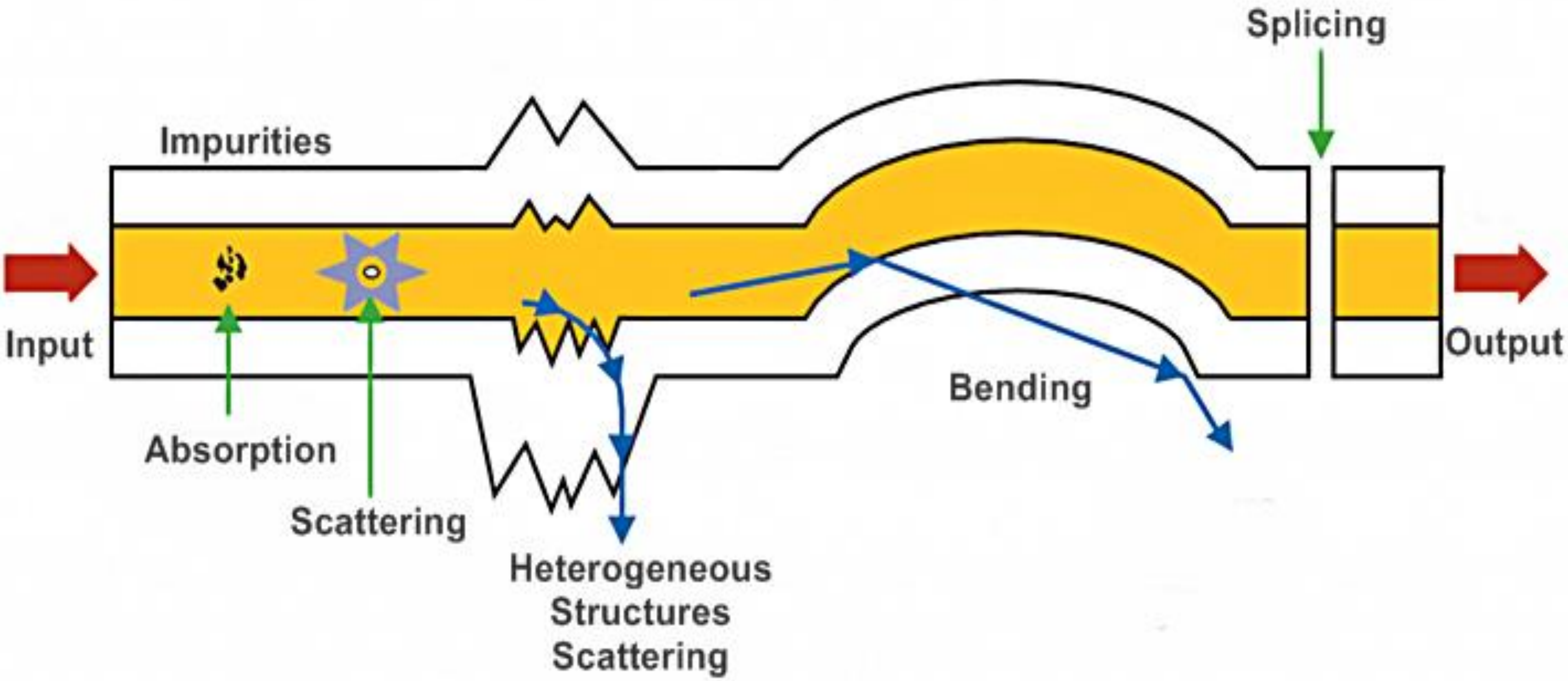
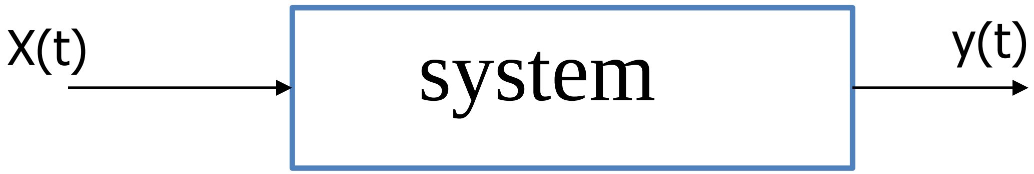
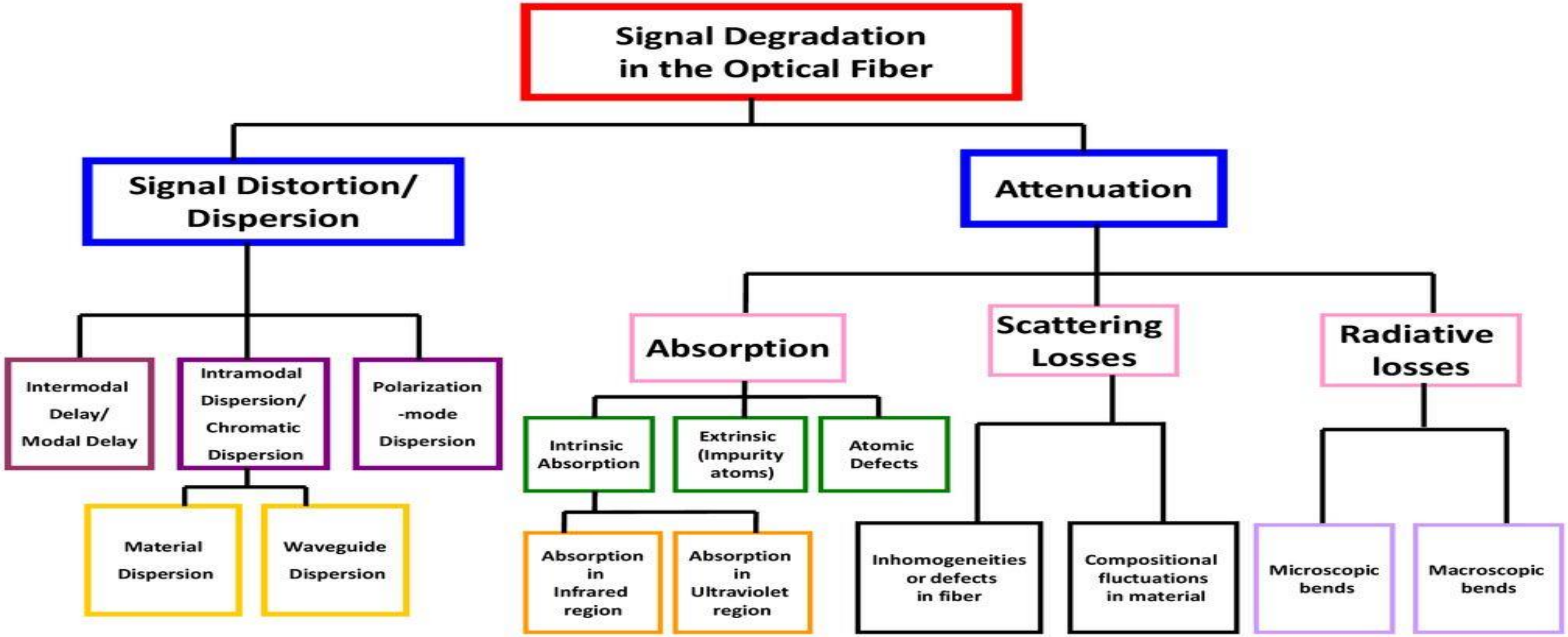


Module – 2
Signal Degradation

Distortion less system



Signal degradation in fiber cable



Attenuation

- Loss of optical power as light travels down a fiber
- Measured in dB/km
- Near Zero attenuation → one of the most important characteristics of optical fibers
- Determines the maximum unamplified or repeaterless separation between a transmitter and a receiver

Implications of attenuation

- Amplifiers and regenerators are expensive to fabricate, install and maintain → degree of attenuation has large influence on system cost

- Over a distance, a fiber with lower attenuation will allow more power to reach its receiver than a fiber with higher attenuation → System requirements

Attenuation units

- As light travels along a fiber, its power decreases exponentially with distance

$$\boxed{P(z) = P(0)e^{-\alpha_P z}}$$

$$\log P(z) = \log P(0) - \alpha z / 10dB$$

$$\boxed{\alpha(\text{dB}/\text{km}) = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right]}$$

$$\alpha_p = \frac{\alpha(km/dB)}{4.3dB}$$

We can convert α from (dB/km) to km^{-1} using

$$\boxed{\alpha(dB/km) = 4.343\alpha_p(km^{-1})}$$

Attenuation units - Examples

- $(P_t)dBW = 10 \log (P_t)W$
- $(P_t)dBm = 10 \log (P_t)mW$
- 1 mW corresponds to 0 dBm or -30 dBW
- 10 mW corresponds to 10 dBm or -20 dBW
- 1 µW corresponds to -30 dBm or -60 dBW

Attenuation units – Numerical problem

$$L = 30\text{km}$$
$$\alpha_{DB} = 0.8\text{dB/km}$$
$$P_{in} = 200\mu\text{W}$$
$$P_{out} = ?$$

Attenuation units – Numerical problem

$$L = 30\text{km}$$
$$\alpha_{DB} = 0.8\text{dB/km}$$
$$P_{in} = 200\mu\text{W}$$
$$P_{out} = ?$$

$$P_{in}(\text{dBm}) = 10\log\left(\frac{200\times10^{-3}\text{mW}}{1\text{mW}}\right) = -7.0\text{dBm}$$

$$P_{out}(\text{dBm}) = -7.0\text{dBm} - (0.8\text{dB/km})(30\text{km}) = -31.0\text{dBm}$$

OR

$$P_{out} = P_{in}\exp(-\alpha_p L)$$

$$\alpha_p = \alpha_{DB} / 4.343 = 0.1842 / \text{km}$$

$$P_{out} = \left(200\times10^{-3}\text{mW}\right)\exp(-0.1842\times30)$$

$$= 0.2\times0.00398\,\text{mW} = 0.8\mu\text{W} = \text{-}31\text{dBm}$$

Attenuation units – Numerical problem

- When the optical power launched into a 10 km fiber is 100 μW and the optical power at fiber output is 5 μW. Calculate

(a).Overall signal attenuation in dB

(b).Signal attenuation per km

(c).The overall signal attenuation for a 12 km optical link using same fiber with splices at 1 km interval, each giving attenuation of 0.5 dB.

Attenuation units – Numerical problem

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(c).The overall signal attenuation for a 12 km optical link using same fiber with splices at 1 km interval, each giving attenuation of 0.5 dB.

$$\alpha_z(\mathrm{dB}) = 10\log\left[\frac{P(0)}{P(z)}\right] = 13.01dB \quad \alpha(dB/km) = \frac{10}{Z}\log\left[\frac{P(0)}{P(z)}\right] = 1.301dB/km$$

$$\alpha_T(\mathrm{dB}) = (\alpha_z \times L) + \alpha_s = 21.1dB$$

Attenuation units – Numerical problem

- A continuous 12 km long optical fiber has a loss of 1.5 dB/km.

(a).What is the minimum optical power that must be launched into the fiber to maintain an optical power level of 0.3μW at receiver end?

(b).What is the required input power if the fiber has a loss of 2.5 dB/km?

Attenuation units – Numerical problem

- A continuous 12 km long optical fiber has a loss of 1.5 dB/km.

(a).What is the minimum optical power that must be launched into the fiber to maintain an optical power level of 0.3μW at receiver end?

(b).What is the required input power if the fiber has a loss of 2.5 dB/km?

$$P_{out} = P_{in} \exp(-\alpha_p L)$$

$$P_{in} = \frac{P_{out}}{\exp(-\alpha_p L)} = 18.92 \mu W$$

$$P_{in} = \frac{P_{out}}{\exp(-\alpha_p L)} = 300 \mu W$$

Attenuation units – Numerical problem

- An optical signal at a specific wavelength has lost 55 % of its power after traversing 3.5 km of fiber. What is the attenuation in dB/km of this fiber?

55% loss :

$P_r = 0.45\, P_t$

$z = 3.5$ km

$P(z) = P(0)\, e^{-\alpha_p z}$

$\cancel{P_t} = 0.45\, \cancel{P_t}\, e^{-\alpha_p (3.5)}$

$2.22 = e^{-\alpha_p (3.5)}$

$\frac{\ln (2.22)}{3.5} = \alpha_{dB}$

Attenuation units – Numerical problem

- An optical signal at a specific wavelength has lost 55 % of its power after traversing 3.5 km of fiber. What is the attenuation in dB/km of this fiber?

Solution:

$$\text{Power lost} = P_t - P_r = 0.55\,P_t$$

$$P_r = 0.45\,P_t$$

$$\frac{10}{3.5}\log\left[\frac{\cancel{P_t}}{0.45\,\cancel{P_t}}\right]$$

$$\text{Attenuation in dB / km} = (10 / L)\log_{10}(P_t / P_r)$$

$$= 0.99\ \text{dB / km}$$

Attenuation units – Numerical problem

- A 15 km optical fiber link contains the loss of 1.5 dB/km. The fiber is jointed every kilometer with connectors that gives the attenuation of 0.8 dB each. Determine the minimum optical power that must be launched into the fiber in order to maintain the output power level of 0.3 μW.

Given,

Attenuation units – Numerical problem

- A 15 km optical fiber link contains the loss of 1.5 dB/km. The fiber is jointed every kilometer with connectors that gives the attenuation of 0.8 dB each. Determine the minimum optical power that must be launched into the fiber in order to maintain the output power level of 0.3 μW.

$$\alpha_z(\mathrm{dB}) = \alpha \times L = 22.5dB$$

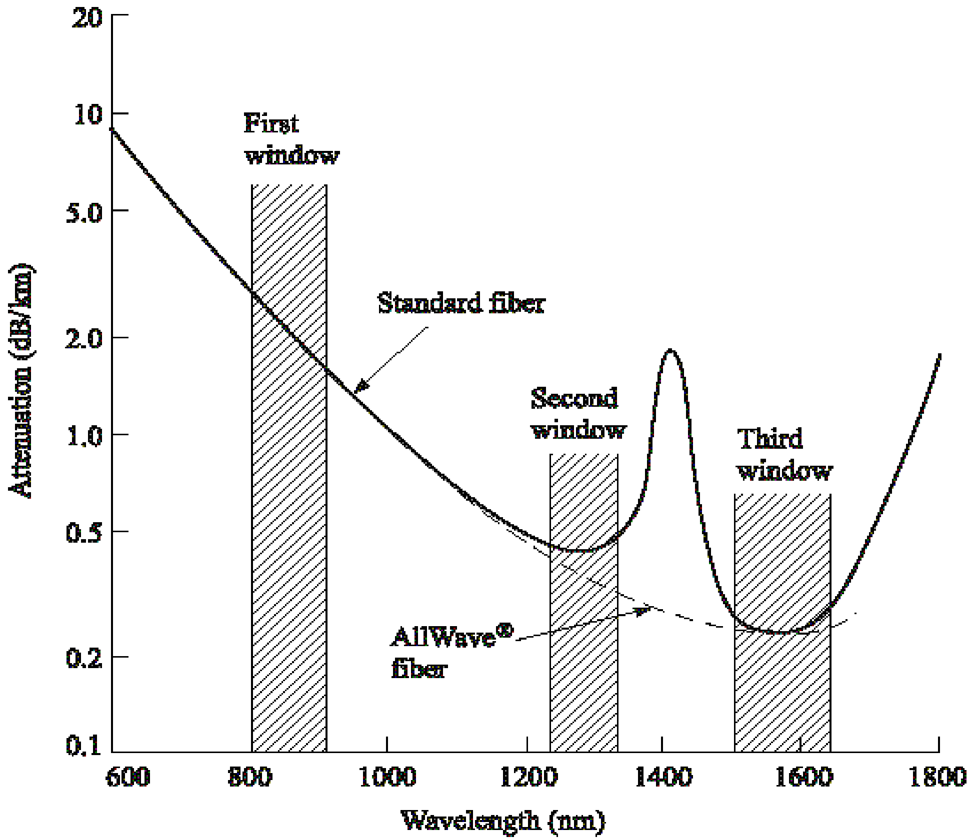
$$10 \log\left[\frac{P_{out}}{P_{in}}\right] = \alpha_p$$

$$\alpha_c(\mathrm{dB}) = 0.8 \times 14 = 11.2dB$$

$$\alpha_T(\mathrm{dB}) = 33.7dB$$

$$P_{in} = \frac{P_{out}}{\exp(-\alpha_p L)} = 0.7mW$$

Attenuation in Optical Fiber



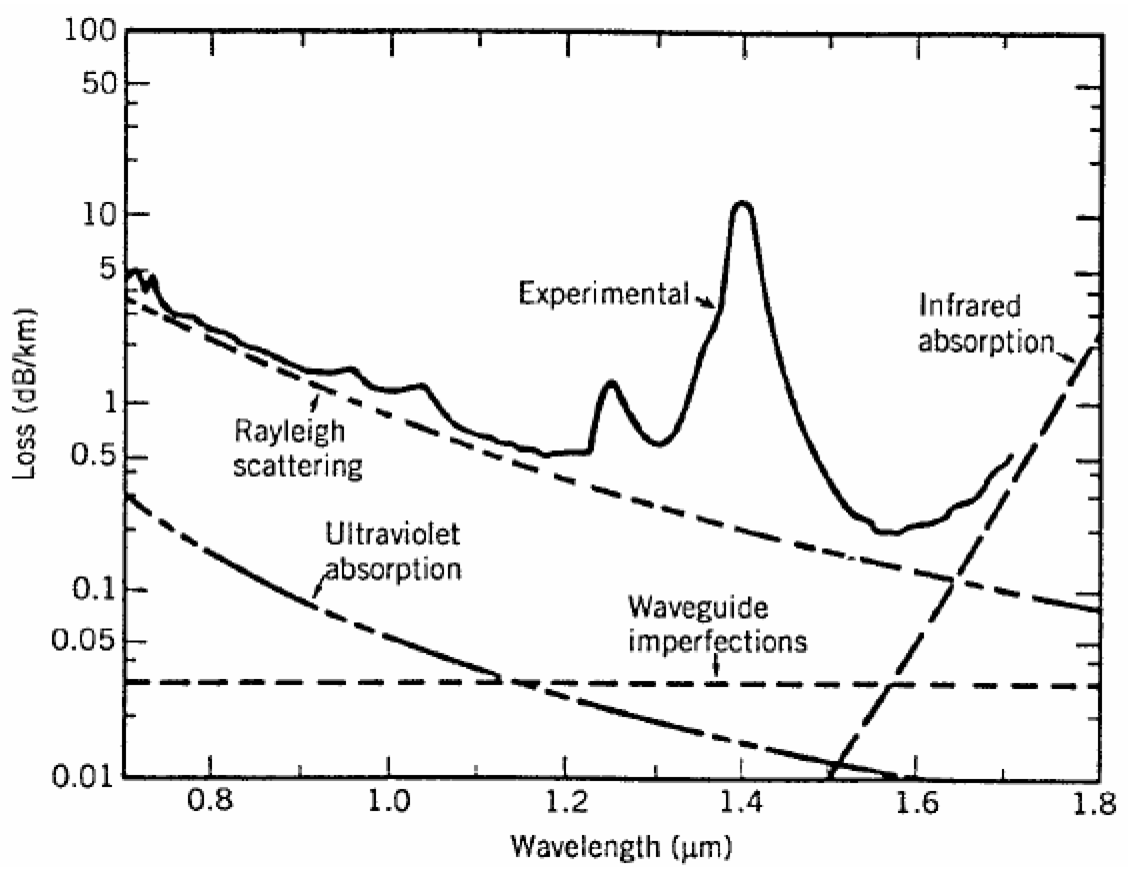
Attenuation Mechanisms

- Absorption
  - Fiber material
    - Intrinsic
    - extrinsic
- Scattering
  - Material density fluctuations
  - Structural imperfections
  - Linear → Rayleigh & Mie
  - Non-linear →Raman & Brillouin
- Radiation
  - Perturbations of fiber geometry

Absorption

- Due to some defects in material distribution in fiber, the transmitted light is dissipated as heat
- Absorption by atomic defects in the glass composition
- Extrinsic absorption by impurity atoms in the glass material
- Intrinsic absorption by the basic constituent atoms of the fiber material

Intrinsic Absorption



Intrinsic absorption

- In near IR region, the intrinsic absorption takes place due to basic fiber material properties
- In pure silica, intrinsic absorption is low
- At shorter wavelength (UV region), intrinsic absorption is more dominant
- Basically an interaction between vibrating SiO band and electromagnetic field of optical region takes place and it produces intrinsic absorption

Extrinsic absorption

- Absorption due to impurities in the fiber material → transition metal impurities, OH ions
- Optical fibers are manufactured using melting techniques and during this process , the metallic ions like Iron, Cobalt, Chromium, Copper gets deposited
- These are metal element impurities, which causes absorption of incoming photons and it is called as extrinsic absorption
- The OH ions from the SiOH band causes the fundamental absorption at 2700 nm
- The harmonics of OH ions also present at the frequencies of 950 nm, 1250 nm and 1380 nm
- The extrinsic absorption can be reduced by reducing the metal impurities and OH ions

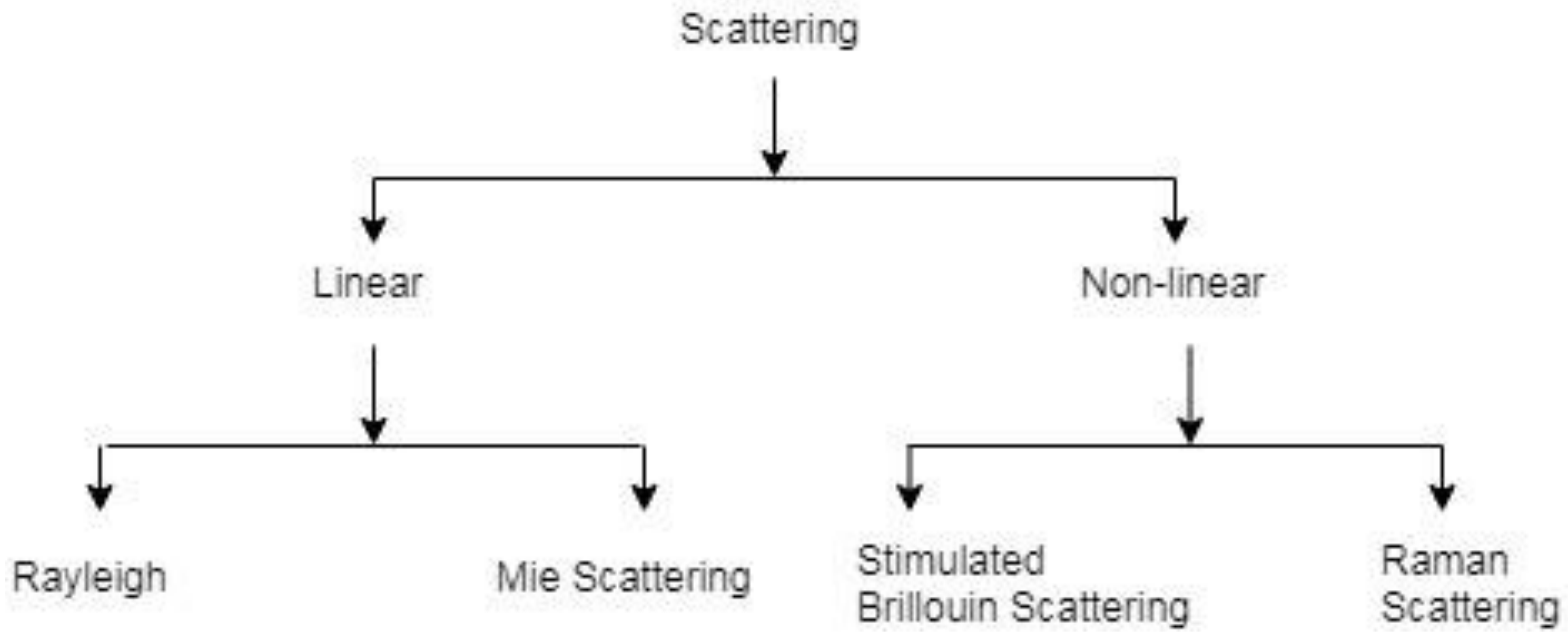
Atomic defects

- Atomic defects are imperfections in the atomic structure of the fiber material
  - Missing molecules
  - high density clusters of atom groups
  - oxygen defects
- Negligible under normal conditions
- Significant when fiber is exposed to ionizing radiation

Basics of Scattering

- Due to non uniformities in fiber cable, a light ray travelling in straight line will get deviated. It is referred as scattering
- Due to scattering, optical power from one propagating mode will get transferred to other mode
- This transfer of power takes place through the leaky mode or radiation mode
- This leaky mode will radiate out of the fiber and it is called scattering loss
- This scattering loss is due to interaction of light with density fluctuations within the fiber
- Basically the glass is composed of randomly connected network of molecules, which is made up of several oxides and it increases the compositional fluctuations
- In case of multimode fibers, there is higher dopant concentration and greater compositional fluctuations
- Therefore, the scattering loss is more in multimode fibers than single mode fibers

Classification of Scattering loss



Rayleigh Scattering

- In case of linear scattering, the optical power will transfer from one to other mode without change in the frequency
- The light from the sun is scattered in the atmosphere which gives the blue sky
- This scattering takes place in all directions
- The Rayleigh scattering produces attenuation in the light rays and this attenuation is proportional to $1/\lambda^4$
- Rayleigh scattering has a λ^{-4} dependence → decreases dramatically with increasing wavelength
- The Rayleigh scattering coefficient is given as

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

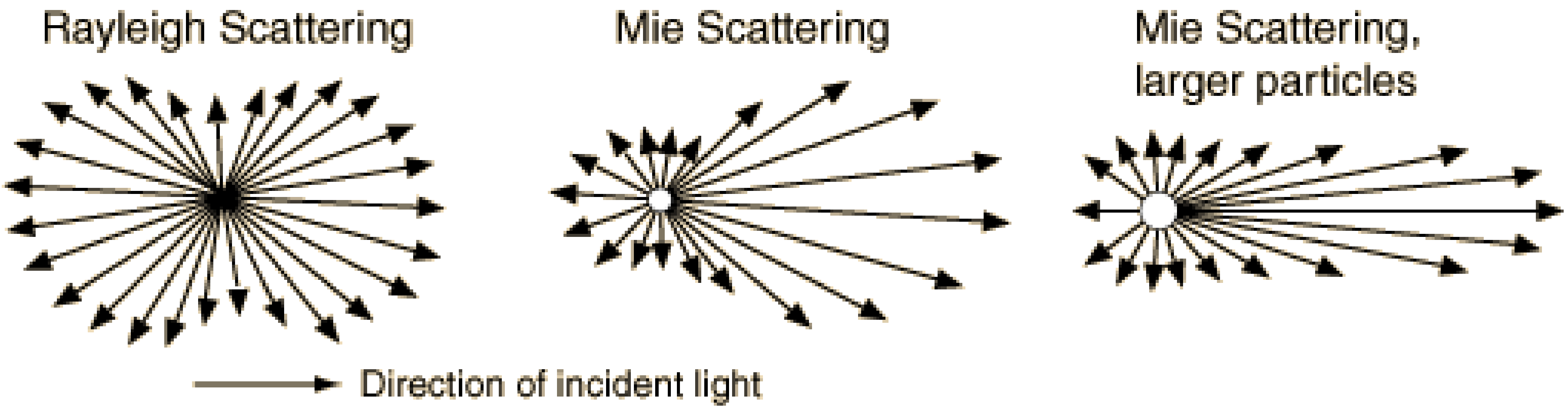
Rayleigh Scattering

- $\lambda < 1\ \mu m$, Rayleigh scattering → dominant loss mechanism
- $\lambda > 1\ \mu m$, IR absorption effect dominate optical signal attenuation
- Rayleigh scattering can be reduced to below 0.01 dB/km for $\lambda > 3\ \mu m$
- Silica fibers cannot be used in this region as IR absorption begins to dominate
- Fluorozirconate fibers have been proposed

Mie Scattering

- The scattering caused by hologenetic which are compared in size with wavelength is called Mie scattering
- This scattering takes place only in forward direction
- Factors responsible for Mie scattering
  - Cylindrical structure of cable is not perfect
  - Imperfect core/cladding interface
  - Core and cladding refractive index is not uniform throughout the fiber
  - Fluctuations in core diameter
  - Bubbles or strains in fiber
- Mie scattering results significant attenuation depending upon the fiber material, size, design and manufacturing process. It can be reduced by
  - Removing imperfections in glass
  - Increase the core/cladding index

Rayleigh & Mie Scattering



Non linear scattering

- In case of non-linear scattering, the optical power will transfer from one to other mode with different frequency

- This scattering takes place in forward and backward direction

- Due to shift in the frequency, there is a loss of signal and attenuation

Stimulated Brillouin Scattering (SBS)

- When the light signal is travelling inside the fiber cable, there are variations in the electric field of the beam
- These variations in electric field produces acoustic vibrations in the fiber cable
- These acoustic vibrations creates the acoustic frequency which results in the scattered photon
- This scattering usually takes place in the opposite direction of the incident light
- During this scattering, a frequency shift is produced and it varies with the scattering angle. This frequency shift in maximum in the backward direction.

Stimulated Raman Scattering (SRS)

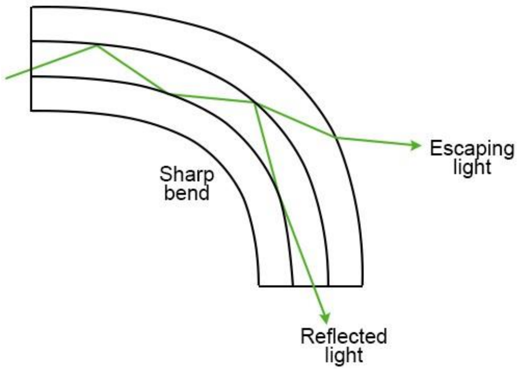
- When the light signal is travelling inside the fiber cable, the spontaneous scattering takes place
- In this process, some of the photons transferred to the near frequencies
- When the scattered photons lose energy it is called as Stokes shift and if the scattered photons gains energy it is called as Anti stokes shift
- If the photons of other frequencies are already present then the scattering of such photons takes place and in this case two photons are generated. It is called as SRS.
- This is similar to SBS. But in SBS high frequency acoustic phonon is created and in SRS high frequency optical phonon is created.
- SRS happens in both forward and backward direction

Basics of Radiative Loss/Bending Loss

- If there is a abrupt change in the radius of curvature of the fiber, then the radiation loss takes place.

- If there is sharp bend in the fiber, then there is probability of mechanical failure of the cable

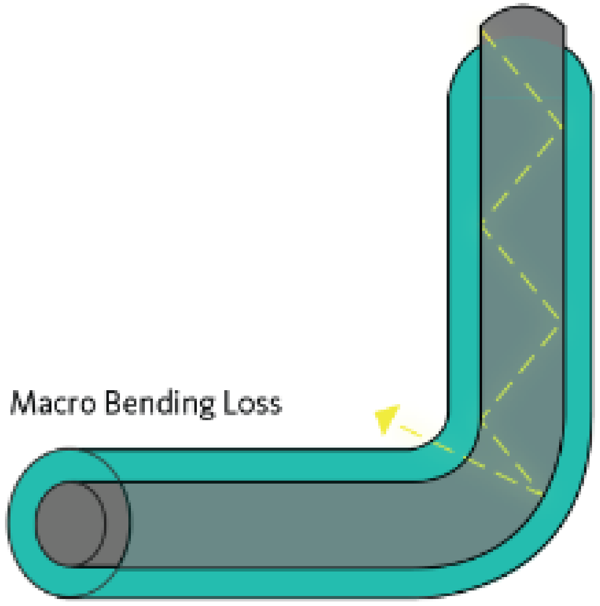
- Usually the higher order modes are weakly coupled to the core then the radiation loss takes place to the higher order modes first

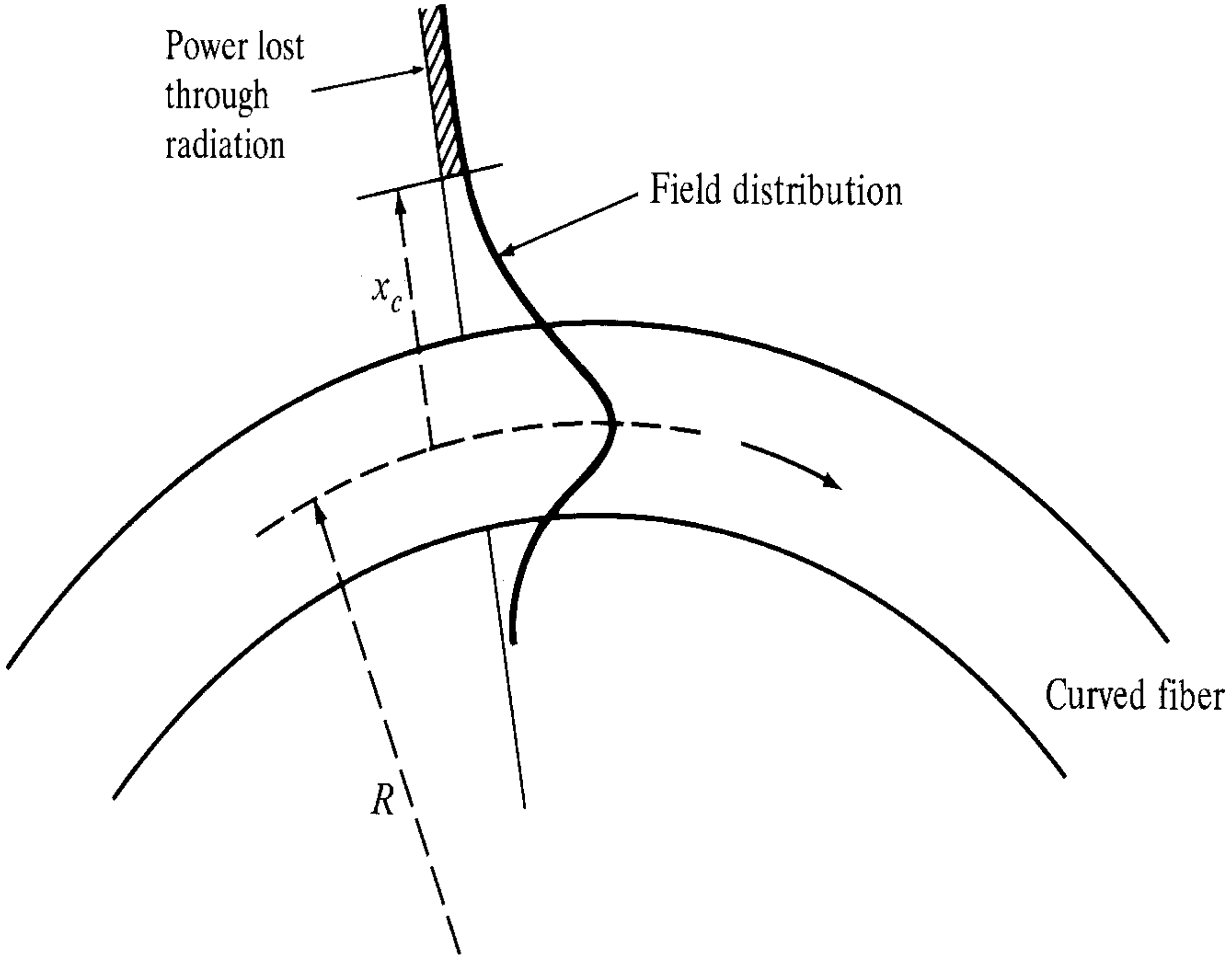


Types of Bending Loss

- Macro-bending Losses
  - Bend radius >> core radius
- Micro-bending Losses
  - Bend radius comparable to core radius

Macro-bending Losses





Macroscopic bends

- Results in the radiation of the evanescent field (of a bound core mode) present in the cladding at a critical distance from the centre of the fiber

- Higher order modes are bounded less tightly to the core than the lower order modes. Hence they are radiated first

- The total number of modes supported by a curved fiber is less than a straight fiber

- Bending loss is negligible when R is > 5 mm

Important expressions for Macroscopic bends

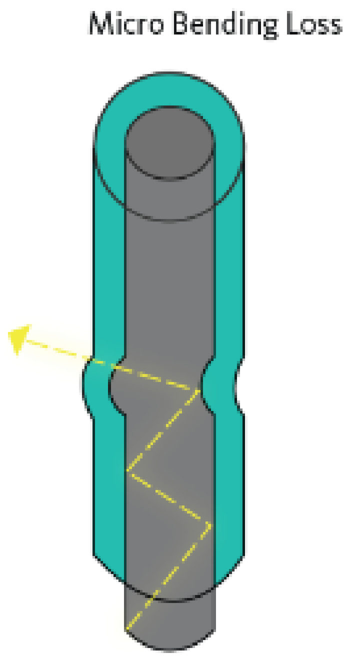
- For SMF, the critical bending radius is given as

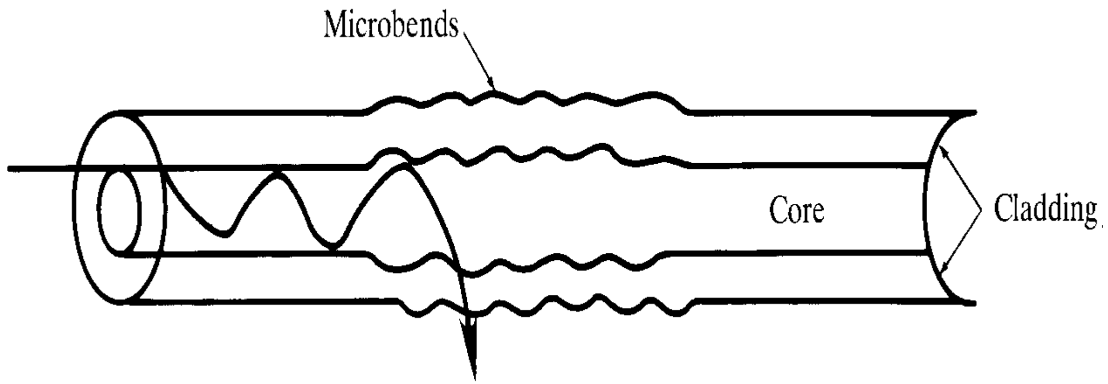
$$Rcs = \frac{20\lambda}{(n1 \;\; - n2 \;\;)^{3/2}}(2.748 - 0.996\frac{\lambda}{\lambda_c})^{-3}$$

- For MMF, the critical bending radius is given as

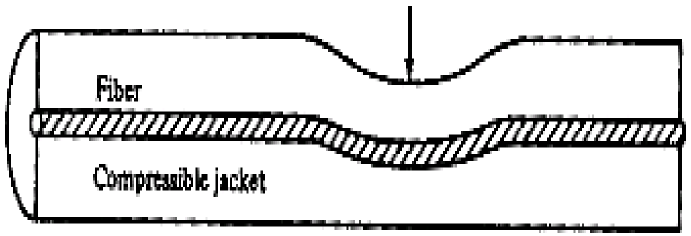
$$R_c = 3\, n_1^2\, \lambda \,/\, [4\pi\, (n_1^2 - n_2^2\,)^{3/2}]$$

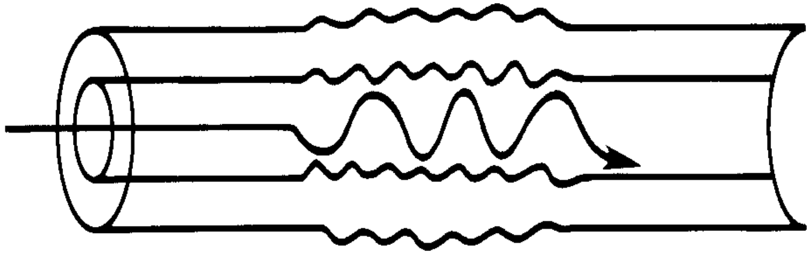
Micro-bending Losses or Mode Coupling Losses





Power Loss from Higher-Order Modes





Power Coupling to Higher-Order Modes

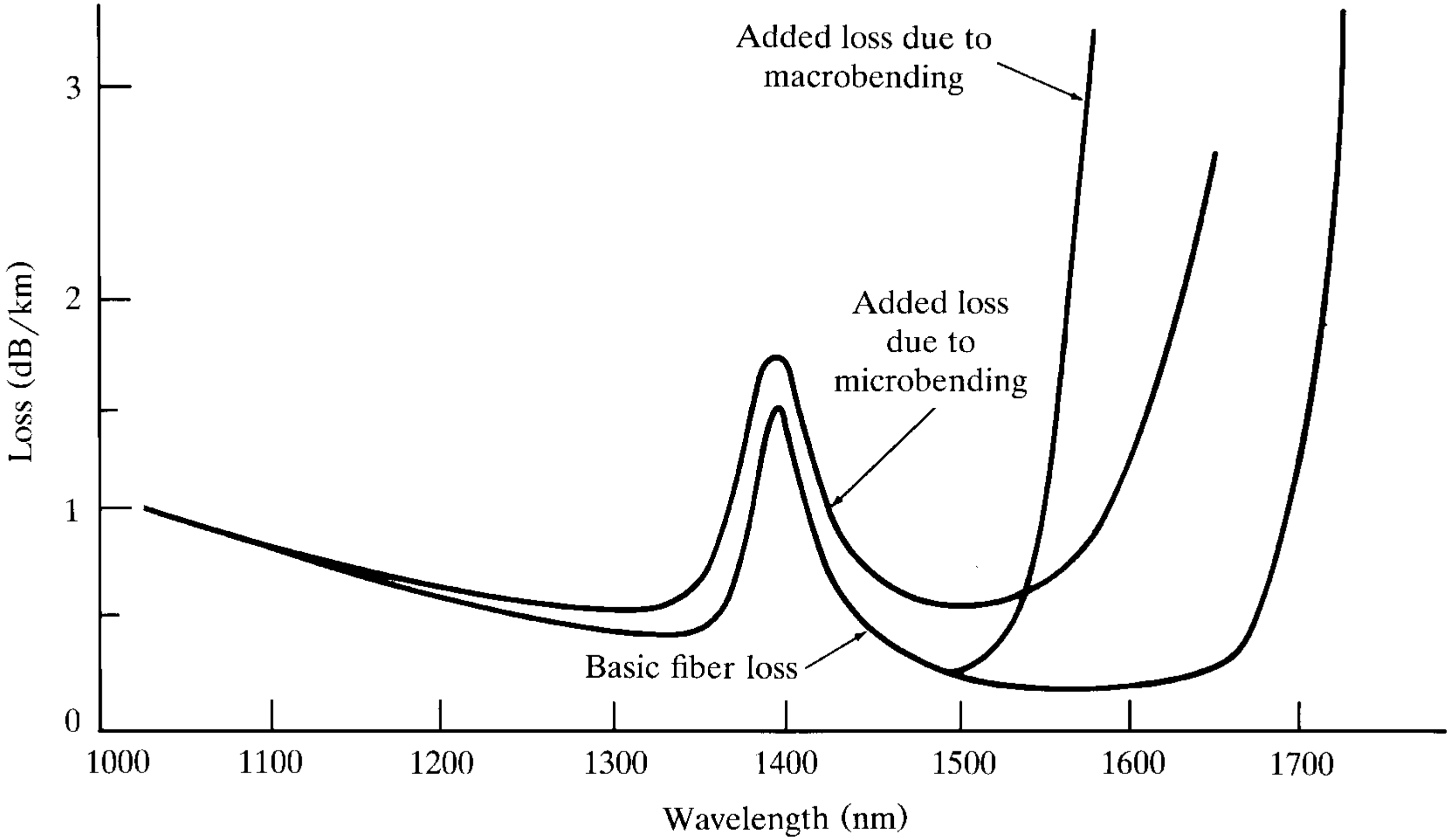
Macroscopic bends

- Microbends are repetitive small scale fluctuations in the radius of curvature of the fiber axis

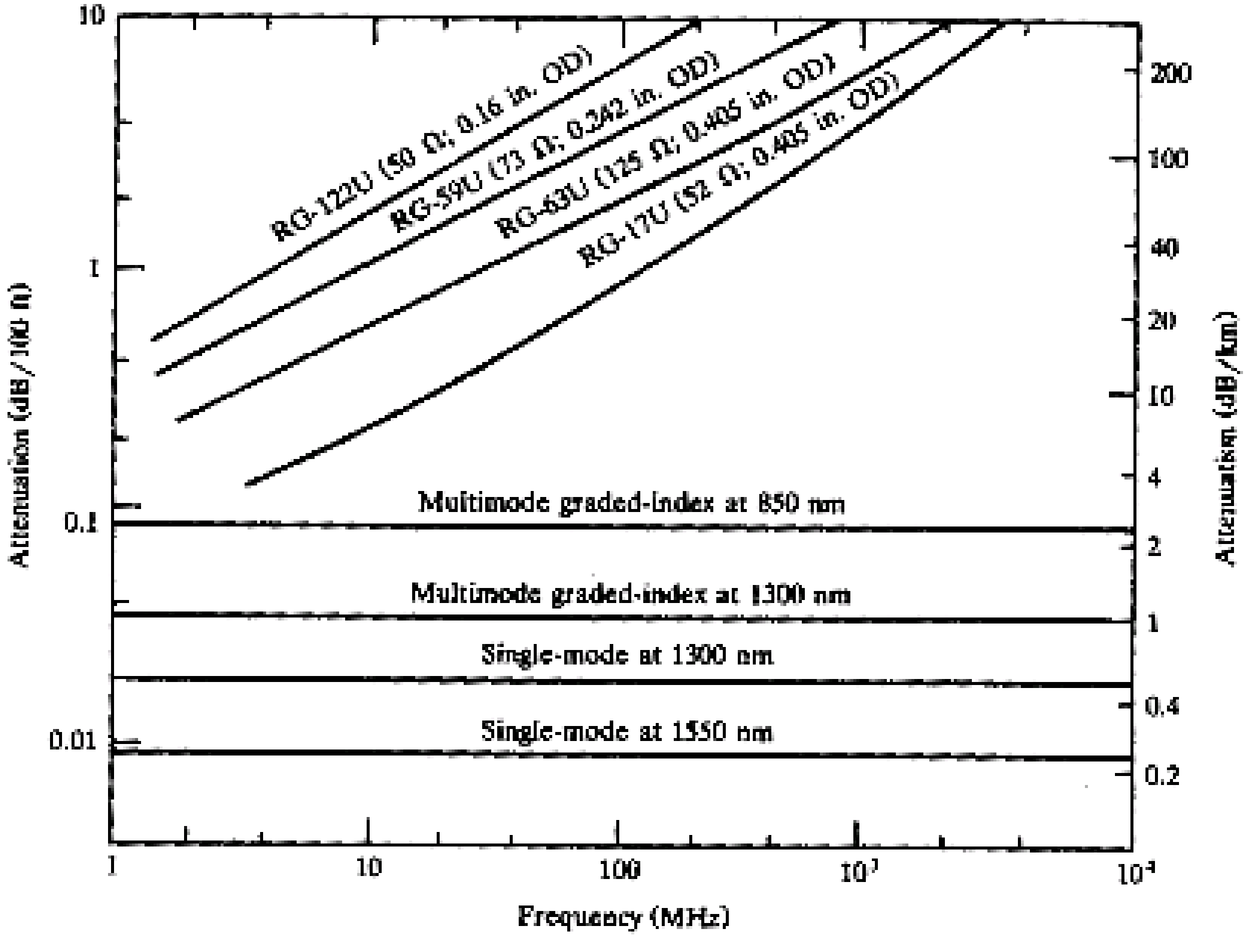
- Caused either by nonuniformities in the manufacturing of the fiber or during cabling.

- An increase in attenuation results due to repetitive coupling of energy between the guided modes and the leaky or nonguided modes in the fiber

Bending Induced Attenuation



Attenuation vs. Frequency



Two step index fibers exhibit the following parameters:

- MMF → Core RI = 1.500
  Δ = 3 %
  λ = 0.82 μm

- SMF → Core RI = 1.500
  Δ = 0.3 %
  λ = 1.55 μm
  Core dia. = 8 μm

- Comment on their Critical Bending Radii ?

Two step index fibers exhibit the following parameters:

- MMF → Core RI $= 1.500$
  $\Delta = 3\,\%$
  $\lambda = 0.82\ \mu m$

$R_c = 9\mu m$

- SMF → Core RI $= 1.500$
  $\Delta = 0.3\,\%$
  $\lambda = 1.55\ \mu m$
  Core dia. $= 8\ \mu m$

$R_{cs} = 33mm$

- Comment on their Critical Bending Radii ?