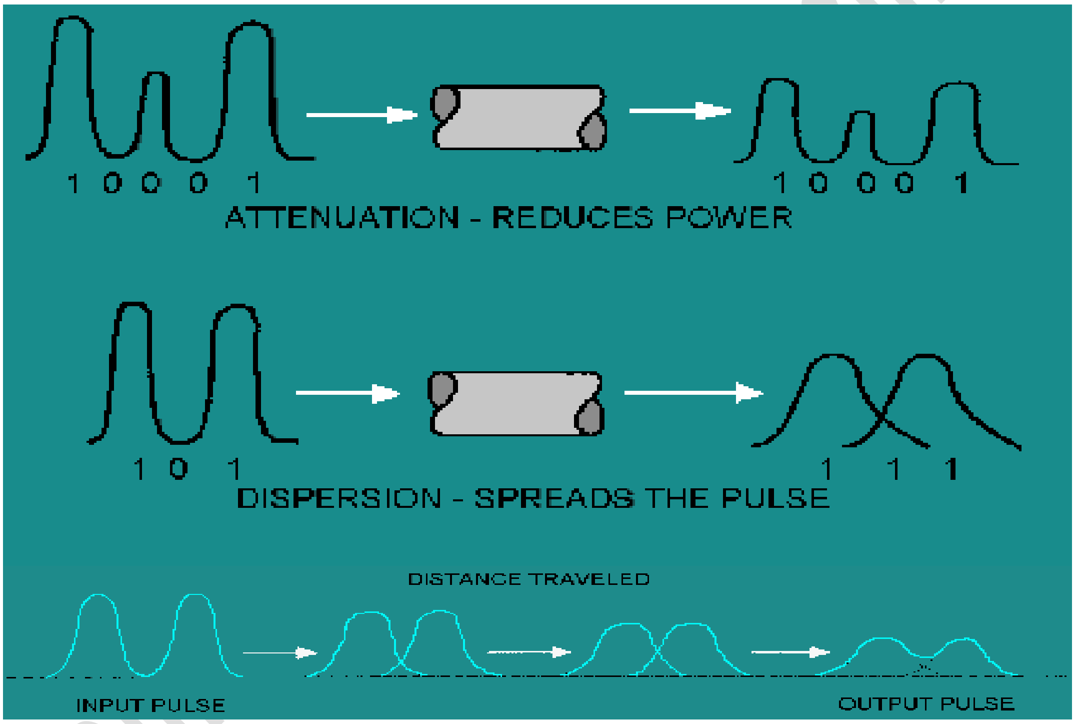
OPTICAL FIBER COMMUNICATIONS SYSTEMS
Lecture Three
Signal degradation in optical fiber

❖ Causes of signal degradation are:
1. **attenuation** or fiber loss. The intensity of the light pulse decreases as the pulses travel along the length of the fiber (usually is expressed in terms of **dB/km**).
2. **dispersion** and it does not involve loss of light intensity, but that do cause the pulse to broaden and to move out of its time slot.



Fiber Loss (attenuation)

Signal attenuation is defined as the ratio of optical input power into the fiber (P_i) to the optical output power (P_o). Optical input power is the power injected into the fiber and travels distance of **z** in km from an optical source. Optical output power is the power received at the fiber end or optical detector. The following equation defines signal attenuation as a unit of length:

$$\alpha z = 10 \log \frac{p_i}{P_o} \qquad in \ \ dB$$

- Where α is the attenuation coefficient of the fiber in dB/km.
- Each mechanism of loss is influenced by fiber material properties and fiber structure. Fiber loss depends on the wavelength of the transmitted light.

dB/km	λ(μm)
0.2	1.55 at 1979
0.35	1.3
0.15	1.3 silica fiber

- Minimum Reduction Expected in future is 0.01dB/Km.
- However, loss is also present at fiber connections. Fiber connector, splice, and coupler losses.

A note on dB and dBm

- **dB**
  - optical signals: $$10\log\left(\frac{P_1}{P_2}\right)$$
  - electrical signals: $$20\log\left(\frac{V_1}{V_2}\right)=20\log\left(\frac{I_1}{I_2}\right)=10\log\left(\frac{V_1 I_1}{V_2 I_2}\right)$$

$$P_{opt} \propto I_{el} \propto \sqrt{P_{el}}$$

- **dBm**

$$10\log\left(\frac{P}{1mW}\right)$$

- absolute power value (with 1 mW as reference)
- power level in dBm.

1. If the data link is perfect, and loses no power. The loss is 0 dB
2. If the data link loses 50% of the power, the loss is 3 dB, or a change of – 3 dB.
3. If the data link loses 90% of the power, the loss is 10 dB, or a change of – 10 dB

4. If the data link loses 99% of the power, the loss is 20 dB, or a change of – 20 dB

- For convenience, we use the dBm units, where

-20 dBm = 0.01 milliwatt

-10 dBm = 0.1 milliwatt

0 dBm = 1 milliwatt

10 dBm = 10 milliwatts

20 dBm = 100 milliwatts

<u>Fiber loss in dB/km</u>

$P(0)[\text{dBm}]$ $\qquad$ $P(l) = P(0)e^{-\alpha_p l}$

$$P(l)[\text{dBm}] = P(0)[\text{dBm}] - \alpha[\text{dB/km}] \times l[\text{km}]$$

- The parameter α_p is called fiber attenuation coefficient in a units of for example [1/km] or [nepers/km]. A more common unit is [dB/km] that is defined by:

$$\alpha[\text{dB/km}] = \frac{10}{l}\log\left[\frac{P(0)}{P(l)}\right] = 4.343\alpha_p[1/\text{km}]$$

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When the mean optical power launched into an 8km length of fiber is 120 μw, the mean optical power at the fiber output is 3 μw.

Determine:

a. the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors and splices;

b. the signal attenuation per kilometerge for the fiber;

c. the overall signal attenuation for a 10km optical link using the same fiber with splices at 1km intervals, each giving an attenuation of 1dB;

d. the numerical input / output power ratio in (c).

Sol.:

a. the overall signal attenuation in decibels through the fiber is:

$$\text{signal attenuation} = 10 \log_{10} \frac{P_i}{P_o} = 10 \log_{10} \frac{120 \times 10^{-6}}{3 \times 10^{-6}}$$
$$= 16.0 \text{ dB}$$

b. $\alpha_{dB} L = 16.0$ dB (طول)

hence;

$$\alpha_{dB} = \frac{16.0}{8} = 2.0 \text{ dB km}^{-1}.$$

c. As $\alpha_{dB} = 2 \text{dB.km}^{-1}$, the loss incurred along 10km of the fiber is given by

$$\alpha_{dB} L = 2 \times 10 = 20 \text{ dB}$$

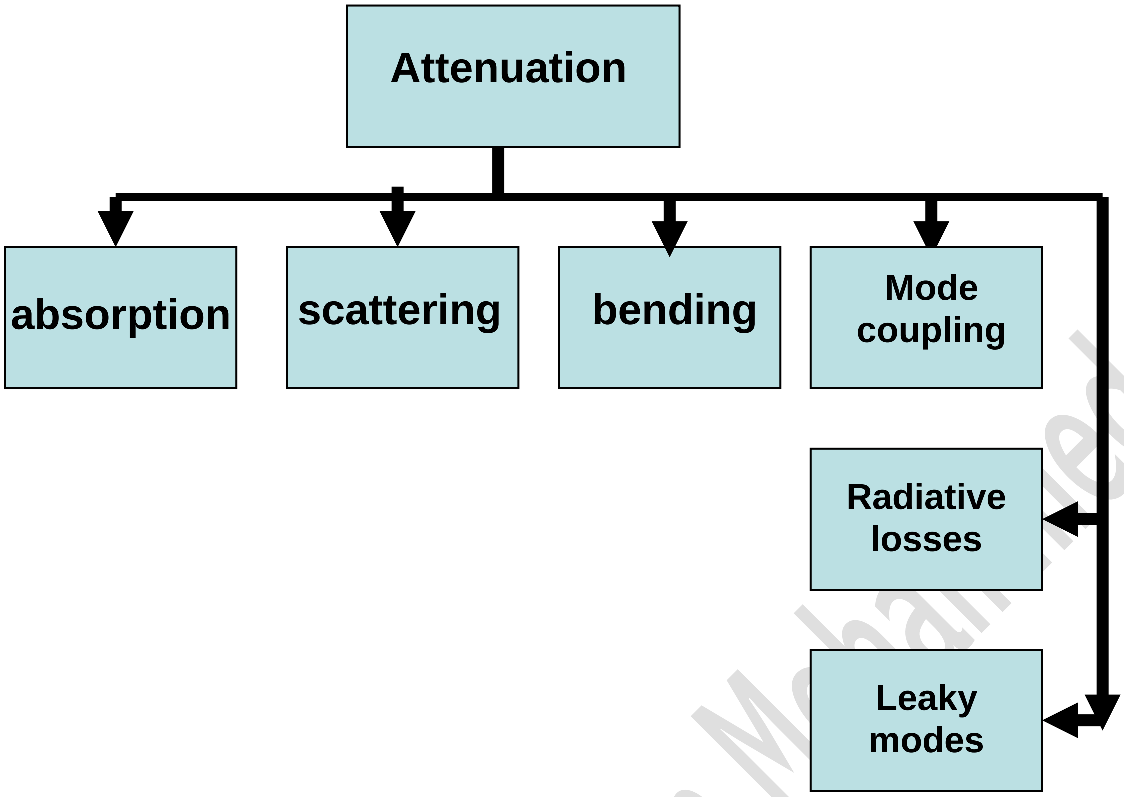
~~Hen~~ However, the link also has nine splices (at 1km inter each with an attenuation of 1dB. Therefore, the loss due to the splices is 9 dB.

Hence, the overall signal attenuation for the link is:

$$\text{Signal attenuation} = 20 + 9$$
$$= 29 \text{ dB}$$

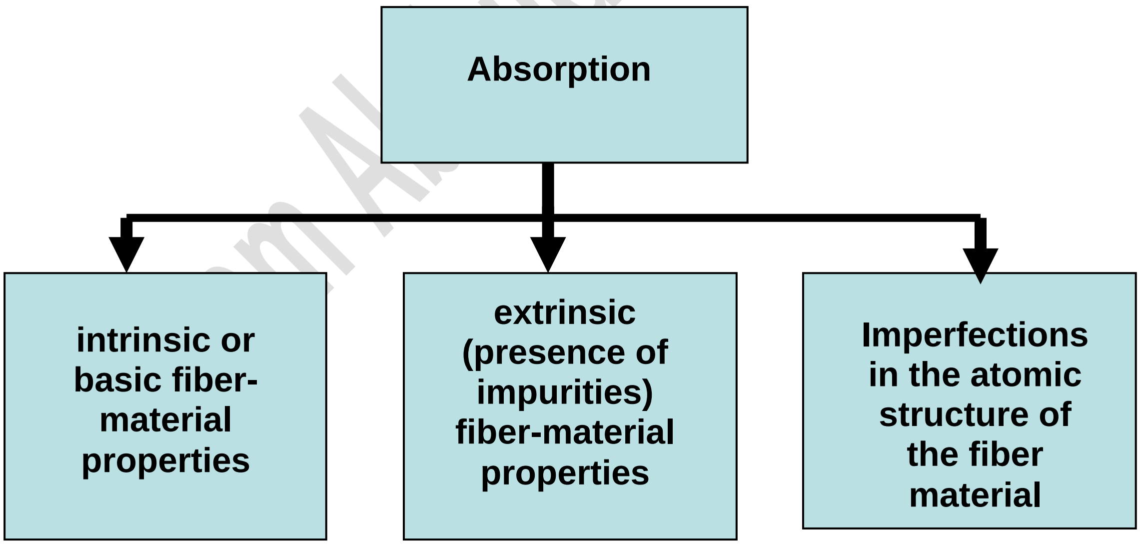
d. To obtain numerical value for the input / output power ratio,

$$\frac{P_i}{P_o} = 10^{29/10} = 794.3$$

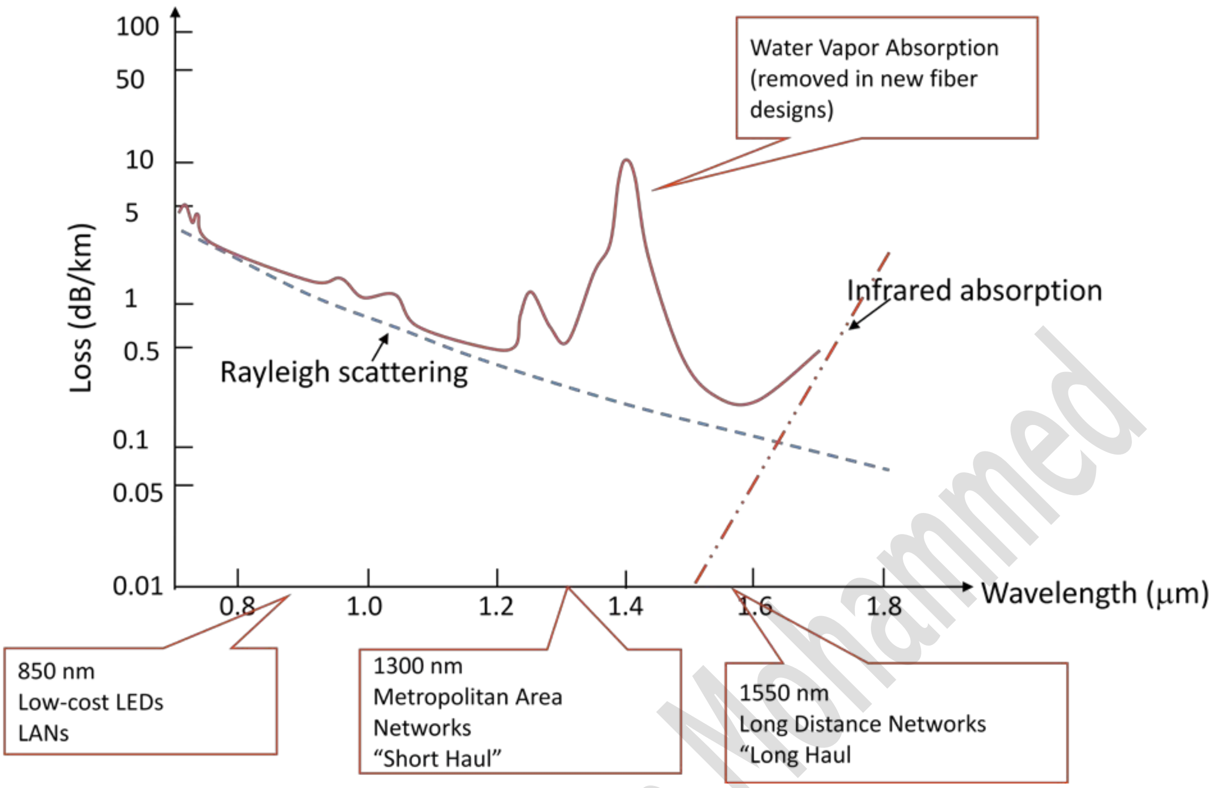


Absorption.

- **Absorption** is a major cause of signal loss in an optical fiber.



Intrinsic Absorption. Intrinsic absorption is caused by basic fiber-material properties. Intrinsic absorption sets the minimal level of absorption. In silica glass, the **wavelengths** of operation range from 700 nm to 1600 nm.



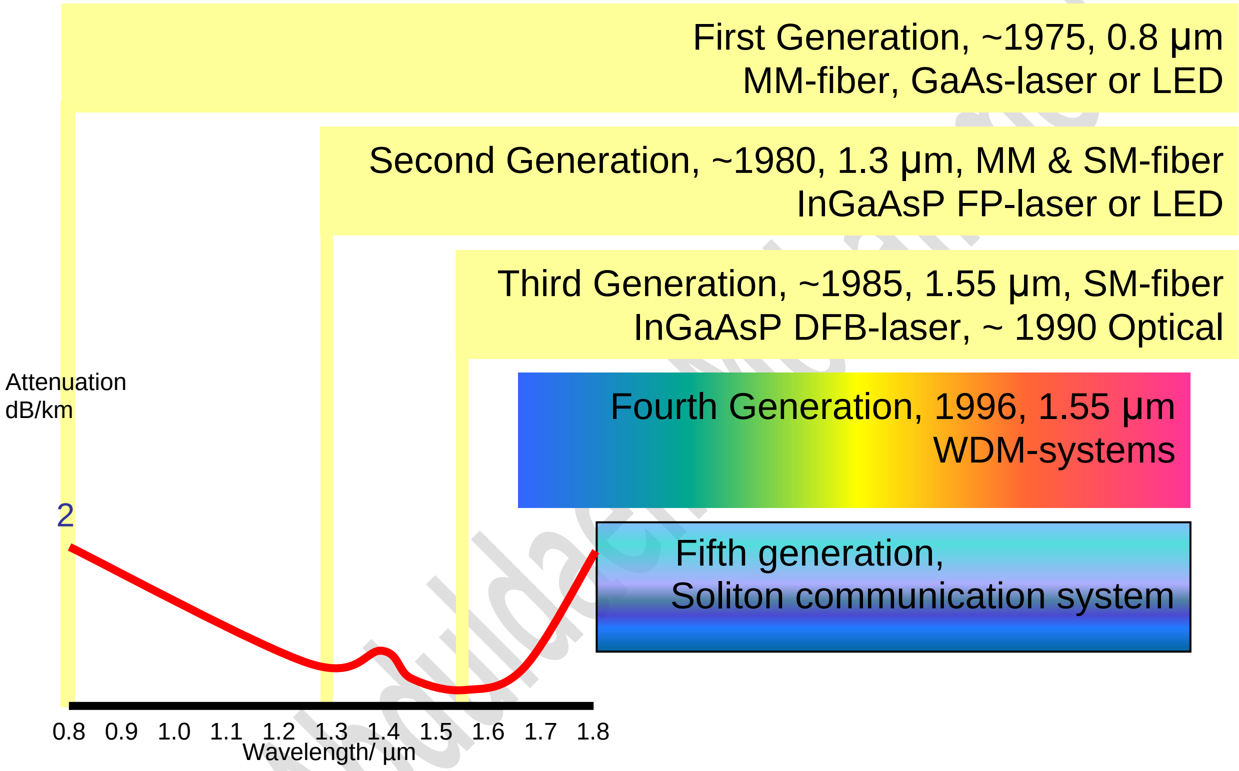
1. ***Fiber attenuation is ~0.2 dB/km at around 1550 nm***
2. ***The bandwidth around low attenuation is 25 Tb/sec***

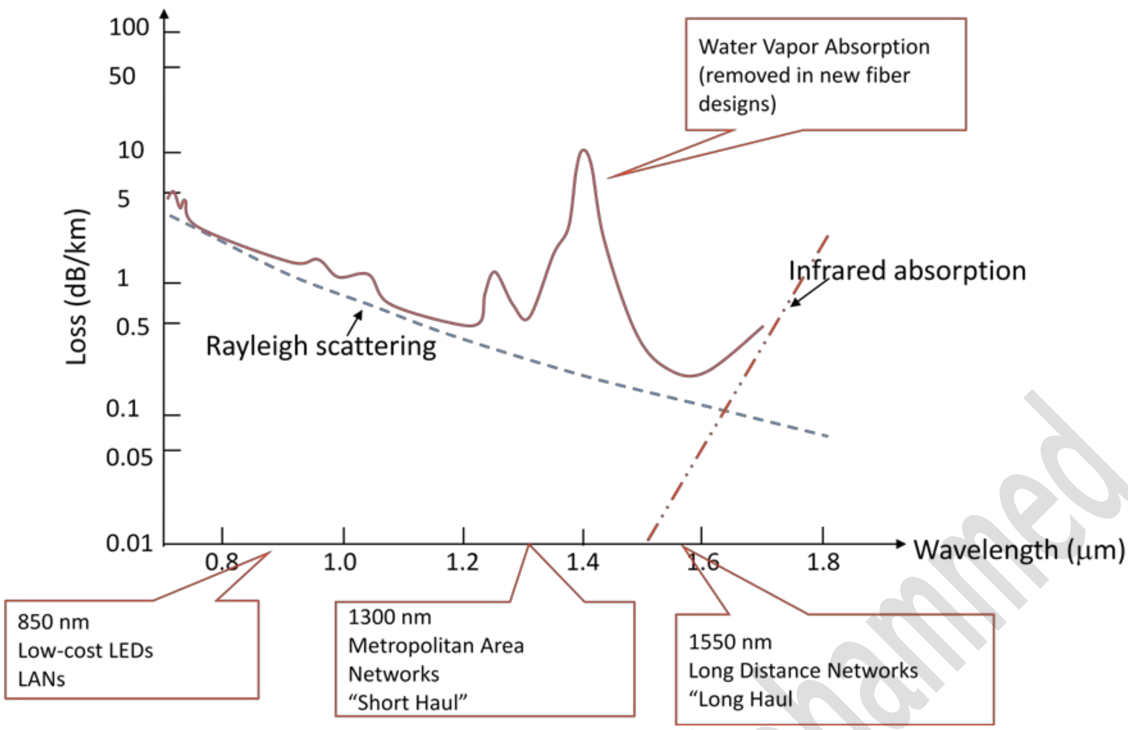
Extrinsic Absorption.

- Extrinsic absorption is caused by impurities introduced into the fiber material, such as iron, nickel, and chromium, are introduced into the fiber during fabrication.
- Extrinsic absorption also occurs when **hydroxyl ions (OH^-)** are introduced into the fiber. Water in silica glass forms a silicon-hydroxyl (Si-OH) bond. This bond has a fundamental absorption at **2700 nm**.
- For **Fe^2** attenuation of 110 nm.
- These losses are effective in the **visible and infrared regions**.
- These absorption peaks define three regions or windows of preferred operation.

window	λ(nm)
first window	**850**
second window	**1300**
third window	**1550**

Fiber optic systems operate at wavelengths defined by one of these windows.

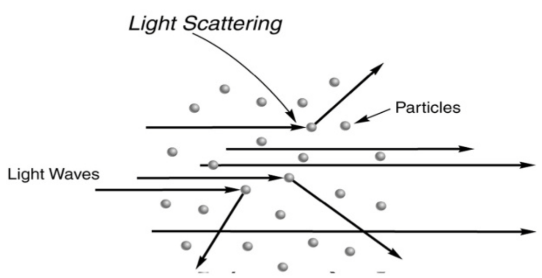




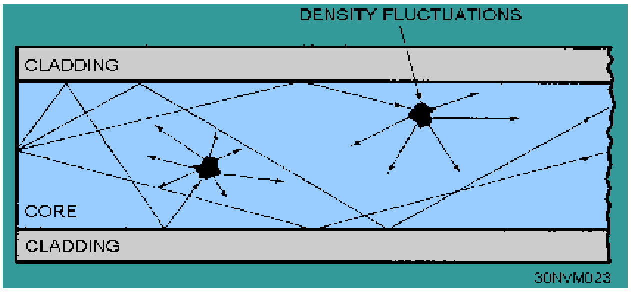
Imperfections in the atomic structure

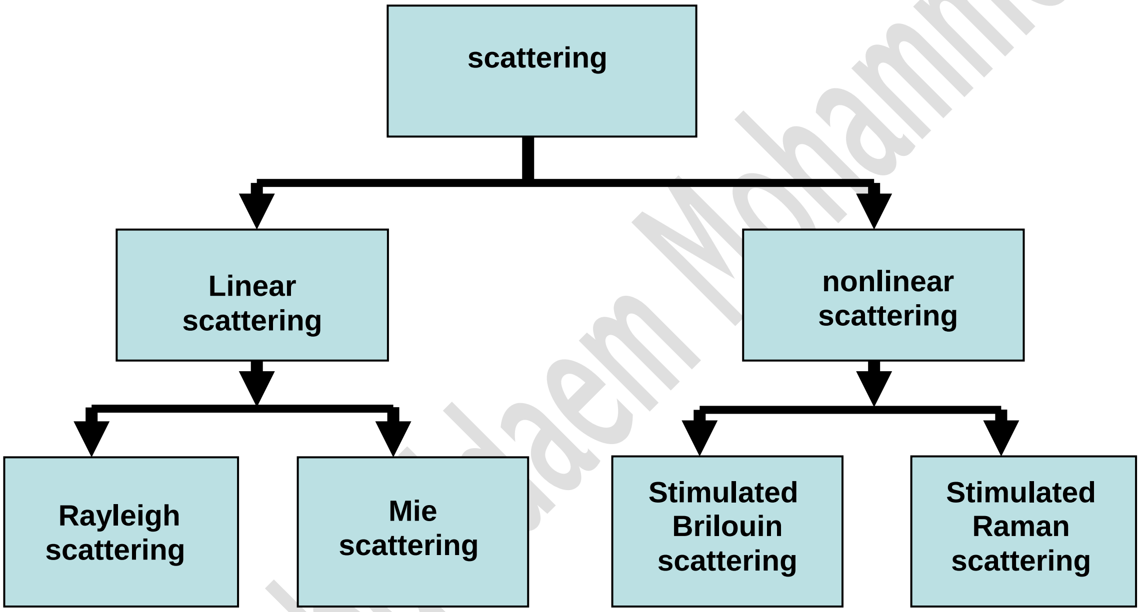
- induce absorption by the presence of missing molecules or oxygen defects. Absorption is also induced by the diffusion of hydrogen molecules into the glass fiber.

Fiber type	Typical loss dB / km
Plastic SI	100 – 500
Glass GRI	1 – 5
Glass SM	0.2 - 3



Scattering: scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured.





1) **Linear Scaterring.** Due to nonideal properties of the manufactured fiber.

Rayleigh losses at a wavelength λ resulting from density fluctuations can be approximated by:

$$\alpha_R = \frac{A_r}{\lambda^4} = \frac{8\pi^3}{3\lambda^4} n^2 \, p^2 \, \beta_c \, k \, T_F \qquad (dB.km^{-1})$$

- The Rayleigh scattering coefficient A_r is a constant for a given material depending on the constituents of the fiber core in the range 0.7- 0.9 (dB/km).μm^4,
- For 1550 nm the loss is approximately 0.18 dB per km.

- ❖ α_R between 0.12 – 0.16 dB/km at wavelength 1.55mm. So Rayleigh scattering is dominate at this wavelength.
- ❖ The Rayleigh scattering is strongly reduced by operating at longer wavelength since the losses caused by Rayleigh scattering is inversely proportional to fourth power of the wavelength ($1/\lambda^4$).

- The Rayleigh scattering coefficient A_r depends:

  -The fiber refractive index profile

  -The doping used to achieve a given core refractive index
- For a step index germanium doped fiber A_r is given by:

  $A_r = 0.63 + 2.06.NA$ dB/km
- For a graded index near-parabolic profile fiber A_r is given by:

  $A_r = 0.63 + 1.75.NA$ dB/km

Exercise: Show that for a graded index fiber with a numerical aperture of 0.275 operating at 1330 nm the Rayleigh scattering loss is approximately 0.36 dB/km.

The Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber **τ** of length of **L** as

$$\tau = \exp(-\alpha_R L)$$

- ❖ Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions.

a) **Mie scattering**

- ❖ If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called **Mie scattering**.

2. Nonlinear Scattering

- it is related to the channel (optical fiber)nonlinearity**.**
- The nonlinear scattering causes a partial power of propagation mode to be transferred to a mode of different frequency.
- Nonlinear scattering depends upon the optical power density within the fiber and hence becomes significant above threshold power levels. The levels are 100mW for Brillouin scattering and 1W for Raman scattering.
- They can be observed only in long single mode fibers, and not in multimode fibers due to its large diameter which makes the threshold level very high.

a) Stimulated Brillouin Scattering (SBS)

- Assuming that the polarization state of the transmitted light is not maintained the threshold power P_B is given by :

$$P_B = 4.4\times10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \qquad (Watts)$$

where

d is the fiber core diameter in μm

λ is the operating wavelength in μm

α_{dB} is the attenuation in decibels per kilometer

υ is the source bandwidth (i.e. injection laser) GHz.

Ex: λ=1.3μm d =60 μm without 10^{-6} P_B= $4.4*10^{-2}$)$(60)^2(1.3)^2$ αν.

- The expression above equation allows the determination of the threshold optical power which must be lunched into a single mode optical fiber before SBS occurs.

b) Stimulated Raman Scattering (SRS)

- The nonlinear Raman scattering effect has been used for optical amplification.
- The threshold optical power for SRS $\mathbf{P_R}$ in a long single mode fiber is given by

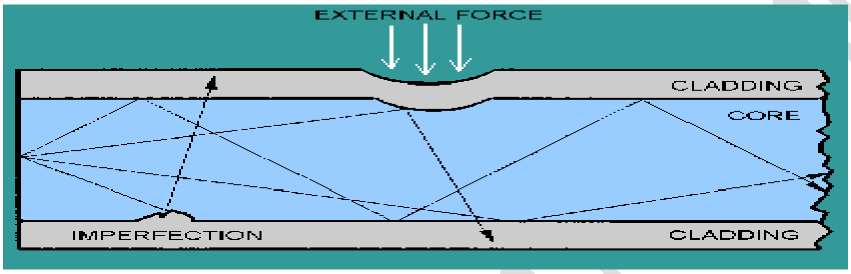
$$P_R = 5.9*10^{-2} d^2 \lambda \alpha_{dB} \qquad (Watts)$$

- Raman scattering is an important issue in Dense WDM systems

Bending Loss.

Bending the fiber also causes attenuation. Bending loss is classified according to the bend radius of curvature: microbend loss or macrobend losses.

1- Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled



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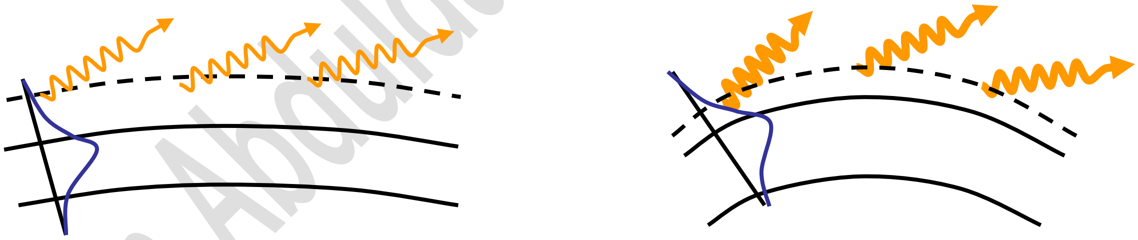
2- Macrobends are bends having a large radius of curvature relative to the fiber diameter.



❖ The loss can be generally represented by a radiation attenuation coefficient ar which has the form

$$\alpha_r = c_1 \exp(-c_2 R)$$

Where **R** is the radius of curvature of the fiber bent and **c_1 & c_2** are constant which are independent on R.

❖ The critical radius of curvature R_c for a multimode fiber can be estimated as:

$$R_c = \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{3/2}} \qquad (1)$$

- The critical radius of curvature for a single mode fiber R_{cs} can be estimated as :

$$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^{1/2}} (2.748 - 0.996 \frac{\lambda}{\lambda_c})^{-3}$$

Where λ_c is the cutoff wavelength of the single mode fiber.

Ex. 98 Two step fiber exhibit the following parameters:

a Amultimode fiber wore a core refractive index of 1.5, a relative refractive index difference of 3% and an operating wavelength of 0.82 μm.

b An 8 μm core diameter single-mode fiber with core refractive index the same as in (a), a relative refractive index difference of 0.3% and an operating wavelength of 1.55 μm.

Sol: Estimate the critical radius of curvature at which large bending losses occur in both cases.

Sol:

a) The relative refractive index is given by:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

hence

$$n_2^2 = n_1^2 - 2\Delta n_1^2 = 2.25 - 0.06 \times 2.25$$

$$= 2.115$$

The critical radius of curvature:

$$R_c \simeq \frac{3n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{1/2}} = \frac{3 \times 2.25 \times 0.82 \times 10^{-6}}{4\pi (1.35)^{1/2}}$$

$$= 9\ \mu m.$$

b Again

$$n_2^2 = n_1^2 - 2\Delta n_1^2 = 2.237$$

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{2.405}$$

$$= 1.214\ \mu m$$

$$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^{1/2}} (2.748 - 0.996 \frac{\lambda}{\lambda_c})^{-3}$$

$$R_{cs} = 34\ mm$$

Mode Coupling

- In real system, pulse distortion will increase less rapidly after a certain initial length of fiber because of mode coupling and differential mode loss.
- Mode coupling is the coupling of energy from one mode to another because of structural imperfections, fiber diameter and refractive index variations and cabling induced microbends.
- Mode coupling tends to average out the propagation delays associated with the modes, therby reducing intermodal dispersion, and its effects can be significant for large fibers.