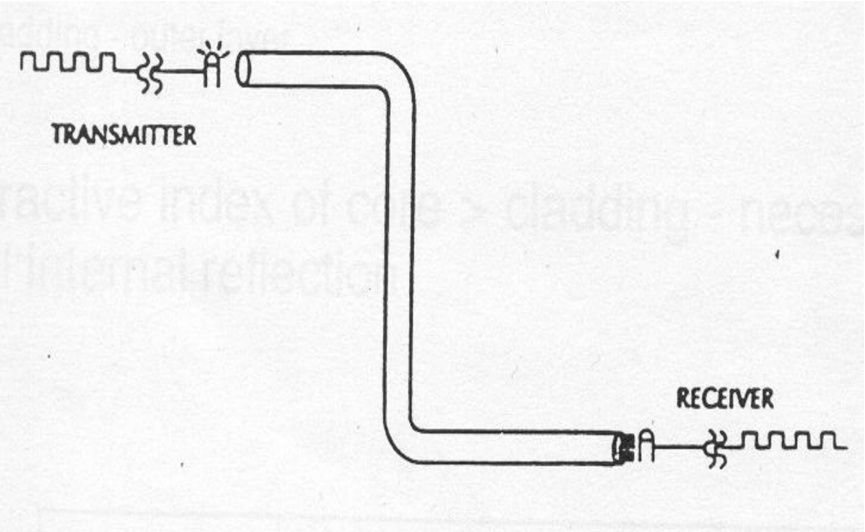
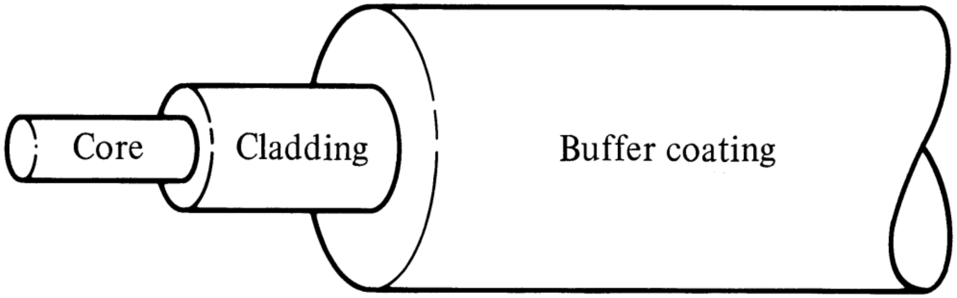
Transmission Characteristics of Optical Fiber - II



OPTICAL FIBER

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

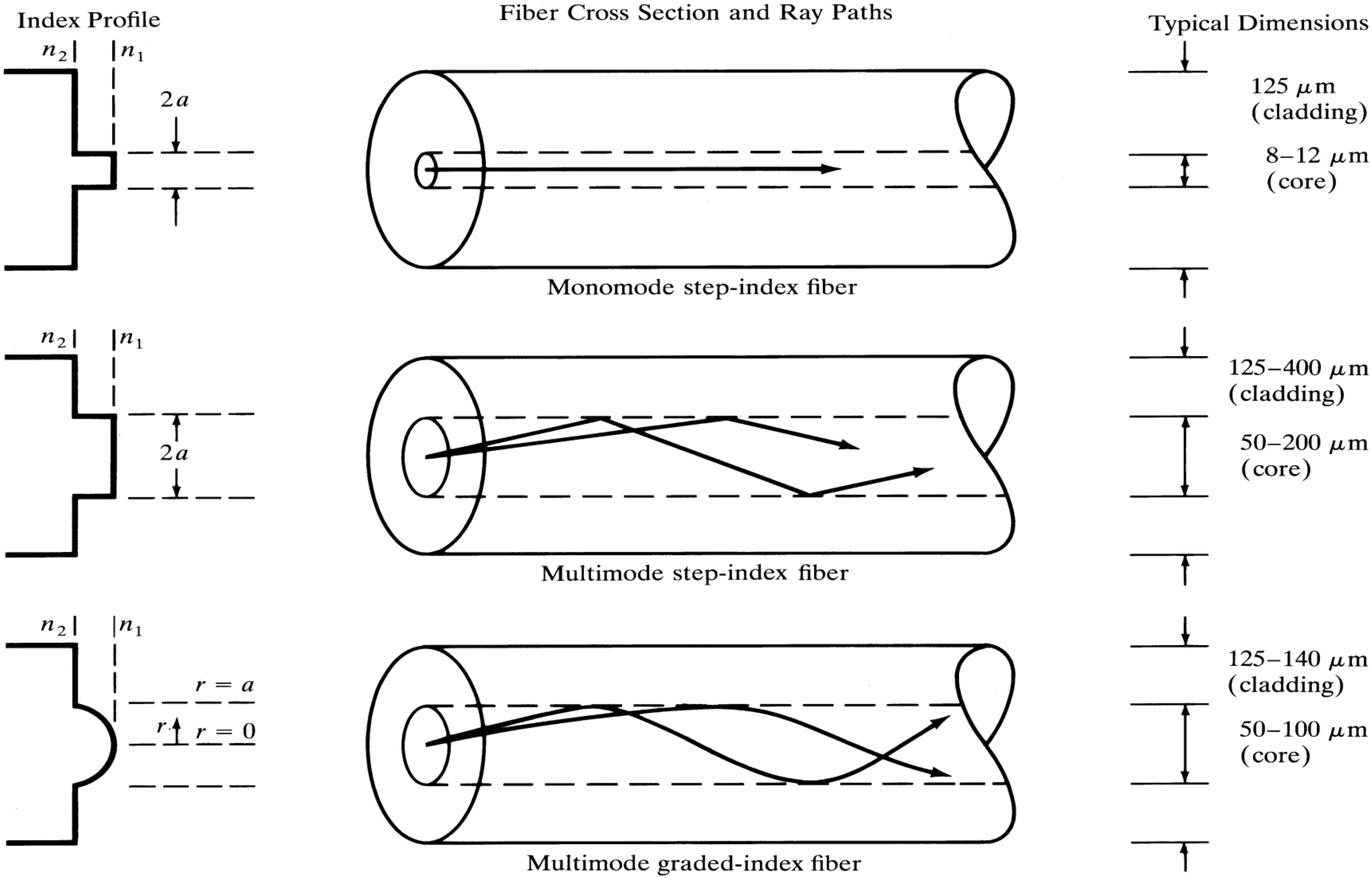
Fiber Structure



- 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



DESIGNER'S PARAMETERS

Numerical Aperture (NA) :

$$NA = \sin\theta_a = [(n_1)^2-(n_2)^2]^{1/2}$$

0.10-0.25 for SMF, 0.20-0.50 for MMF

Relative Refractive Index Difference (Δ):

$\Delta = (n_1 - n_2)/n$; n- the average refractive index

<0.4% for SMF, >1% for MMF

Normalized Frequency or **V-Number:**

$$V = [(2\pi a)/\lambda]\ NA$$

$V \leq 2.405$ for SMF; ≥ 10 for MMF

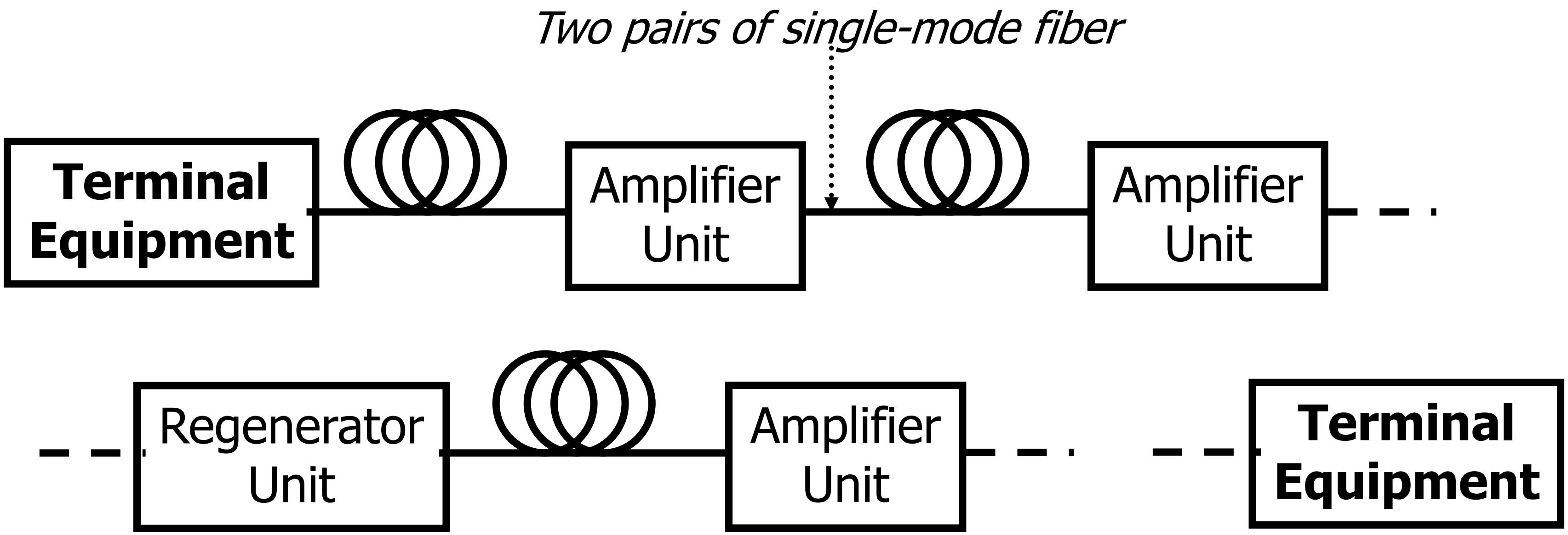
Transmission Characteristics

- **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

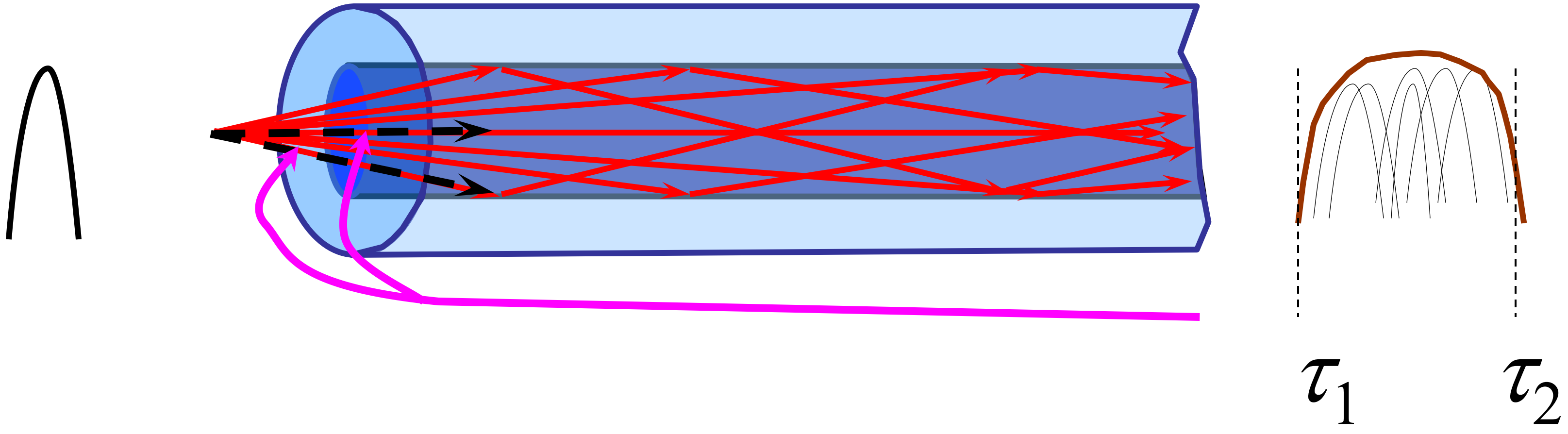
Typical Long-haul Telecom System



- **Amplifier spans**: 30 to 120 km
- **Regenerator spans**: 50 to 600 km
- **Terminal spans**: 600 km (without regenerators)
  9000 km (with regenerators)

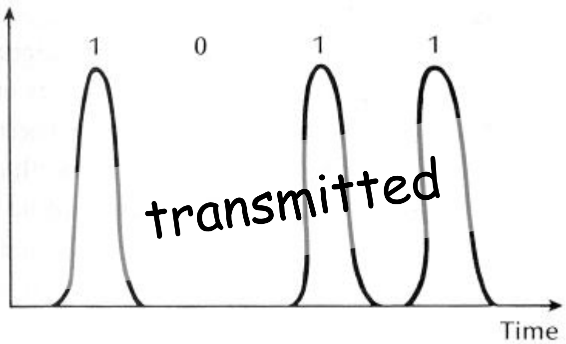
Pulse Broadening

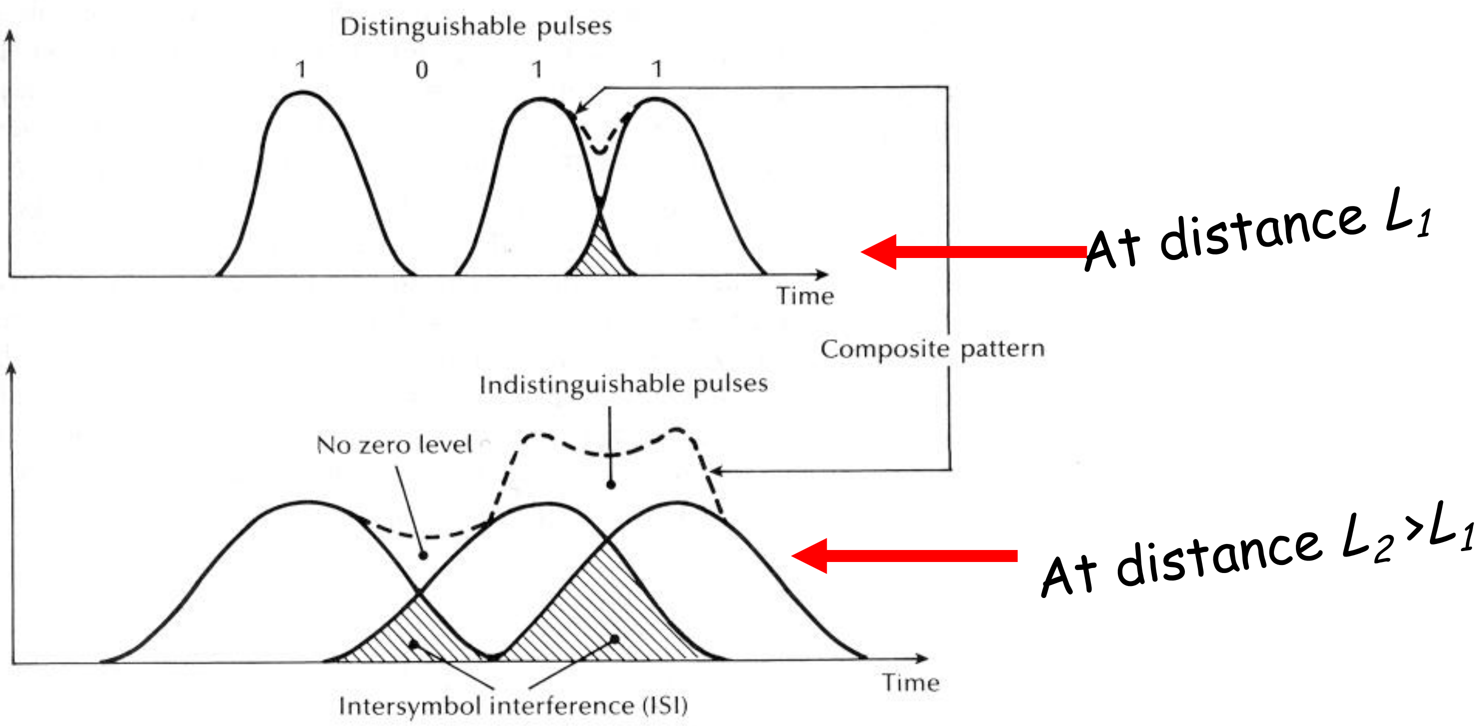
- In the ray model there are a continuum of ray directions between the axial ray and the critical angle a_c
- The axial ray takes the shortest route and arrives at the far end first, whereas the ray at the critical angle takes the longest route and arrives last.
  - ➢ A short input pulse will be broadened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

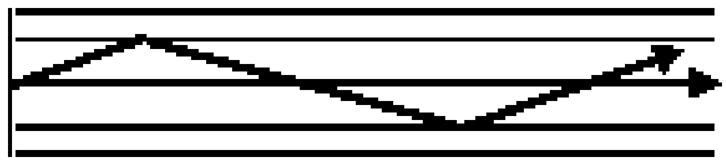
Most important types

1. Intramodal (Chromatic) dispersion
   i) Material dispersion
   ii) Waveguide dispersion
2. Intermodal (Modal) dispersion

Intermodal Dispersion

Fiber Dispersion: C. Modal Dispersion

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

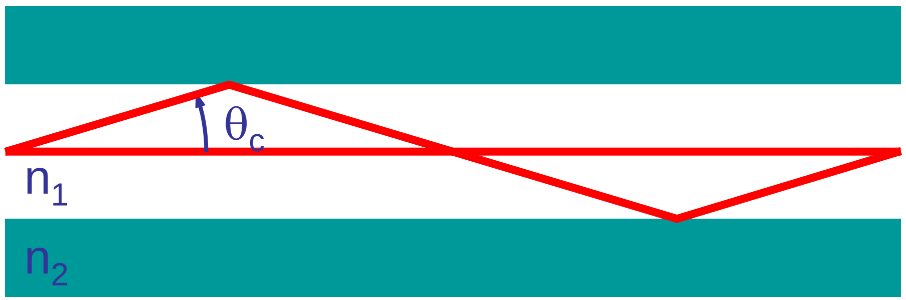


- Time delay between fastest and slowest is modal pulse delay distortion and in SI fiber is...

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

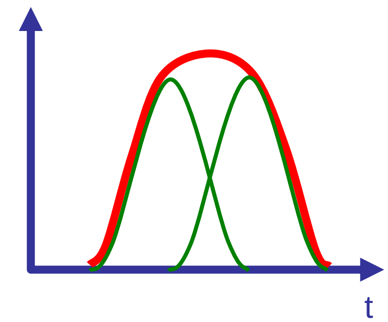
  - $D_{modal} = \Delta\tau_{modal}/L$ [ps·km^{-1}]

Intermodal Dispersion



$$T_{min} = L \cdot \frac{n_1}{c} \qquad T_{max} = L \cdot \frac{n_1}{c \cdot \cos\theta_c}$$

$$\cos\theta_c = \frac{n_2}{n_1}$$



$$D = \Delta T / L = \frac{n_1}{n_2} \cdot \frac{\Delta n}{c} \approx \frac{\Delta n}{c} \approx \frac{NA^2}{2nc} \quad [ns/km]$$

$$B \cdot L = \frac{L}{\Delta T} = \frac{2nc}{NA^2} \quad [(Mb/s)km]$$

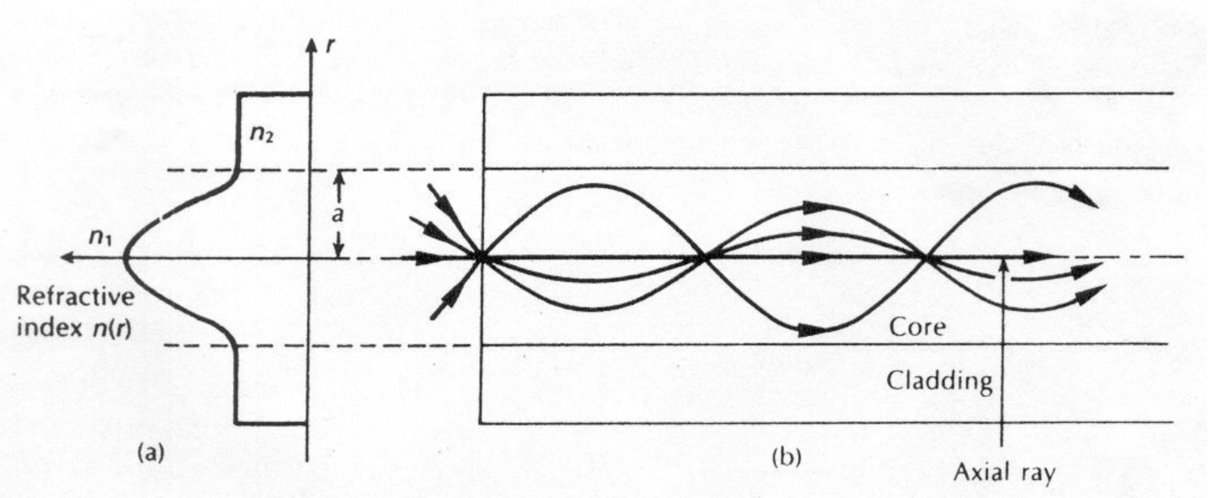
Intermodal Dispersion

- **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 - single-mode fiber 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**.

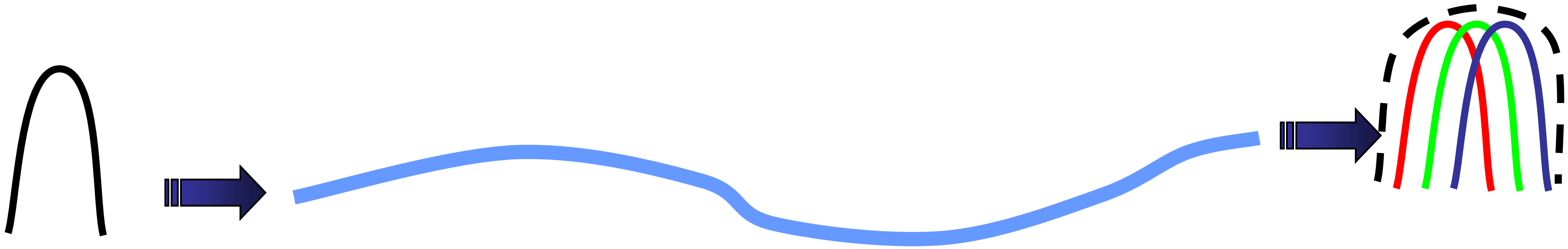
Intramodal Dispersion

- **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**

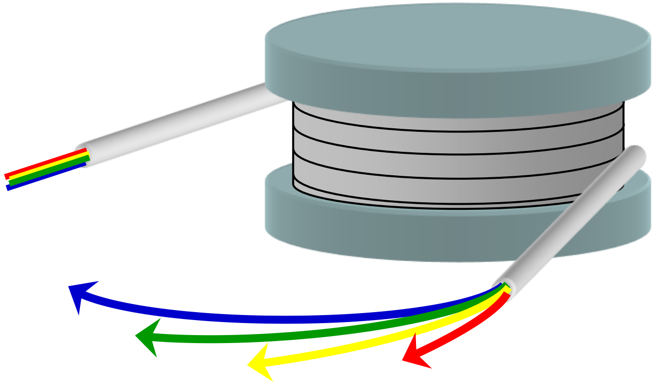


Broadband input pulse

Spectrally dispersed output pulse

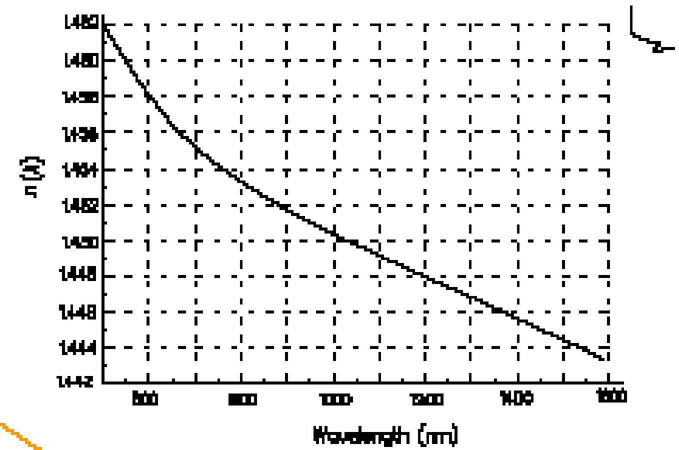
Intramodal (Chromatic) Dispersion

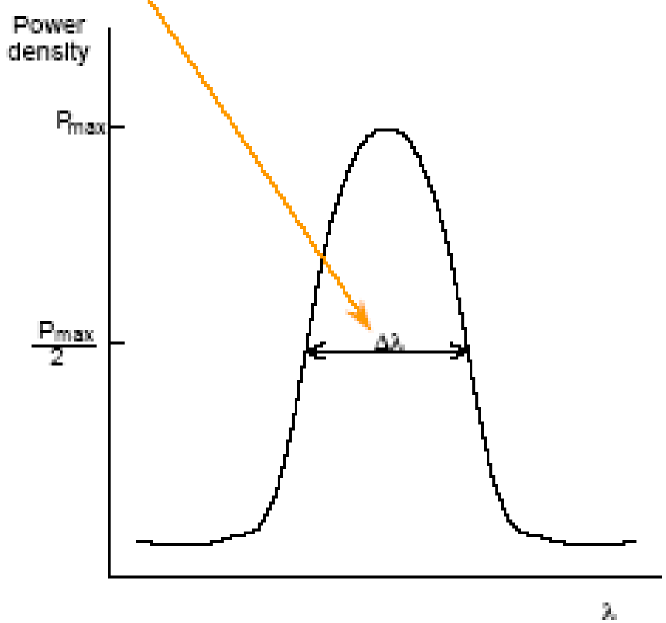
- **Light sources are NOT monochromatic (linewidth of source, chirp effects, modulation sidebands)**
- **Different wavelengths travel at slightly different speeds (this effect is called "Chromatic Dispersion")**
- **Chromatic dispersion causes pulse broadening (problem at high bit rates over long distances)**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

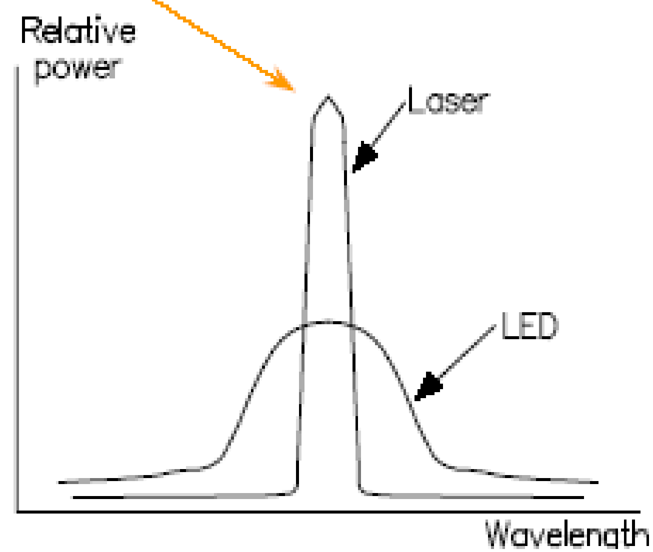


Fiber Dispersion: A. Material Dispersion

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





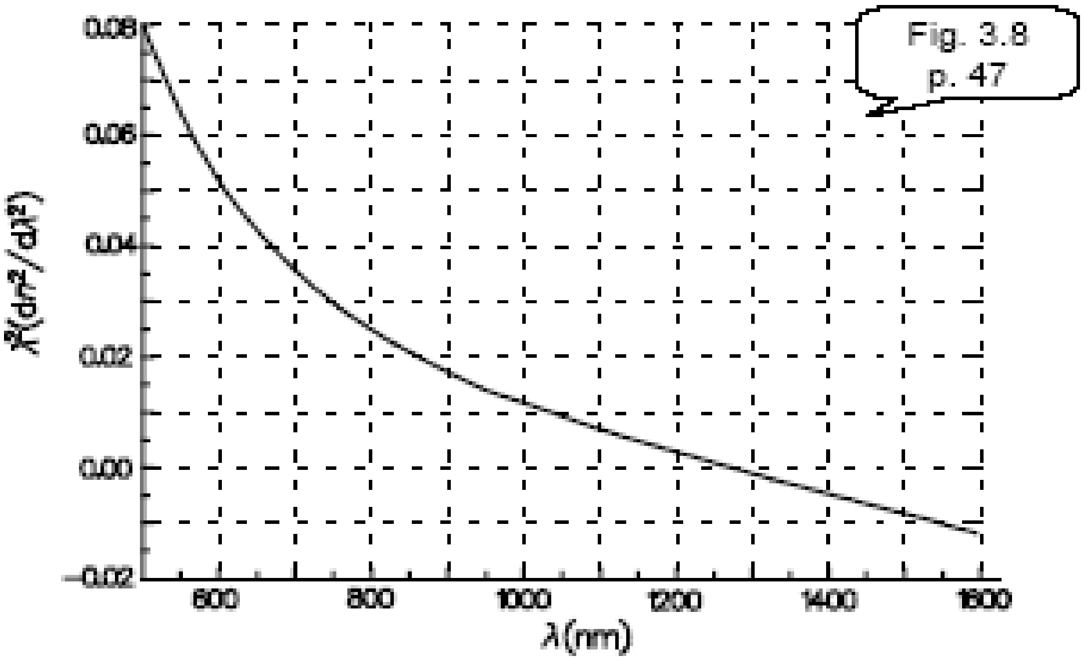


Material Dispersion (cont.)

- **Pulse spread due to material dispersion**

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

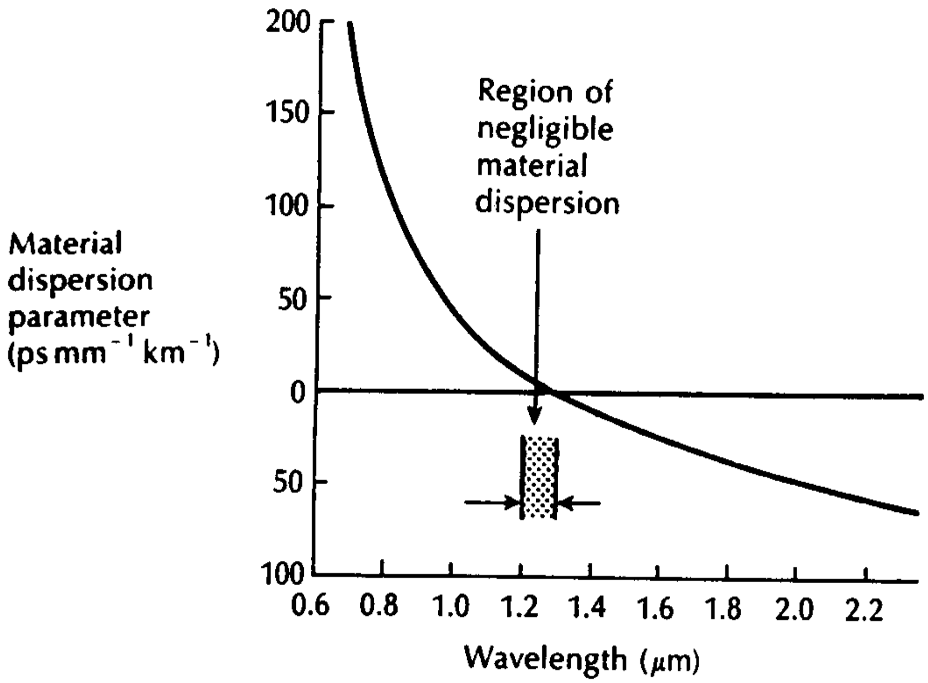
- **Frequently normalized:** $D_{mat}=\Delta\tau_{mat}/(L\Delta\lambda)$ **[ps·km⁻¹·nm⁻¹]**



Material dispersion Parameter (M)

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda}$$

is expressed in ps.nm^{-1}.km^{-1}



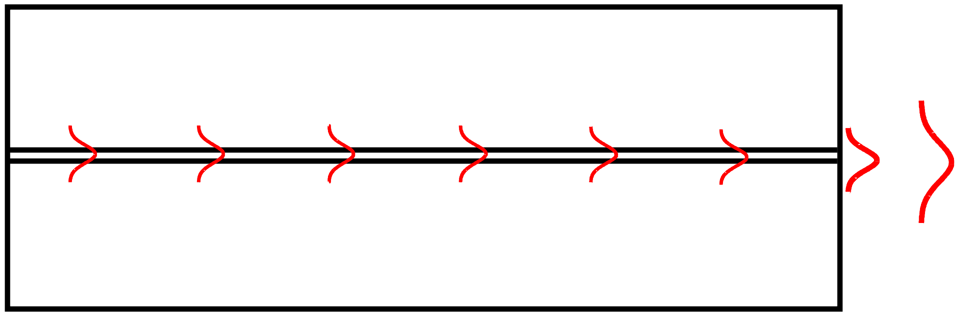
The material dispersion parameter for silica as a function of wavelength

- 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),

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

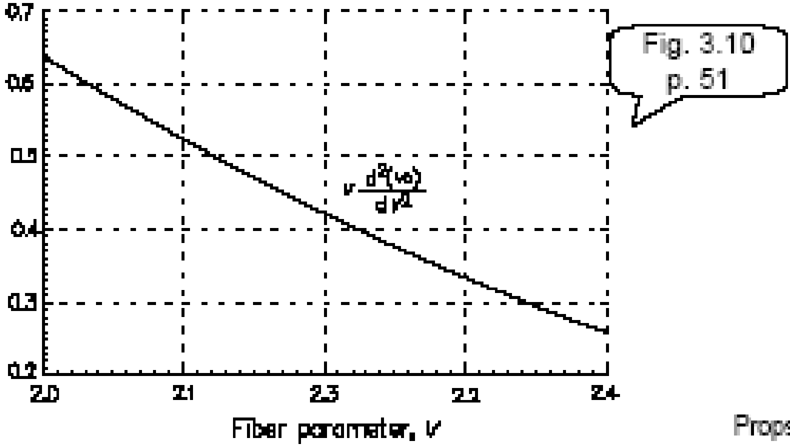


Fiber Dispersion:
B. **Waveguide Dispersion**

- 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}]

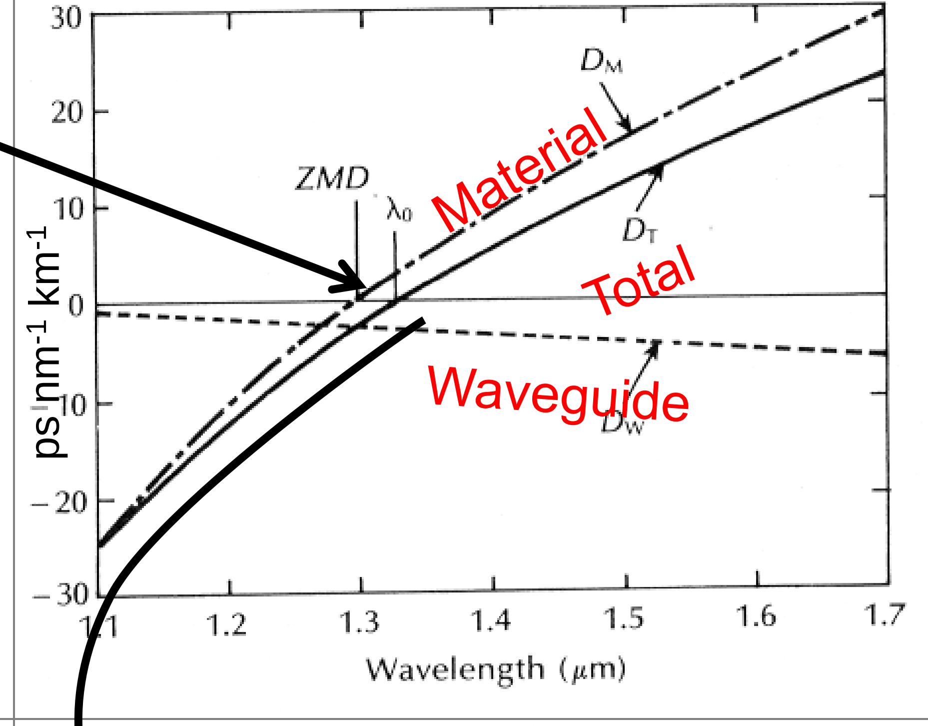


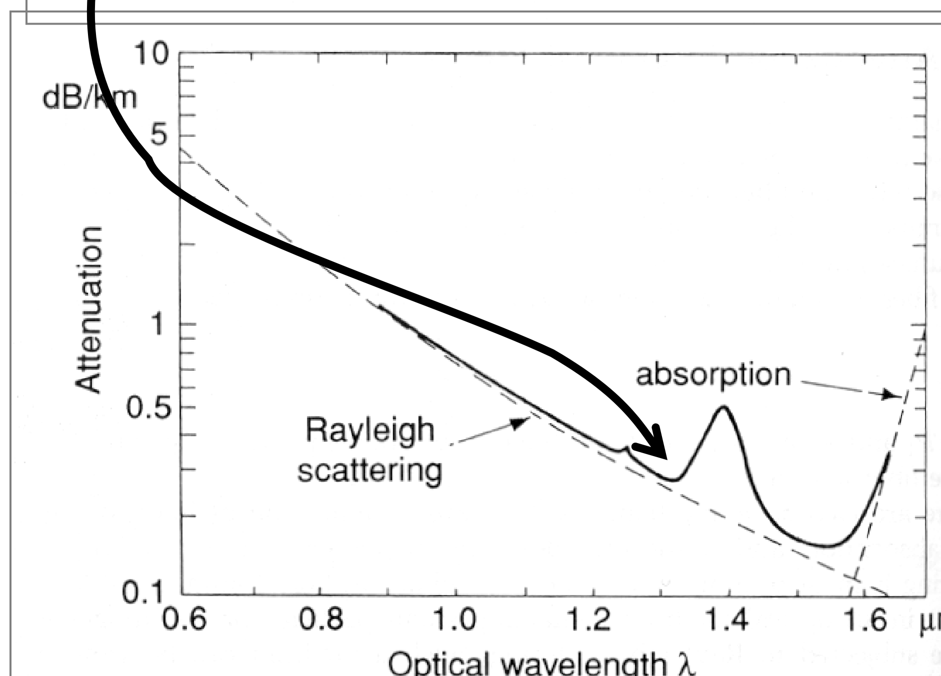
- **Dispersion is sum of material and waveguide components**

- 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

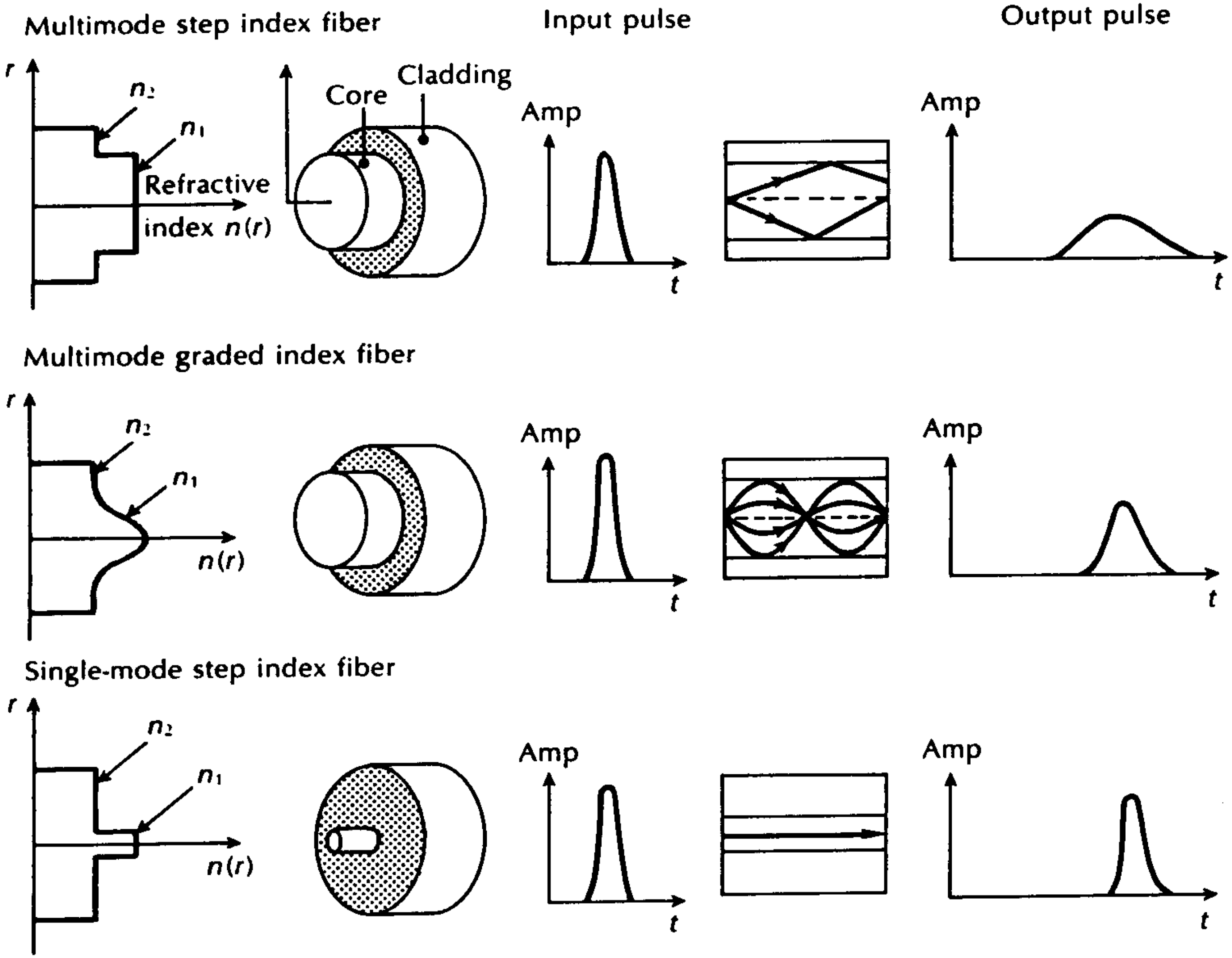
Total Dispersion

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

- **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.

Dispersion Modified SMFs

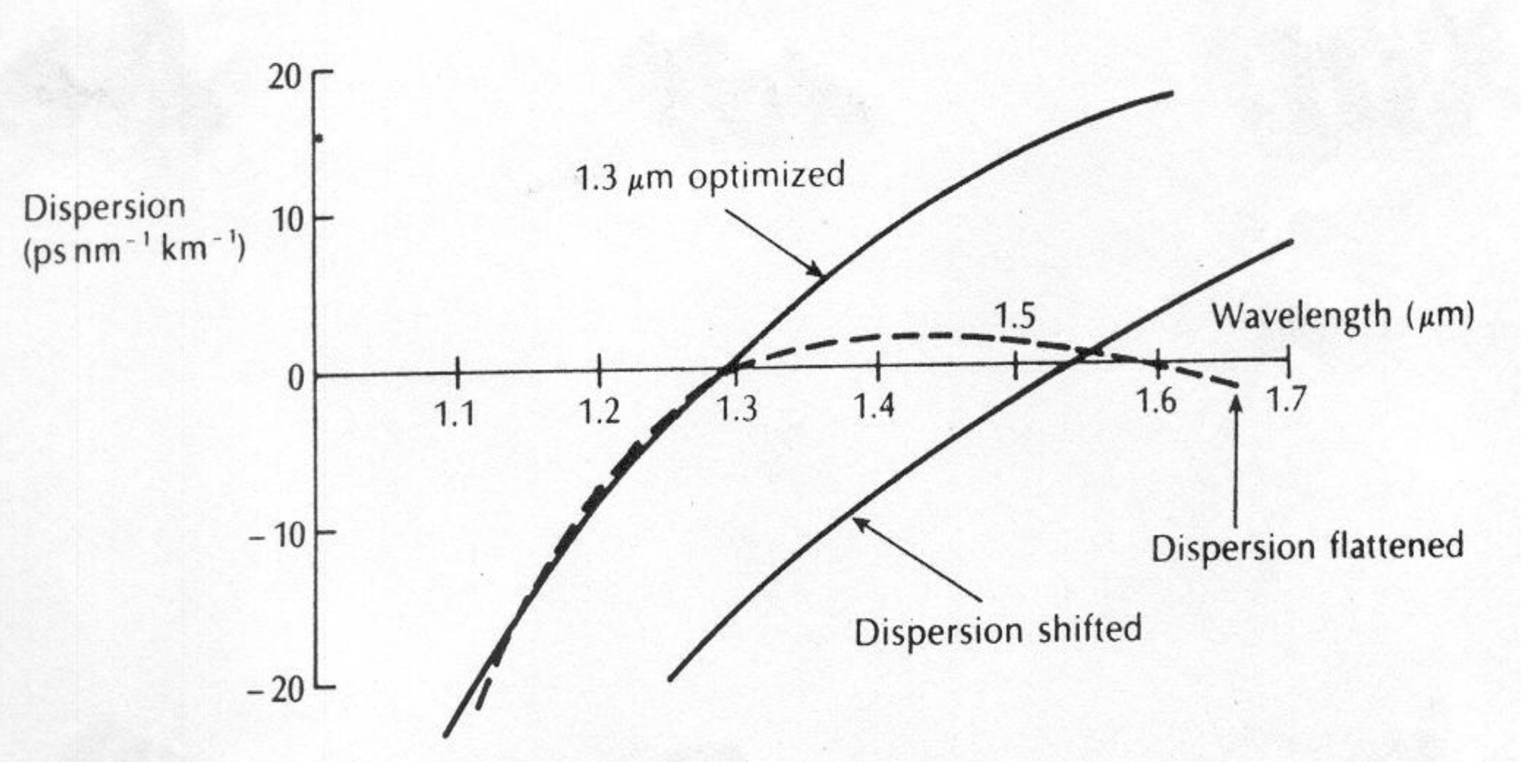
Total Dispersion :

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

- 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, $\boldsymbol{\lambda}_{\mathbf{ZMD}}$ 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**

TRANSMISSION RATE

Bit-Rate and Dispersion

- Maximum bit rate

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

where

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

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

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**

THANK YOU