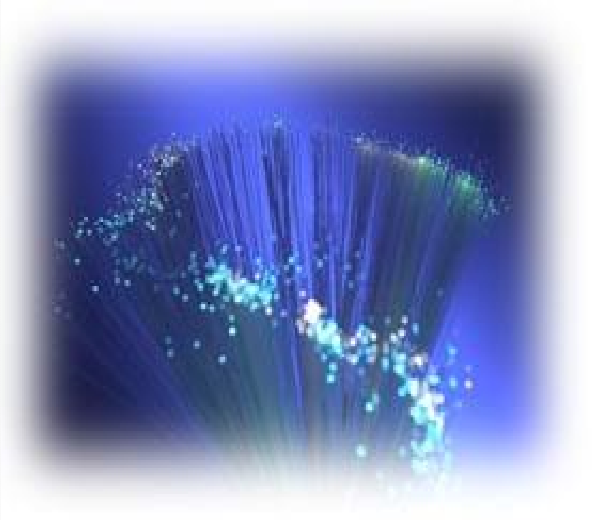
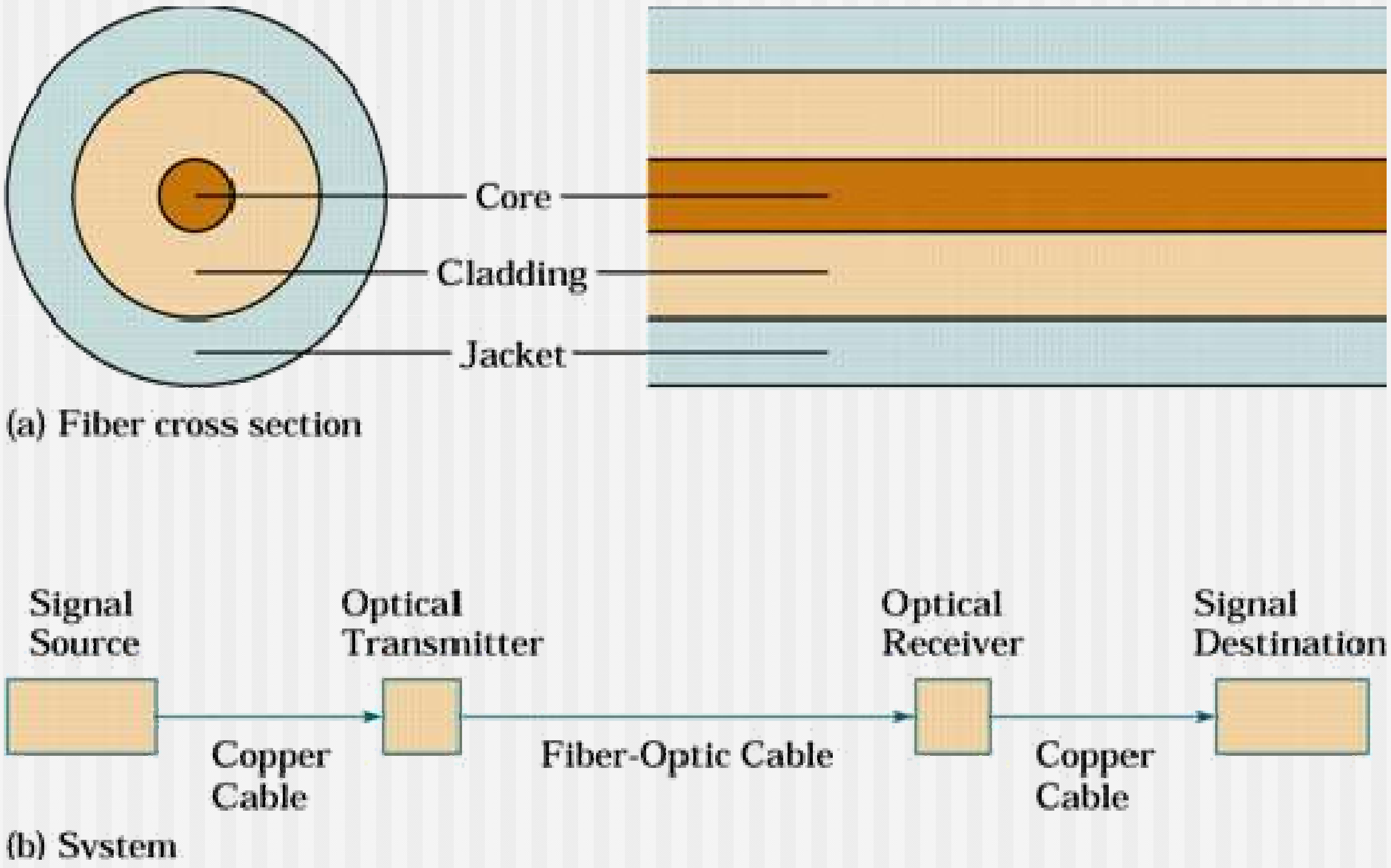
# Introduction to Fiber Optics



# What are optical fibers

- Thin strands of pure glass
- Carry data over long distances
- At very high speeds
- Fiber can be bent or twisted

# Optical Fiber & Communications System



# Fiber optic technology

- Sources
- Transmission medium
- Detectors

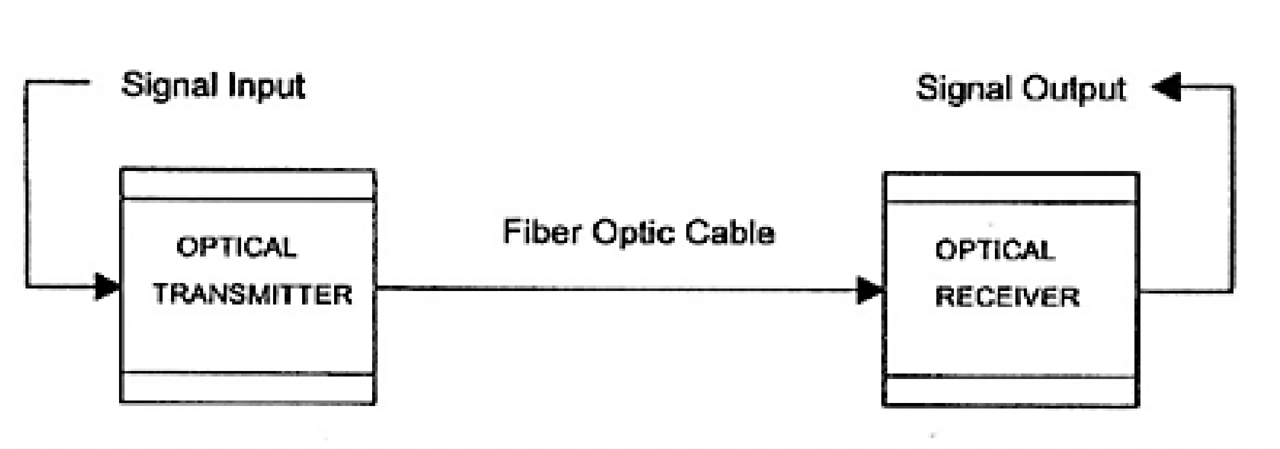


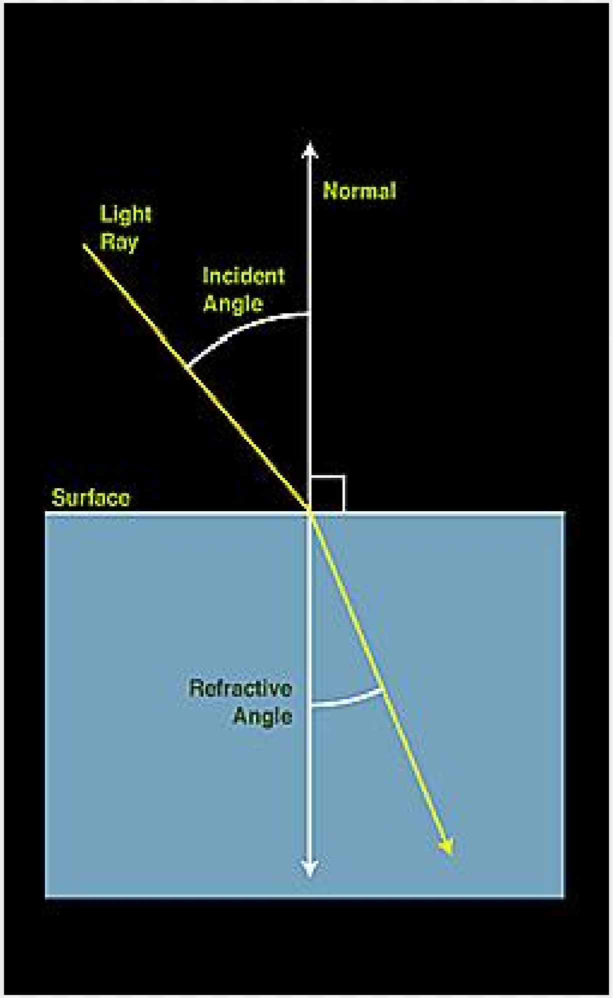

Fig: The fiber optic communication system

# Physics of optical fibers

- Index of refraction of material : ratio of speed of light in vacuum to speed of light in medium
- Refraction of light : bending of light as it travels from one media to another

# Refraction of light

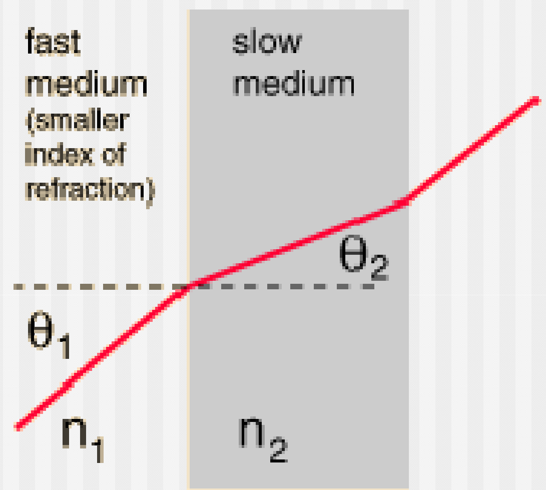
- Speed of light changes as it across the boundary of two media
- Angles w.r.t normal



# Snell’s Law

Snell's Law

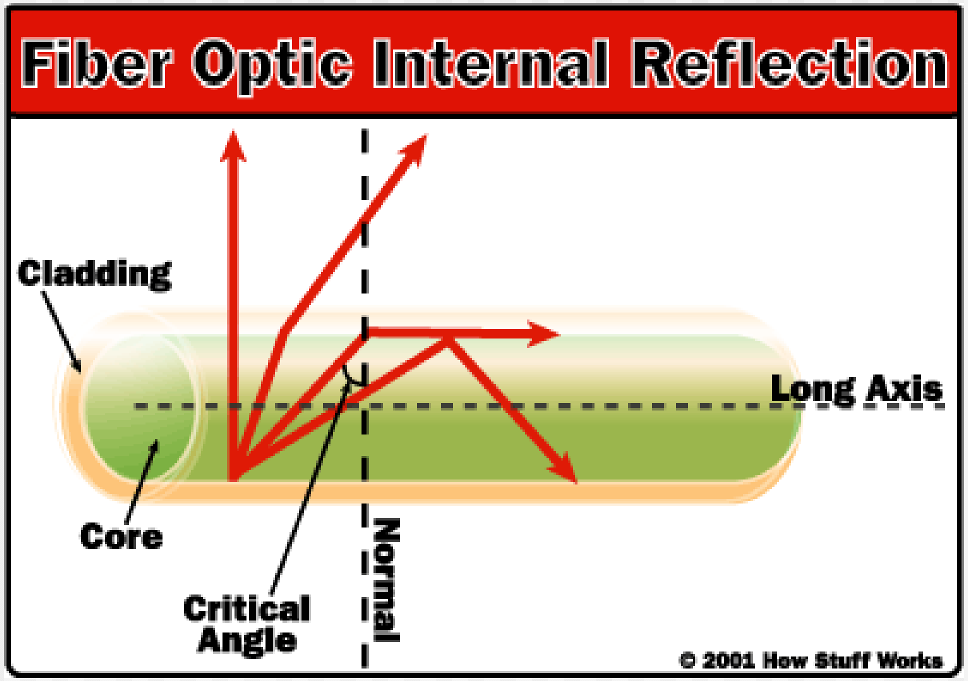
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$




- Critical angle: Angle of incidence at which angle of refraction = $90^0$

# Total internal reflection

- Trapping light in the fiber

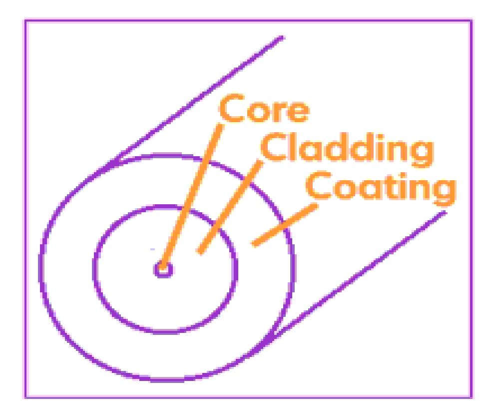


# Sources

- Modulate electrical signals into optical signals
- Mostly modulate at 850nm, 1300nm and 1550 nm
- Lasers give high intensity, high frequency light
- LEDs are economical

# Transmission medium

- Optical fiber is replacing copper
- Light is used as the carrier of information
- Much higher data rate




The optical fiber

# Types of optical fibers

- Single mode
  - only one signal can be transmitted
  - use of single frequency
- Multi mode
  - Several signals can be transmitted
  - Several frequencies used to modulate the signal

# Splices and Connectors

- To connect to fibers mechanically or by fusion
- Lot of signal loss possible
- Very accurate alignment necessary
- Most important cost factor
- Now being replaced by optical amplifiers

# Optical Receivers

- Must be very sensitive
- Capable of picking up and amplifying signals of nanowatts
- Photodiodes and phototransistors
- These devices get ‘turned ON’ by light
- Produce photocurrent

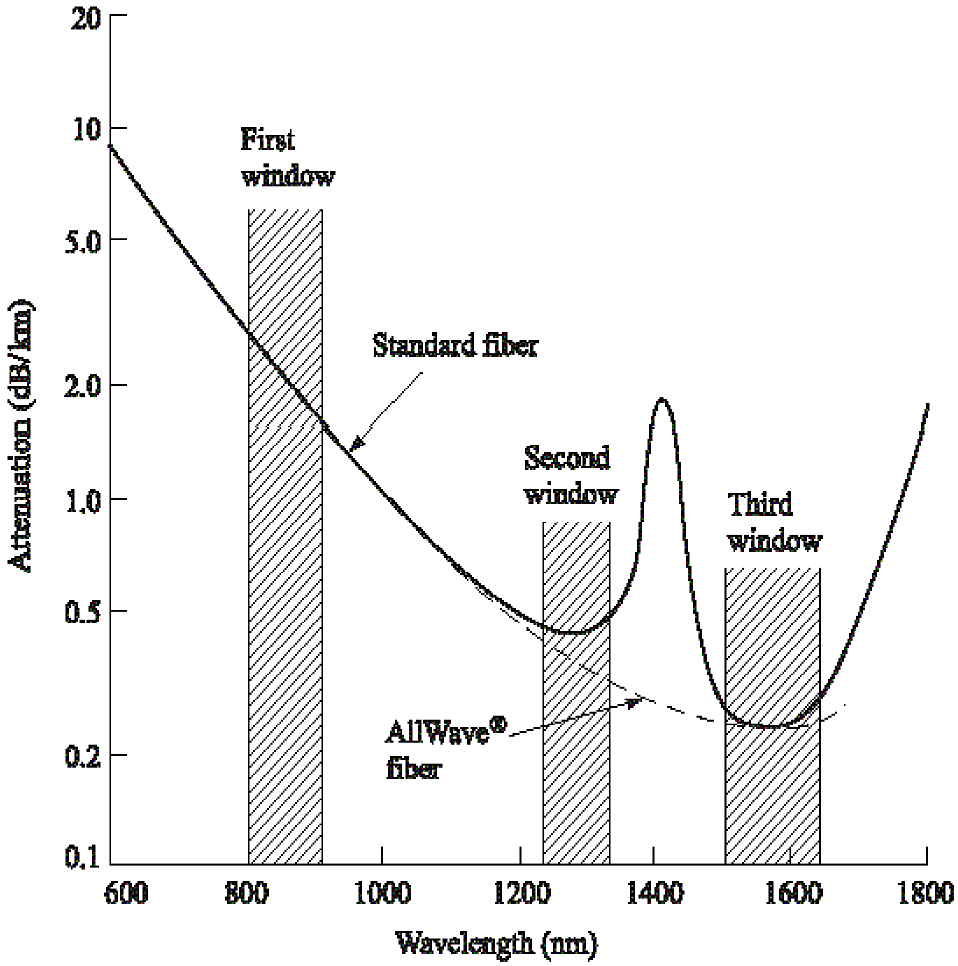
# Advantages of optical fibers

- Can carry much more information
- Much higher data rates
- Much longer distances than co-axial cables
- Immune to electromagnetic noise
- Light in weight
- Unaffected by atmospheric agents

# Signal Attenuation & Distortion in Optical Fibers

- 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.

# Optical fiber attenuation vs. wavelength

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# 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 SiO2.

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.

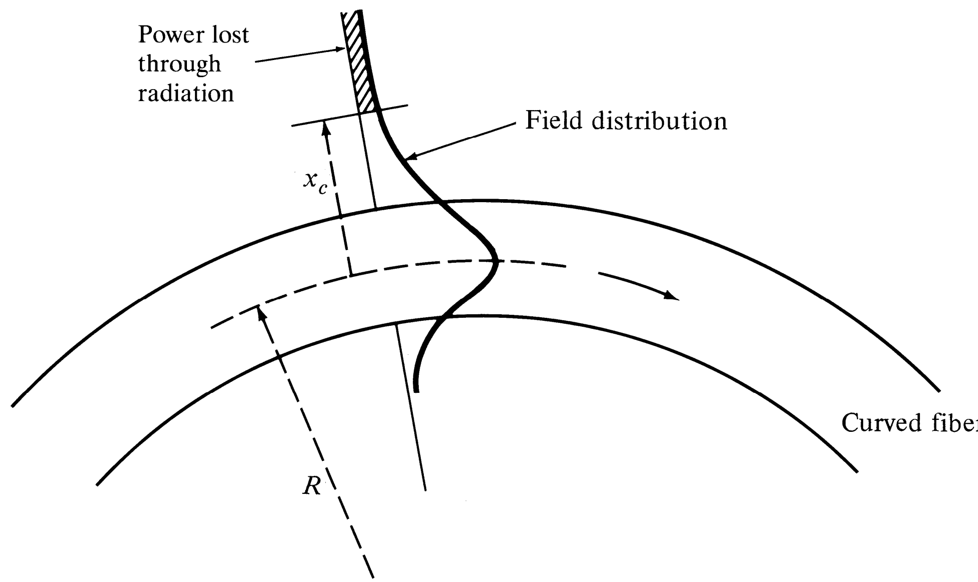
- The essential mechanism is the Rayleigh scattering. Since the black body radiation classically is proportional to $\lambda^{-4}$ (this is true for wavelength typically greater than 5 micrometer), the attenuation coefficient due to Rayleigh scattering is approximately proportional to $\lambda^{-4}$. 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

$$\alpha_{scat} \propto \lambda^{-5}\left[\exp\left(\frac{hc}{\lambda k_B T}\right)\right]^{-1}$$

$$h = 6.626\times10^{-34}\ \text{Js},\quad k_B = 1.3806\times10^{-23}\ \text{JK}^{-1},\ T: \text{Temperature}$$

# 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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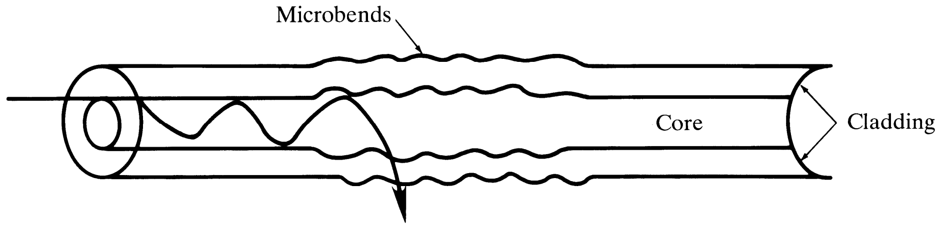
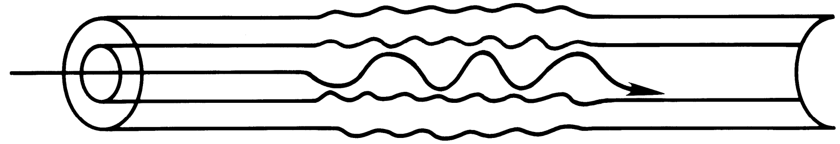
# Microbending Loss

- **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.




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.**

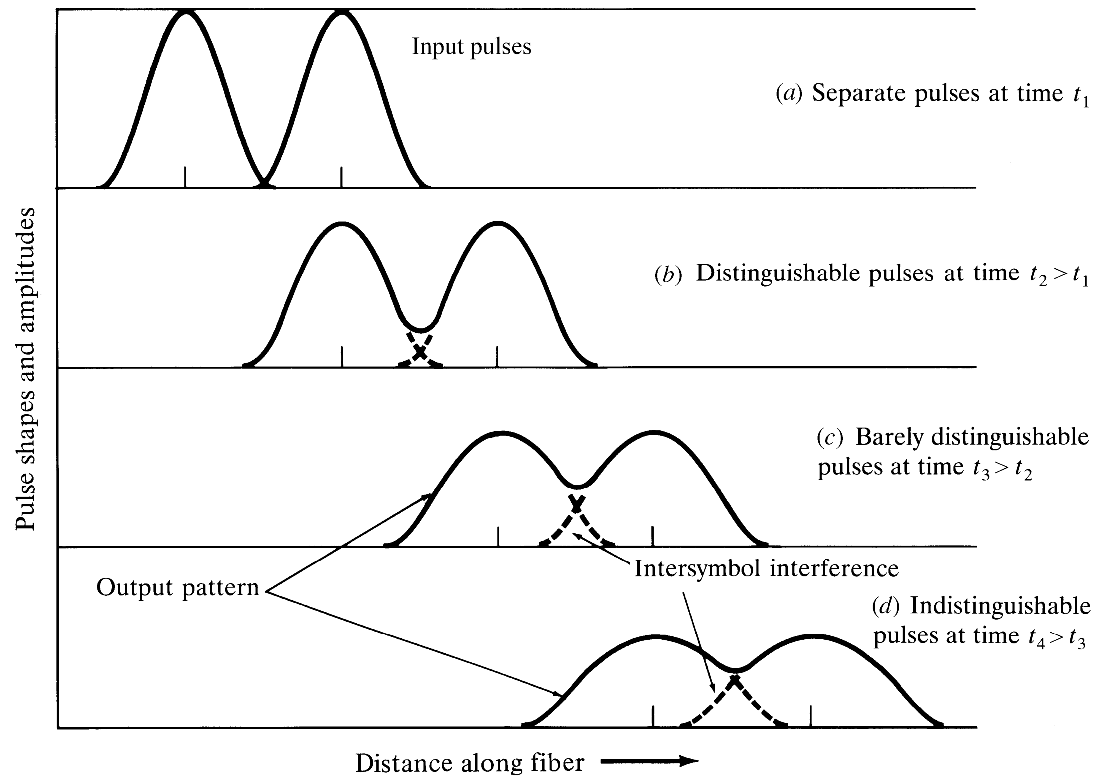
# Intramodal Dispersion

- 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 $\omega_c$, 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**.

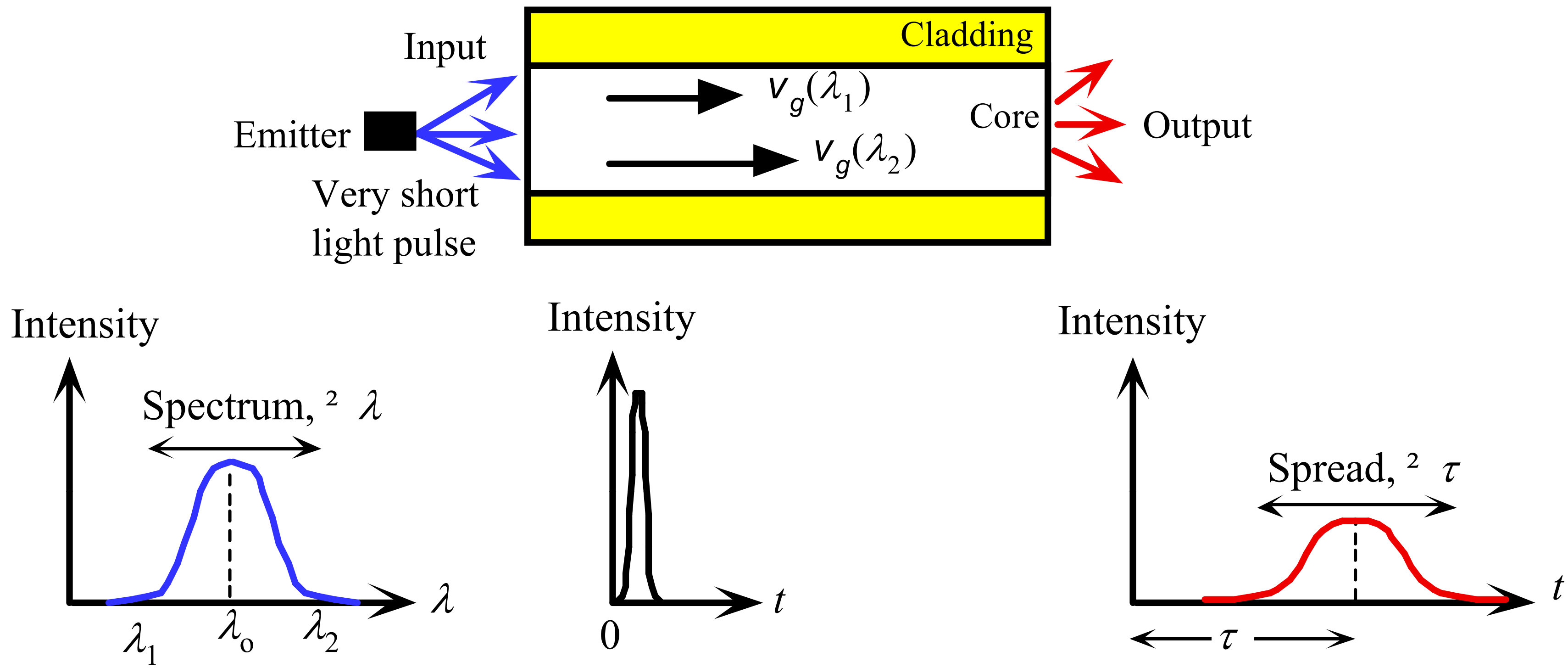
- In the case of optical pulse propagation down the fiber, GVD causes pulse broadening, leading to Inter Symbol Interference (ISI).

# 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.



# Material Dispersion




All excitation sources are inherently non-monochromatic and emit within a spectrum, ² $\lambda$, 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.

# 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*:

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

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

- The pulse spread due to material dispersion is therefore:

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

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

# 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, (see Fig 2-18 of the textbook). In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

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

- solving for propagation constant:

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

- Using *V* number:

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

# Waveguide Dispersion

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

$$\tau_{wg} = \frac{L}{c}\left[ n_2 + n_2 \Delta \frac{d(Vb)}{dV} \right] \qquad [3\text{-}24]$$

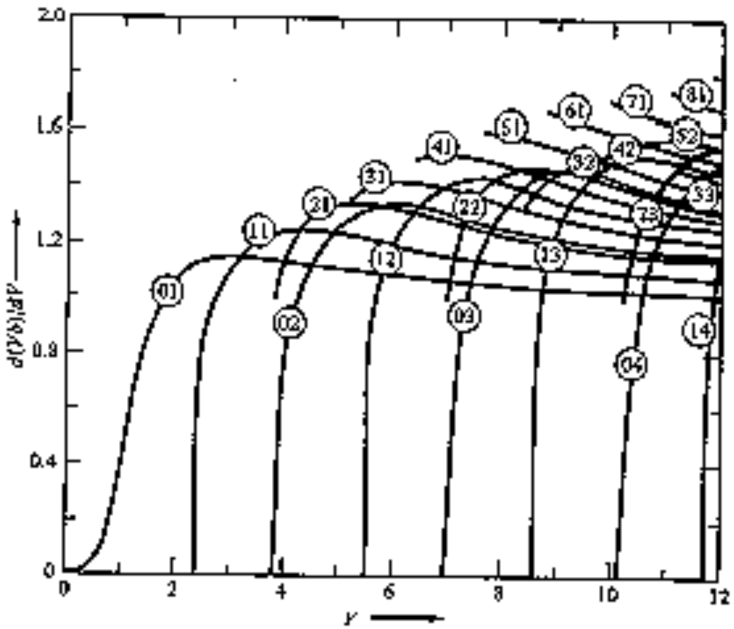
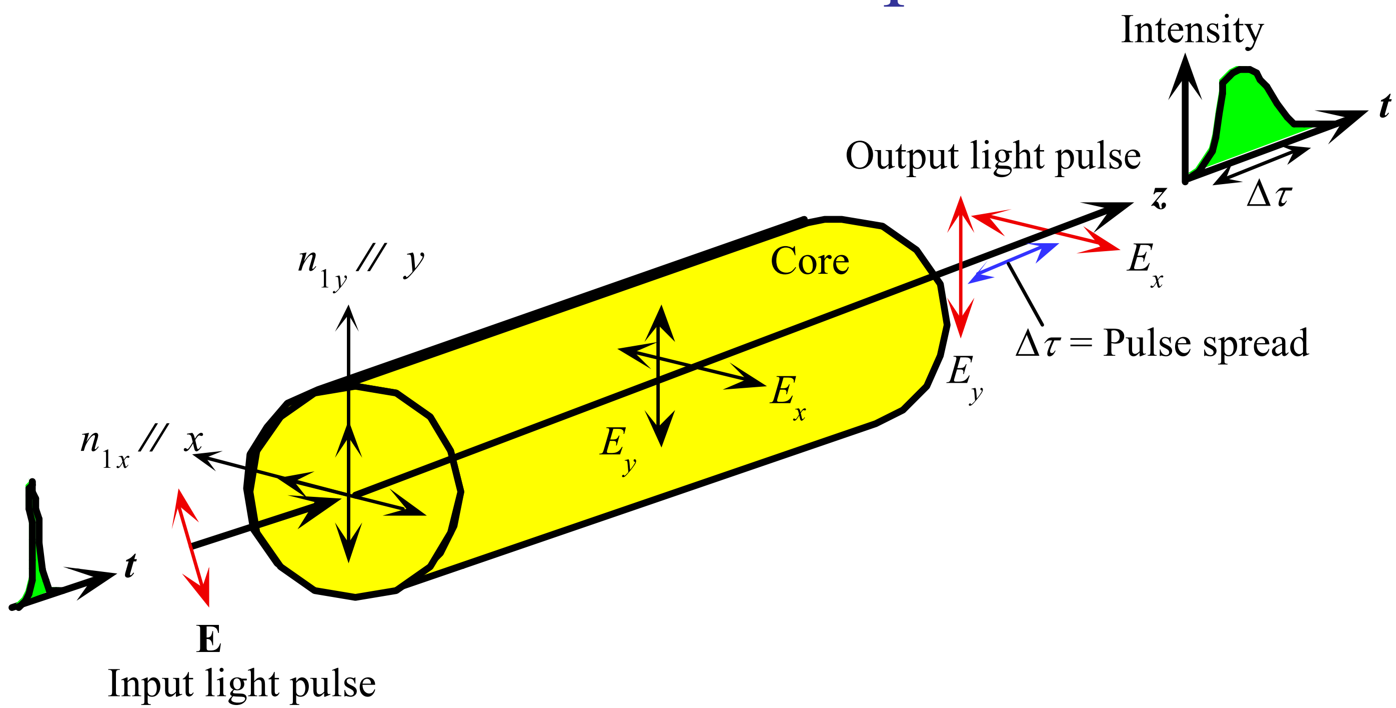



**FIGURE 3-14**
The group delay arising from waveguide dispersion as a function of the $V$ number for a step-index optical fiber. The curve numbers $j\mu$ designate the $LP_{j\mu}$ modes. (Reproduced with permission from Gloge.[37])

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

# Polarization Mode dispersion




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

$$\Delta\tau_{pol} = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| \qquad [3\text{-}26]$$

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

$$\langle \Delta\tau_{pol} \rangle \approx D_{PMD}\sqrt{L} \qquad [3\text{-}27]$$

# 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:

$$D_{total} \approx \left| D_{ch} + D_{pol} + \ldots \right|$$
$$\sigma_{total} = D_{total} L \sigma_{\lambda}$$

[3-29]

# 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 $100\,\mu m^2$ ).

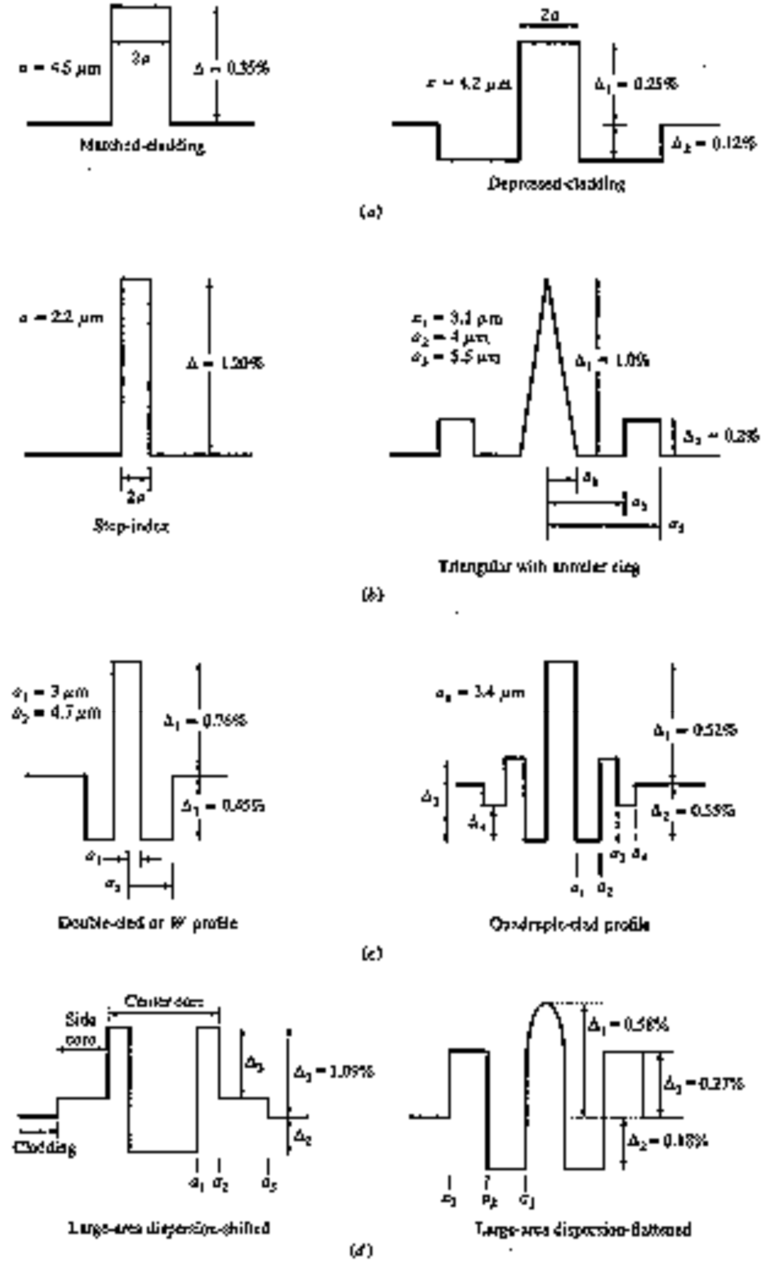



FIGURE 3-22
Representative cross sections of index profiles for (a) 1500-nm-optimized, (b) dispersion-shifted, (c) dispersion-flattened, and (d) large-effective-core-area fibers.

# Single mode Cut-off wavelength & Dispersion

- Fundamental mode is $HE_{11}$ or $LP_{01}$ with V=2.405 and $\lambda_c = \frac{2\pi a}{V}\sqrt{n_1^2 - n_2^2}$ [3-30]
- Dispersion:

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

$$\sigma = D(\lambda) L \sigma_\lambda \qquad [3\text{-}32]$$

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