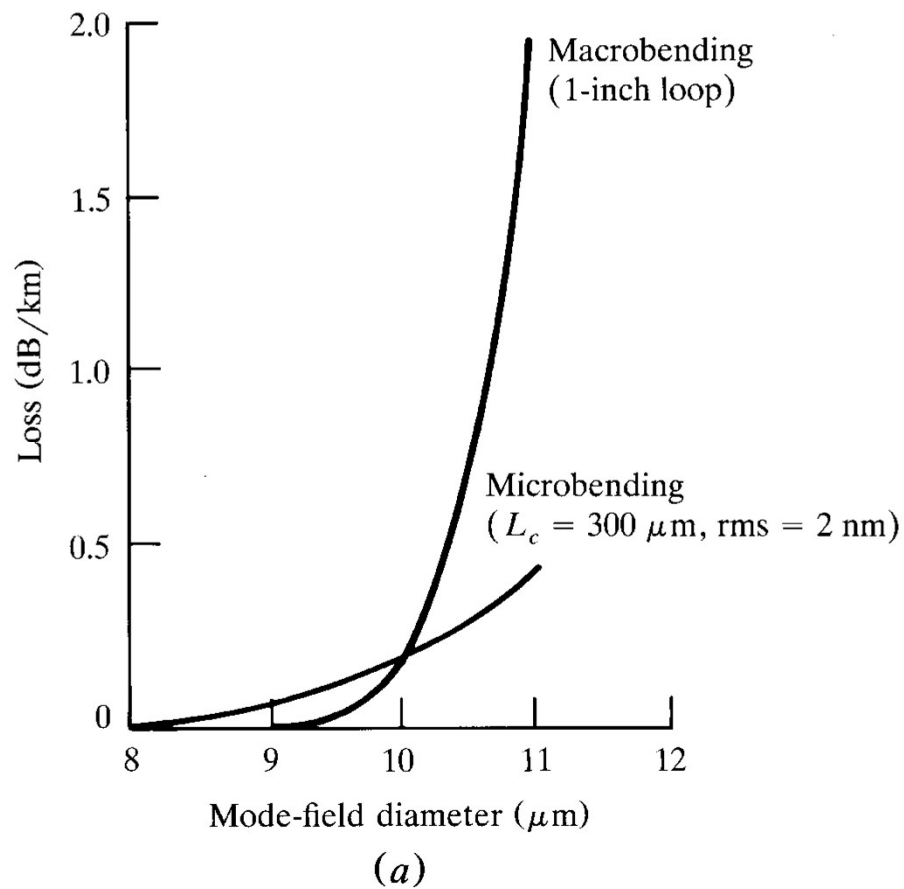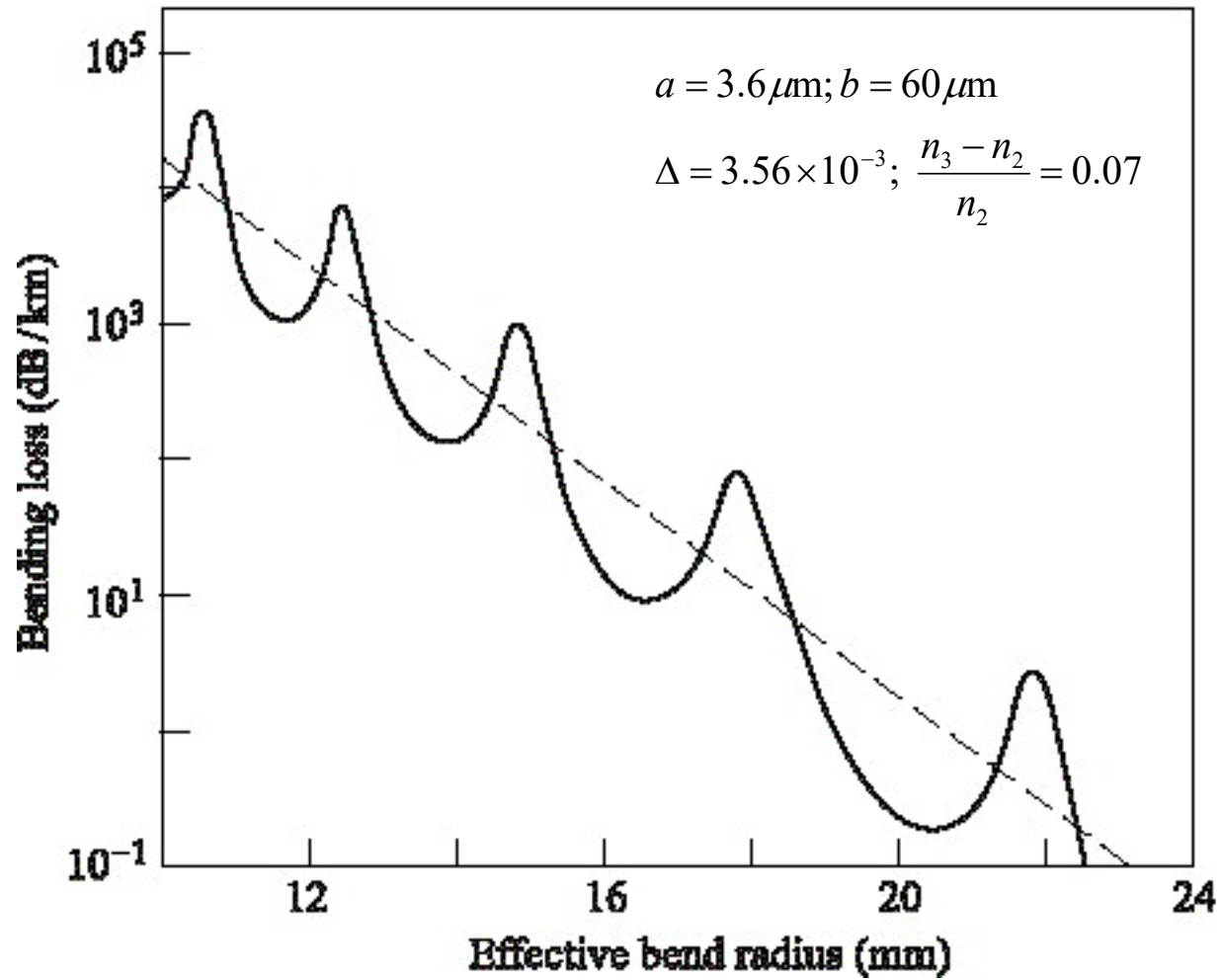Example of BW vs wavelength for various optical sources for SM-fiber.

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000
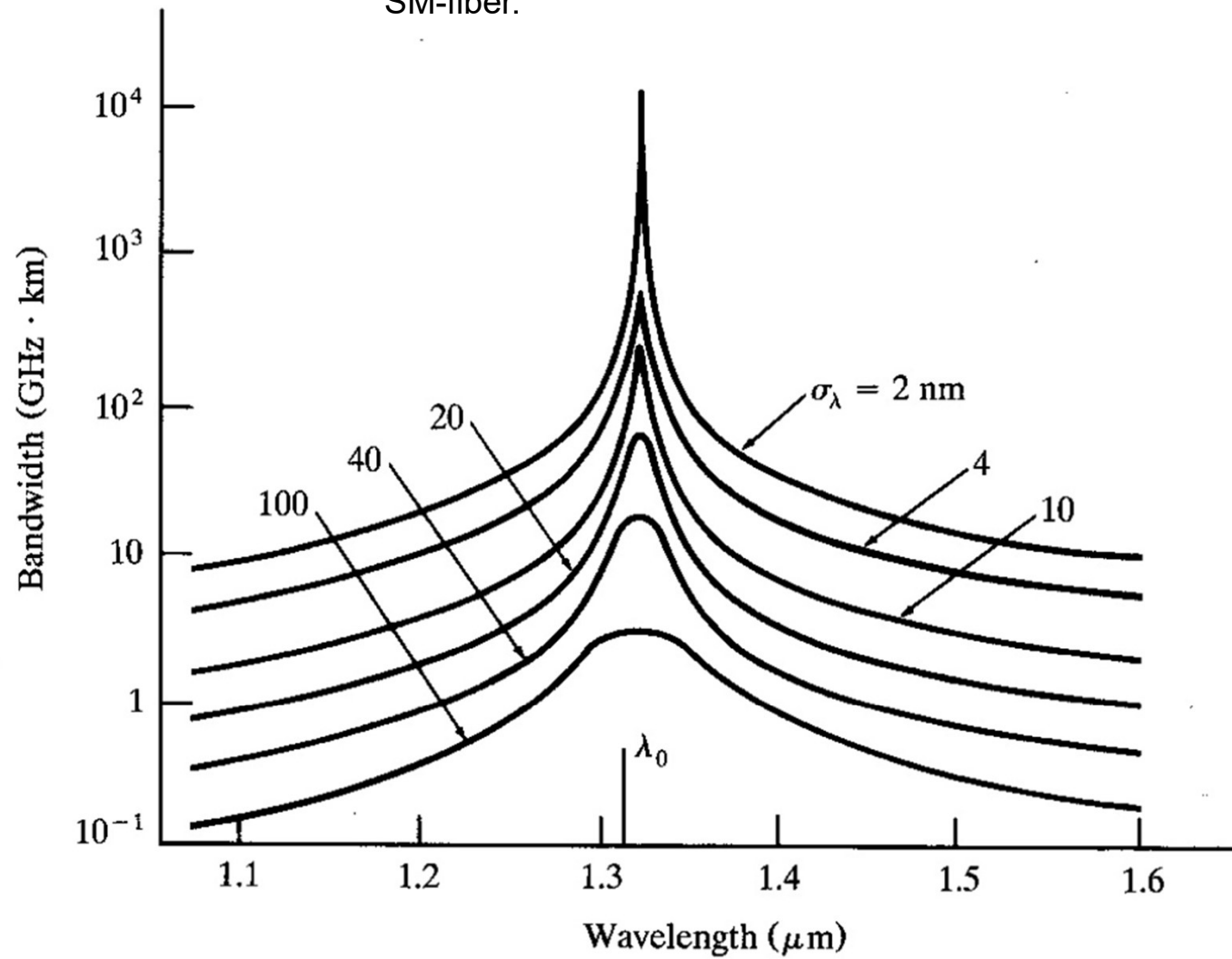
MFD

Bending Loss

Bending effects on loss vs MFD

Bend loss versus bend radius

$a = 3.6\,\mu\mathrm{m}; b = 60\,\mu\mathrm{m}$

$\Delta = 3.56 \times 10^{-3}; \dfrac{n_3 - n_2}{n_2} = 0.07$

Bending loss (dB/km)

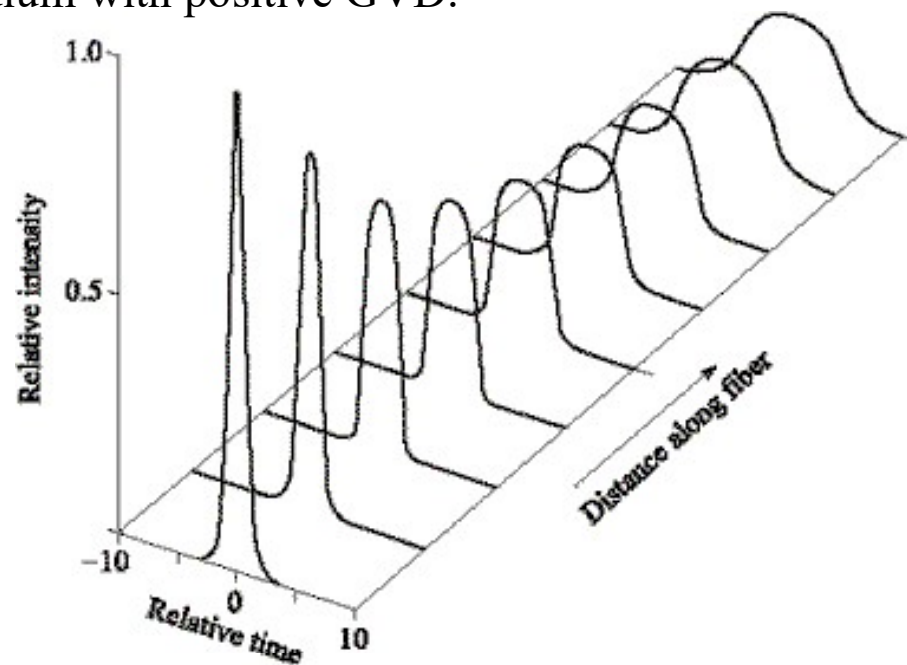Effective bend radius (mm)

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000
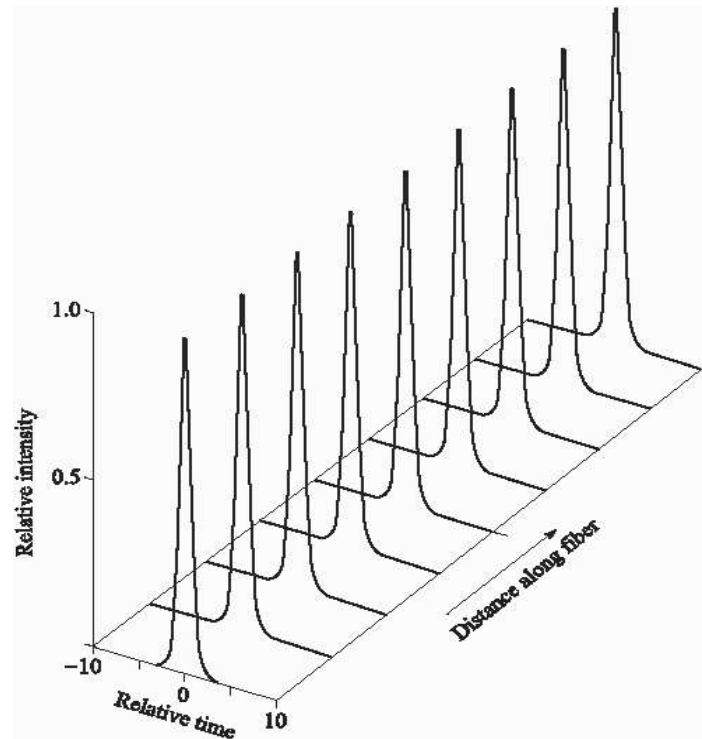
Kerr effect

Temporal changes in a narrow optical pulse that is subjected to Kerr nonlinearity in
A dispersive medium with positive GVD.

$$n = n_0 + n_2 I$$

Kerr nonlinearity in fiber, where I is the intensity of
Optical wave.

First-order Soliton

Temporal changes in a medium with Kerr nonlinearity and negative GVD. Since dispersion tends to broaden the pulse, Kerr Nonlinearity tends to squeeze the pulse, resulting in a formation of **optical soliton.**