BUDDHA SERIES

(Unit Wise Solved Question & Answers)

Course – B. Tech (ECE)

College – Buddha Institute of Technology

(AKTU CODE-525)

Department: Electronics and Communication Engineering

Subject: Optical Communication (BEC-057)

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Unit – 2

Q1. What do you mean by attenuation? What are the causes of attenuation in optical fiber communication?

ANS:

Attenuation – or Fiber Loss Parameter –

* Attenuation in optical fiber is the loss of signal strength or light power that occurs as light travels through an optical fiber. It is measured in decibel per kilometer (dB/Km).

Signal attenuation (dB) $= 10 \log_{10} \frac{P_i}{P_o}$

where P_i = input (transmitted) optical power

P_o = output (received) optical power

$$\alpha_{dB} L = 10 \log_{10} \frac{P_i}{P_o}$$

α_{dB} = signal attenuation per unit Length

L = Length of the fiber.

$$\frac{P_i}{P_o} = 10^{(dB/10)}$$

Attenuation in optical fiber communication occurs due to –

(1) Absorption and scattering – Absorption removes signal energy while scattering redirects light out of the core to the cladding.

(2) Bending – Bending of optical fiber can contribute to attenuation.

(3) Polarization – The state of polarization of light can change as it propagates through optical components, which can lead to attenuation.

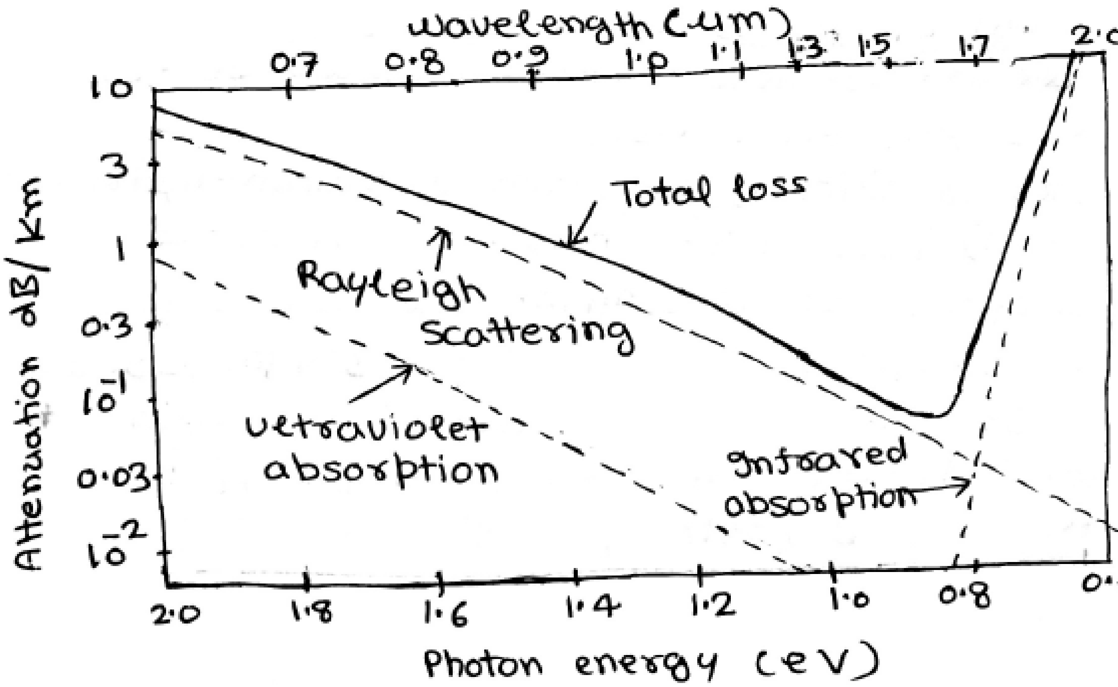
(4) Splicing – Splicing fiber optic cable is very common, and can cause attenuation.

(5) Passive media components – cable, cable splices and connectors can all cause attenuation.

Q2. Explain intrinsic & extrinsic absorption loss in silica glass fiber. **[AKTU; 2020-21]**

(1) Intrinsic Absorption - The intrinsic absorption is caused by the interaction of light with one or more of the major components of the glass.

* An absolutely pure silica glass has little intrinsic absorption due to its basic material structure in the near infrared region.
* The silica glass fiber has a low intrinsic absorption window over the 0.8 to 1.7 um wavelength range.



Intrinsic absorption (attenuation) spectra of pure $GeO_2 - SiO_2$ glass

* In the near-infrared spectral region, around 1.5 um wavelength, silica has extremely low absorption and scattering losses of the order of 0.2 dB/Km.
* Intrinsic absorption can be minimized by suitable choice of both core and cladding compositions.

(ii) Extrinsic Absorption - Extrinsic absorption is caused by impurities within the glass. The metal impurities, such as iron, nickel and chromium are introduced into the fiber during fabrication. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another.

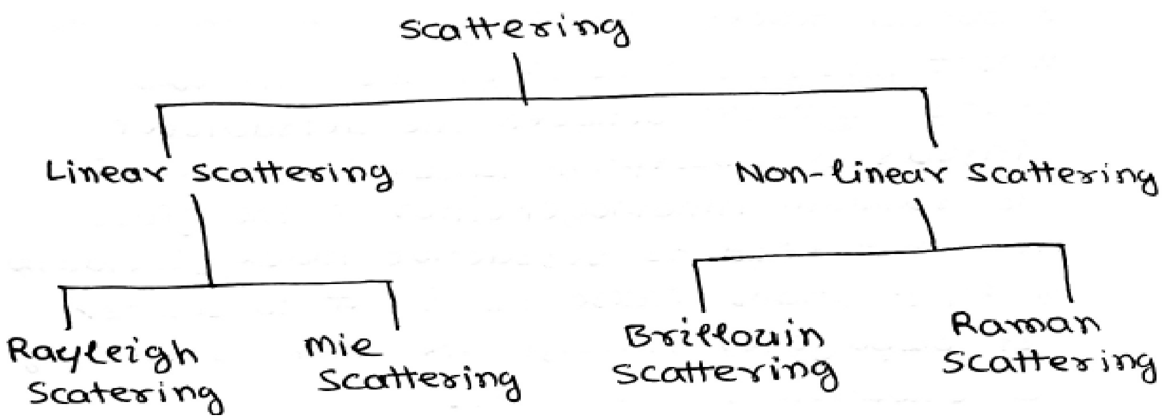
* Transition - metal impurities like Fe, Cu, Co, Ni, Mn, and Cr absorb strongly in the 0.6 to 1.6 um wavelength range. To reduce loss to below 1 dB/Km, the amount of these impurities should be less than 1 part per billion.

* Water in silica glass forms a silicon-hydroxyl (Si-OH) bond, which has a fundamental absorption at 2.7 um. The harmonics of this absorption occur at 1.38 um, 1.25 um and 0.95 um wavelengths, which increase extrinsic absorption in these regions. To reduce absorption loss in a fiber, the amount of water impurities should be less than a few part per billion.

* Low water peak fiber (LWPF) or dry fibers has a low concentration of hydroxyl ions, which reduces the 1.38 um absorption peak. This LWPF fiber permits the transmission of optical signals over the full 1.26 um to 1.675 um wavelength range with losses less than 0.4 dB/Km and very suitable for wavelength division multiplexing (WDM).

Q3. Illustrate the linear scattering losses in optical fibers with respect to
a) Rayleigh Scattering
b) Mie Scattering **[AKTU: 2023-24]**
ANS:

<u>Scattering</u> - Scattering is a phenomenon that occurs when light comes into contact with an object or a material. The light is then redirected in different directions. This can cause the light to spread out, change direction or change the way it vibrates.



<u>Linear Scattering Losses</u> –

* Linear scattering is a type of elastic scattering where the scattered light has the same wavelength frequency and phase as the incident light (wave). The energy and momentum of the scattered wave are conserved in linear scattering.

(1) <u>Rayleigh Scattering</u> - Rayleigh scattering is a form of an elastic (linear) scattering that occurs when light interacts with small particles or objects that are much smaller than the wavelength of the incident light.

* In optical fibers, Rayleigh scattering is the dominant intrinsic loss mechanism in low absorption window between the ultraviolet and infrared absorption tails. This occurs due to random inhomogeneities in the glass lattice that lead to refractive index fluctuations. These fluctuations cause the light to scatter as it propagates through the fiber, resulting in attenuation of the transmitted light. The Rayleigh scattering formula is given by -

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

where γ_R = Rayleigh scattering coefficient
λ = optical wavelength
p = average photoelastic coefficient
β_c = Isothermal compressibility
T_F = Fictive Temperature
K = Boltzman constant

The transmission Loss factor (transmissivity) of the fiber is given by -

$$\mathcal{L} = \exp(-\gamma_R L)$$

L = Length of the fiber

(2) Mie Scattering - mie scattering is a scattering of light by particles approximately equal to the wavelength of light, which may be individual atoms or molecules.

* Mie scattering occurs due to —
  (i) inhomogeneities in composition of silica. (i.e. inhomogeneities in density of SiO_2.
  (ii) Irregularities in the core-cladding interface, difference in core cladding refractive index, diameter fluctuations.
  (iii) Due to presence of strains and bubbles.
* The scattering caused by such inhomogeneities is mainly in forward direction depending upon the fiber material, design and manufacture.

* Mie scattering can be reduced by carefully removing imperfections from the glass material, carefully controlling the quality and cleanliness of manufacturing process.

Q4. Describe the various types of nonlinear scattering losses in optical wave guide

[AKTU: 2022-23]

ANS:

Non-linear Scattering Losses -

Non-linear scattering losses result in uneven attenuation of the light while traveling through the fiber at high optical power levels. The transfer of optical power from one mode to other mode at a different frequency in either the forward or backward direction result in non-linear scattering losses. It depends on the optical power density inside the fiber and becomes significant only above threshold power levels. There are two types of non-linear scattering.

(1) Stimulated Brillouin Scattering (SBS)
(2) Stimulated Raman Scattering (SRS)

(1) Stimulated Brillouin Scattering (SBS) –

* Stimulated Brillouin scattering is a nonlinear scattering process that happens when light interacts with the acoustic waves in a medium.
* Simulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibration within the fiber.
* The scattered light appears as upper and lower sidebands which are seperated from the incident light by the modulation frequency.
* The incident photon in this scattering process produces a photon of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle. This frequency shift is a maximum in the backward direction and zero in forward direction. Thus SBS is a mainly backward process.

* Brillouin scattering is only occurs when incident optical power density is above a threshold power density which is given by –

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts}$$

where, d = Fiber core diameter
λ = operating wavelength
α_{dB} = Fiber attenuation in dB
ν = source bandwidth in gigahertz.

(2) Stimulated Raman Scattering (SRS) –

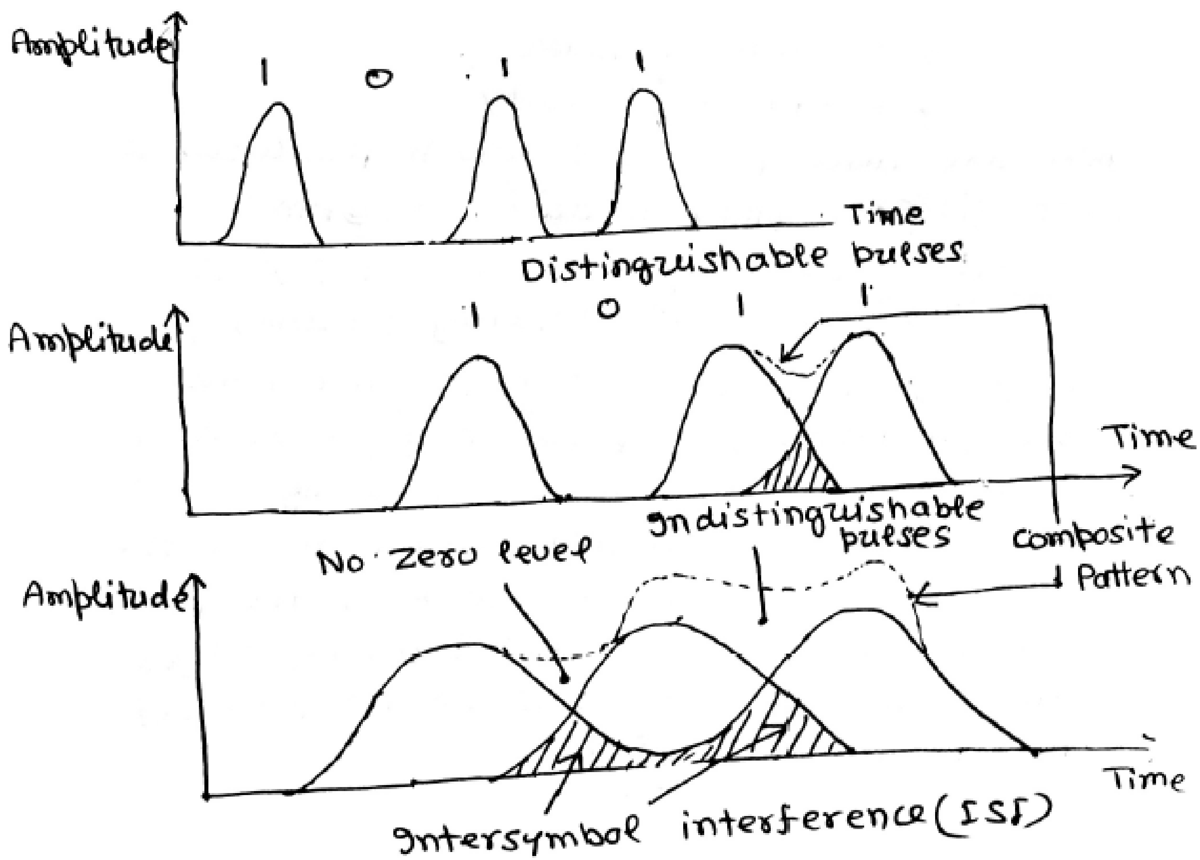
* In Stimulated Raman scattering a high frequency optical photon rather than acoustic photon is generated in the scattering process.
* Stimulated Raman scattering can occur in both the forward and backward directions in an optical fiber.

* The threshold optical power for SRS, P_R in a long single mode fiber is given by –

$$P_R = 5.9 \times 10^{-2} \, d^2 \lambda \alpha_{dB} \text{ watts}$$

Q5.What is mean by dispersion? Describe the Intramodal dispersion. **[AKTU: 2022-23]**

<u>Dispersion</u> – Dispersion in optical fiber is the phenomenon where different wavelengths of light experience varying velocities as they travel through the fiber. It causes pulses of light to spread out over time, leading to signal degradation and limitting the transmission capacity of the fiber.



Intramodal or Chromatic Dispersion-

* Chromatic or intramodal dispersion may occur in all types of optical fiber. since optical sources do not emit just a single frequency but a band of frequencies hence there may be propagation delay differences between the different spectral components of the transmitted signal. This cause broadening of each transmitted mode and produces intramodal dispersion.

There are two types of intramodal or chromatic dispersion. (i) material dispersion
(ii) waveguide dispersion

(i) **Material Dispersion** - material dispersion is caused by the variation in the refractive index of the material used in the optical fiber. Since the refractive index of the material determines the speed at which light propagates through the fiber hence different wavelengths of light travel at different speeds, causing the signal to spread out and become distorted. The sign of material dispersion may be positive or negative depending on the material properties and the wavelength of the transmitted light.

* The pulse spread due to material dispersion may be obtained by considering the group delay τ_g in optical fiber.

$$\text{Group delay } \tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)$$

The pulse delay τ_m due to material dispersion in a fiber of Length L is given by—

Pulse delay $\tau_m = \frac{L}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)$

Material dispersion, $\sigma_m \simeq \sigma_\lambda \frac{d\tau_m}{d\lambda} \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2 n_1}{d\lambda^2}\right|$

σ_λ = rms spectral width

material dispersion parameter

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

Unit of material dispersion parameter is $ps\ nm^{-1}\ km^{-1}$

(ii) Waveguide Dispersion— The waveguide dispersion is due to the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength. Due to this transmission times for the rays are different which produces dispersion.

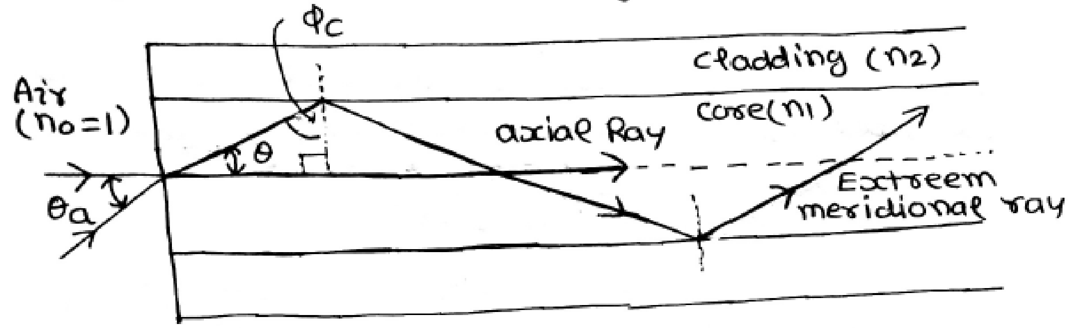
* For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$.
* Multimode fibers are almost free of waveguide dispersion and it is generally negligible compared with material dispersion ($\simeq$ 0.1 to 0.2 ns km^{-1}).
* In single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

Q6.Determine the rms pulse broadening (σ_s) due to intermodal dispersion in terms of core refractive index (n_1), cladding refractive index (n_2) and the length of fiber for a multimode step index fiber.

[AKTU: 2021-22]

ANS:

Intermodal Dispersion in Multimode Step index Fiber – The multimode step index fiber exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening.



The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber is shown in fig. As the both rays are traveling at the same velocity within the constant refractive index fiber core hence the delay difference is directey related to their respective path lengths within the fiber. If Length of fiber is L then minimum delay

$$T_{min} = \frac{\text{distance}}{\text{velocity}} = \frac{L}{c/n_1} = \frac{Ln_1}{c}$$

$$T_{max} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta}$$

$$\sin\phi_C = \frac{n_2}{n_1} = \cos\theta$$

$$T_{max} = \frac{Ln_1}{c.\frac{n_2}{n_1}} = \frac{Ln_1^2}{cn_2}$$

Delay difference betwen extreme meridional ray and axial ray

$$\delta T_s = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

$$= \frac{Ln_1^2}{cn_2}\left(1 - \frac{n_2}{n_1}\right) = \frac{Ln_1^2}{cn_2}\left(\frac{n_1-n_2}{n_1}\right)$$

$$\delta T_s = \frac{Ln_1^2\Delta}{cn_2} \quad \text{when } \Delta << 1$$

$$\delta T_s = \frac{L n_1^2 \Delta}{c n_2} \simeq \frac{L n_1 \Delta}{c}$$

$$= \frac{L(NA)^2}{2 n_1 c}$$

NA = numerical aperture

The rms pulse broadening at the fiber output due to intermodal dispersion for the multimode step index fiber σ_s (standard deviation) is given as–

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\, c} \simeq \frac{L(NA)^2}{4\sqrt{3}\, n_1 c}$$

Q7. A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1 %. Estimate the delay difference between the slowest and fastest modes.

[AKTU: 2021-22]

ANS:

$L = 6$ km,
$n_1 = 1.5$
$\Delta = 1\% = 0.01$

(a) The delay difference

$$\delta T_s \simeq \frac{L n_1 \Delta}{c} = \frac{6 \times 10^3 \times 1.5 \times 0.01}{3 \times 10^8} = 300\,\text{ns}.$$

(b) The rms pulse broadening due to intermodal dispersion,

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\, c} = \frac{1}{2\sqrt{3}} \times \frac{6 \times 10^3 \times 1.5 \times 0.01}{3 \times 10^8}$$

$$= 86.7\,\text{ns}$$

(c) The maximum bit rate

$$B_T(\text{max}) = \frac{1}{2\tau} = \frac{1}{2\delta T_s} = \frac{1}{2 \times 300 \times 10^{-9}}$$

$$= 2.3\,\text{Mbit/sec}.$$

(d) Bandwidth – Length product

$$B_{opt} \times L = 2.3\,\text{MHz} \times 6\,\text{Km}$$

$$= 13.8\,\text{MHz Km}$$

Q8. What is kerr effect in optical fiber communication? **[AKTU: 2022-23]**

Kerr Effects - The Kerr effect is a nonlinear optical effect which can occur when light propagates in crystals or glasses. It can be described as a change in refractive index caused by electric fields and being proportional to the square of electric field strength. Optical kerr effect is based on the electric field of a light wave only. The light wave creates a nonlinearly polarized wave which acts back on it. The effect of that can be described as modifying the refractive index. The refractive index for the high intensity light beam itself is modified according to -

$$\Delta n = n_2 I$$

where n_2 = nonlinear index
I = optical intensity

There are three processes which produces Kerr effect
(i) Self-phase modulation (SPM)
(ii) Cross-phase modulation (XPM)
(iii) Four-wave mixing (FWM)

* The intensity-dependent refractive index causes an intensity-dependent phase shift in the fiber. Hence for a light pulse propagating in the fiber, Kerr nonlinearities result in a different transmission phase for the peak of the pulse compared with leading and trailing edges of the pulse. This effect is known as self phase modulation (SPM).

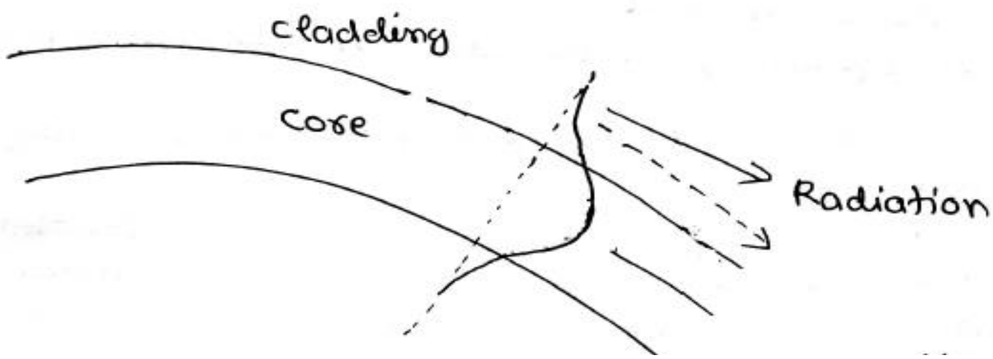
* Cross - phase modulation occurs in case of overlapping pulses, where different wavelengths or polarizations are involved. In this case, variations in the intensity of one pulse will modulate the refractive index of fiber which cause phase modulation of the overlapping pulses.

Q9. Describe the fiber bend losses in optical fiber. **[AKTU:2022-23]**

ANS:

Fiber bend Loss - (Fiber bending Loss)

Fiber bending losses are the radiative losses that occur in optical fibers due to its bending. It occur when the fiber optical cable is bent too tightly or two sharply, causing some of the light to escape from the fiber core. This results in a loss of signal strength.



* The part of the mode in cladding outside arrowed line may be required to travel faster than the velocity of light in order to maintain a plain wavefront. since it can not do this, the energy contained in this part of the mode is radiated away.

* The bending loss is generally represented by Radiation attenuation coefficient,

$$\alpha_r = C_1 \exp(-C_2 R)$$

where R = Radius of curvature of the fiber bend

C_1, C_2 = constants

* Large bending loss occurs in multimode fiber at a critical radius of curvature R_c.

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

For single mode fiber

$$R_c = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c}\right)^{-3}$$

λ_c = cutoff wavelength.

* Bending loss can be reduced by –
  (i) designing fibers with large relative refractive index difference.
  (ii) operating at the shortest wavelength possible.

Q10. Explain polarization and birefringence in fiber optical communication.

Polarization and Birefringence –

* In fiber optics, polarization – maintaining optical fiber (PMF or PM fiber) is a single mode optical fiber in which linearly polarized light, if properly launched into the fiber, maintains a linear polarization during propagation. In this case, light exiting the fiber is in a specific polarization state, there is little or no cross-coupling of optical power between the two polarization modes. Such fiber is used in special applications where no change in polarization state during propogation is essential.

* Cylindrical optical fiber do not generally maintain the polarization state of the light input for more than a few meters and hence for many applications involving optical fiber transmission some form of intensity modulation of the optical source is used. The optical signal is thus detected by a photodiode which is insensitive to optical polarization within the fiber. But now systems and applications have been investigated which require the polarization states of input light to be maintained over significant distances and fibers have been designed for this purpose. These fibers are single mode and the maintenance of the polarization state is described in terms of a phenomenon known as fiber birefringence.

* Single mode fiber with circular symmetry about the core axis allow the propagation of two modes with orthogonal polarizations. In an optical fiber with an ideal circularly symmetric core both polarization modes propagates with same velocities.

* Manufactured optical fibers, exhibit some birefringence due to differences in core geometry (i.e. ellipticity), variation in internal and external stresses and fiber bending. The fiber therefore behaves as a birefringence medium due to difference in the effective refractive indices.

Due to this velocities of these two orthogonally polarized modes become different. The modes therefore have different propagation constants β_x and β_y. In this case β_x and β_y are the propagation constants for the slow mode and fast mode respectively.

* when fiber cross-section is independent of fiber Length L in z-direction, then modal Birefringence B_F for the fiber is given by

$$B_F = \frac{\beta_x - \beta_y}{2\pi/\lambda}$$

where λ = optical wave length.

* The birefringent coherence is maintained over a length of fiber L_{bc} (i.e Coherence Length) when,

$$L_{bc} = \frac{c}{B_F \delta f} = \frac{\lambda^2}{B_F \delta\lambda}$$