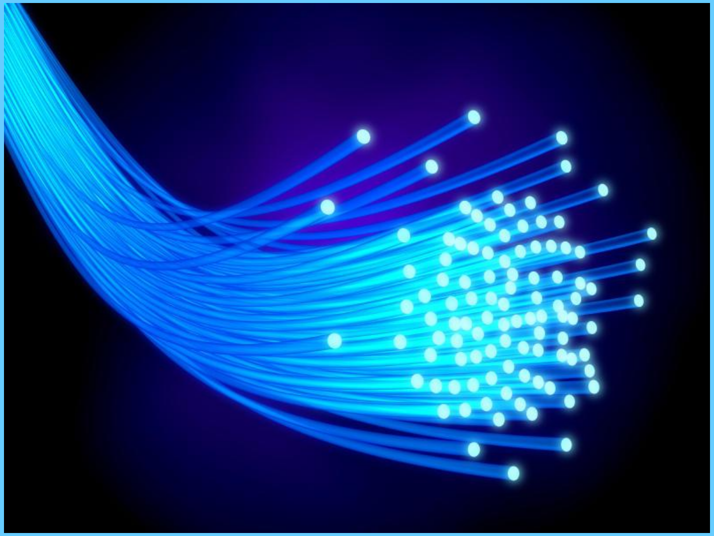
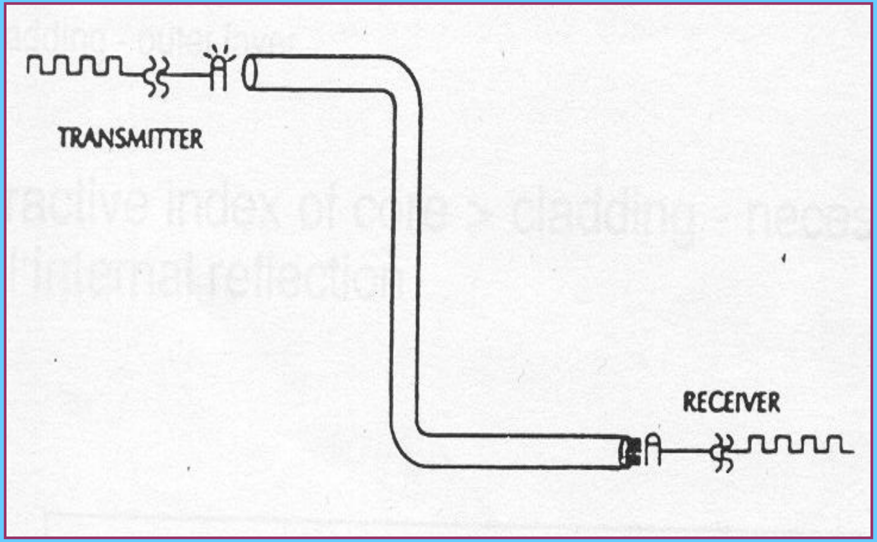
Optical Fibers and Transmission Characteristics





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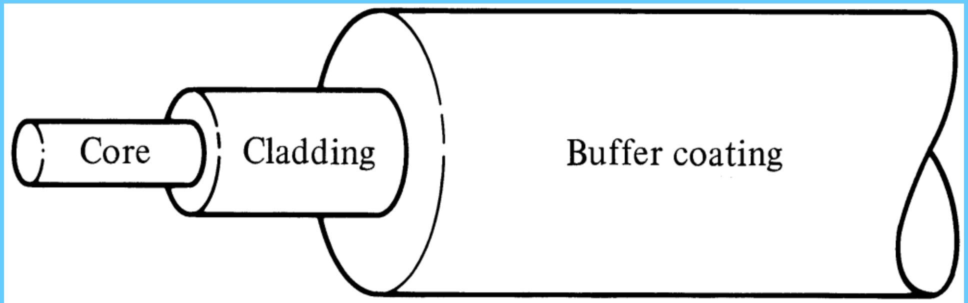
OPTICAL FIBER

- An optical fiber is a long cylindrical dielectric waveguide, usually of circular cross-section, transparent to light over the operating wavelength.

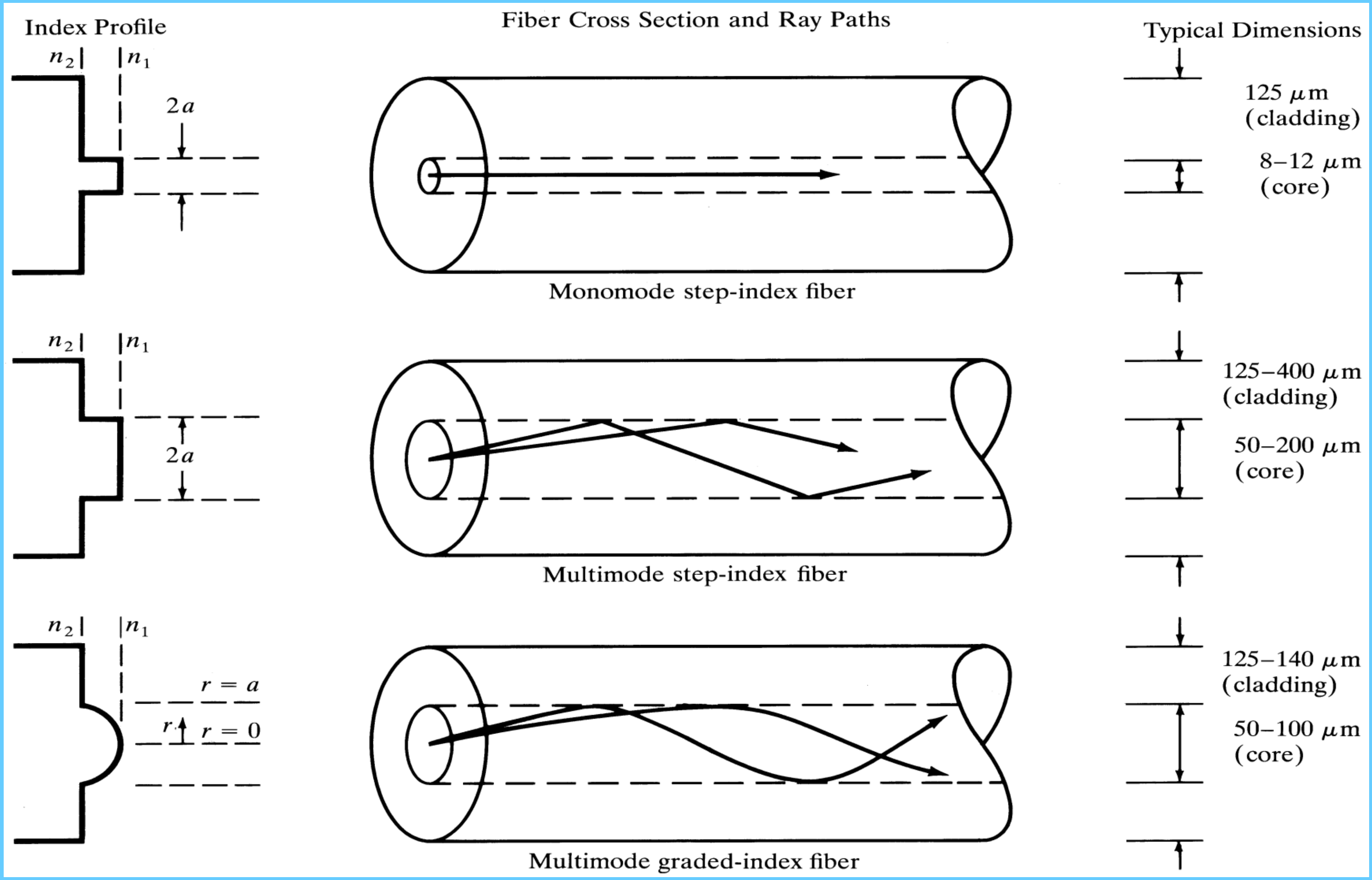
Fiber Structure



- A single solid dielectric of two concentric layers. The inner layer known as **Core** is of radius ‘a’ and refractive index ‘$\mathbf{n_1}$’. The outer layer called **Cladding** has refractive index ‘$\mathbf{n_2}$’.

$$n_2 < n_1 \rightarrow \textbf{condition necessary for TIR}$$

Step Index / Graded Index



Transmission Characteristics

- **Factors which affect the performance of optical fibers as a transmission medium**
  - **Important, when the suitability of optical fibers for communication purposes is investigated.**

- **Characteristics of Primary Importance:**
  - **Attenuation (or Transmission loss):** determines the maximum ***repeater less separation*** between a transmitter and receiver.
  - **Dispersion**: limit the information – carrying capacity of a fiber i.e. ***Bandwidth***

Fibre Performance

Optical Fiber Attenuation

- **Logarithmic relationship between the optical output power and the optical input power**

  - Measure of the decay of signal strength or light power

$$P(z) = P_o e^{(-\alpha z)}$$

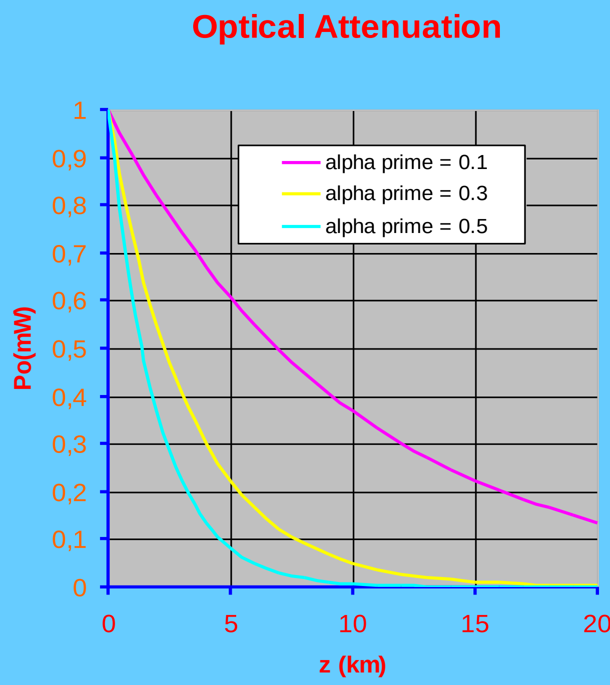
where,

P(z) **:** Optical power at distance z from the input

P_o **:** Input optical power

α **:** Fiber attenuation coefficient, [dB/km]

$$\text{Power ratio } (\text{dB}) = 10 \log \frac{P_O}{P_I}$$



- Convenient method to establish, measure and interrelate signal levels is to reference the signal level either to some absolute value or to a noise level.

Examples of decibel measures of power ratios

Power ratio	10^N	10	2	1	0.5	0.1	10^{-N}
dB	+10N	+10	+3	0	-3	-10	-10N

Power levels in dBm : Decibel power level referred to 1mW.

$$\text{Power level} = 10 \log \frac{P}{1\text{mW}}$$

Examples of dBm units

Power (mW)	100	10	2	1	0.5	0.1	0.01	0.001
Value (dBm)	+20	+10	+3	0	-3	-10	-20	-30

Fiber Attenuation (Loss)

- Usually, attenuation is expressed in terms of decibels (dB) or mostly dB/km – ***attenuation coefficient***

$$\alpha = \frac{1}{z} 10 \log\left(\frac{P_{out}}{P_{in}}\right)$$

- **Attenuation is because of different mechanisms**

$$\alpha_{\mathbf{Total}} = \alpha_{\mathbf{scattering}} + \alpha_{\mathbf{absorption}} + \alpha_{\mathbf{bending}}$$

Basic Attenuation Mechanisms

- **Material Absorption (Intrinsic and Extrinsic)**
- **Scattering (Linear and Non-linear)**
- **Bending loss (Macrobends and Microbends)**

Material Absorption

- **A loss mechanism related to the *material composition and the fabrication process* for the fiber**
  - Results in the dissipation of some of the transmitted optical power in the waveguide

- **<u>Absorption of light</u> (Optical Energy)**

a. Intrinsic : caused by the interaction with one of the major components of the glass

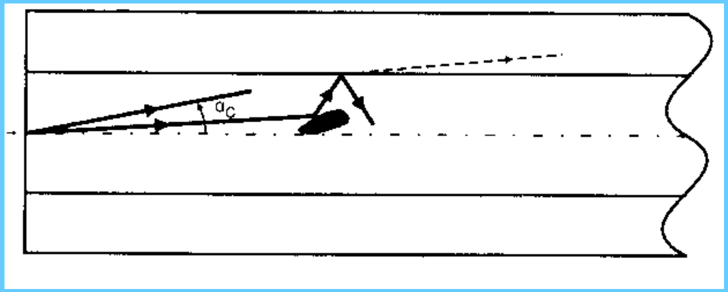
- Absorption in the IR-wavelength region (Molecular absorption)
- Absorption in UV wavelength region (Electronic absorption)

b. **Extrinsic** : caused by impurities within the glass

- Mainly absorption by **transition metal** impurities (Cr, Cu, Fe, Mn, Ni, V etc.)
  - ➢ Reduced to acceptable levels (i.e. one part in 10^{10}) by glass refining techniques.
- Another major extrinsic loss mechanism is caused by absorption due to water (Hydroxyl- OH ion) dissolved in the glass
  - ➢ Hydroxyl groups are bonded to glass structure and have fundamental stretching vibrations depending on group position.

SCATTERING

- Scattering effect prevents attainment of total internal reflection at the core cladding boundary – resulting in power loss
  - Due to Obstacles or inhomogeneities



Scattering Loss

☛ Even very small changes in the value of the core’s refractive index will be seen by a traveling beam as an optical obstacle and this obstacle will change the direction of original beam.

Scattering Loss

- Wave interacts with "particle" or molecules
- Transfers power to other directions

a. Linear scattering:

» Scattered power proportional to incident power

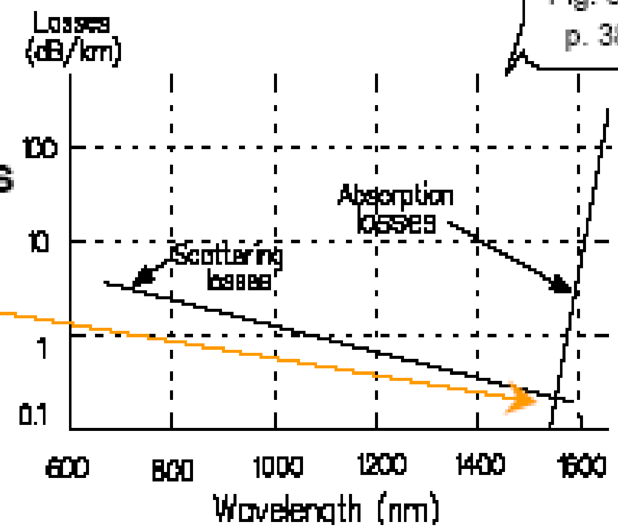
» No change in frequency of scattered light

» ***Rayleigh scattering***: *Dominant intrinsic loss mechanism*

- Particles << λ
  - Molecules, changes in *n* (change in composition), changes in density
- Scattering strength ~$1/\lambda^4$
- Fundamental loss at low wavelengths
  - Minimum loss at 1550 nm in silica (SiO_2)
  - Theoretical minimum ~0.15 dB/km

"Magic wavelength #1"

Fig. 3.2 p. 38



Rayleigh Scattering Loss

- **Rayleigh scattering coefficient (γ_R)** is proportional to (**$1/\lambda^4$**) and is related to transmission loss factor of the fiber as

$$\Gamma = \exp(-\gamma_R L)$$

- **Rayleigh scattering component can be reduced by operating at the longest possible wavelength.**

- **Theoretical attenuation due to Rayleigh scattering in silica at different wavelengths:**

630nm	**5.2 dB km^{-1}**
1000 nm	**0.8 dB km^{-1}**
1300 nm	**0.3 dB km^{-1}**

Scattering Loss (cont…)

a. *Linear scattering* (cont)

– ***Mie scattering***

» **Particles ~λ**

- *occurs at inhomogeneities comparable in size to guided wavelength*

• Inhomogeneities
  – Core-cladding refractive index variations
  – Core-cladding interface impurities
  – Diameter fluctuations

• Strains in fiber

• Bubbles in fiber

☞ **Mainly in the forward direction**

» Solution:

• Remove imperfections

• **Controlled extrusion &cabling of the fiber**

• **Increasing fiber guidance by increasing ‘Δ’**

Scattering Loss : Nonlinear

b. *Nonlinear Scattering* **:** ***Usually occurs at high optical power levels***

– Cause: high *E* field (V/m) (i.e., combination of power, area, and distance)

– Power scattered forward, backward, or side directions, depending on interaction

A. Brillouin scattering: **SBS**

» Photon undergoes nonlinear interaction to produce...

- Vibrational energy ("phonons") and
- Scattered light ("photons")

(Acoustic frequency)

» Upward and downward frequency shifts

- Strength of scattering varies with scattering angle
  - Maximum in backward direction; minimum of zero in forward direction

» Solution: keep power level below threshold

- Nonlinear scattering imposes "ceiling" on source power
- Threshold power level

$$P_B = \left(17.6\times10^{-3}\right)a^2\,\lambda^2\,\alpha\,\Delta\upsilon' \quad \text{(typically } \leq 1 \text{ W in SM fiber)}$$

b. Nonlinear Scattering (cont)

B. Raman scattering: SRS

» Nonlinear interaction produces….

- High-frequency phonon (instead low-frequency phonon of Brillouin scattering) $\Rightarrow$ Optical frequency
- Scattered photons

» Scattering predominantly in *forward* direction (power not lost)

» Power level threshold:

$$P_{\text{Raman}} = \left(23.6\times10^{-2}\right)a^{2}\,\lambda' \alpha \quad \text{(typically few W)}$$

» Solution: keep power level below threshold

- Single channel fiber
  - – Brillouin threshold lower than Raman and determines power "ceiling"

❖ *Normally, SBS threshold occurs at 100 mW, and SRS threshold at 1W*

Material Absorption & Scattering Losses

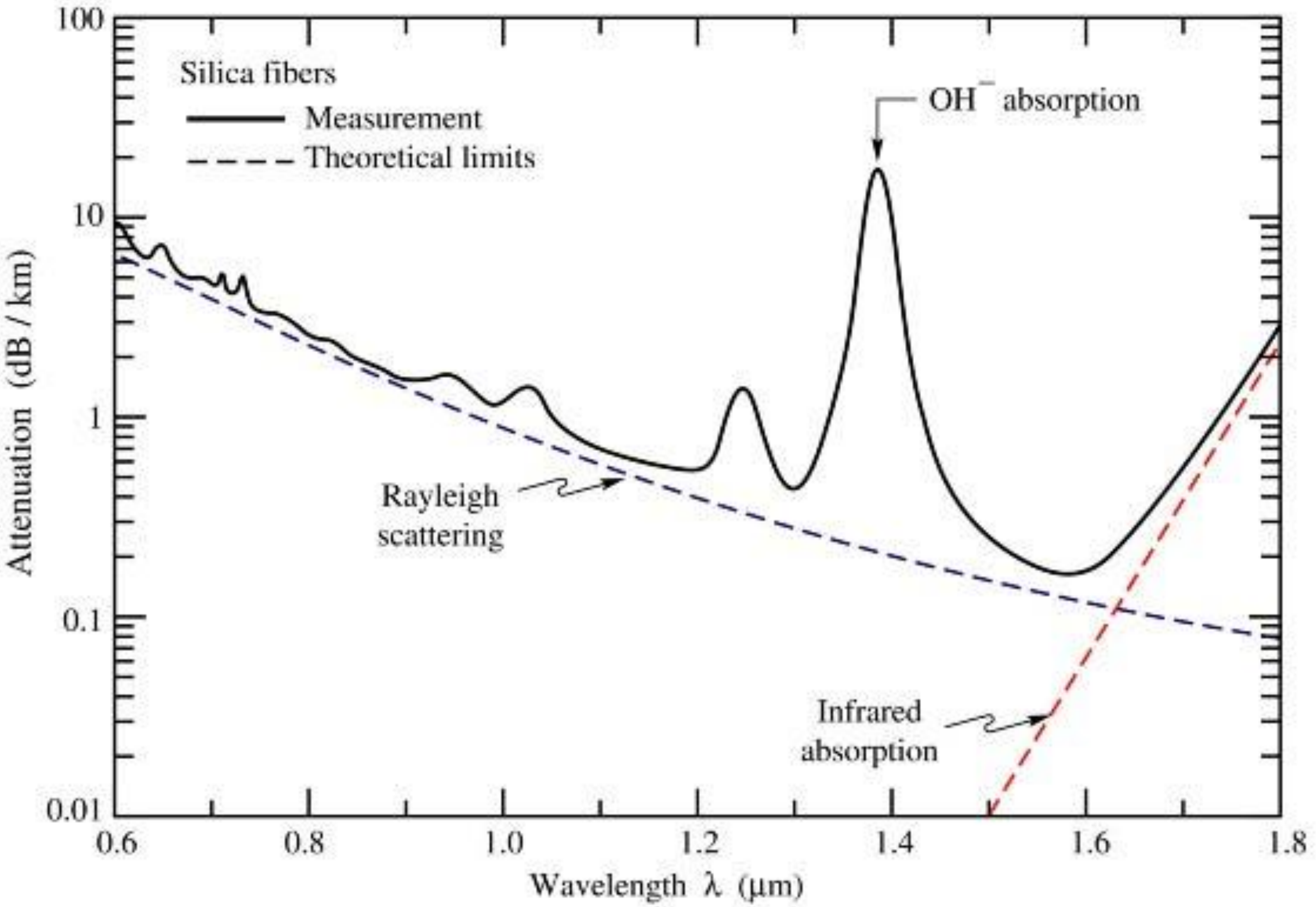
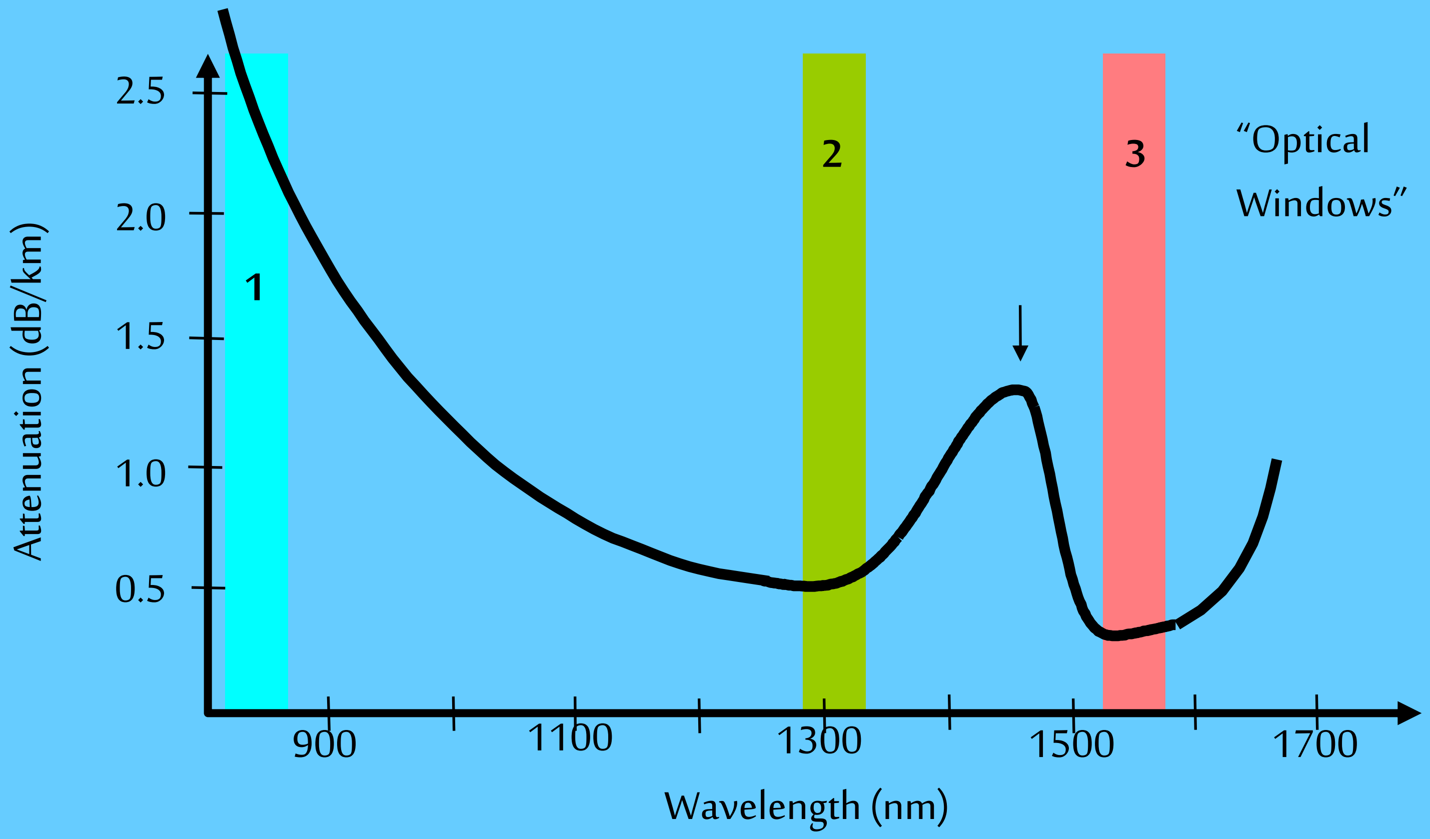


Fig. 12.2. Measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.

Attenuation in Silica Fibers



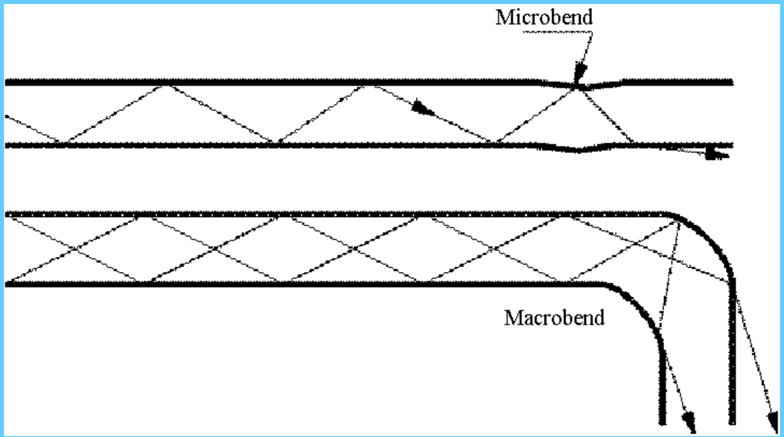
850 nm

1310 nm **1550 nm**

BENDING LOSSES

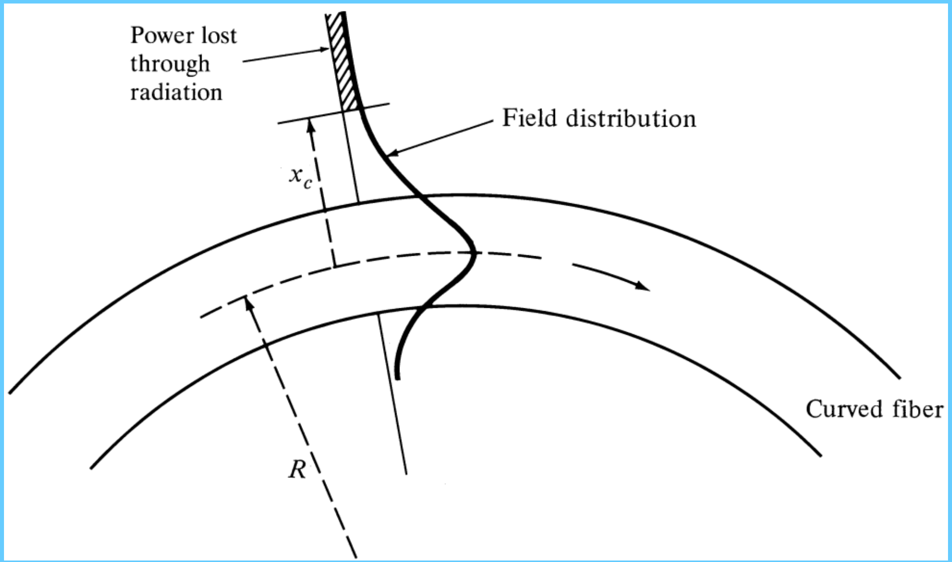
- **Bending an optical fiber introduces a loss in light power**

  - **Macrobends**
  - **Microbends**



- **Microbending - Result of microscopic imperfections in the geometry of the fiber**
- **Macrobending - Fiber bending with diameters on the order of centimeters or less.**

Power loss in a curved fiber



☞Velocity of evanescent field at the bend exceeds the velocity of light in the cladding

- ➢ the guidance mechanism is inhibited

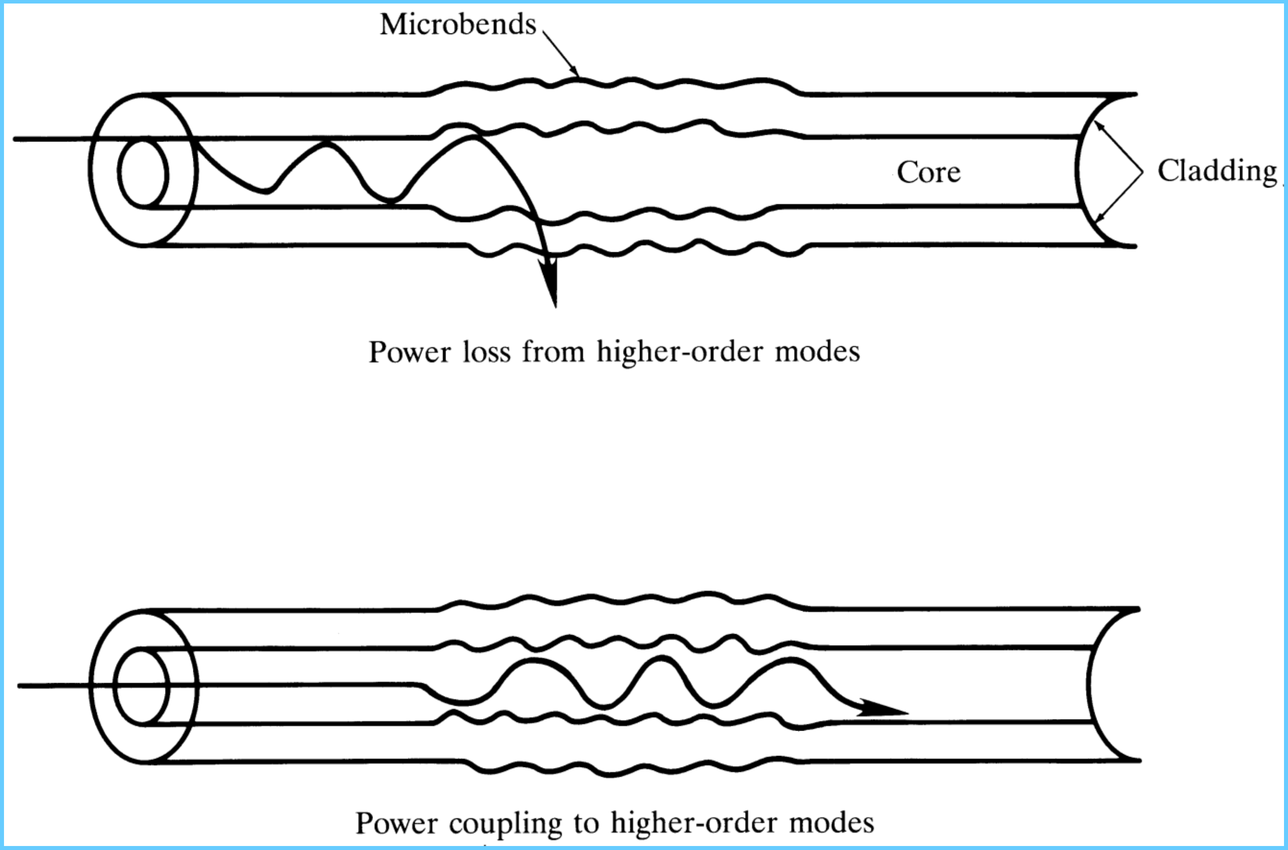
Critical radius of curvature :

$$R_c \cong \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{\frac{1}{2}}}$$

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

Microbending losses

- Results from non-uniform lateral pressures of fiber surface (core-cladding interface)



➢ Minimized by extruding a compressible jacket over the fiber.

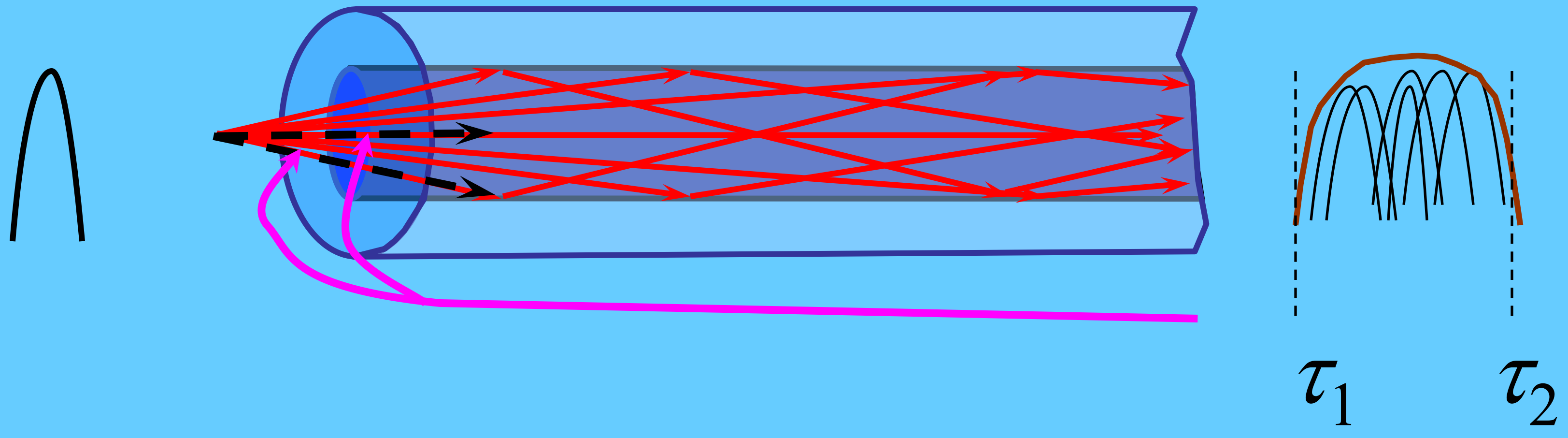
LOSS SUMMARY

- **Losses in fiber are due to**
  - **Material Absorption**
  - **Scattering (Linear and Nonlinear)**
  - **Bending (Macrobends & Microbends)**
  - **Interface inhomogenities**

- **Minimum loss is at 1550 nm**
  - Theoretical minimum loss **(≈ 0.15 dB/km)** almost achieved in practice with Silica fibers.

Pulse Broadening

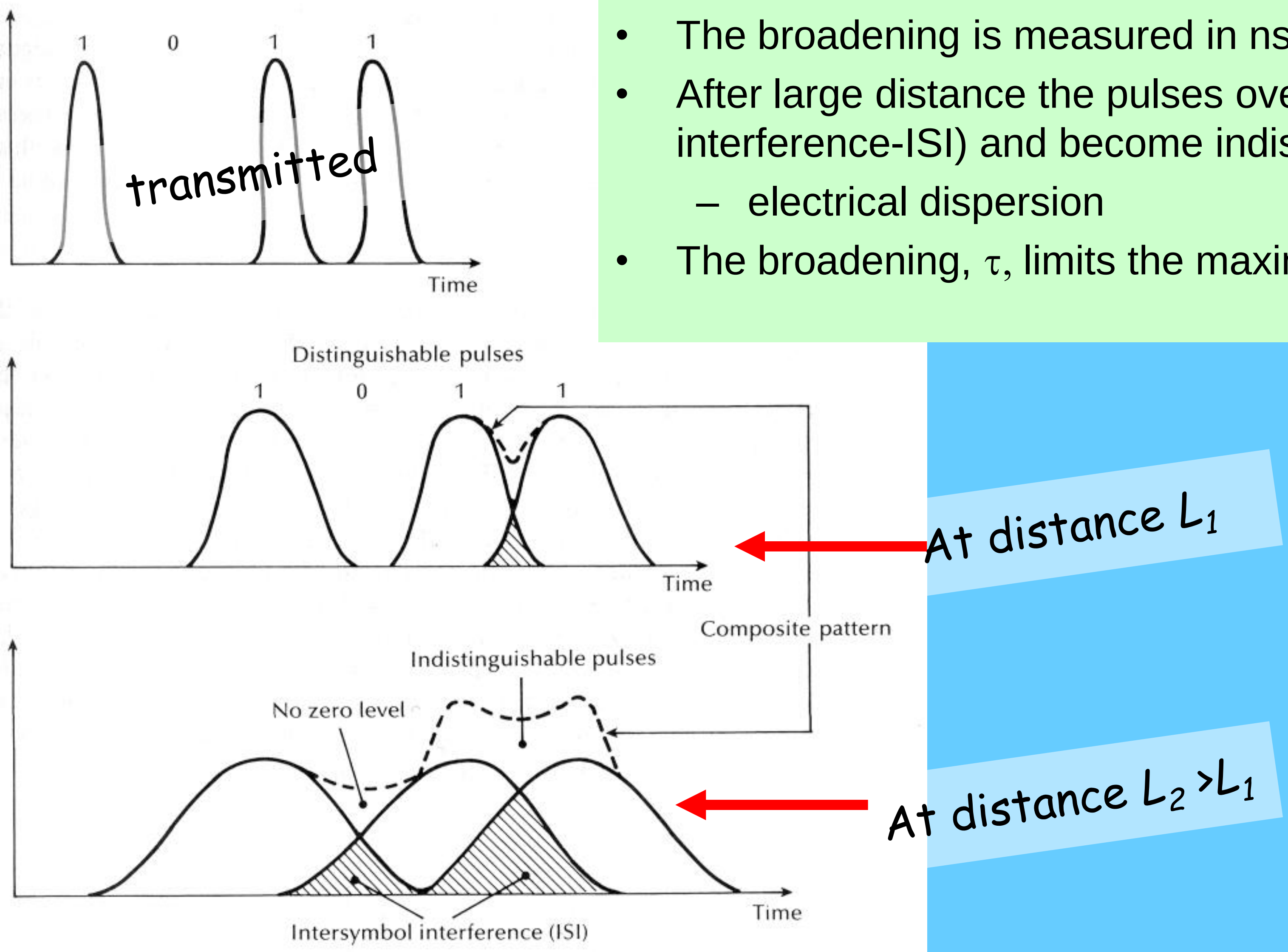
- In the ray model there are a continuum of ray directions between the axial ray and the critical angle a_c
- The axial ray takes the shortest route and arrives at the far end first, whereas the ray at the critical angle takes the longest route and arrives last.
  - A short input pulse will be broadened by the range of paths travelled



Dispersion

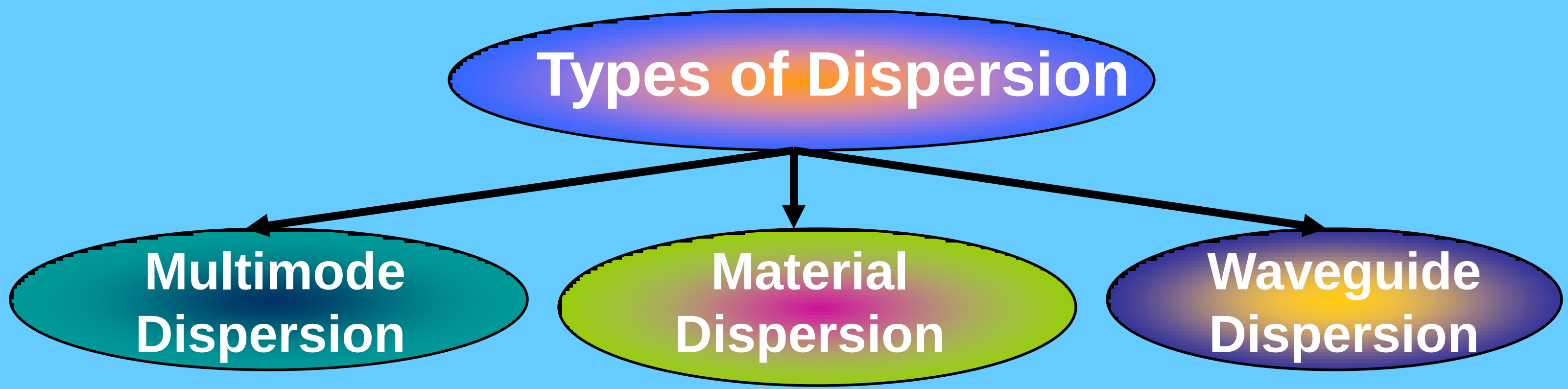
- Dispersion effects broaden the pulse as it propagates along the fibre
- The broadening is measured in nsec/km
- After large distance the pulses overlap (intersymbol interference-ISI) and become indistinguishable
  - electrical dispersion
- The broadening, τ, limits the maximum data rate:

$$B_T \leq \frac{1}{2\tau}$$



Dispersion

- **Dispersion** - Spreading of light pulses in a fiber
  - limits ***Bandwidth***



Most important types

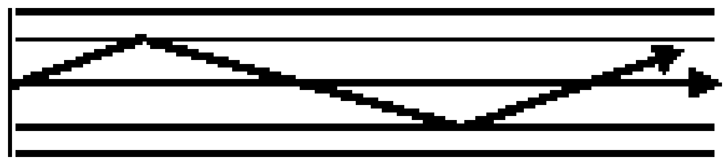
- Intermodal (Modal) dispersion – MMFs
- Intramodal or Chromatic dispersion – SMFs
  - Material dispersion
  - Waveguide dispersion

- Pulse broadens linearly with distance so that the maximum bandwidth reduces inversely with distance
  - **Bandwidth-distance** is a constant for a fibre and is a quoted parameter
  - Best bandwidth-length products:
    - For a multimode fibre ~20 MHz km
    - For a single-mode fibre ~100 GHz km
- This bandwidth limit is due to ***intermodal dispersion***
  - Each mode travels at a different speed

Intermodal Dispersion

Fiber Dispersion: C. Modal Dispersion

- *Only* in multimode fibers
- Cause:
  - Each mode has slightly different path to receiver



- Time delay between fastest and slowest is modal pulse delay distortion and in SI fiber is...

$$\Delta\tau_{\text{SI modal}} = \frac{L(n_1 - n_2)}{c}\left(1 - \frac{\pi}{V}\right) \approx \frac{L(n_1 - n_2)}{c} = \frac{L\Delta n_1}{c}$$

  - $D_{modal} = \Delta\tau_{modal}/L$ [ps·km^{-1}]

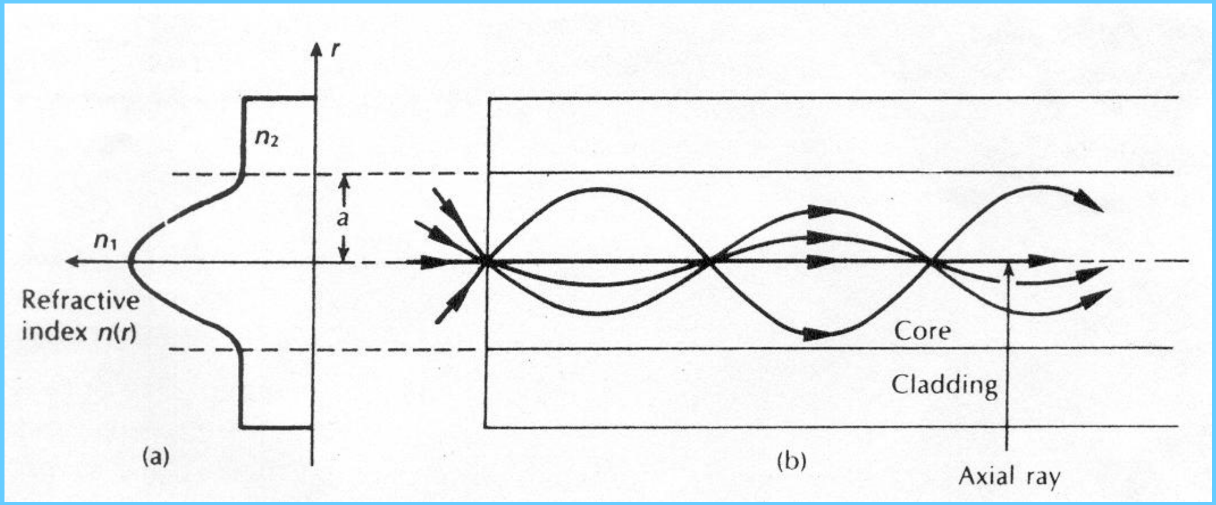
Intermodal Dispersion

- **Intermodal Dispersion** (also Modal Dispersion)
  - can be minimized by:
    - using a smaller core diameter
    - using graded-index fiber (less by a factor of 100)
    - use single-mode fiber - SMF is only single-mode at wavelengths greater than the cutoff wavelength

- When multimode dispersion is present, it usually dominates to the point that other types of dispersion can be ignored.

Modal Dispersion in Graded Index Fibers

- **Graded Index Fibers: Solution to modal dispersion**



A multimode graded index fiber: (a) Parabolic refractive index profile; (b) Meridional ray paths within the fiber core.

- Core is designed with different refractive index layers so that the beam traveling the **farthest distance** does so at the ***highest velocity*** and the beam traveling the **shortest distance** propagates at the **slowest velocity**.

Intramodal Dispersion

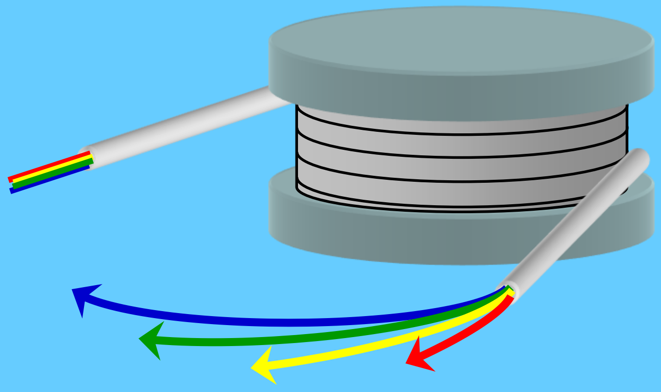
- **Intramodal dispersion occurs due to the differing propagation delays of different wavelengths of light *within a single mode (intra-modal*)**
  - **Caused by *material dispersion* and *waveguide dispersion***

❖ **Light sources have a finite spectral width (±Δλ)**
  - **a fraction of a per cent of the centre frequency for a laser**
  - **several per cent for a LED**

- **Each spectral component of a pulse travels at a different rate leading to pulse broadening**

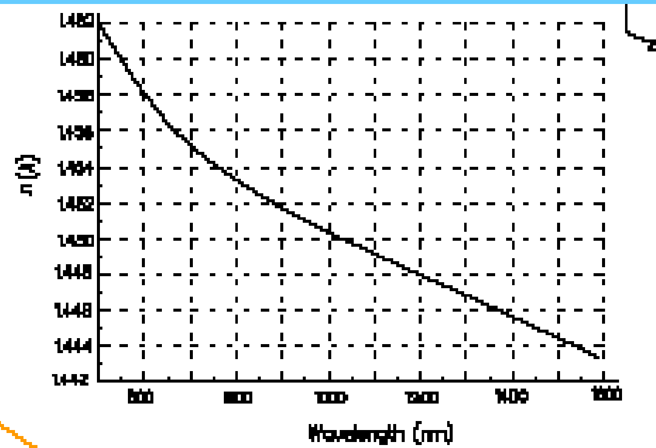
Intramodal (Chromatic) Dispersion

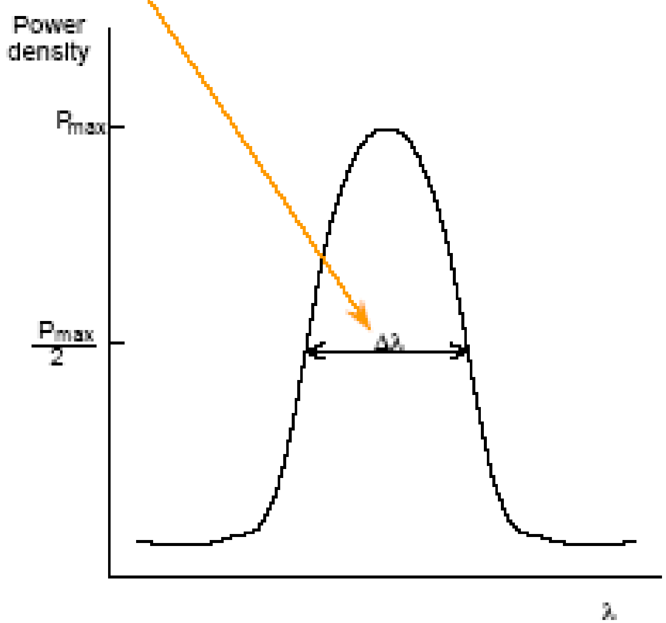
- **Light sources are NOT monochromatic (linewidth of source, chirp effects, modulation sidebands)**
- **Different wavelengths travel at slightly different speeds (this effect is called "Chromatic Dispersion")**
- **Chromatic dispersion causes pulse broadening; (problem at high bit rates over long distances)**
- **Standard single-mode fiber:**
  - **1300 nm window has lowest CD**
  - **1550 nm lowest loss**

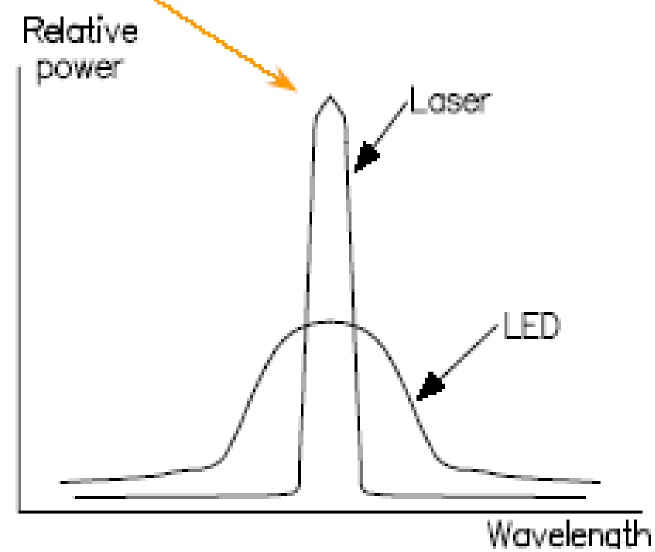


Fiber Dispersion: A. Material Dispersion

- Velocity of light in SiO_2 is weak function of wavelength, *$n(\lambda)$*
- All light sources have ***spectral width*** $\Delta\lambda$
  - Lasers narrower spectrum than LEDs
- Longer λs arrive at RCVR before shorter λs





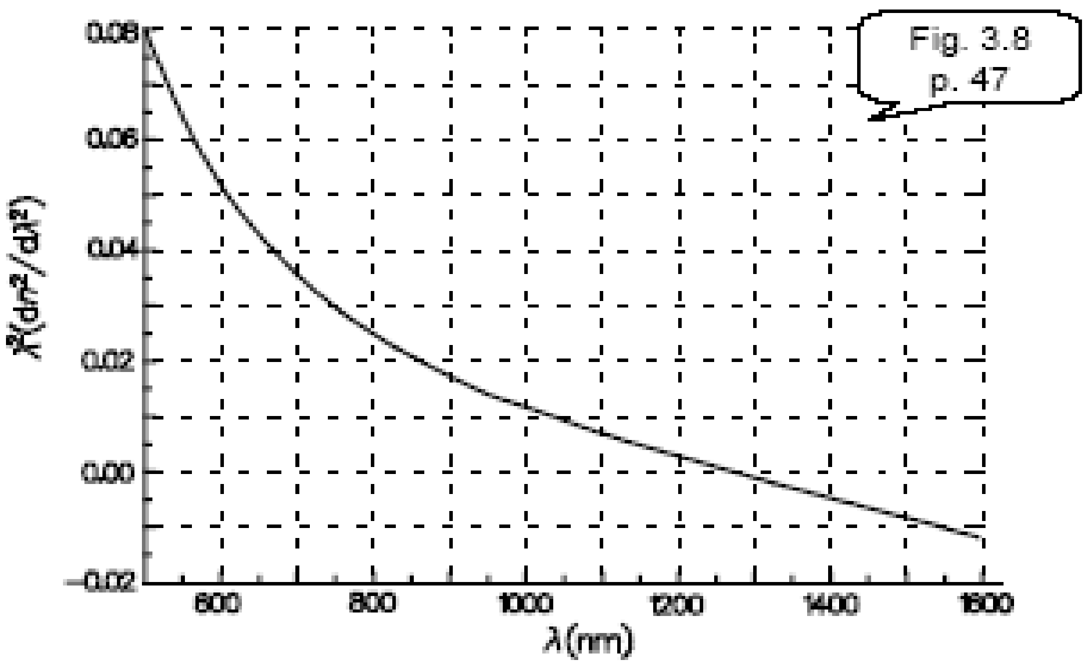


Material Dispersion (cont.)

- **Pulse spread due to material dispersion**

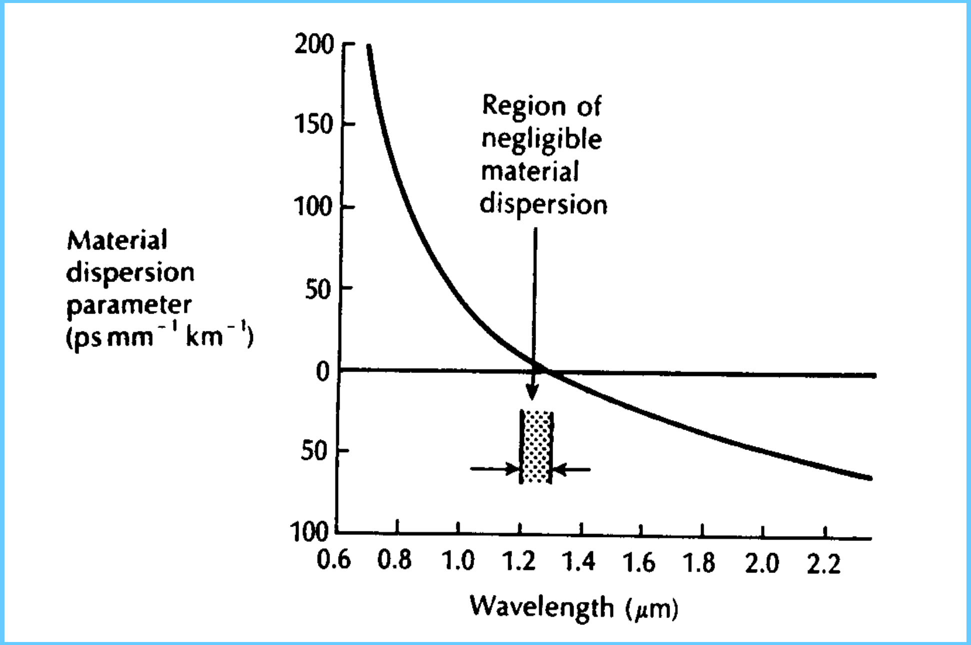
$$\Delta\tau_{\text{mat}} = -\frac{L}{c}\frac{\Delta\lambda}{\lambda}\underbrace{\left(\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right)}_{\text{Figure 3.8, p. 47}}$$

- **Frequently normalized:** $D_{mat} = \Delta\tau_{mat}/(L\Delta\lambda)$ [ps·km⁻¹·nm⁻¹]



Material dispersion Parameter (M)

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda}$$ **is expressed in ps.nm^{-1}.km^{-1}**



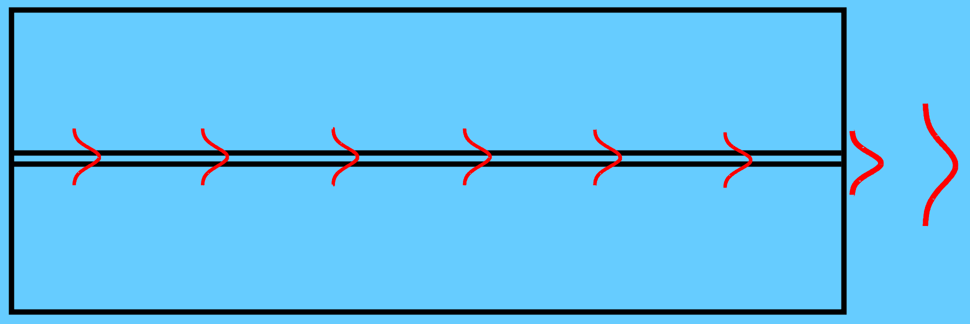
The material dispersion parameter for silica as a function of wavelength

- Material dispersion may be minimized by control of system parameters.

Waveguide Dispersion

- Light travels at different speeds in core and cladding.
- Results from the ***variation in group velocity with wavelength*** which leads to a ***variation in transmission time*** for the modes.
- Variation of propagation constant (β) with wavelength (λ),

$$\frac{d^2\beta}{d\lambda^2} \neq 0$$



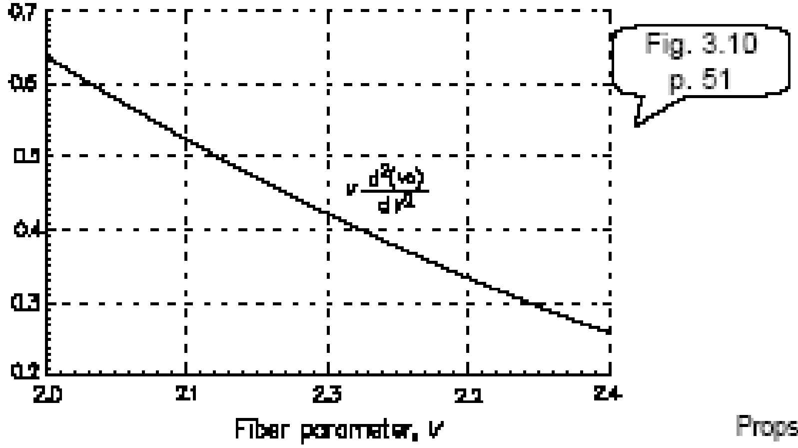
Fiber Dispersion: B. **Waveguide Dispersion**

- In low material-dispersion region of 1000 to 1600 nm in SM fibers...
  - *Waveguide dispersion* becomes important
  - Negligible in MM fibers and in SM fibers operated below 1,000 nm and above 1600 nm
- Cause: velocity of mode is function of a/λ
- Waveguide dispersion

$$\Delta\tau_{wg} \approx -\left(\frac{n_2 L\Delta}{c}\right)\left(\frac{\Delta\lambda}{\lambda}\right)\underbrace{\left(V\frac{d^2(Vb)}{dV^2}\right)}_{\text{Fig. 3.10, p. 51}}$$

$D_{WG} = \Delta\tau_{WG}/L\,\Delta\lambda$ [ps·km^{-1}·nm^{-1}]

⇒Waveguide dispersion Parameter

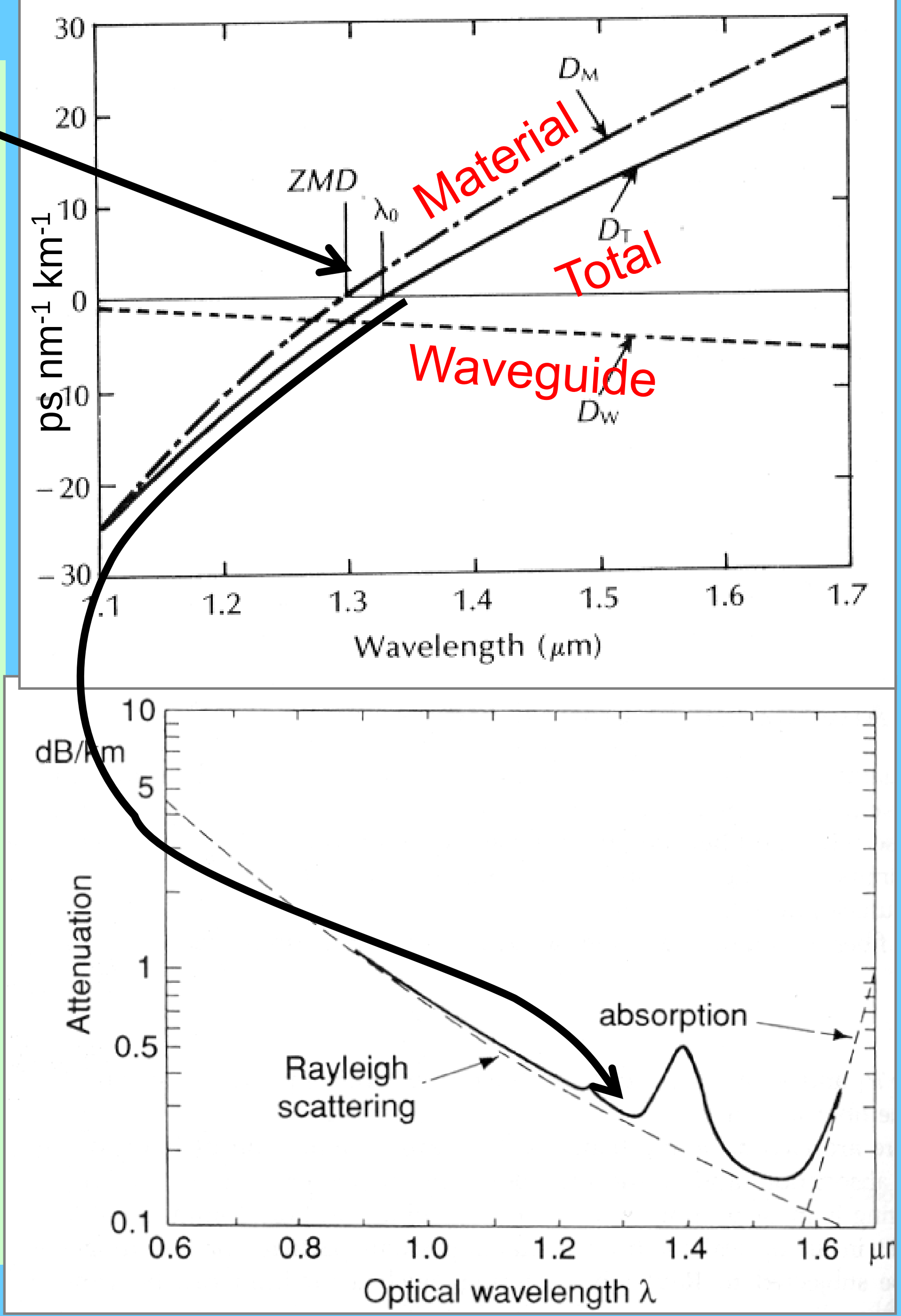


- **Dispersion is sum of material and waveguide components**

- Minimum dispersion occurs at λ=1.3 μm
  - dispersion negligible
  - attenuation ~0.3 dB km $^{-1}$

- Minimum attenuation occurs at λ=1.5 μm
  - dispersion 15 ps nm^{-1} km^{-1}
  - attenuation 0.2 dB km^{-1}

- *Dispersion flattening* enables 2 ps nm^{-1} km^{-1} over 1.3-1.6 μm range
  - enables low-loss AND low dispersion at 1.5 μm



Overall Fiber Dispersion

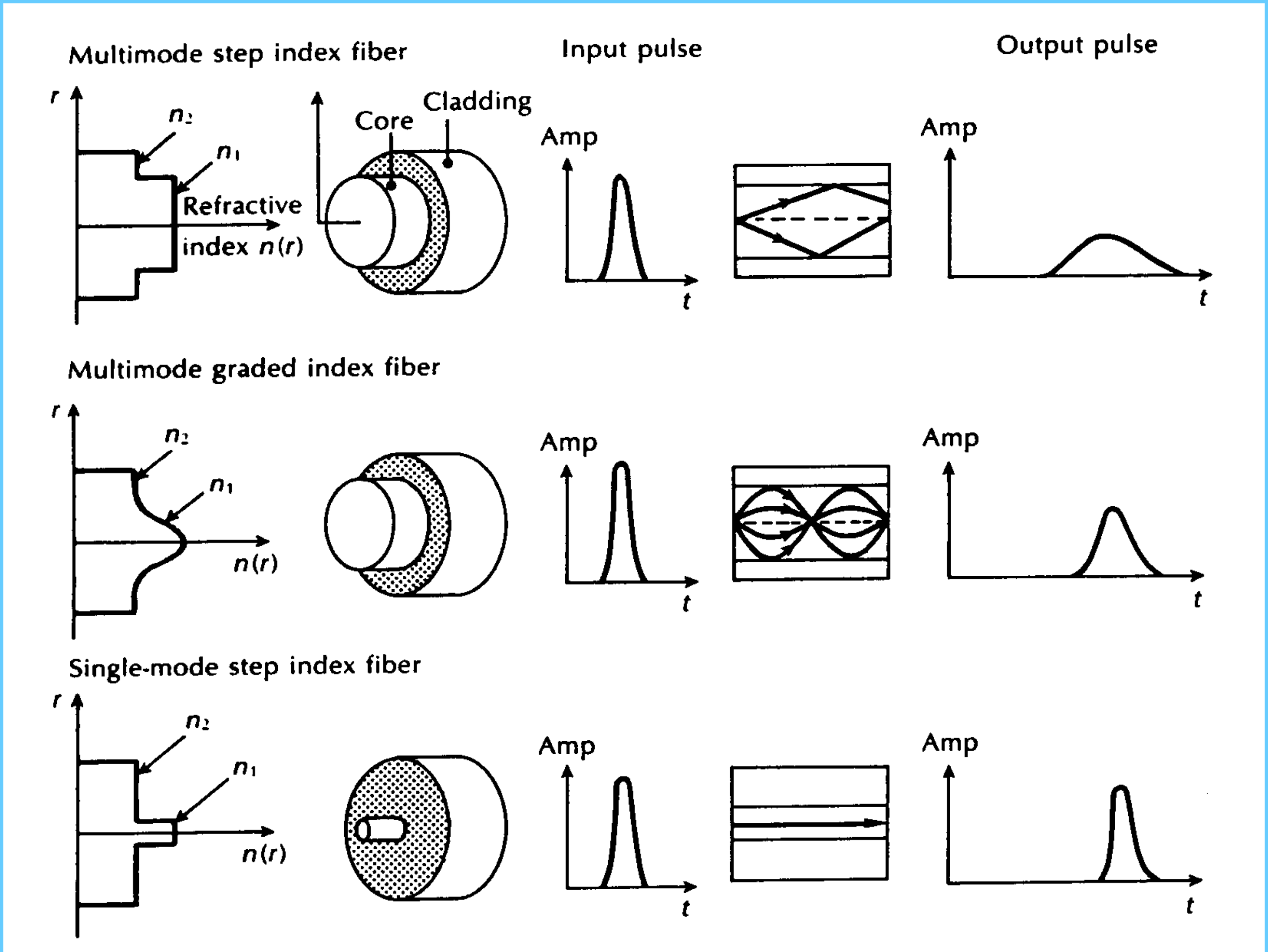
❑ Total Dispersion

$$D_T = D_I + D_M + D_W \text{ (ps nm}^{-1}\text{ km}^{-1}\text{)}$$

- **In MMFs,** the overall dispersion comprises both
  - Intermodal
  - Intramodal (Material & Waveguide)

❖ **Note**: In MMFs, waveguide dispersion is negligible compared to material dispersion

- **In SMFs**, dispersion is entirely from Intramodal or Chromatic dispersion
  - BW is limited by finite spectral width of the source ($\Delta\lambda$)
  - Dominated by material dispersion of fused silica
  - Zero Material Dispersion by control of dopants



Schematic diagram showing a multimode step index fiber, multimode graded index fiber and single-mode step index fiber, and illustrating the pulse broadening due to intermodal dispersion in each fiber type.

TRANSMISSION RATE

Bit-Rate and Dispersion

- Maximum bit rate

$$B_{R\,\max} \approx \frac{1}{4\Delta\tau_{\text{total}}}$$

where

$$\Delta\tau_{\text{total}} = \sqrt{\Delta\tau^2_{\text{modal}} + \Delta\tau^2_{\text{GVD}}} \quad \text{and} \quad \Delta\tau_{\text{GVD}} = \Delta\tau_{\text{material}} + \Delta\tau_{\text{waveguide}}$$

- Note that $B_{R\,max} \sim 1/L$
- (bit-rate)-distance product is constant for a given fiber

Dispersion Modified SMFs

Total Dispersion :

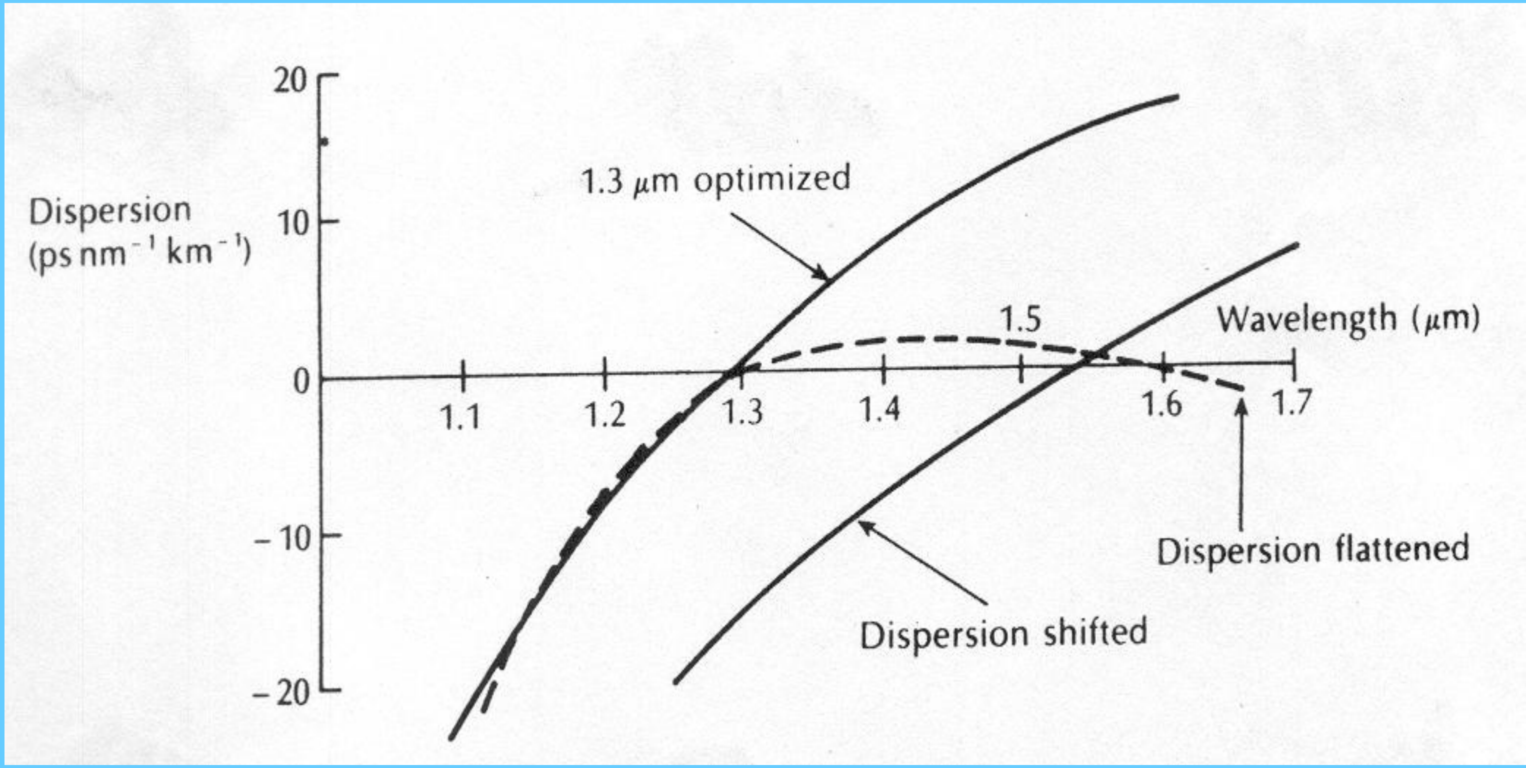
$$D_T = D_M + D_W = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| - \left[\frac{n_1 - n_2}{\lambda c}\right]\frac{V d^2(Vb)}{dV^2}$$

- At wavelengths longer than the **ZMD point** in most common fiber designs, the D_M and D_W are of opposite sign and can therefore be made to cancel at some longer wavelengths.
- Hence, $\boldsymbol{\lambda_{ZMD}}$ can be shifted to the lowest loss wavelength for silicate glass fibers at 1550 nm to provide both low dispersion and low loss fiber.

❑ Dispersion Modified SM Fibers

- **Dispersion Shifted**
- **Dispersion flattened**

Dispersion Shifted& Dispersion Flattened SMFs

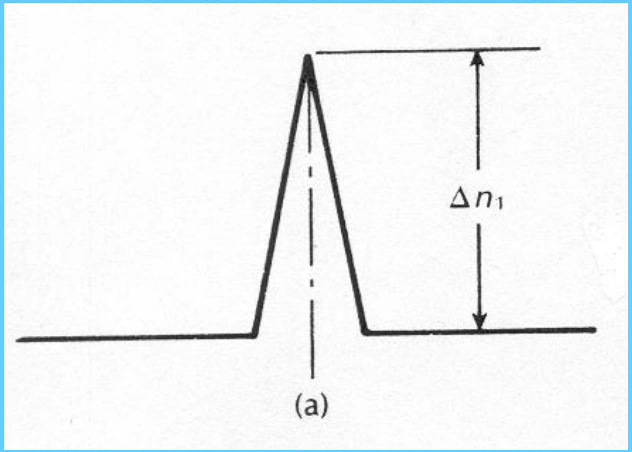


Total dispersion characteristics for various types of SMFs

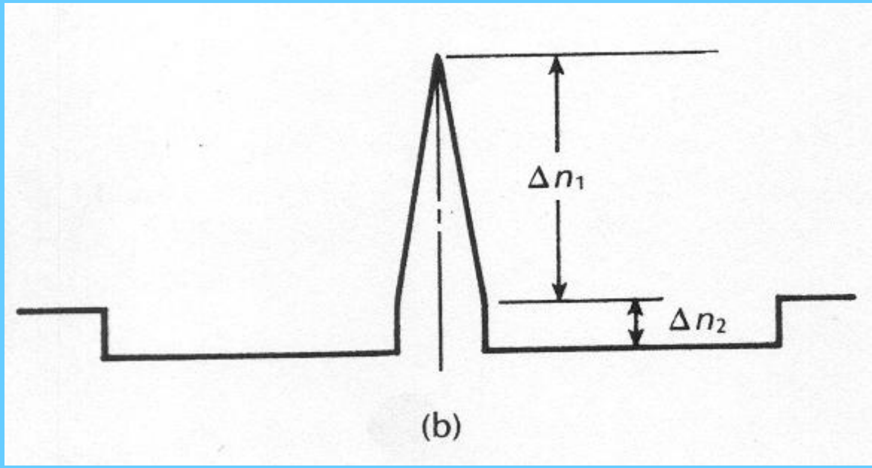
- **Achieved by mechanisms such as; Reduction in fiber core diameters, Increase in relative or fractional index difference and Variation in fiber material composition**

RI Profiles for GI DSFs

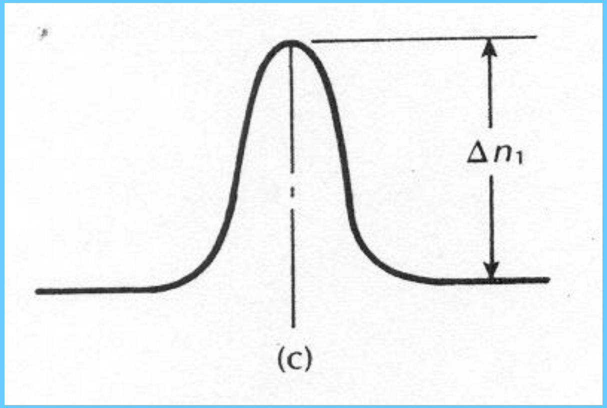
- Several GI profiles investigated and proposed for DSFs.



Triangular profile



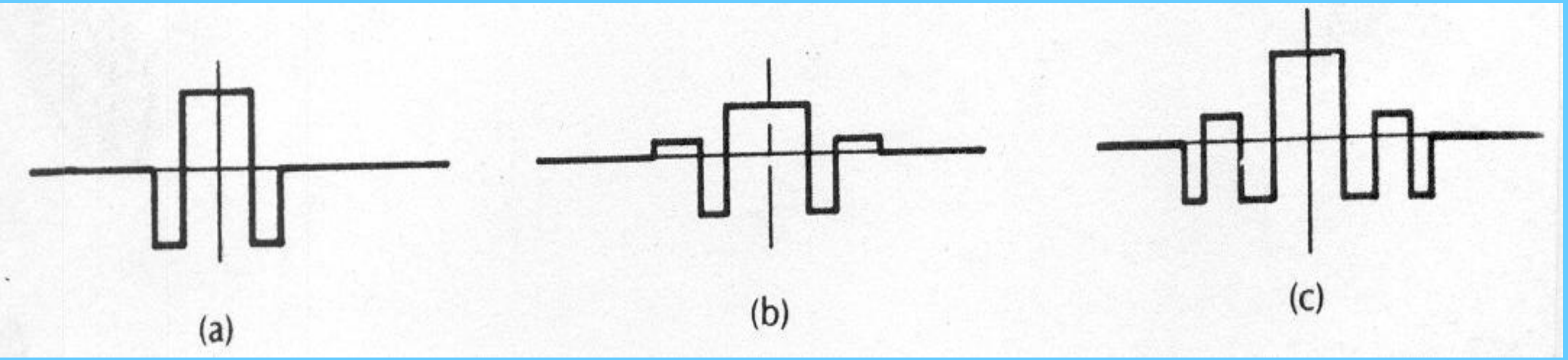
Depresses-cladding triangular profile



Gaussian profile

- **Alternate approaches for DS-SMFs involve use of multiple index designs.**
  - Doubly clad or W-fiber
  - Multiple index triangular profile
  - Segmented –core-triangular profile
  - Dual shaped core

Profiles for Dispersion Flattened Fibers



(a) Double clad fiber (W fiber) **(b) Triple clad fiber** **(c) Quadruple clad fiber**

❖ **First demonstrated using W-fiber structure**

- Require high degree of dimensional control
- Comparatively higher overall fiber loss (0.3 dB km^{-1})
- High sensitivity to bend losses (DFFs operation is very close to cutoff to obtain flat dispersion characteristics)

❑ **Alternate designs to reduce sensitivity to bend losses.**

- Light penetrating outer cladding can be retrapped by introducing region of raised index $\Rightarrow$ ***(lower attenuation ≈ 0.19 dB km^{-1}), less sensitive to bends***

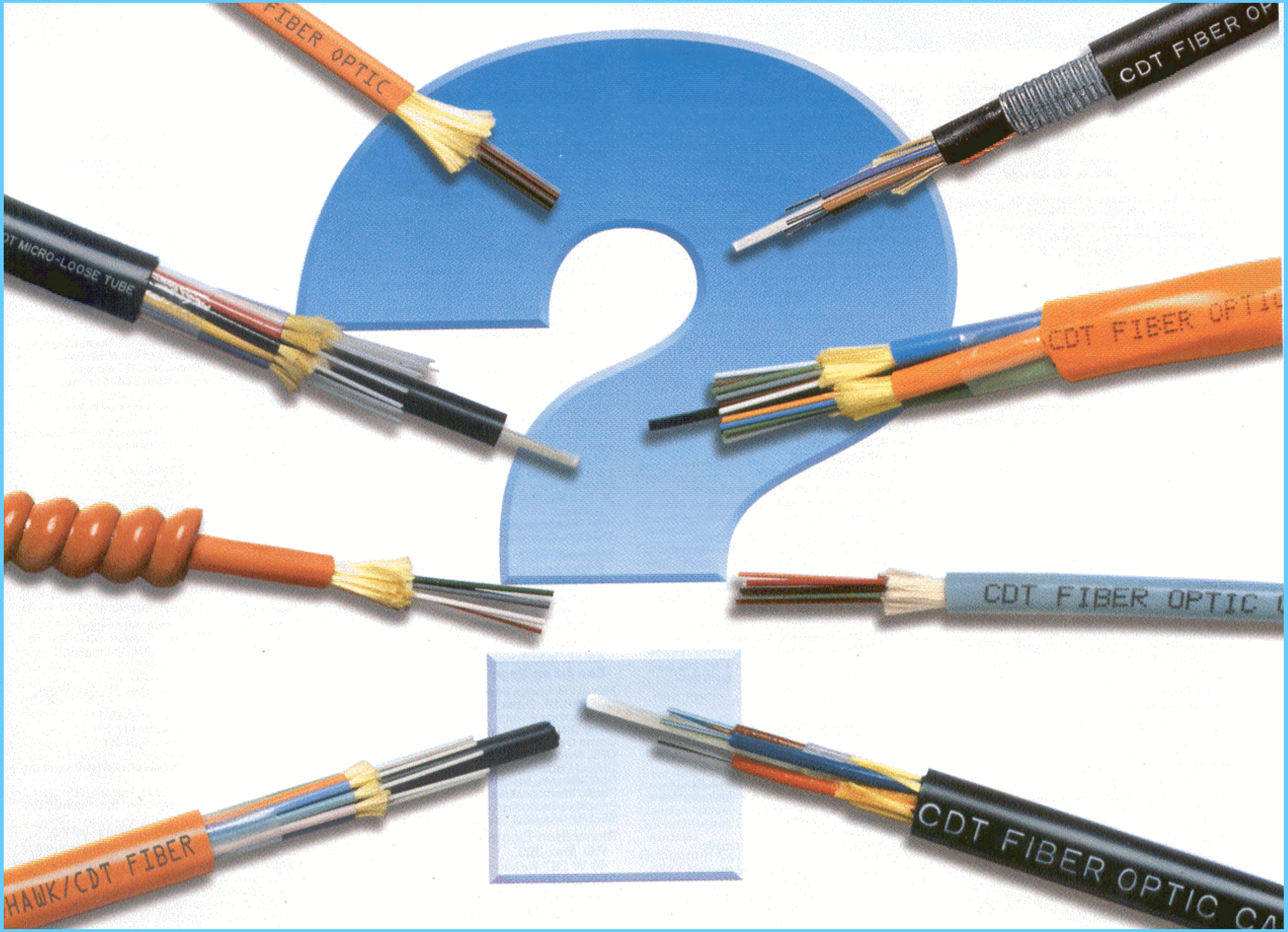
SMFs For Telecom

- **SMF : (Standard, 1310 nm Optimized, unshifted)**
  - **Most widely deployed by far distances**

- **SMF DS (Dispersion shifted) :**
  - **For single channel operation at 1550 nm**

- **SMF DF (Dispersion flattened):**
  - **For WDM/DWDM operation in the 1550 nm region**

Variety of Optical Fiber Cables



THANK YOU