Photonic Communications Engineering I

Module 3 - Attenuation in Optical Fibers

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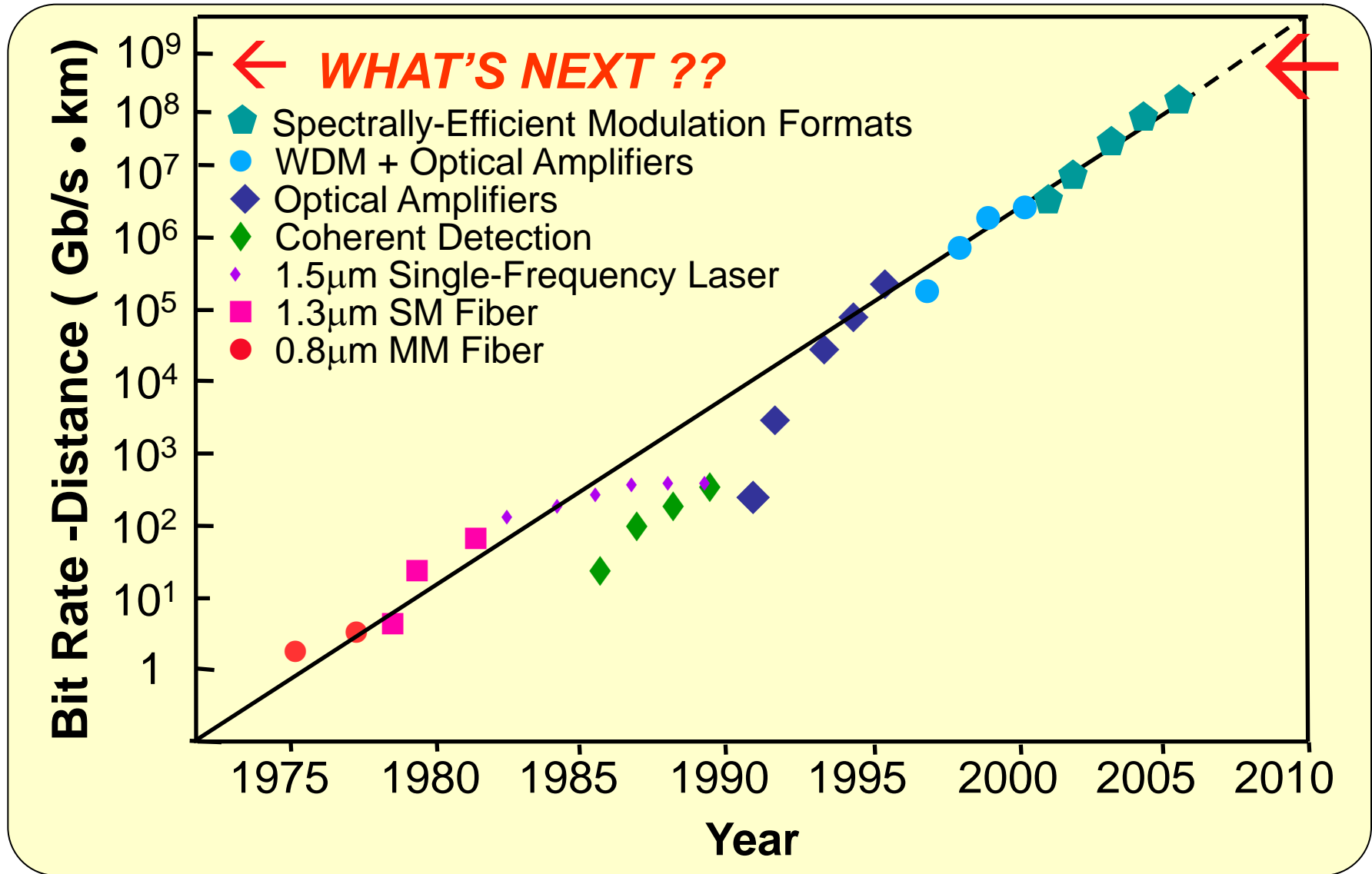**Professor, Material Science and Engineering Dept, University of Arizona
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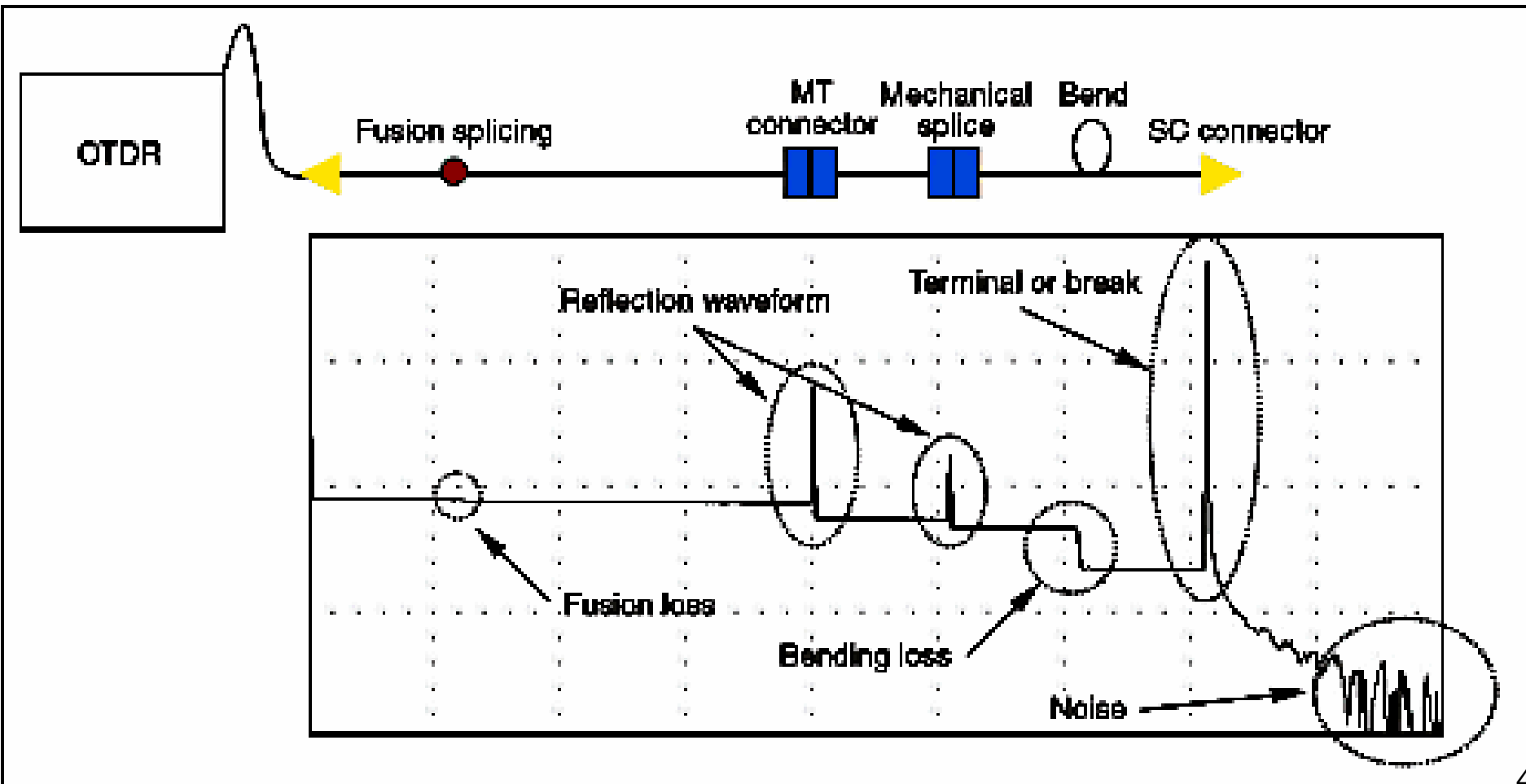Sept. 8, 2010

"You can transmit ∞ bandwidth over 0 distance !!"

L. Mollenauer, 1990

Bit-Rate Distance Product

Source: Tingye Li and Herwig Kogelnik

Optical Link Loss Budget

The range of optical Loss over which a Fiber optic Link will operate and meet all specifications. The loss is relative to the Transmitter Output Power and affects the required Receiver input power.

Optical Loss

The overall optical throughput (transmission) of an optical fiber can be quantified in terms of the input optical power, P(0), and the output power, P(z) observed after light propagates a distance, z, along the fiber length:

$$P(z) = P(0)e^{-\alpha_{total} z}$$

(Equation 3.1)

and

$$\%T = \frac{P(z)}{P(0)}$$

(Equation 3.2)

α_{total} = the total attenuation coefficient (i.e. involving all contributions to attenuation).

%T is the percentage optical power transmission.

Equation 3.1 is referred to as Beer's Law and shows that transmitted power decreases exponentially with propagation distance through the fiber.

Optical Loss

In an optical fiber transmission context, the attenuation coefficient is often expressed in Base-10 or Logarithmic form:

$$\alpha_{total}(\text{dB/km}) = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right] = 4.343\alpha_{total}(\text{km}^{-1})$$

(Equation 3.3)

This final parameter is often referred to as the "fiber loss".

Parameter	DSF	SMF	DCF
α (dB/km)	0.25	0.25	0.50

Complex Index of Refraction

The propagation of light within a material can be described in terms of a complex refractive index (n^*):

$$n^* = n(\omega) + i\kappa(\omega)$$

(Equation 3.4)

$n(\omega)$ = real portion of the refractive index; $\kappa(\omega)$ = extinction coefficient. and:

$$\alpha(\omega) = \frac{2\omega\kappa}{c}$$

(Equation 3.5)

$\alpha(\omega)$ = absorption coefficient; c = speed of light.

Thus, via equation (3.1), the absorption coefficient contributes directly to the output power observed through its participation in the overall attenuation coefficient, α_{total}.

Intrinsic Absorption

➤ The intrinsic optical absorption responses of the core and clad glasses used are the primary factor dictating the transmission window (and ultimately the operational wavelengths) for an optical fiber.

➤ The frequency dependence of α at the absorption onsets for both the electronic and vibrational (phonon) processes can be generally described with an exponential function form. For the electronic-transition band-edge, the absorption coefficient is described by the Urbach relationship:
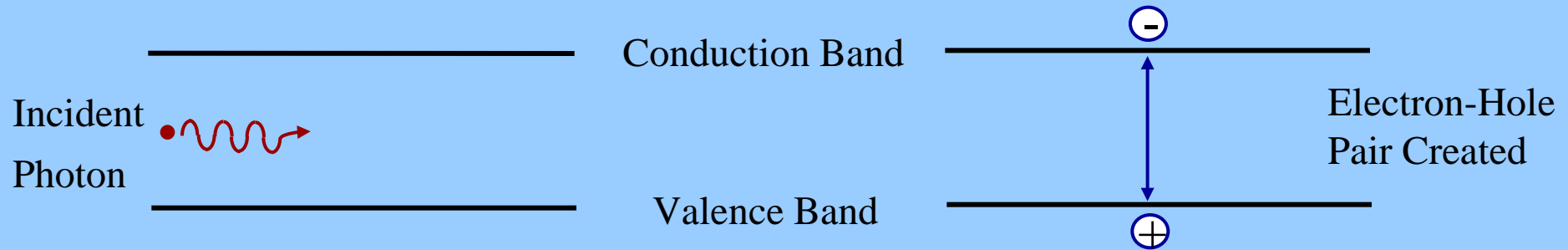
$$\alpha(\omega) = A\exp\left[\sigma(\hbar\omega - \hbar\omega_o)/kT\right]$$

(Equation 3.6)

A, σ, and ω_o are parameters characteristic of the material.

Photoabsorption
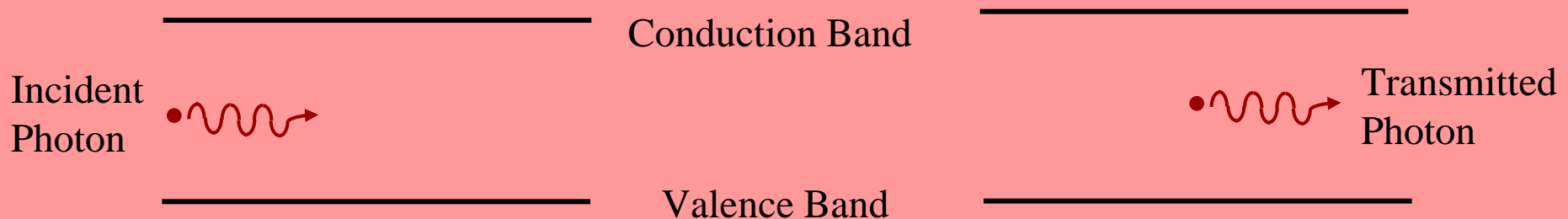
* $E_{photon} > E_{gap}$: Absorption of light (direct bandgap material)

Conduction Band
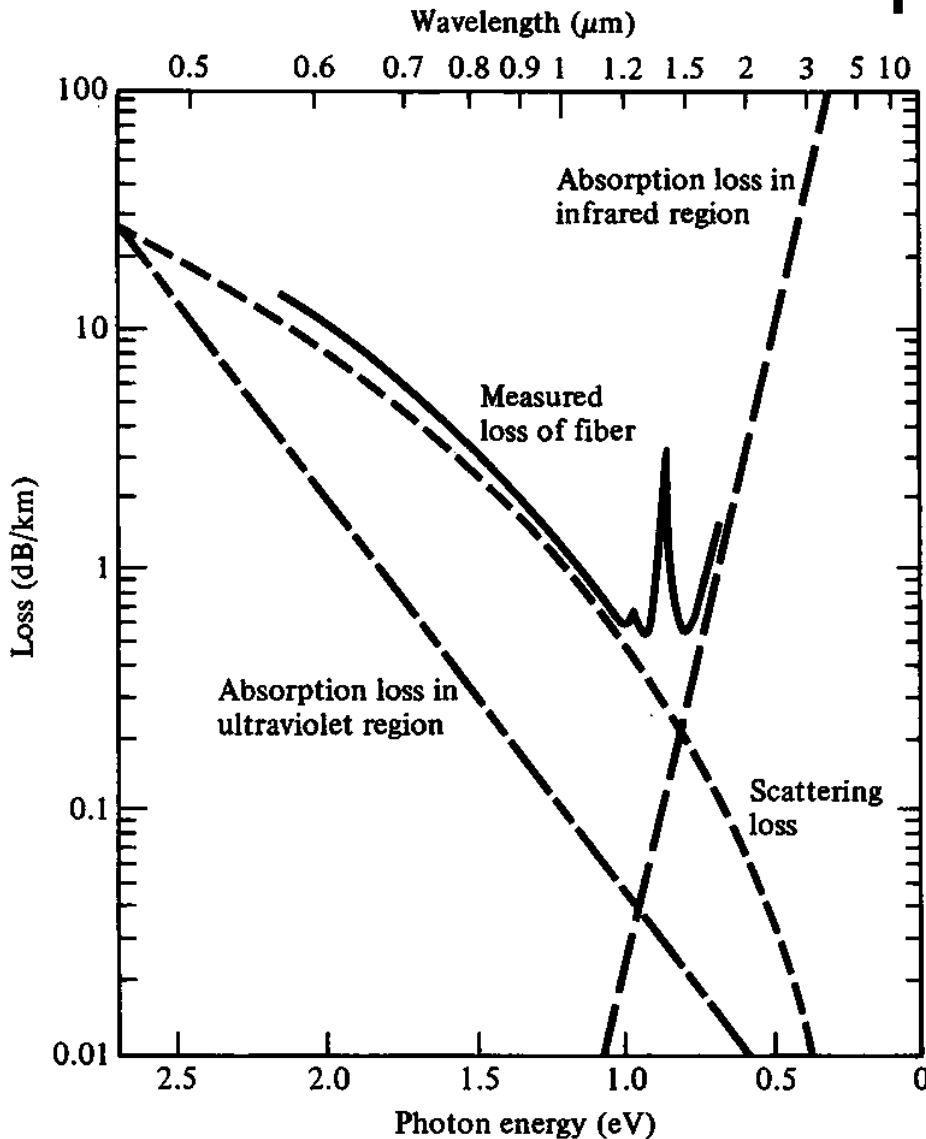
Incident Photon

Valence Band

Electron-Hole Pair Created

−

+

* $E_{photon} < E_{gap}$: Transparent to light

Conduction Band

Incident Photon

Valence Band

Transmitted Photon

Before   After
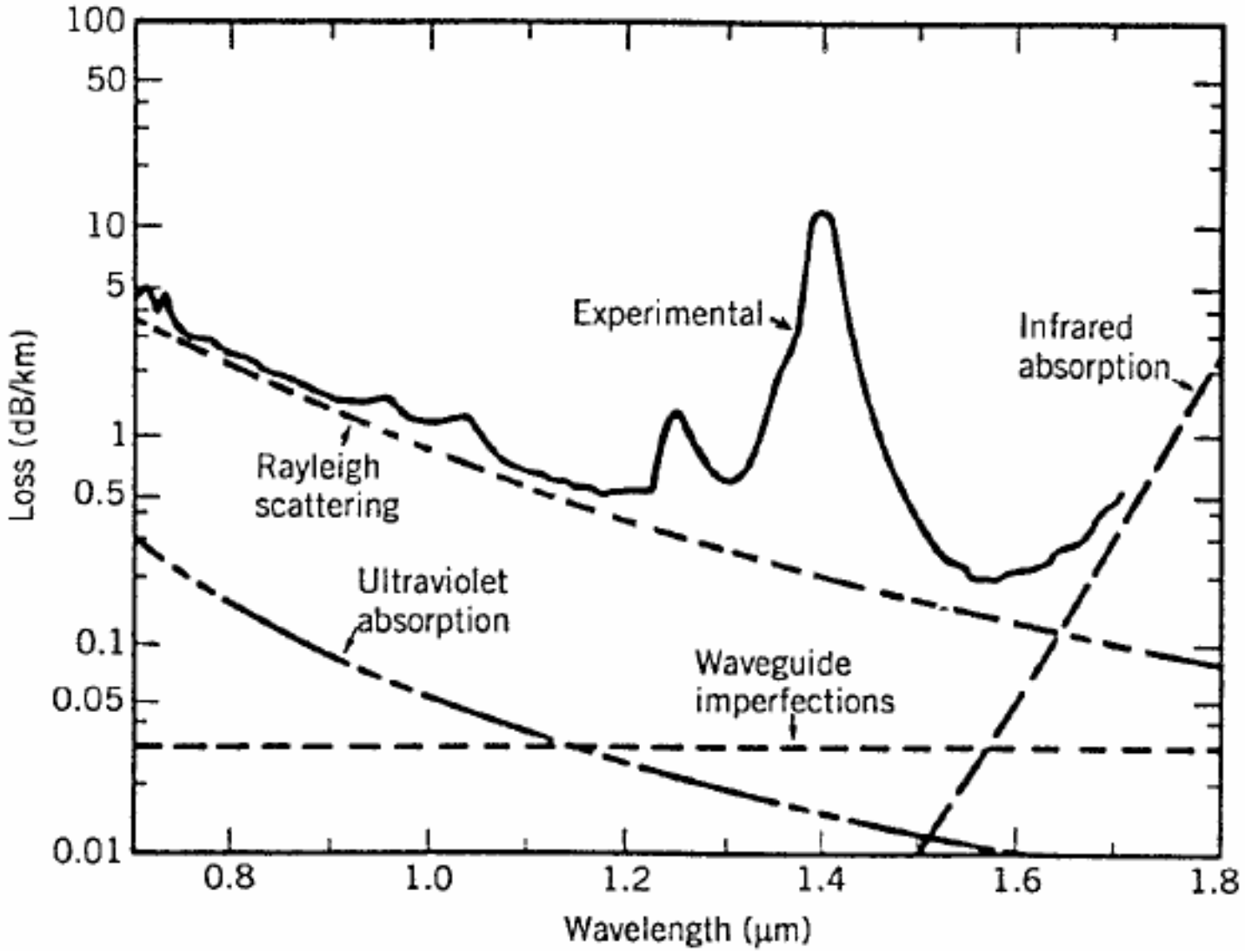
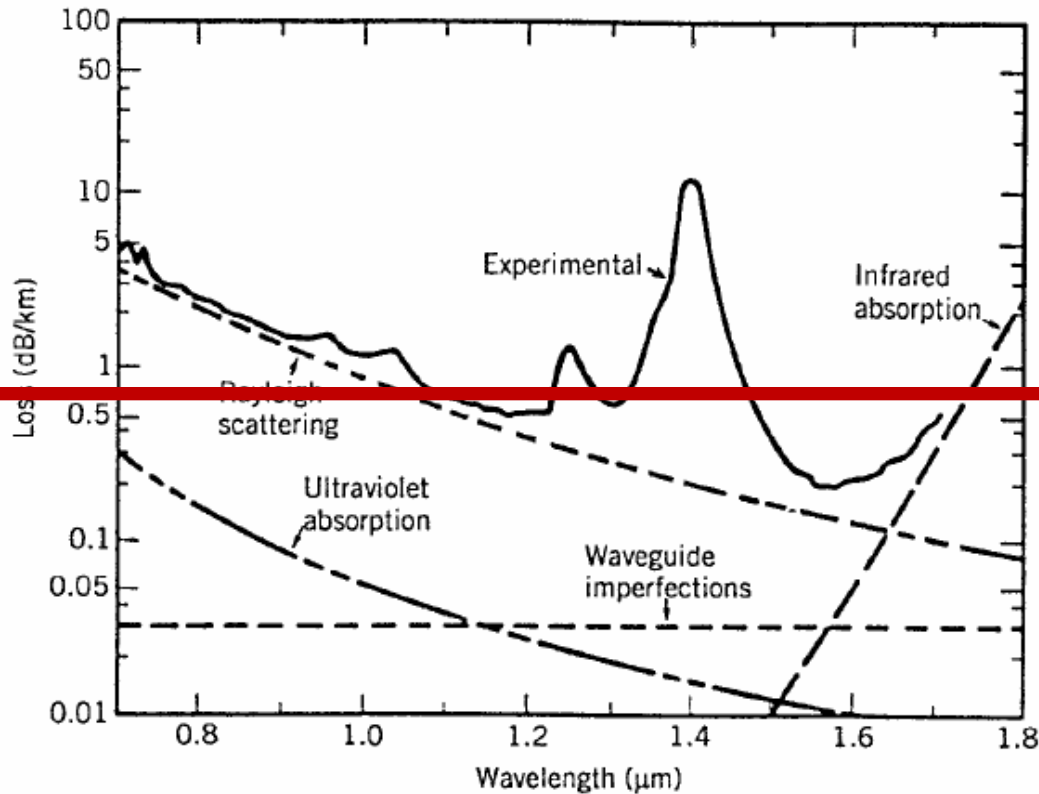USC *Optical Communications Laboratory*

Intrinsic Fiber Absorption

Figure 3.1: *Optical fiber attenuation characteristics that bound the transmission window in GeO2-doped, low-loss, low-OH-content silica fiber.*

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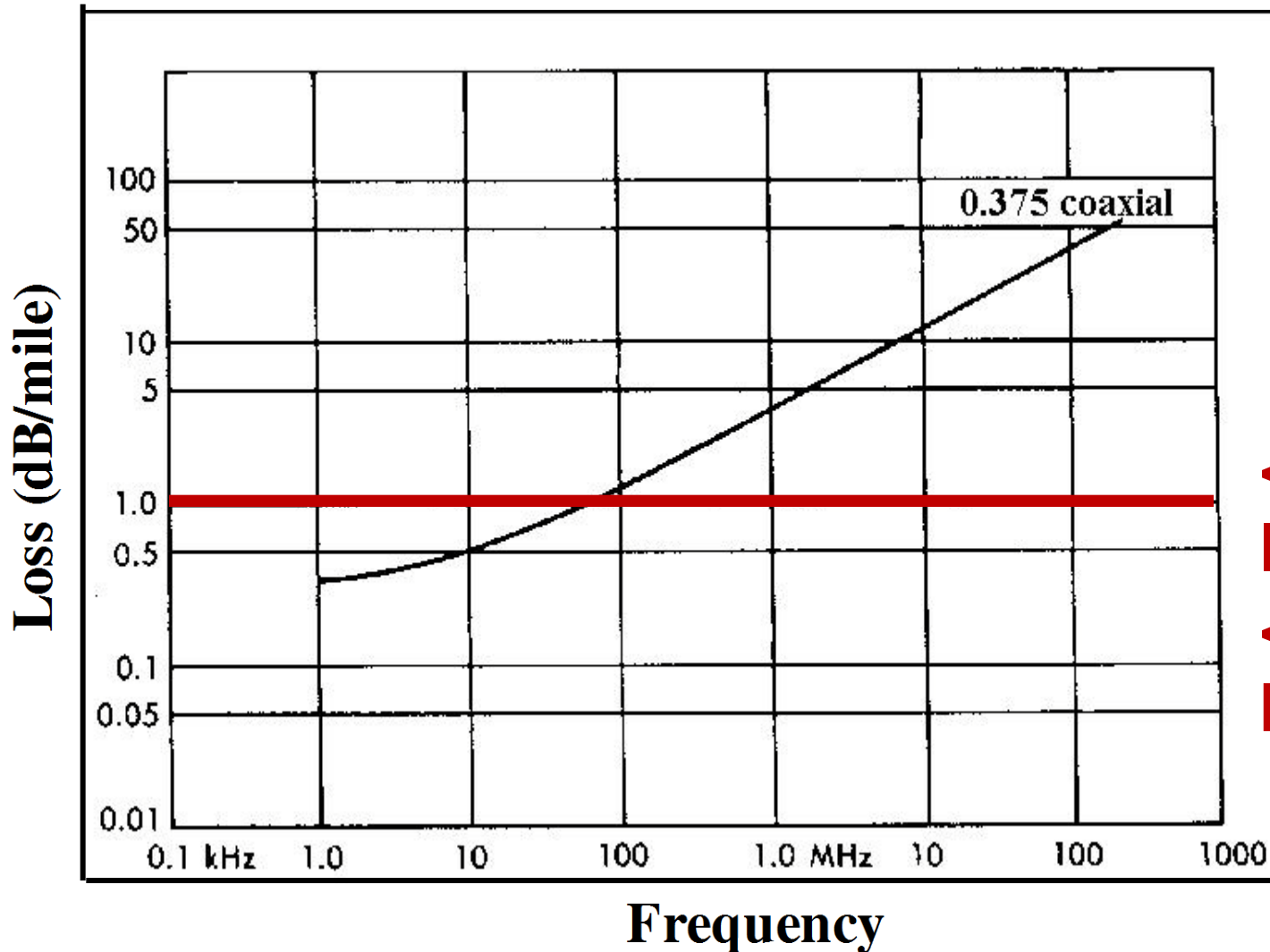# Low Loss Region in Silica Based Fiber

Low Loss Region in Silica Based Fiber


< 1dB/mile of loss over >100 THz of bandwidth.

http://www.fiberoptics4sale.com/wordpress/optical-fiber-attenuation/

Power Attenuation vs. Modulation Speed for Coaxial Cable (TV Cable)

< 1dB/mile of loss over <100 kHz of bandwidth.

Extrinsic Fiber Absorption (Water)

➤ Defects in the glass structure (e.g. vacancies, over/under coordinated atoms) and/or dopants and impurities can produce localized absorption states. For silica-based fibers, water (hydroxyls (OH-)) within the glass structure is a common impurity.
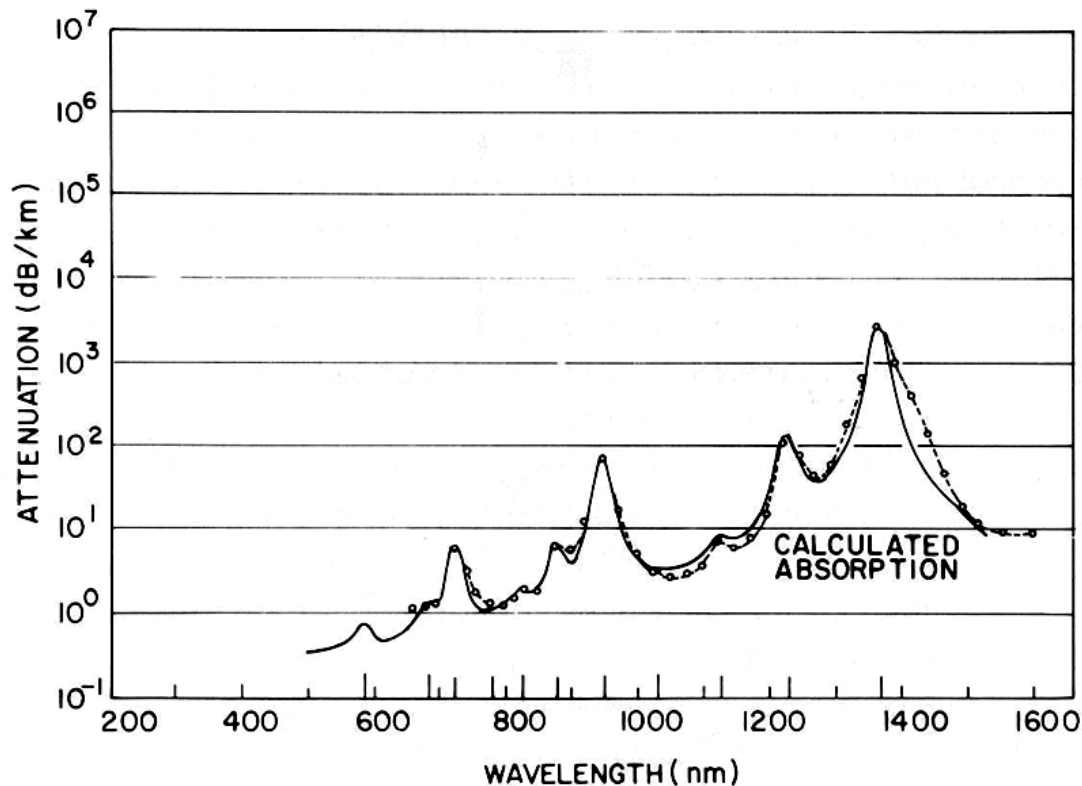
Calculated absorptive attenuations as a function of wavelength (Keck *et al.*, 1973).

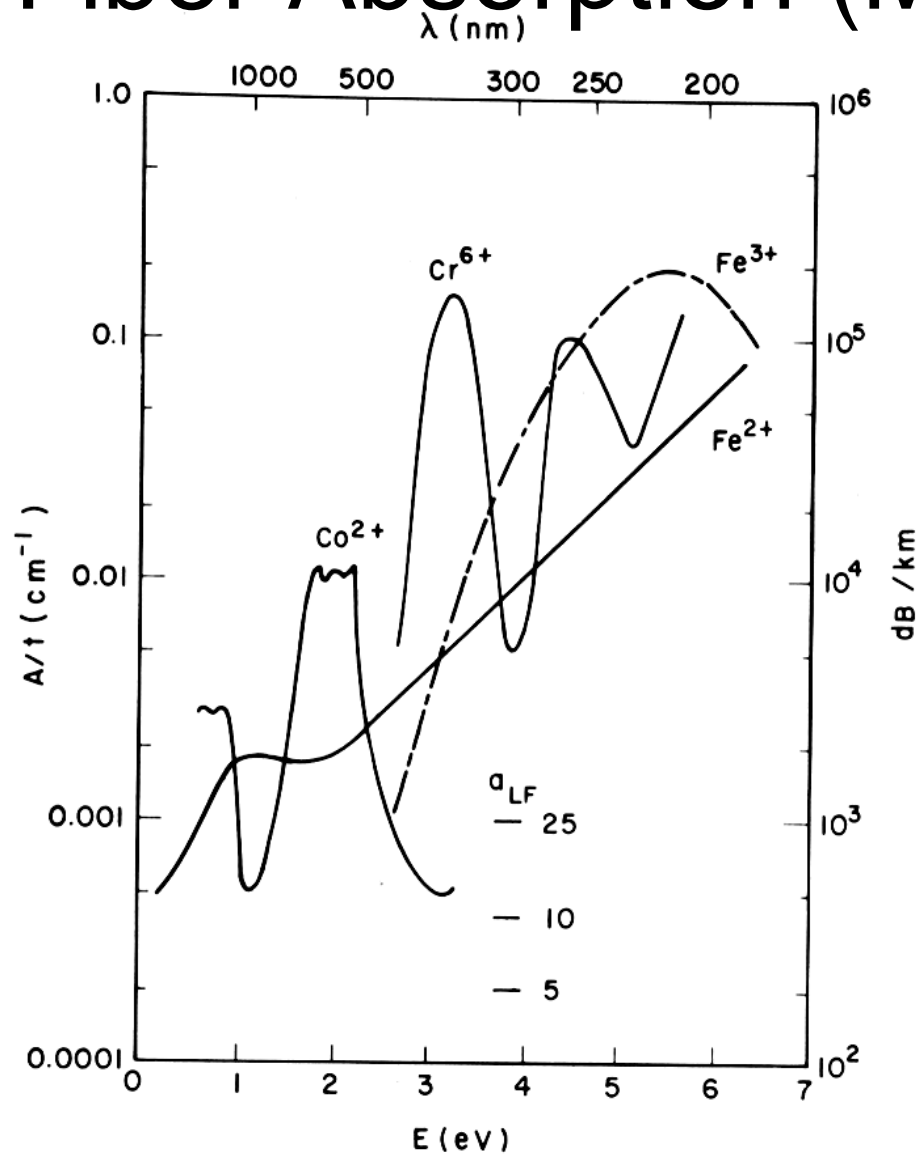**Figure 3.2:** *Absorptive attenuation in silicate fiber.*

Extrinsic Fiber Absorption (Glass Dopants)
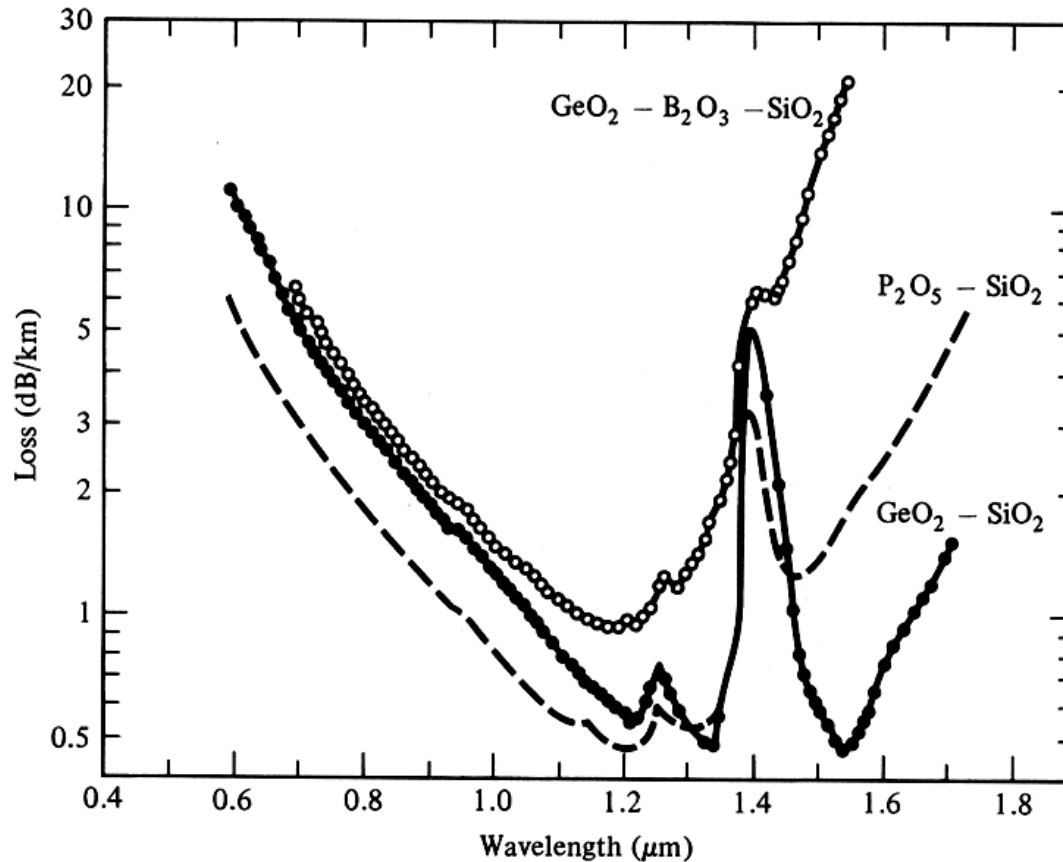
A comparison of the infrared absorption induced by various doping materials in low-loss silica fibers. (Reproduced with permission from Osanai et al.[13])

Figure 3.3: *A comparison of the effects of dopants on infrared absorption in silicate fibers.*

Extrinsic Fiber Absorption (Metal Ions)

Absorption of some ligand field and charge transfer transitions in glass (Kurkjian and Peterson, 1974).

Figure 3.4: *Representative attenuation spectrum for transition metal ions in silica*

Optical Scattering

➢ Modification in the glass structure associated with missing atoms (vacancies) or disturbances in the anticipated bond topology of the glass network also contribute states within the forbidden band.

➢ These states typically result in an extension of absorption into the transparency region (band tail states).

➢ Such defect structures often form as the result of thermal processing atmosphere (e.g. redox conditions) or through the stress-induced structural modification (residual strain) produced during fiber drawing.

$$* \ E_{photon} > E_{gap} : \text{ Absorption of light (direct bandgap material)}$$

Conduction Band

Incident Photon

Valence Band

Electron-Hole Pair Created
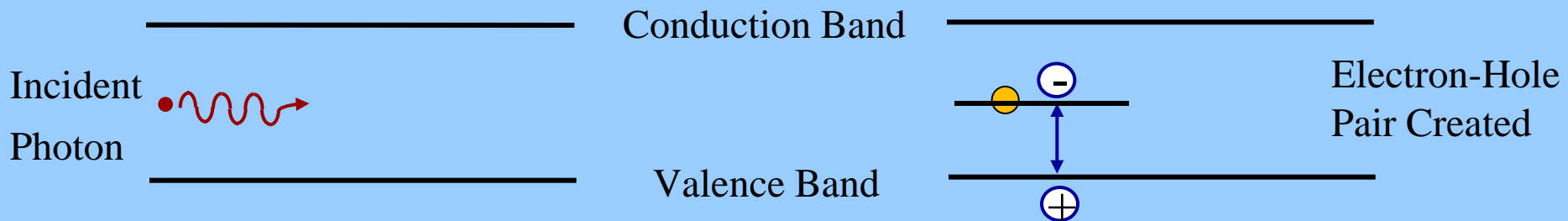
Optical Scattering

➤ These defects also lead to the scattering (reflection and refraction) of light as it passes through the fiber
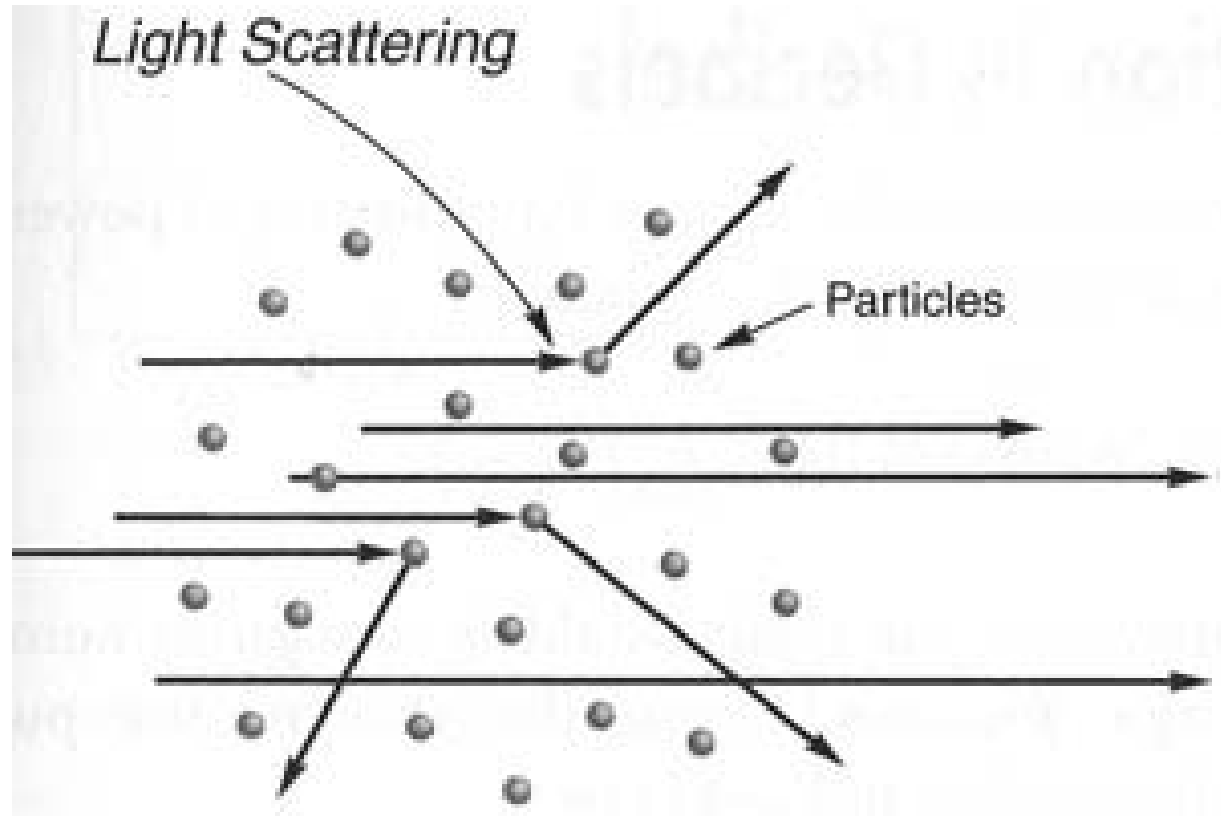
Types of scattering:

• **Rayleigh**

• **Mie**

• **Brillouin**

Light Scattering

Particles

Rayleigh Scattering

➤ Scattering centers whose sizes are much less than the wavelength of the light (typically λ/10).

$$\alpha_{Rayleigh} = \frac{8\pi^3}{3\lambda^4}\left(\frac{n_1^2}{n_o^2}-1\right)^2 \beta\, k T_f$$

(Equation 3.7)

n_1, n_o = refractive index of the scattering center, medium;
β = isothermal compressibility of the medium,
k = Boltzman's constant,
T_f = the fictive temperature of the glass (corresponding to the temperature at which density fluctuations are frozen into the glass as it is cooled through the transformation range).

➤ Rayleigh scattering thus exhibits a characteristic $1/\lambda^4$ behavior that favors scattering (and larger attenuation parameters) at shorter (i.e. visible) wavelengths.

*The characteristic scattering loss associated with Rayleigh scattering is contained in **Figure 3.1.**

Mie Scattering

➢ For larger scattering centers that approach the wavelength of light, the scattering light intensity has a greater angular dependence and the process is governed by Mie scattering theory.

For a spherical inclusion with a complex dielectric function given by:

$$\varepsilon^* = \varepsilon_1 + i\varepsilon_2$$

(Equation 3.8)

the attenuation parameter associated with Mie scattering from N spheres/unit volume embedded in a medium with a refractive index of n_o is:

$$\alpha_{Mie} = \frac{18\pi N n_o^3 \varepsilon_2}{\lambda(\varepsilon_1 + 2n_o^2) + \varepsilon_2^2}$$

(Equation 3.9)

➢ Typically fluctuations in density or composition from phase separation in the glass and/or the development of crystallinity.

➢ Further increases in scattering center size results in a largely wavelength-independent scattering attenuation behavior, governed by the absorption and reflection behavior at the interfaces involved.

Bending Loss

➢ Propagating modes within an optical fiber can be characterized by an electric field distribution with maxima inside the fiber core and evanescent fields that extend outside the fiber core into the cladding**.** Thus, some of the optical energy in the mode is actually propagating in the cladding.
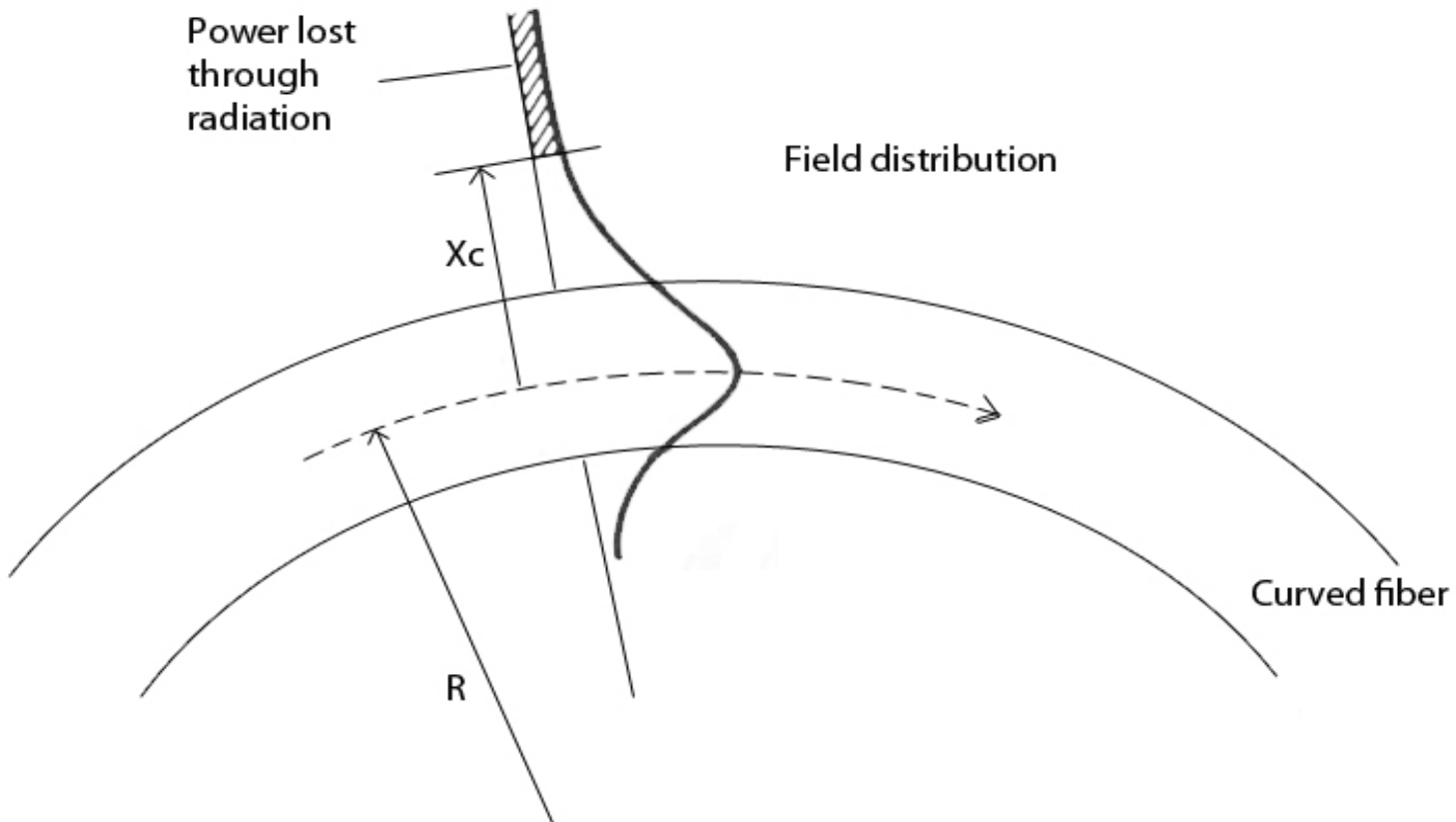
Figure 3.5: *Sketch of the fundamental mode filed in a curved optical waveguide.*

Macrobending Loss

➢ If the fiber is curved around a corner, different portions of the same mode must travel at different speeds to maintain the integrity of the mode. For portions of the mode traveling through the "outside" of the curve, a small enough radius of curvature will require that this portion of the mode travel essentially faster than light speed. Under these conditions, the mode integrity cannot be maintained and the energy radiates away from the fiber structure.

➢ The total number of modes supported in a curved, multimode fiber is therefore related to the index profile, the propagating wavelength, and the radius of curvature:
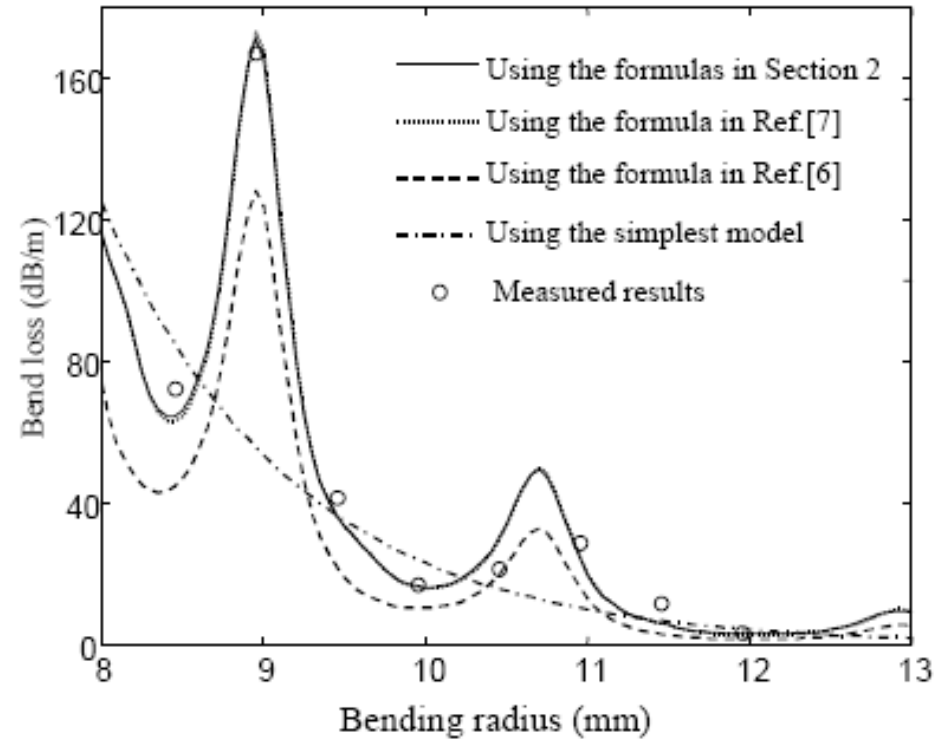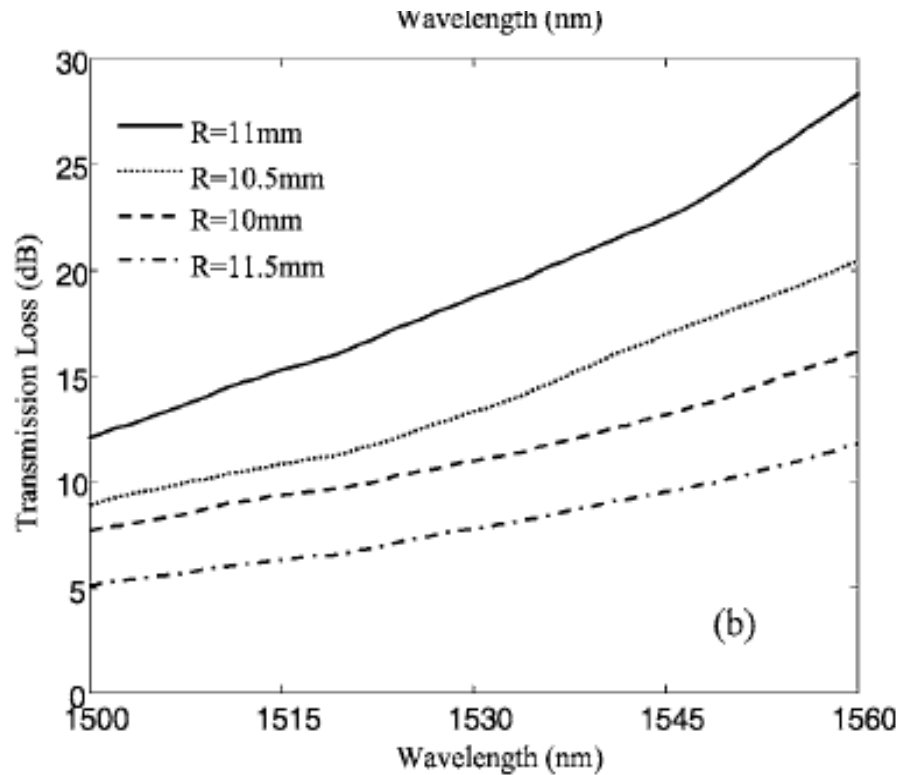
$$N_{eff} = N_\infty \left\{ 1 - \frac{\alpha+2}{2\alpha\Delta} \left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR} \right)^{2/3} \right] \right\}$$

(Equation 3.10)

N_∞ = number of modes supported in a straight fiber;
α defines the index profile, Δ = core-cladding index difference;
n_2 = cladding index, $k = 2\pi/\lambda$; R = radius of curvature of the bend.
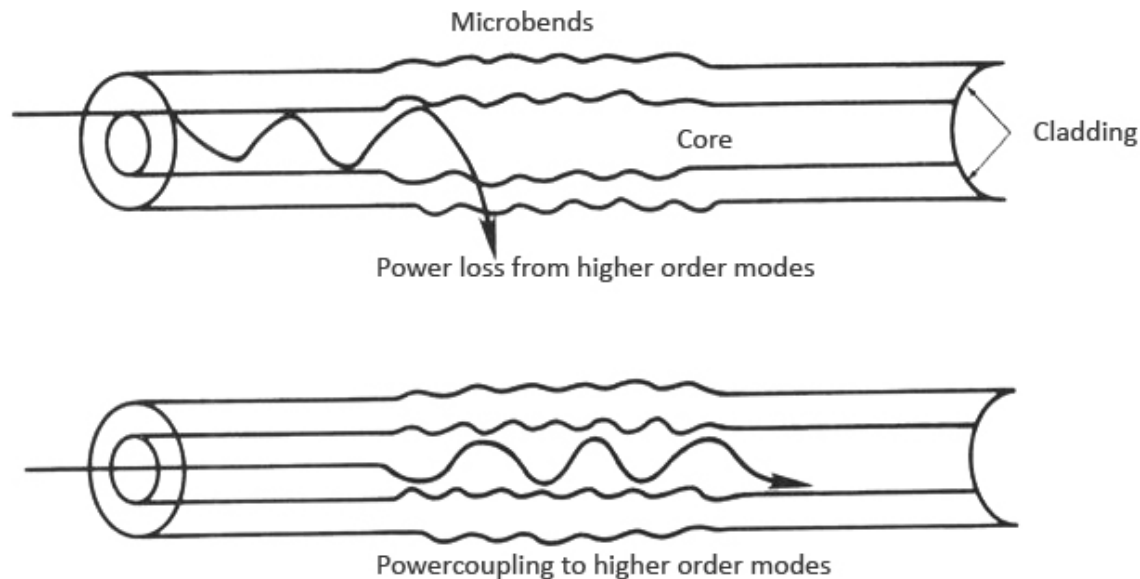
Macrobending Loss In SMF

Q. Wang, G. Farrell, T.Freir, G. Rajan and P. Wang "Low-cost Wavelength Measurement based on a Macrobending Singlemode Fiber", **Optics Letters**, Vol. 31, No. 12, pp. 1785-1787, 2006.

Q. Wang, G. Farrell and T. Freir, "Theoretical and experimental investigations of macro-bend Losses for standard single mode fibers", **Optics Express**, Vol.13, No.12, 4476-4484, 2005.

Microbending Loss

➢ Associated with microscale fluctuations in the fiber radius typically due to nonuniformity in fiber diameter arising during the fiber drawing process or in response to radial pressures.

➢ Random variation in the fiber geometry (and propagating mode characteristics) along the propagation direction. The result is a coupling between guided wave modes and non-guiding (leaky) modes. Careful packaging of fibers and control of draw conditions during fabrication are critical to reducing these effects.

Figure 3.6: *Microbending losses arising from small-scale fluctuations in the radius of curvature of the fiber axis.*

Core and Cladding Loss

➤ Fiber is not a homogenous medium. The guided wave field profile actually intersects both the core and the clad materials comprising the fiber structure. The overall attenuation observed will reflect this sampling of these two propagation media. For a step index fiber, the effective attenuation will be weighted according to the fraction of the optical power transmitted in each material (i.e. core vs. clad). For the attenuation associated with a mode indices ν,m of a step-index fiber:

$$\alpha_{\nu m} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P} \qquad \textit{(Equation 3.11)}$$

$P_{core,clad}$ /P = the fractional power carried in the core and cladding regions;
P = the total power transmitted;
$\alpha_{1,2}$ = attenuation coefficients for the core and cladding, respectively.

➤ The total power is then the sum of the fractional powers for each propagating mode. A more complicated relationship, involving the radial behavior of the refractive index, is used for graded index fibers.

Splicing/Connector Loss

➤ Successful connections will minimize lateral offset of the core centers, angular misalignment, tilt, and longitudinal displacement (i.e. the formation of a gap). It is also possible that the two fibers to be joined have different absolute core dimensions and varied core-clad diameter ratios as well as different core and cladding glass compositions.

➤ High end fiber splicing requires the alignment of any elipticity in the core and can routinely produce splices with losses of less than 0.02 dB.
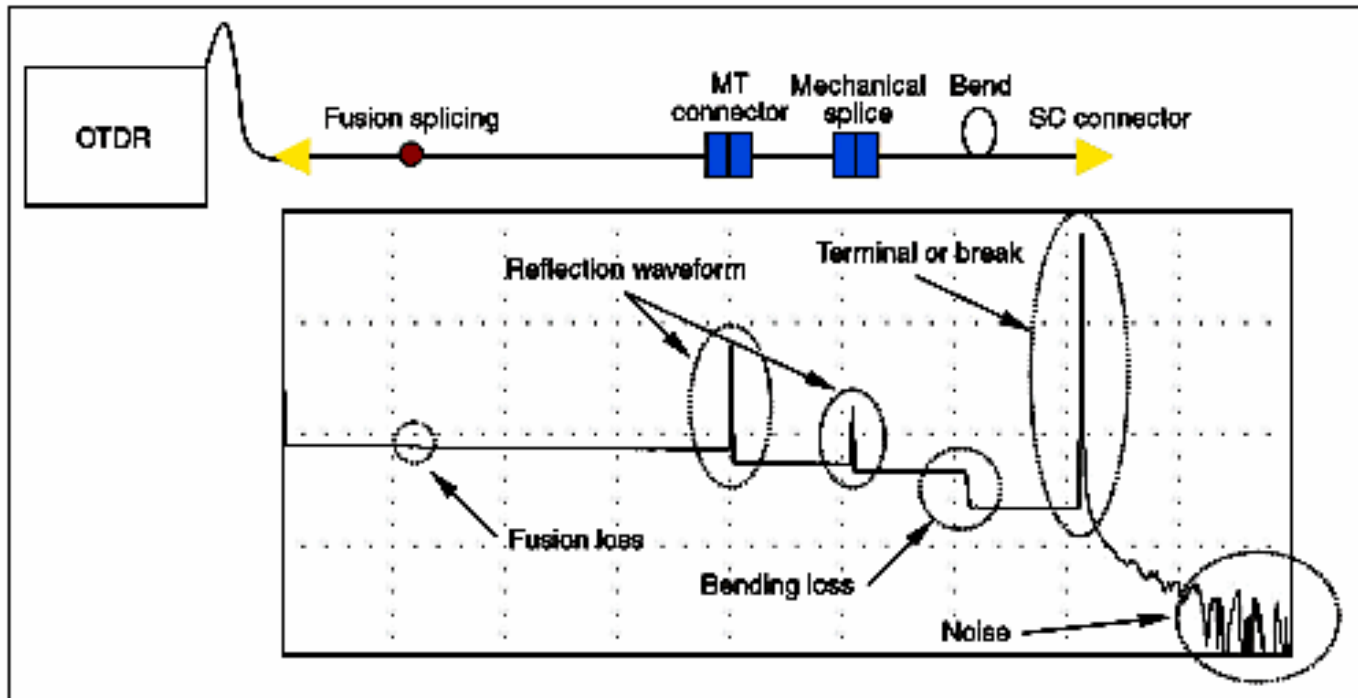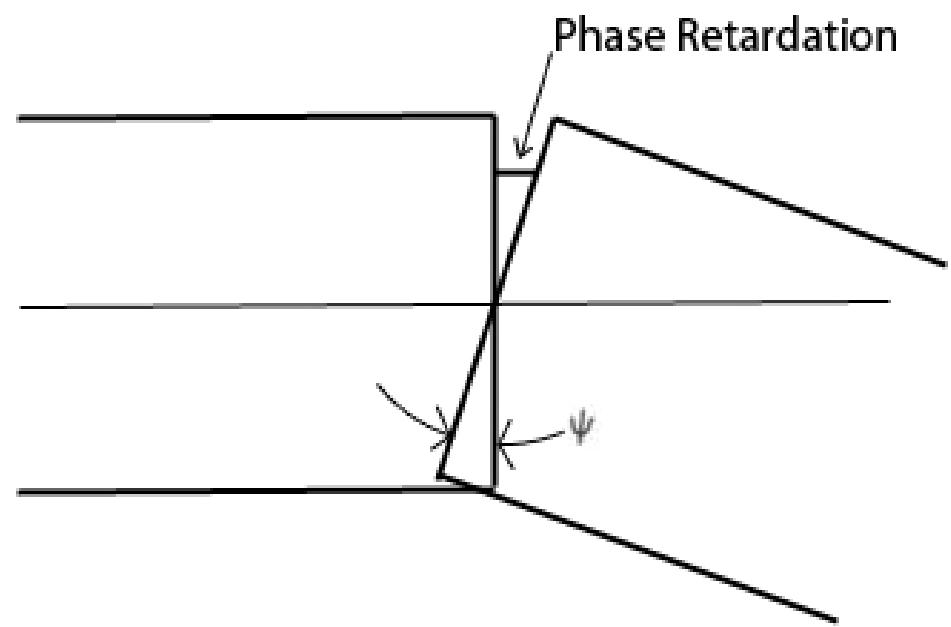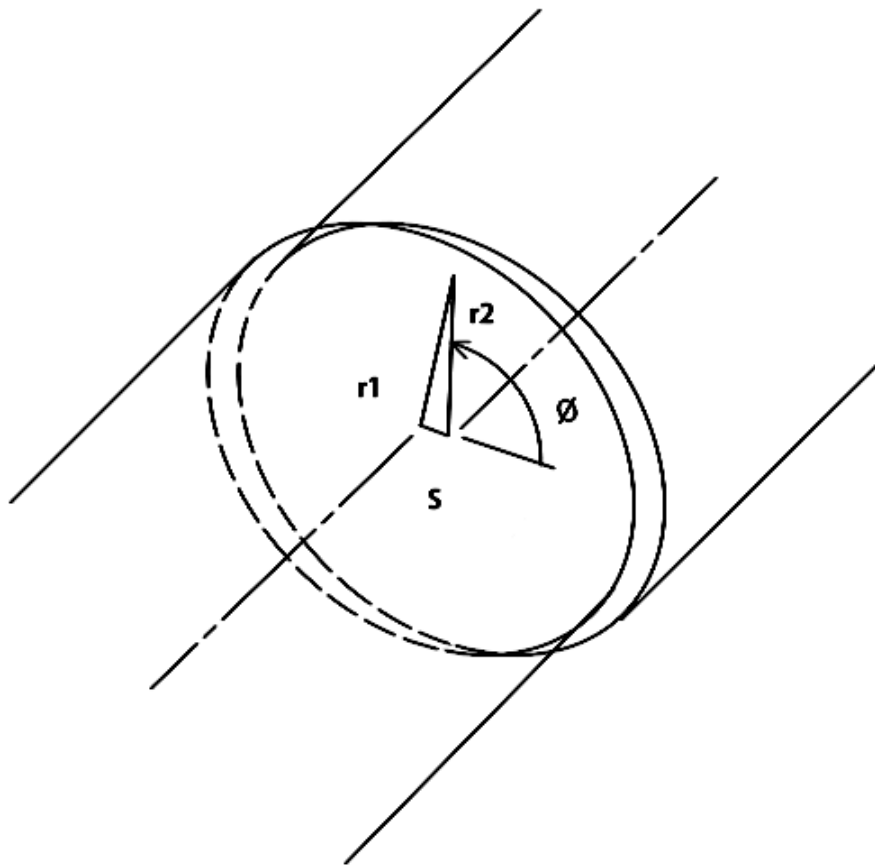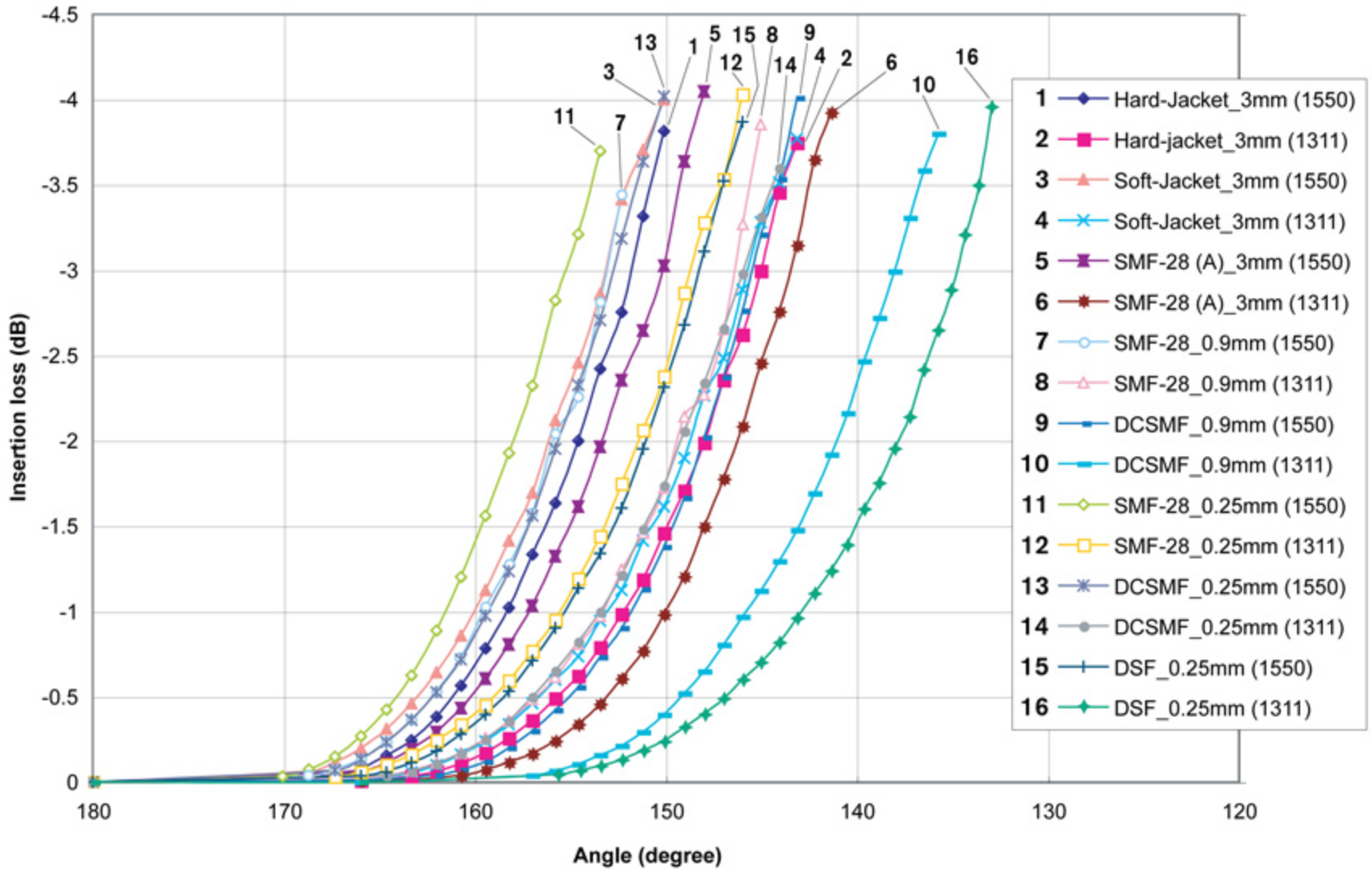
Figure 3.7: *Lateral offset of spliced fibers.*   **Figure 3.8:** *Tilt angle of two spliced fibers.*

Typical Fiber Connectors

Fiber Connector Loss vs Angle

Insertion loss vs Angle

Reference Material

- **"Optical Fiber Telecommunication IV", Academic Press**

- **"Optical Fiber Communication Systems", (Artech House), Kazovsky, Benedetto, Willner**

- **IEEE Photonics Technology Letters**

- **IEEE/OSA J. of Lightwave Technology**

- **Optical Fiber Communications Conference**

- **European Conference on Optical Communications**

- **Lightwave Magazine**