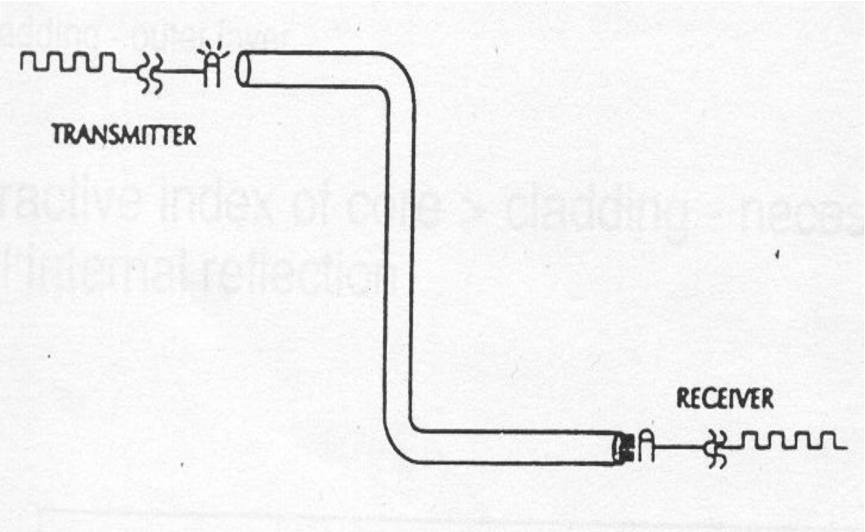
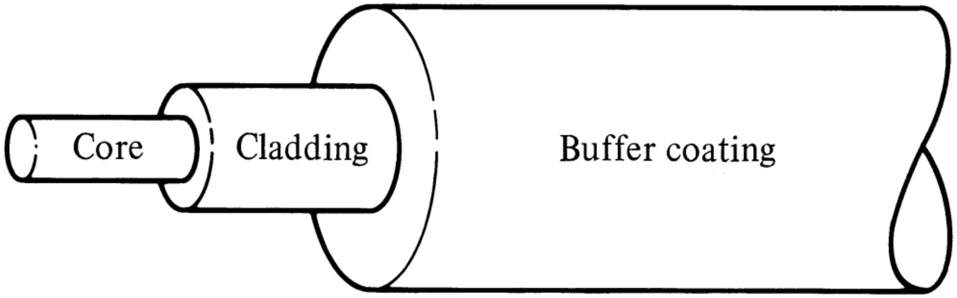
Transmission Characteristics of Optical Fiber I



OPTICAL FIBER

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

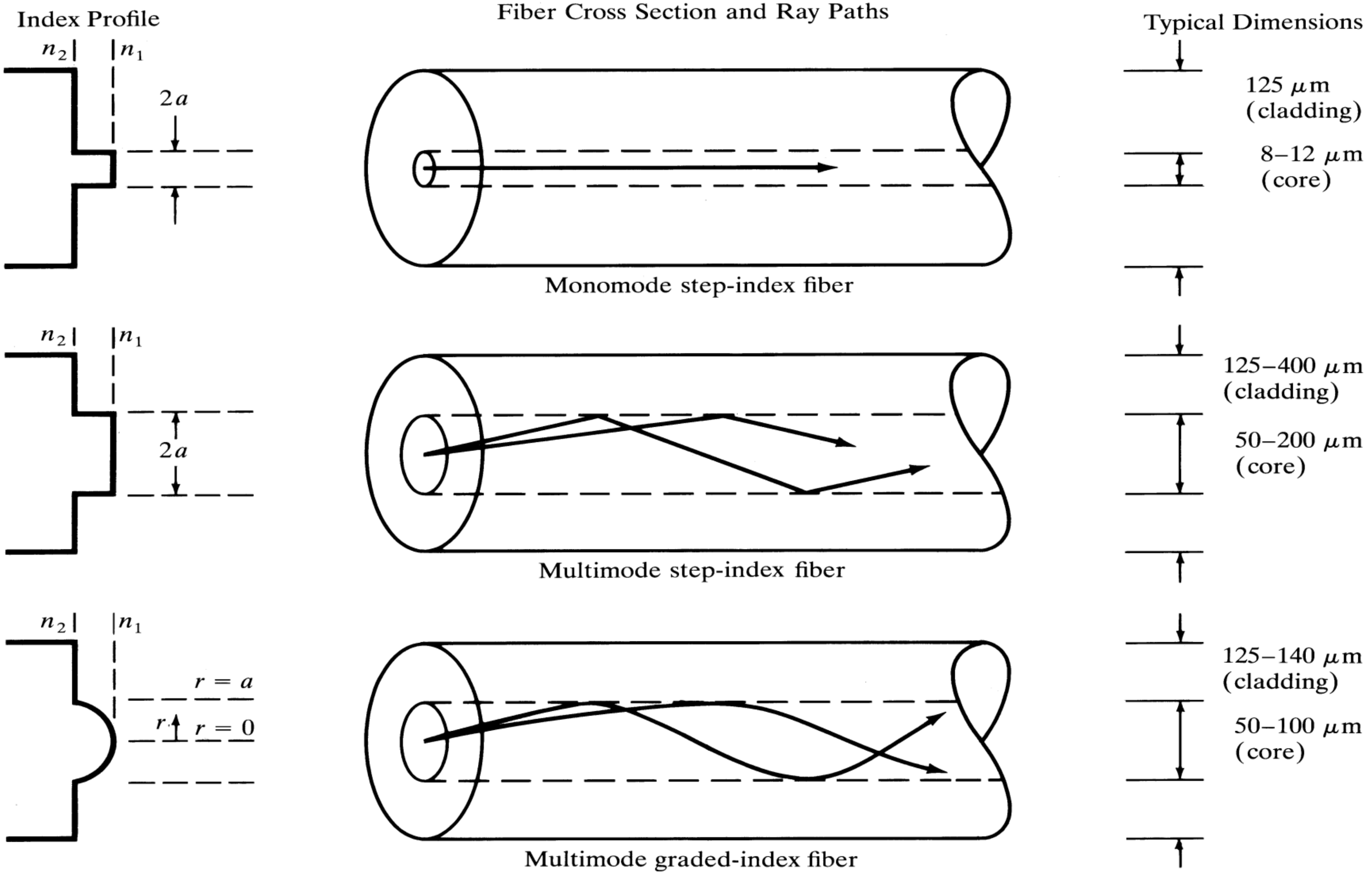
Fiber Structure



- 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

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***

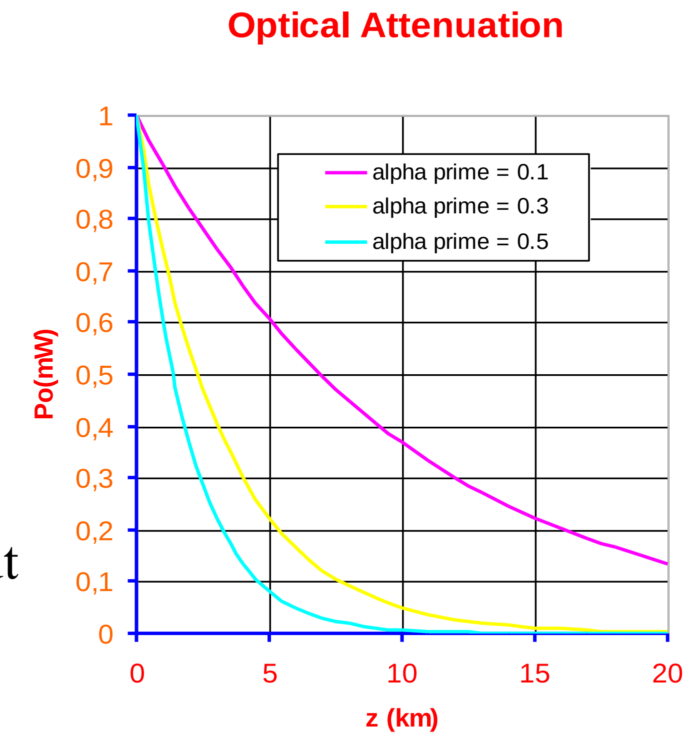
Fibre Performance

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

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



where,

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

P_o **:** Input optical power

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

Optical Fiber Attenuation

- Usually, attenuation is expressed in terms of decibels or mostly dB/km

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

- **Attenuation is because of different mechanisms**

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

Basic Attenuation Mechanisms

1. **Material Absorption (Intrinsic and Extrinsic)**

2. **Scattering (Linear and Non-linear)**

3. **Bending loss (Macrobends and Microbends)**

Material Absorption

A loss mechanism related to the bulk materials and the fabrication process for the fiber

- Results in the loss of some of the transmitted optical power in the waveguide

Absorption of light (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^{15}) by traditional glass refining techniques.

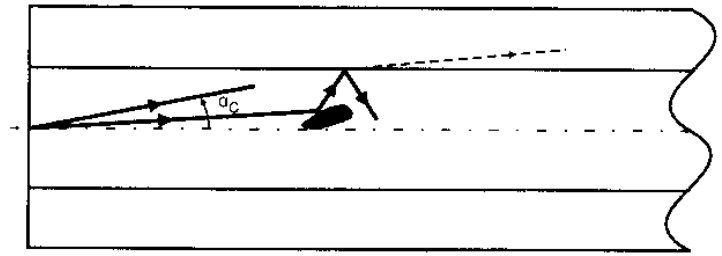
- Another major extrinsic loss mechanism is caused by absorption due to water (Hydroxyl- OH ion) dissolved in the glass

  > 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"

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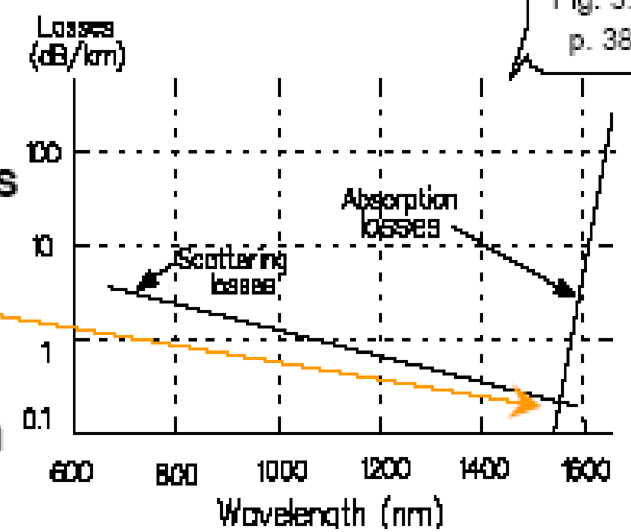


Rayleigh Scattering Loss

- **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*
  - ➢ *occurs at inhomogeneities comparable in size to guided wavelength*
  - » Particles ~λ
    - • 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 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

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

b. Nonlinear Scattering (cont)

B. Raman scattering: SRS

» Nonlinear interaction produces….

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

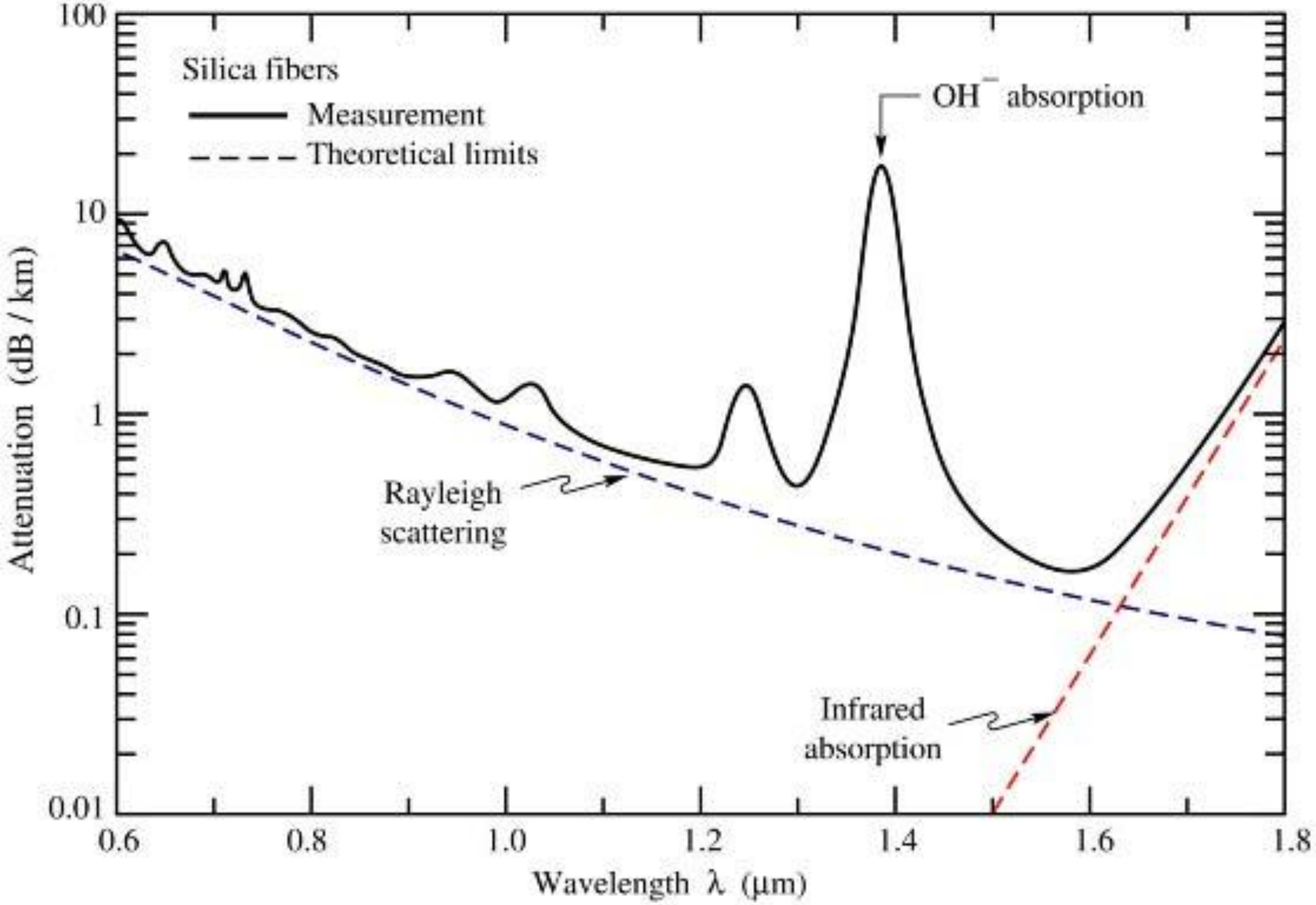
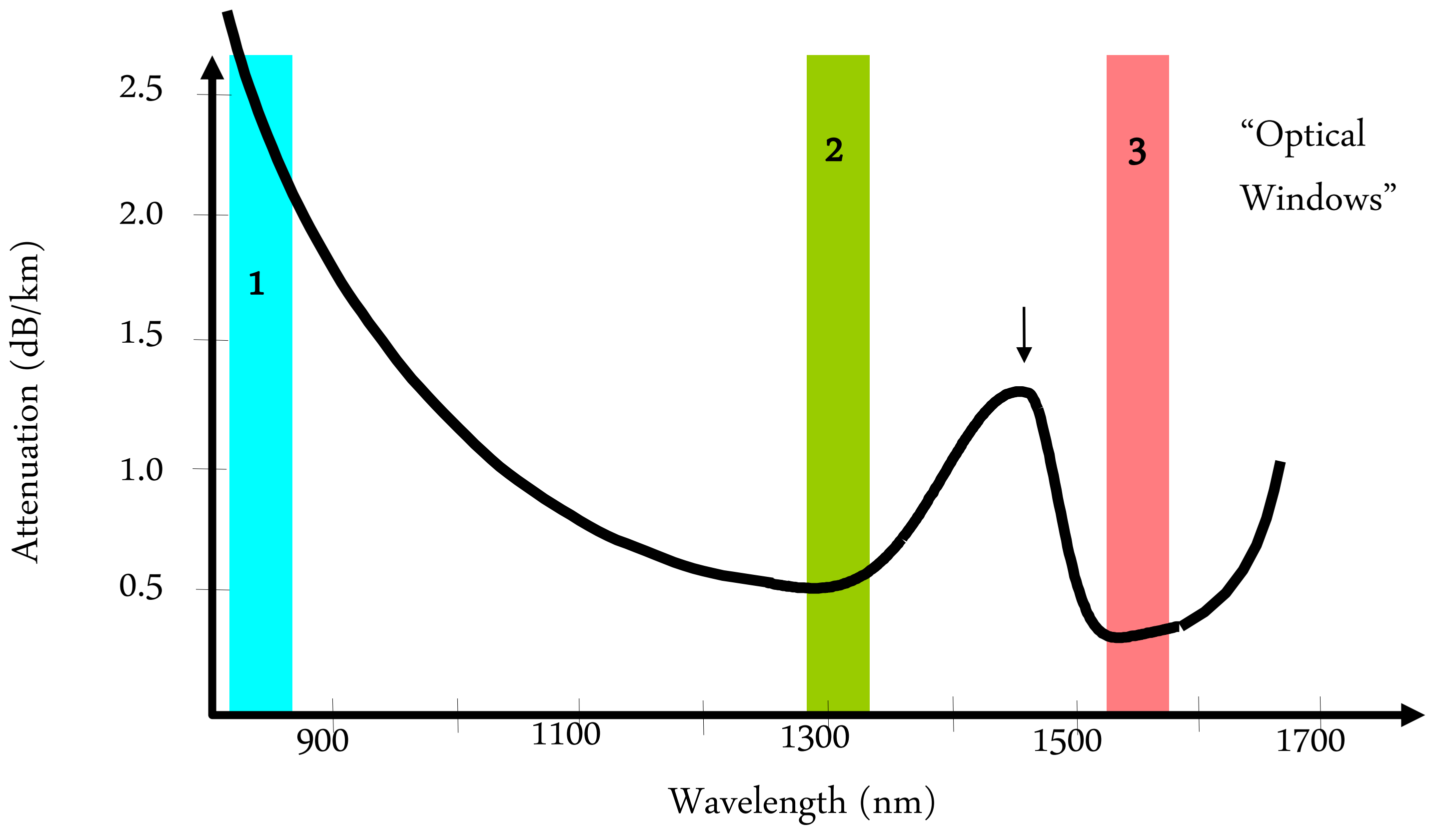


Fig. 12.2. Measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.

Attenuation in Silica Fibers



850 nm

1310 nm **1550 nm**

BENDING LOSSES

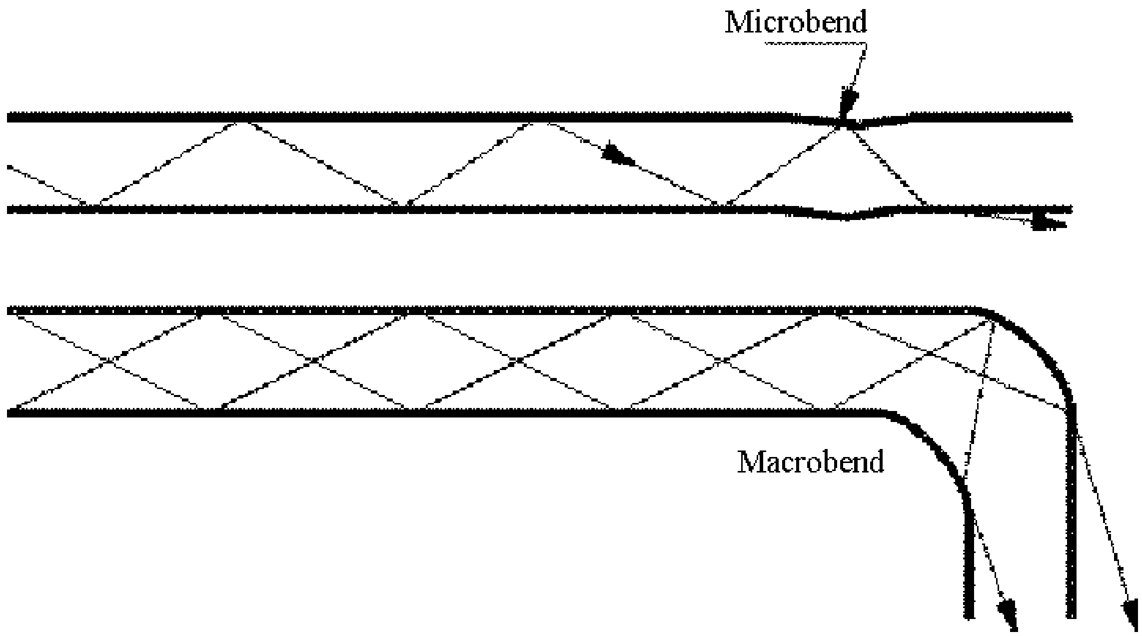
Bending an optical fiber introduces a loss in light power

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

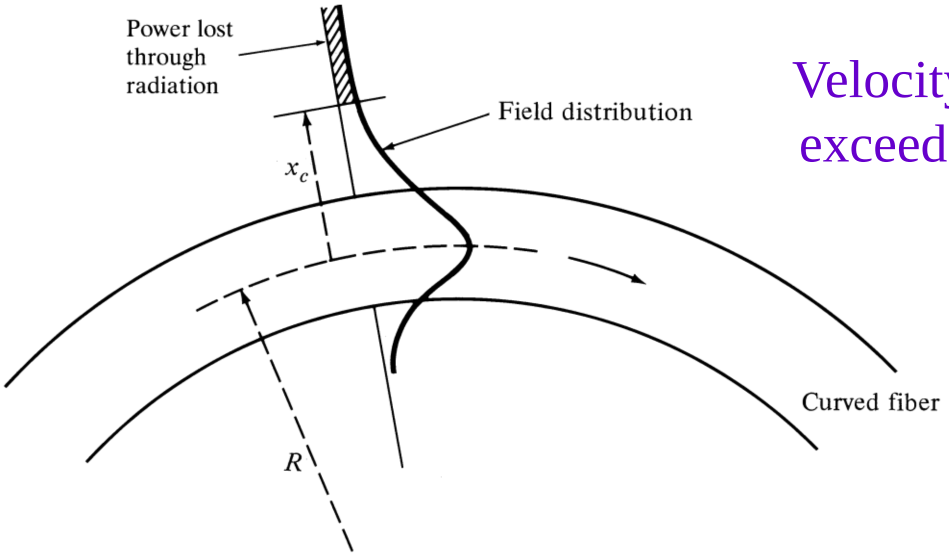
Micro- and Macro- bending

- **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 :

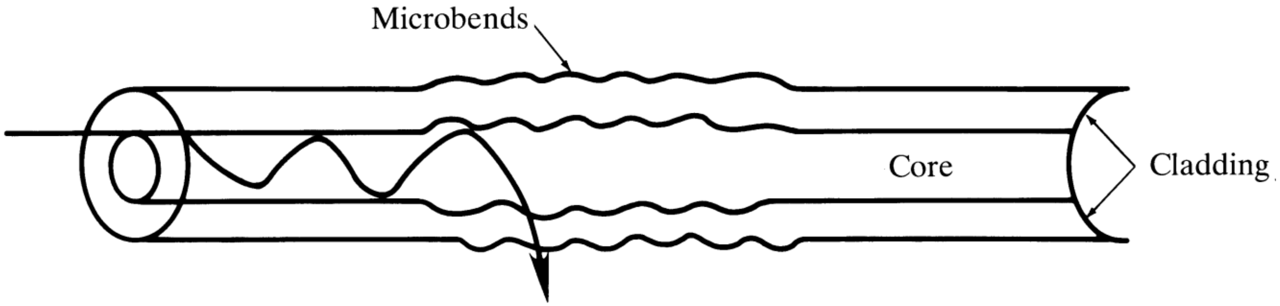
$$R_c \cong \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{\frac{1}{2}}}$$

> Designing fibers with large relative refractive index differences

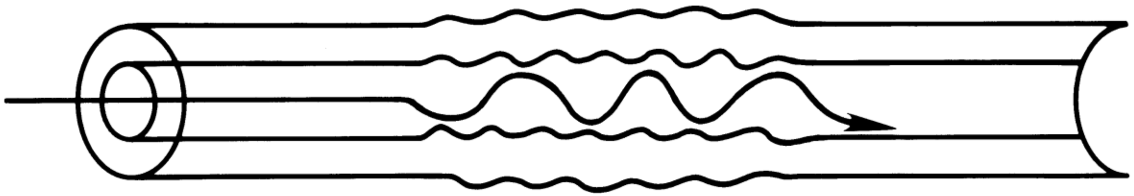
Operating at the shortest wavelength possible.

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