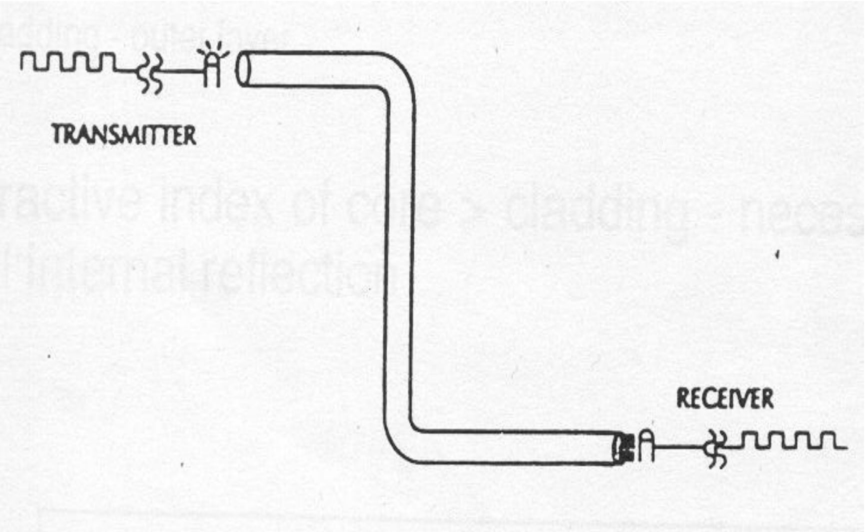
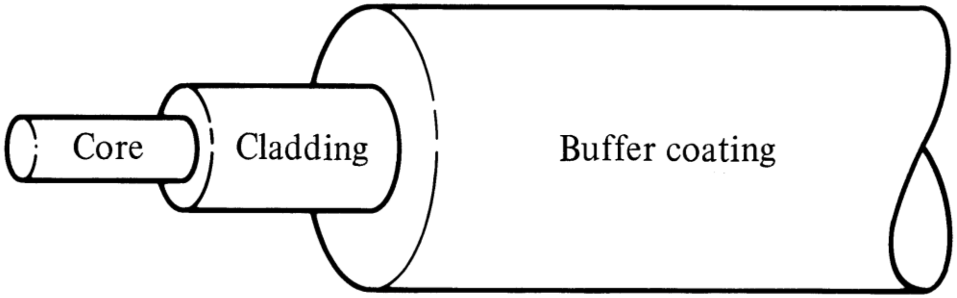
# Transmission Characteristics of Optical Fiber II



# OPTICAL FIBER

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

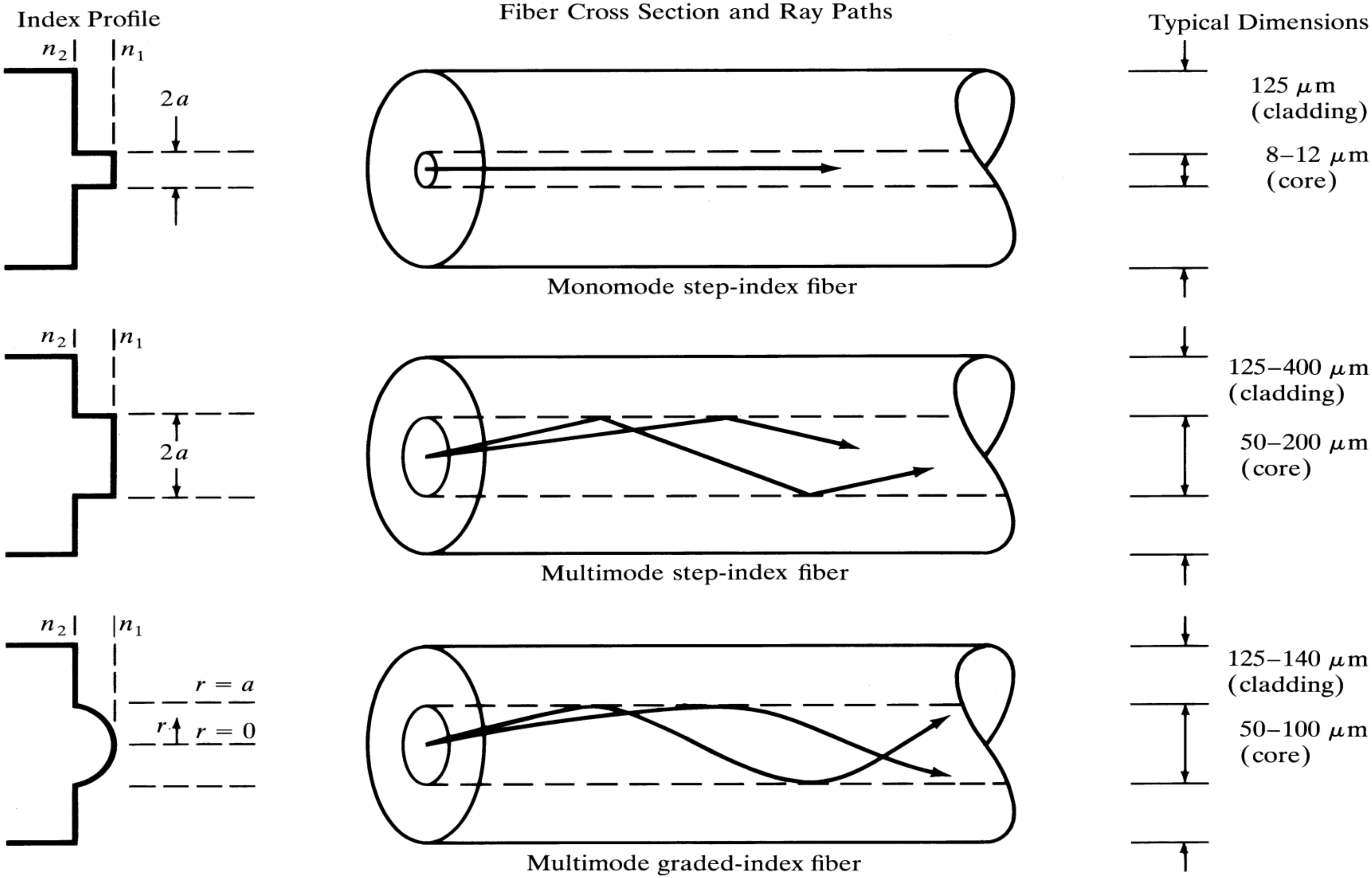
**Fiber Structure**




- 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; $\geq 10$ for MMF

# Transmission Characteristics

## Characteristics of Primary Importance

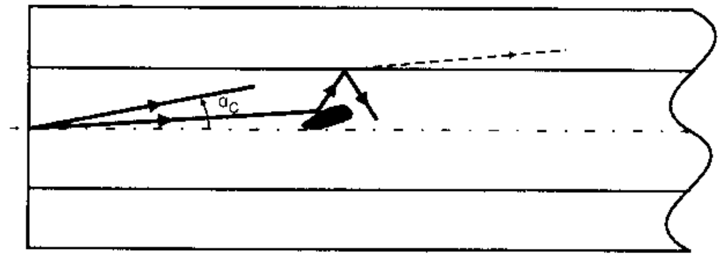
- **Attenuation (or Transmission loss):** determines the maximum ***repeater less separation*** between a transmitter and receiver.

- **Dispersion**: limit the information – carrying capacity of a fiber i.e. ***Bandwidth***

# 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*:

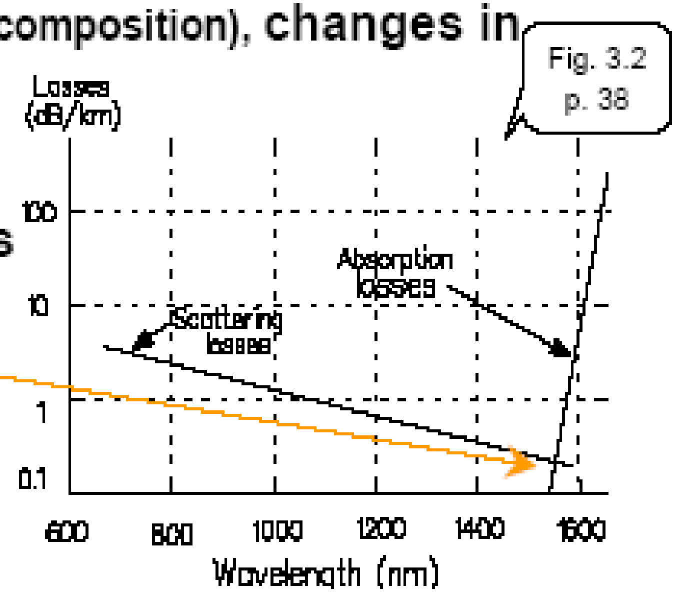
  » Scattered power proportional to incident power

  » 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"



# Rayleigh Scattering Loss

- **Rayleigh scattering coefficient ($\gamma_R$)** 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
    - Inhomogeneities
      - Core-cladding refractive index variations
      - Core-cladding interface impurities
      - Diameter fluctuations
    - Strains in fiber
    - Bubbles in fiber
  - » Solution:
    - Remove imperfections
    - **Controlled extrusion &cabling of the fiber**
    - **Increasing fiber guidance by increasing ‘Δ’**

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

☞ **Mainly in the forward direction**

# Scattering Loss : Nonlinear

b. *Nonlinear Scattering* : Usually 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") (of 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) ⇒ Optical phonon
- Scattered photons

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

» Power level threshold:

$$P_{\text{Raman}} = \left(23.6\times 10^{-2}\right) a^{2}\,\lambda' \alpha \quad \text{(typically few W)}$$

» 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

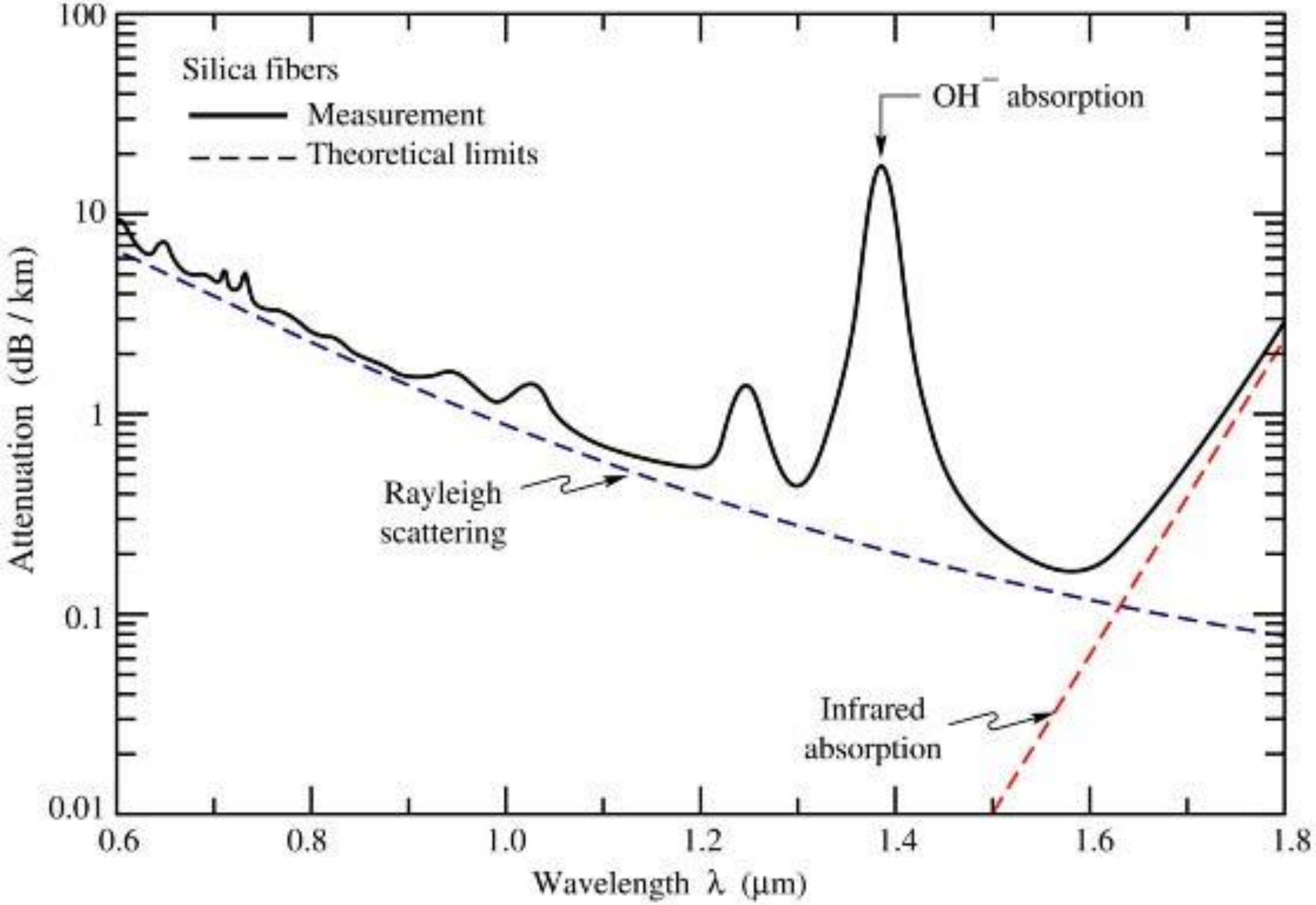
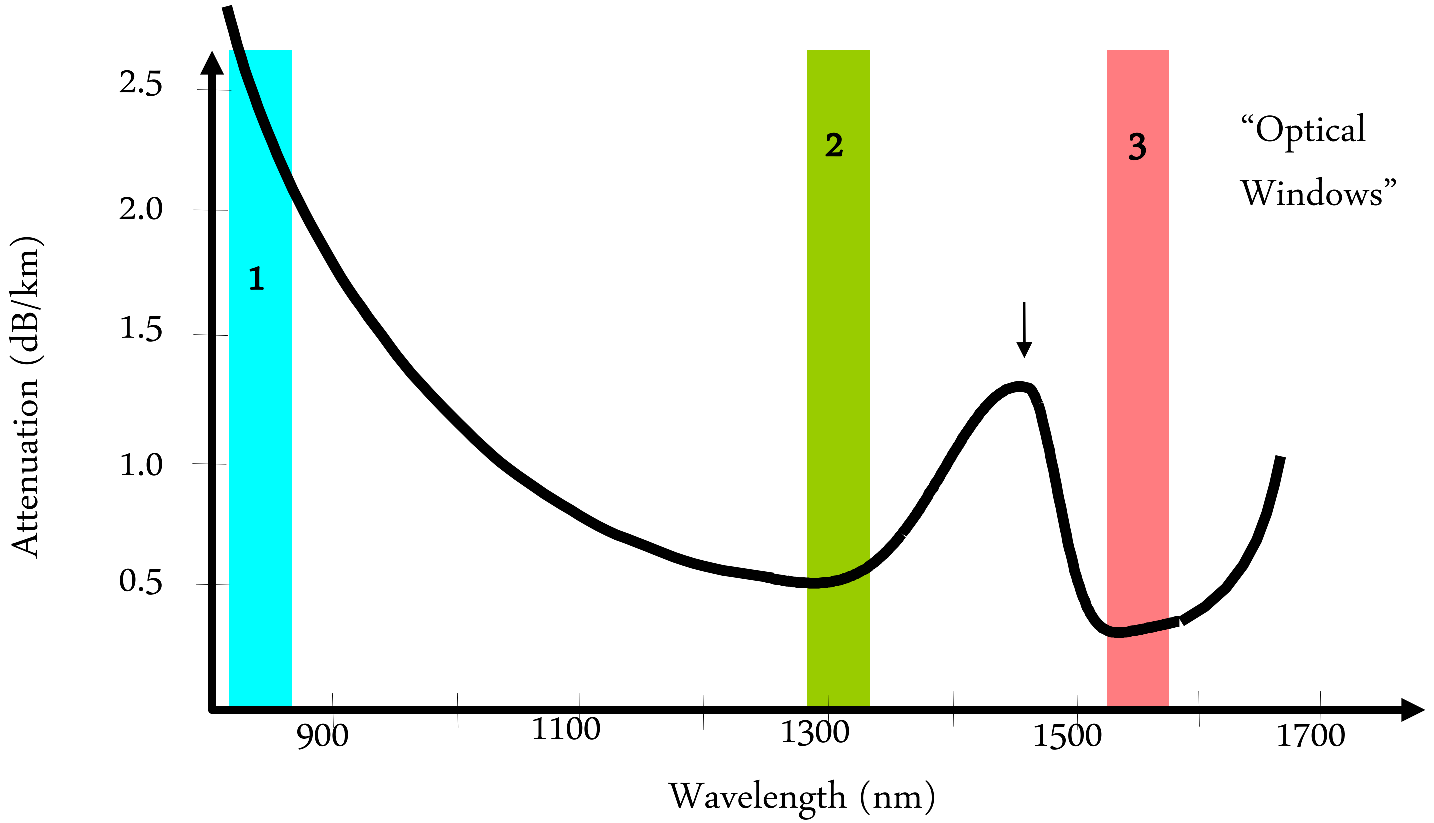



Fig. 12.2. Measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.

# Attenuation in Silica Fibers




**850 nm**

**1310 nm** **1550 nm**

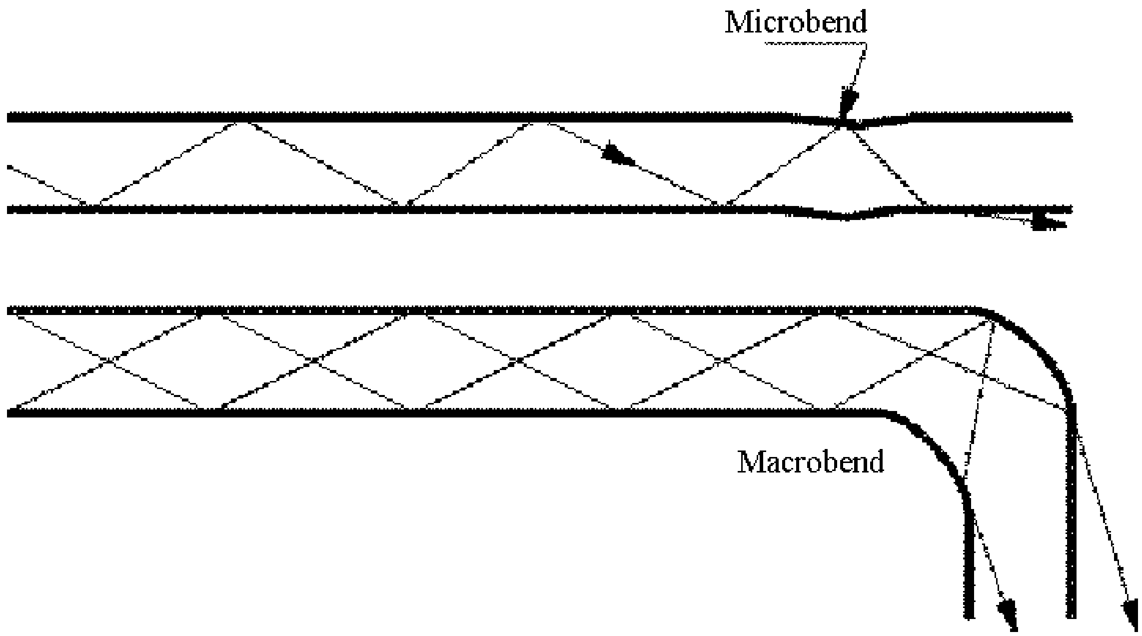
# BENDING LOSSES

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

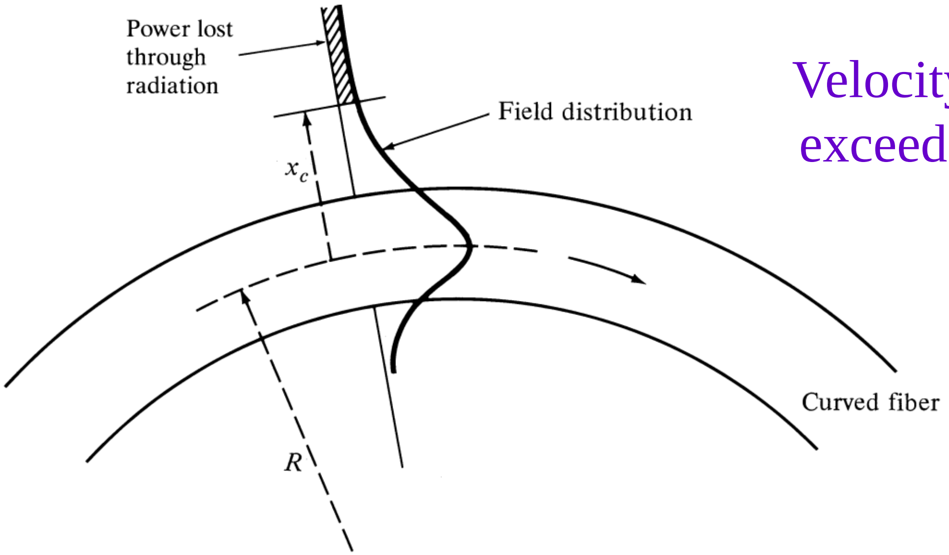
- **Macrobends**
- **Microbends**

# Micro- and Macro- bending

- **Microbending** - **Result of microscopic imperfections in the geometry of the fiber**
- **Macrobending** - **Fiber bending with diameters on the order of centimeters (usually if the radius of the bend is larger than 10 cm)**



# 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 :**

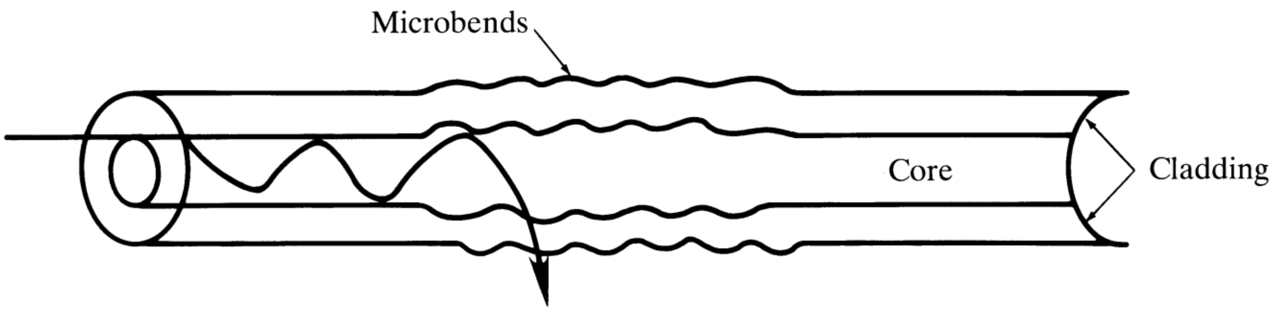
$$R_c \cong \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{\frac{1}{2}}}$$

**> Designing fibers with large relative refractive index differences**

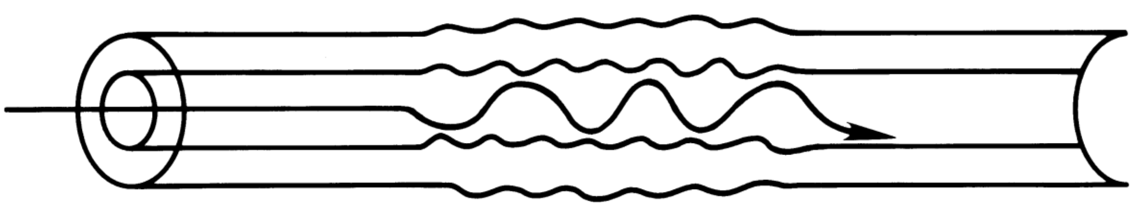
**Operating at the shortest wavelength possible.**

# Microbending losses

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




Power loss from higher-order modes



Power coupling to higher-order modes

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 based optical fiber.

*THANK YOU*