UNIT- 2

OBJECTIVES:

Fiber materials: - Glass, Halide, Active glass, Chalgenide glass, Plastic optical fibers. Signal distortion in optical fibers-Attenuation, Absorption, Scattering and Bending losses, Core and Cladding losses, Information capacity determination, Group delay, Types of Dispersion:- Material dispersion, Wave-guide dispersion, Polarization-Mode dispersion, Intermodal dispersion, Pulse broadening in Graded index fiber, Related problems.

FIBER MATERIALS:

Most of the fibers are made up of glass consisting of either Silica (SiO_2) or .Silicate. High loss glass fibers are used for short-transmission distances and low-loss glass fibers are used for long distance applications. Plastic fibers are less used because of their higher attenuation than glass fibers. Glass Fibers The glass fibers are made from oxides. The most common oxide is silica that's refractive
Index is 1.458_at 850 nm. To get different index fibers, the do pants such as GeO_2, $P2O_5$ are added to silica. GeO_2 and P_2O_3 increase the refractive index whereas fluorine or B203 decreases the refractive index. Few fiber compositions are given below as follows,

(i) $GeO_2 – SiO_2$ Core: SiO_2 Cladding

(ii) $P_2Q_5 – SiO_2$, Core; SiO_2 Cladding

The principle raw material for silica is sand. The glass composed of pure silica is referred to as silica glass, nitrous silica or fused silica. Some desirable properties of silica are,

(i) Resistance to deformation at temperature as high as 1000°C.
(ii) High resistance to breakage from thermal shock.
(iii) Good chemical durability.
(iv) High transparency in both the visible and infrared regions.

BASIC REQUIREMENTS AND CONSIDERATIONS IN FIBER FABRICATION:

(i) Optical fibers should have maximum reproducibility.
(ii) Fibers should be fabricated with good stable transmission characteristics i.e., the fiber should have invariable transmission characteristics in long lengths.
(iii) Different size, refractive index and refractive index profile, operating wavelengths material. Fiber must be available to meet different system applications.

(iv) The fibers must be flexible to convert into practical cables without any degradation of their characteristics.
(v) Fibers must be fabricated in such a way that a joining (splicing) of the fiber should not affect its transmission characteristics and the fibers may be terminated or connected together with less practical difficulties.

FIBER FABRICATION **IN A TWO STAGE PROCESS:**

1. Initially glass is produced and then converted into perform or rod.

GLASS FIBER:

Glass fiber is a mixture of selenides, sulfides and metal oxides. It can be classified into,
1. Halide Glass Fibers
2. Active Glass Fibers
3. Chalgenide Glass Fibers

Glass is made of pure SiO_2 which refractive index 1.458 at 850 nm. The refractive index of SiO_2 can be increased (or) decreased by adding various oxides are known as dopant. The oxides GeO_2 or P_2O_3 increases the refractive index and B2O3 decreases the refractive index of SiO_2 the various combinations are,

(i) GeO_2 SiO_2 Core; SiO_2 cladding

(ii) P_2 O_3 – SiO_2 Core; SiO_2 cladding

(iii) SiO_2 Core; B_2O_3, - SiO_2 cladding

(iv) GeO_2- B_2O_3- SiO_2, Core; B_2O_3 - SiO_2 cladding.

From above, the refractive index of core is maximum compared to the cladding.

(1) Halide Glass Fibers

A halide glass fiber contains fluorine, chlorine, bromine and iodine. The most common Halide glass fiber is heavy "metal fluoride glass". It uses ZrF_4 as a major component. This fluoride glass is known by the name ZBLAN. since it is constituents are ZrF_4, BaF_2, LaF_3 $A1F_3$, and NaF

The percentages of these elements to form ZBLAN fluoride glass is shown as follows,

Materials	Molecular percentage
ZrF_4	54%
BaF_2	20%
LaF_3	4.5%
$A1F_3$	3.5%
NaF	18%

These materials add up to make the core of a glass fiber. By replacing ZrF_4 by HaF_4, the lower refractive index glass is obtained.

The intrinsic losses of these glasses is 0.01 to 0.001 dB/km

(2) Active Glass Fibers

Active glass fibers are formed by adding erbium and neodymium to the glass fibers. The above material performs amplification and attenuation

(3) Chalgenide Glass Fibers

Chalgenide glass fibers are discovered in order to make use of the nonlinear properties of glass fibers.

It contains either "S", "Se" or "Te", because they are highly nonlinear and it also contains one element from “Cl”, "Br”, “Cd”,”Ba” or”Si”.

The mostly used chalgenide glass is AS_2-S_3, $AS_{40}S_{58}Se_2$ is used to make the core and AS_2S_3 is used to make the cladding material of the glass fiber. The insertion loss is around 1 dB/m.

PLASTIC OPTICAL FIBERS:

Plastic optical fibers are the fibers which are made up of plastic material. The core of this fiber is made up of Polymethylmethacrylate (PMMA) or Perflourmated Polymer (PFP). Plastic optical fibers offer more attenuation than glass fiber and is used for short distance applications. These fibers are tough and durable due to the presence of plastic material. The modulus of this plastic material is two orders of magnitude lower than that of silica and even a 1mm diameter graded index plastic optical fiber can be installed in conventional fiber cable routes. The diameter of the core of these fibers is 10-20 times larger than that of glass fiber which reduces the connector losses without sacrificing coupling efficiencies. So we can use inexpensive connectors, splices and transceivers made up of plastic injection-molding technology. Graded index plastic optical fiber is in great demand in customer premises to deliver high-speed services due to its high bandwidth.

ATTENUATION:

When a decrease in light power occurs during light propagation along an optical fiber then such a phenomenon is called attenuation. The major causes for attenuation in fiber optic communications are,

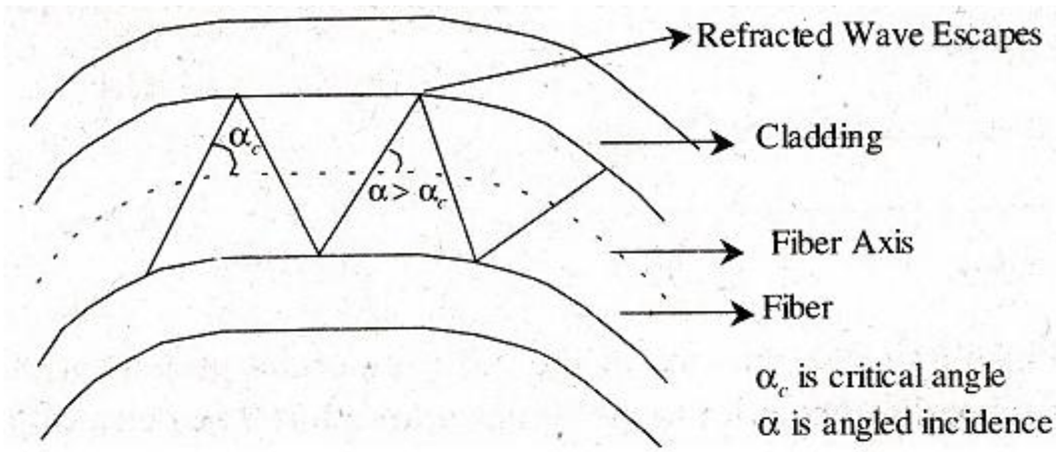
1. Bending loss
2. Scattering loss
3. Absorption loss

1. Bending Loss:

Bending loss is further classified into,
(i) Macro bending loss-and
(ii) Micro bending loss.

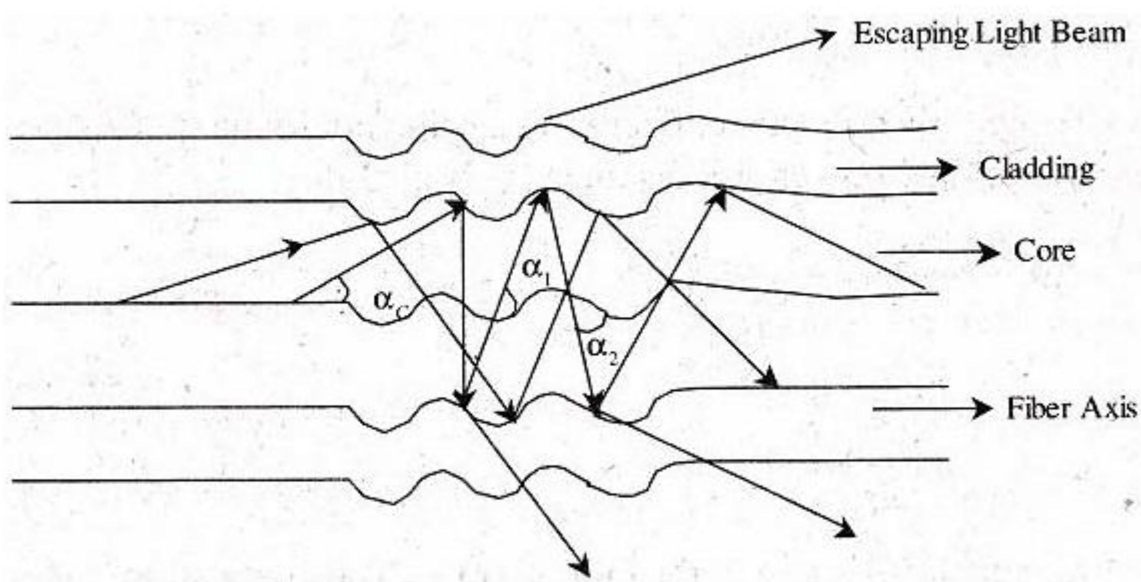
(i) Macro bending Loss:

The light travels in fiber due to occurrence of total internal reflection inside the fiber at the interface of core and cladding. However the light beam forms a critical angle with the fiber's central axis at the fiber face. When the fiber is bend and the light beam travelling through fiber strikes at the boundary o f core at an angle greater than critical angle then the beam fails to achieve total internal reflection. Hence this beam is lost through the cladding.



Macro Bending of optical Fiber

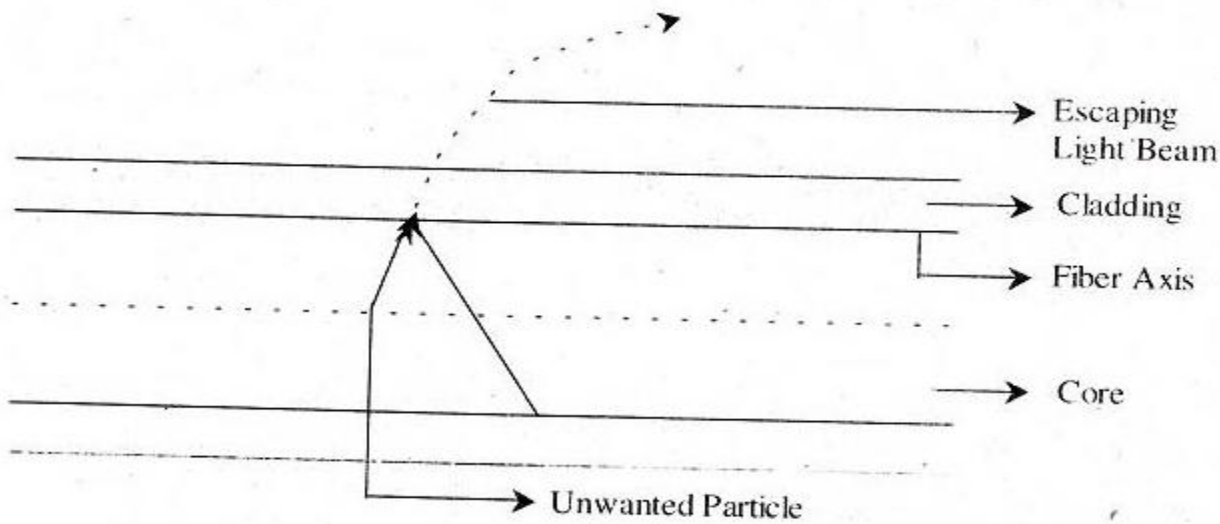
(ii)Micro bending Loss:



α_C is Critical Angle where $\alpha_1 > \alpha_C$, $\alpha_2 > \alpha_C$

2. Scattering Loss:

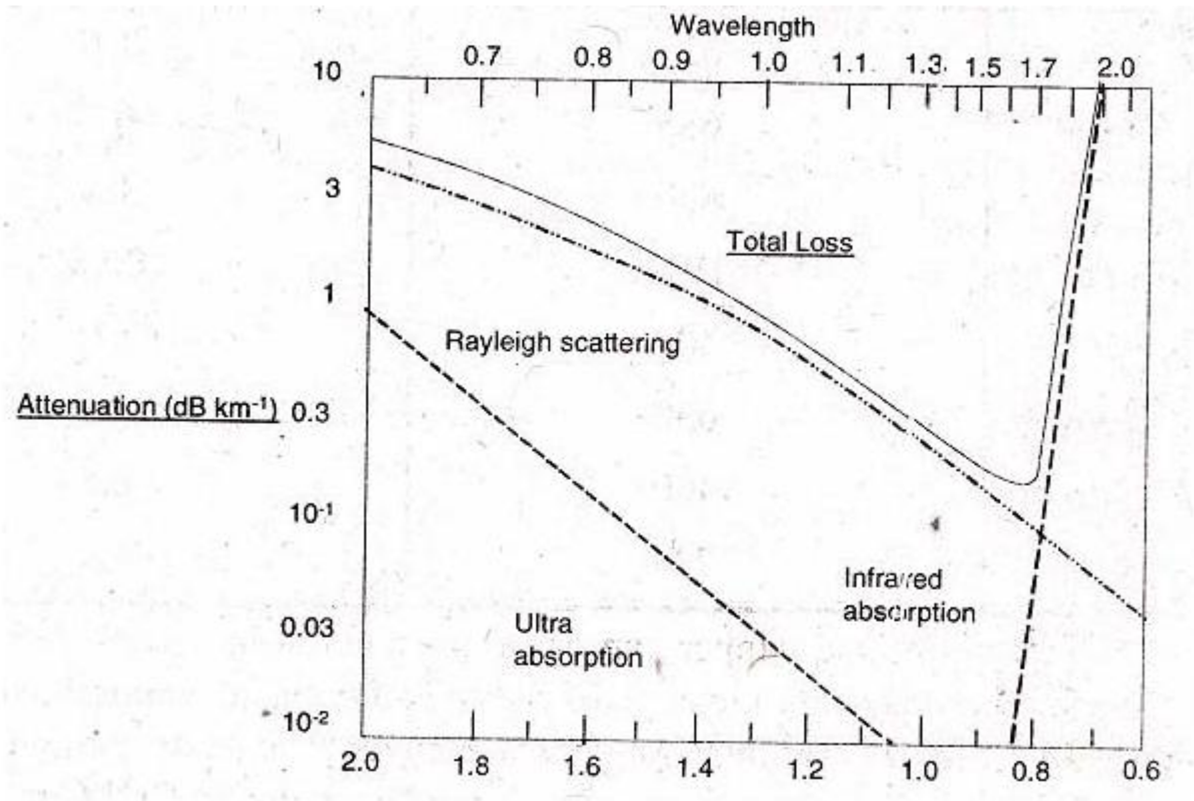
A light beam propagating through the fiber core at critical angle or less will change its direction after hitting on an obstacle in the core region. The obstacle can be any particle in core that may have diffused inside the core at the time of manufacturing when the light beam hits the particle it get scattered and due to this total internal reflection is not achieved hence, the beam is lost through the cladding.



Scattering Loss

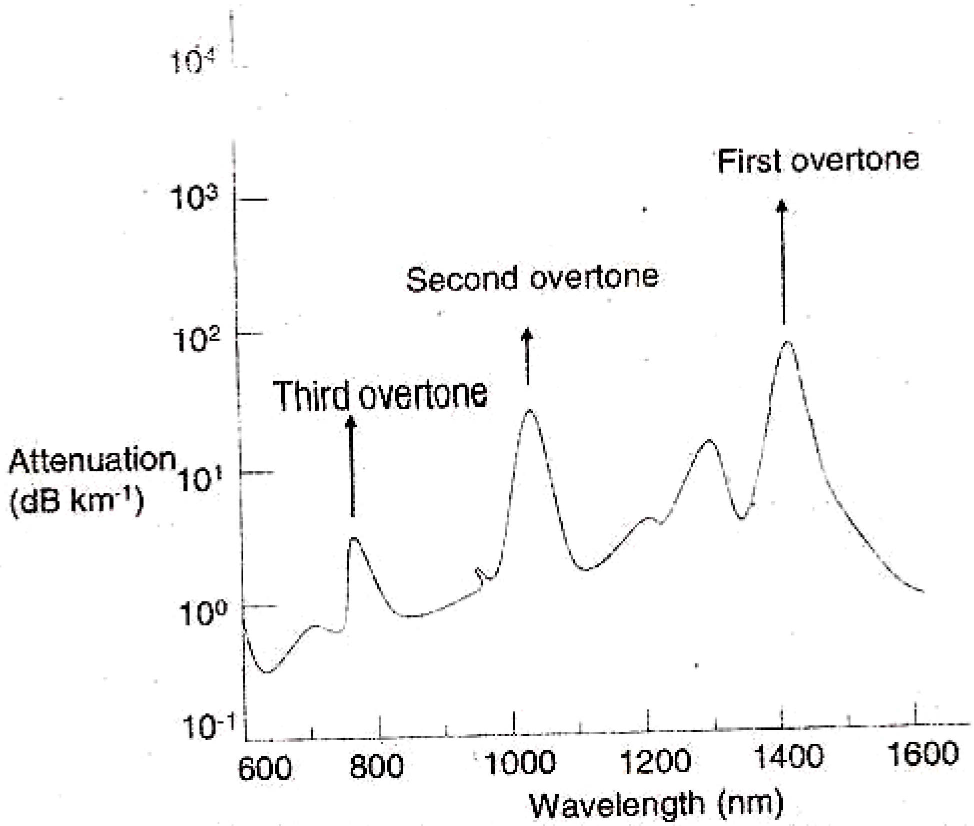
3. Absorptions Loss:

Whenever a beam of light photon having energy equal to energy band gap then the light photon is absorbed by the material resulting in absorption loss. Absorption loss occur due to presence of anions OH~ in silica fibers and due to metallic ions like Iron (Fe), Chromium (Cr) and Nickel (Ni). The absorption loss peak is observed in the region of 2700 nm and 4200 nm wavelength with low-loss at 7200 nm, 9500 nm and 13800 nm wavelength windows.
An absolutely pure silicate glass has little intrinsic absorption due to its, basic material structure in the near infrared region. However it does have two major intrinsic absorption mechanisms at optical wavelengths as illustrated in the following figure which shows a possible optical attenuation against wavelength characteristic for absolutely pure glass (i.e., SiO2). There is a fundamental absorption edge, the peaks of which are centered in the ultraviolet wavelength region. This is due to the stimulation of electrons transitions within the glass by higher energy excitation. The tail of this peak may extend into the window region at the shorter wavelengths. Also in the infrared and far-infrared, normally at wavelengths above 7µm. Absorption bands from the interaction of photons with molecular variations within the glass occur. These give absorption peaks which again extend into the window region. Hence, above 1.5µm, the tails of these largely far-infrared absorption peaks tend to increase the pure glass losses.



The Attenuation Spectrum for intrinsic Loss mechanism in pure GeO2 ,SiO2 Glass

In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic (doped) absorption from transition metal element impurities. Certain impurities, namely Chromium and Copper, in their worst valence state can cause attenuation is excess of 1 dB/km in the near infrared region. Transition element contamination may be reduced to acceptable levels i.e., one part is 1010 by glass refining techniques such as vapor -phase oxidation. It may also be observed that the only significant absorption band in the region below a wavelength of 1urn is the second overtone at 0.95 am which causes attenuation of about 1 dB/km for one part per million (ppm) of hydroxyl. At longer wavelengths the first overtone at 1.38 urn and its side band at 1.24 am are strong absorbers giving attenuation of about 2 dB/km ppm and 4 dB/km respectively.



The Absorption Spectrum for the Hydroxyl (OH) Group In silica

Since most resonances sharply peaked, narrow window exist in the longer wavelength region around 1.3 and 1.55μm which are essentially unaffected by OH absorption, once the impurity, level has been reduced below one part in 10^7. This situation is illustrated in the above figure which shows the attenuation spectrum of an ultra-low-loss single mode fiber. It may be observed that the lowest attenuation for this fiber occurs at a wavelength of 1.55μm and is 0.2dB/km. This approaching is the minimum possible attenuation of around 0.18 dB/km at this wavelength.

SIGNAL DISTORTION IN OPTICAL FIBERS:

One of the important properties of optical fiber is signal attenuation. It is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair. Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes broader. After sufficient length the broad pulses starts overlapping with adjacent pulses. This creates error in the receiver. Hence the distortion limits the information carrying capacity of fiber.

Attenuation:

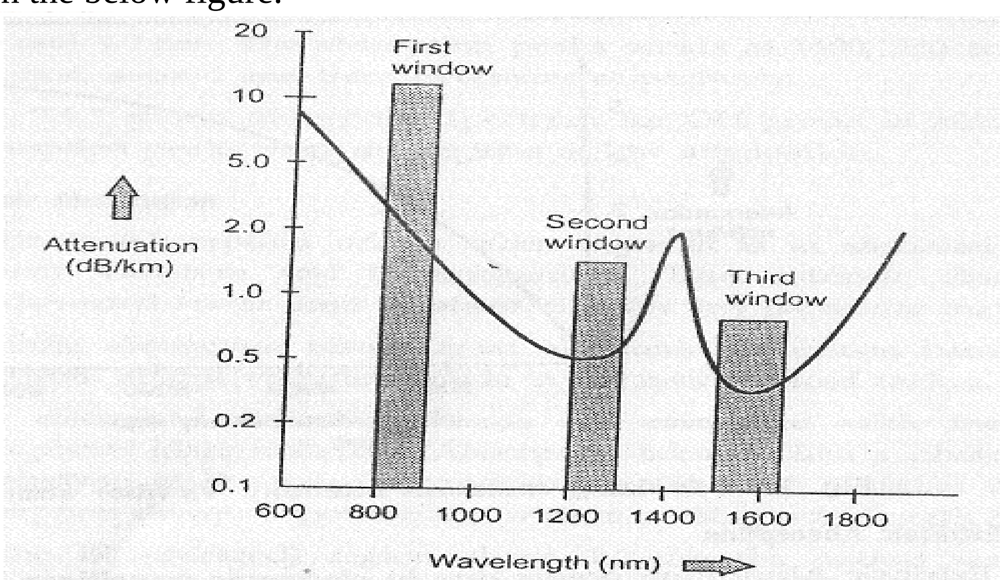
Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber. In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural Imperfections within the fiber. Nearly 90% of total attenuation is caused by Rayleigh scattering only. Micro bending of optical fiber also contributes to the attenuation of signal. Attenuation Units As attenuation leads to a loss of power along the fiber, the output power is significantly less than the coupled power. Let the coupled optical power is P (0) i.e. at origin (z = 0) Then the power at distance z is given by

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

Therefore $$\alpha_p = \left(\frac{1}{z}\right)\ln\left[\frac{P(0)}{P(Z)}\right]$$

$$\alpha_{dB/Km} = 10.\left(\frac{1}{z}\right)\ln\left[\frac{P(0)}{P(Z)}\right]$$

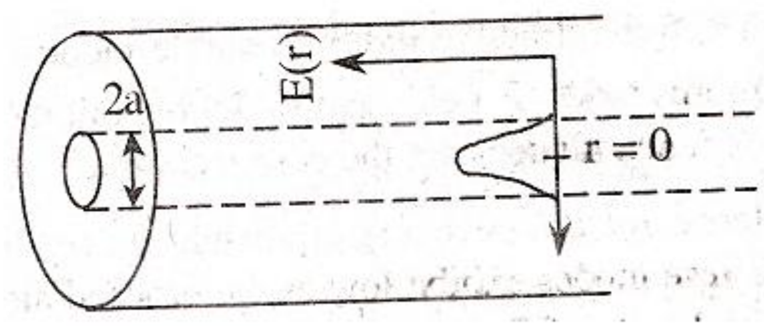
This parameter is known as fiber loss or fiber attenuation. Attenuation is also a function of wavelength. Optical fiber wavelength as a function of wavelength is shown in the below figure.



Fiber Attenuation As a function of Wave length

Mode field diameter:

Mode field diameter is\a primary parameter of single-mode fibers. It is obtained from the mode field distribution of the fundamental mode. The below figure shows, the distribution of light in a single mode fiber.



Mode Field Diameter

In order to find the MFD for field intensity $E_2(r)$ must be calculated by using $E_2(r)$ MFD can be calculated as,

$$MFD = 2\omega_0$$

$$= 2\sqrt{\frac{2\int_0^\infty E^2(r) r^3\, dr}{\int_0^\infty E^2(r) . r\, dr}}$$

Where

$$2\omega_0 = \text{spot size}$$

To avoid complexity, E(r) can be taken as,

$E(r) = E\ (0) \exp\ (r^2 / \omega_0^2)$

Where r= radius

E (0) = field at (r=0)

By using this relation, we can write

MFD = $1/e^2$ width of optical power.

(ii) Modal Birefringence

The propagation of two approximately degenerate modes with orthogonal polarizations is allowed in single mode fibers with nominal circular symmetry about the core axis. Thus, these are referred as bimodal supported HE_{11}^{x} and HE_{11}^{y} modes. Here, the super scripts x and y denotes the principle axes and are calculated using the symmetry elements of the fiber cross section. The difference in the effective refractive indices and phase velocities for these orthogonally polarized modes makes the fiber to function as a birefringent medium. The independency of fiber cross section with the fiber length in the z-direction yields the expression for modal birefringence B_F as,

Where,

β_x = Propagation constant for the mode'x'

β_y= Propagation constant for the mode 'y'

λ = Optical wavelength.

The difference in phase velocities is responsible for linear retardation Φ (z) exhibited by the fiber. The expression for linear retardation is given by,

$$\Phi(z) = (\beta x - \beta_y) L$$

Where,

L = Length of the fiber.

If the coherence time of the source is greater than the delay between the two transit times then only, the phase coherence of the two mode components is achieved. However, the expression for coherence time of the source is given by,

$$t_c = 1/\delta f$$

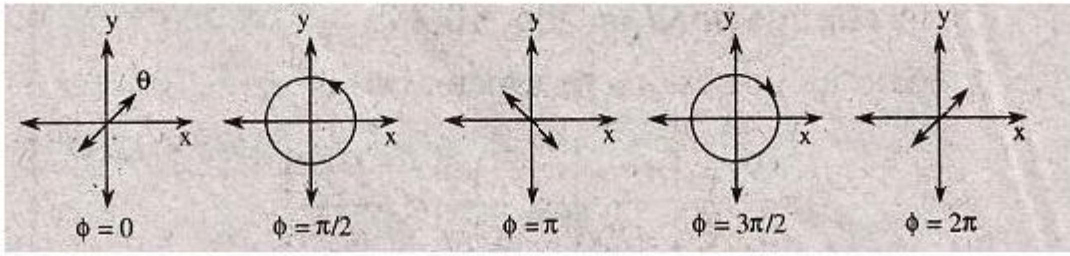
Where, δf = Uncorrelated source frequency width

Then, the length of fiber over which birefringent coherence is maintained is given by

Where, c = Velocity of light in vacuum

$\delta\lambda$ = Source line width

The below figure illustrates the variations of polarization state periodically along the fiber



Polarization

The characteristic length L_B corresponding to the above process is referred as beat length and is given by,

$$L_B = \lambda/B_F \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

From equation (1), we have

$$L_B = \frac{2\Pi}{(\beta_x - \beta_y)} \ldots\ldots\ldots\ldots (6)$$

And expression 2 can be written as.

$\Phi (L_B) = (\beta x - \beta_{y)\,LB}$

$$= (\beta x - \beta_{y)} \frac{2\Pi}{(\beta_x - \beta_y)} = 2\Pi \ldots\ldots\ldots\ldots (7)$$

Based on the above observation of beat length, we can determine the modal birefringence B_F.

PROBLEMS

***Commonly available single mode fiber have beat length in the range 10cm<L_P<2m .What rate of refractive index difference does this corresponds to for λ =1300nm?**

Solution:

Give that

For a single mode fiber,

Beat length L_P = 10cm to 2cm

Operating wavelength λ = 1300nm

The refractive index difference is known as birefringence and is denoted by β_f

$$\beta_f = 2\Pi/L_p$$

Case 1

For Lp =10cm

$\beta_f = 2\Pi/10$

$\beta_f = 62.83\ m^{-1}$

Case 2

For Lp =2cm

$\beta_f = 2\Pi/2$

$\beta_f = 3.14\ m^{-1}$

Therefore, the range of refractive index differences is $3.14 m^{-1} < \beta_f < 62.83 m^{-1}$

***A 10 km length of fiber is 100 µW and the average output power is 25 (J.W.) Calculate,**

(i) The signal attenuation in dB through the fiber. It is assumed that there Are no connectors or splices

(ii) Signal attenuation per km of the fiber

(iii) Overall signal attenuation for the 11 km optical link using the same Fiber with 3 splices, each having an attenuation of 0.8 dB

(iv) Numerical value of the ratio between input and output power.

Solution:

Given that

L = 10Km

P_{input} =100µm

P_{output} = 25µm

(i) Attenuation

$$(\alpha_{dB}) = 10 \log_{10} (P_{input} / P_{output})$$

$$\alpha_{dB} = 10 \log_{10} \left[\frac{100*10^{-6}}{25*10^{-6}}\right]$$

α_{dB} = 6.02dB.

(ii) The signal attenuation per Km of the fiber is,

$\alpha_{dB}.L$ =6.02

α_{dB} = 6.02/10

α_{dB} =0.602dBKm^{-1}

***A 10 km length of fiber is 100 µW and the average output power is 25 (J.W. Calculate,**
(i) The signal attenuation in dB through the fiber. It is assumed that there are No connectors or splices
(ii) Signal attenuation per km of the fiber
(iii) Overall signal attenuation for the 11 km optical link using the same fiber With 3 splices, each having an attenuation of 0.8 dB
(iv) Numerical value of the ratio between input and output power.

Solution:
Given L=10
Pinput = 100µm
Poutput =25µm

(i) Attenuation
(α) dB =10 log10 (Pinput/Poutput)
α(dB) = 10 log10 (100*10-6/25*10-6)
α (dB) =6.02 Db

(ii) The signal Attenuation per Km of the fiber is

α (dB) .L =6.02

α (dB) = 6.02/10 $dBKm^{-1}$

= 0.602 $dBKm^{-1}$

(iii) Attenuation per unit length *α* (dB)

The loss produced along 11Km of the fiber is,

α (dB) .L = 0.602*11(Km* $dBKm^{-1}$)

= 6.622dB

The number of splices are 3, each having attenuation of 0.8 dB

Therefore Total loss due t splices is 0.8*3 =2.4

Therefore Total signal attenuation = 6.622 dB + 2.4dB

α (dB) = 9.022dB

(iv) Numerical values of the ratio between input and output power is,

$$\text{Pinput/Poutput} = 10^{\left(\frac{\alpha_{dB}}{10}\right)}$$

$$= 10^{\left(\frac{9.022}{10}\right)} = 7.98$$

***A graded index fiber with a parabolic refractive index profile core has a Refractive index at the core axis of 1.5 and a relative index difference of 1% .Estimate the maximum possible core diameter which allows single mode Operation at a wave length of 1.3µm?**

Solution:
Given that,
For a graded index fiber with parabolic refractive index profile,
Refractive index of core is n1=1.5.

Relative index difference, $\Delta = 1\% = 0.01$

Operating wave length, λ =1.3µm

Maximum possible core diameter = 2a =?

For a graded index fiber, we have,

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

$$n_2 = \sqrt{n_1^2 - 2n_1^2\,\Delta}$$

$$n_2 = \sqrt{1.5^2 - 2 * 1.5^2 * 0.01}$$

$$n_2 = 1.485$$

we have,

$$V = \frac{2a\Pi}{\lambda}(n_1^2 - n_2^2)^{\frac{1}{2}}$$

For a single mode operation $V \leq 2.4$

$$2.4 \geq \frac{2a\Pi}{\lambda}(n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$a \leq \frac{2.4\lambda}{2\Pi(1.5^2 - 1.485^2)^{\frac{1}{2}}}$$

$$a \leq 2.346\mu m$$

Where a is the radius of the core.
Therefore the maximum possible diameter of the of the core is given by,

$$2\ a_{max} = 4.692\mu m$$

BROADENING OF PULSE IN THE FIBER DISPERSION:

The dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. If we consider the major implementation of optical fiber transmission which involves some form of digital modulation, then the dispersion technique within the fiber causes broadening of the transmitted light pulses as they travel along the channel. This phenomenon is depicted in figure (a), where it may be observed that each pulse broadens and coincides with its neighbors, eventually becoming indistinguishable at the receiver input.

The effect of overlapping of pulses shown in figure (a)' is called Inter Symbol Interference (ISI). Thus, ISI becomes more pronounced when increasing numbers of errors are encountered on the digital optical channel

For no overlapping of pulses down on an optical fiber link, the digital bit rate BT must be less than the reciprocal of the broadened pulse duration through dispersion (2τ) and hence,

$$B_T \leq 1/2\tau \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Equation (1) assumes that the pulse broadening due to dispersion on the channel is T which follows the input pulse duration which is also τ.Another more accurate estimate of the maximum bit rate for an optical channel with dispersion may be obtained by considering the light pulses at the output to have a Gaussian shape with an r.m.s. width of τ.

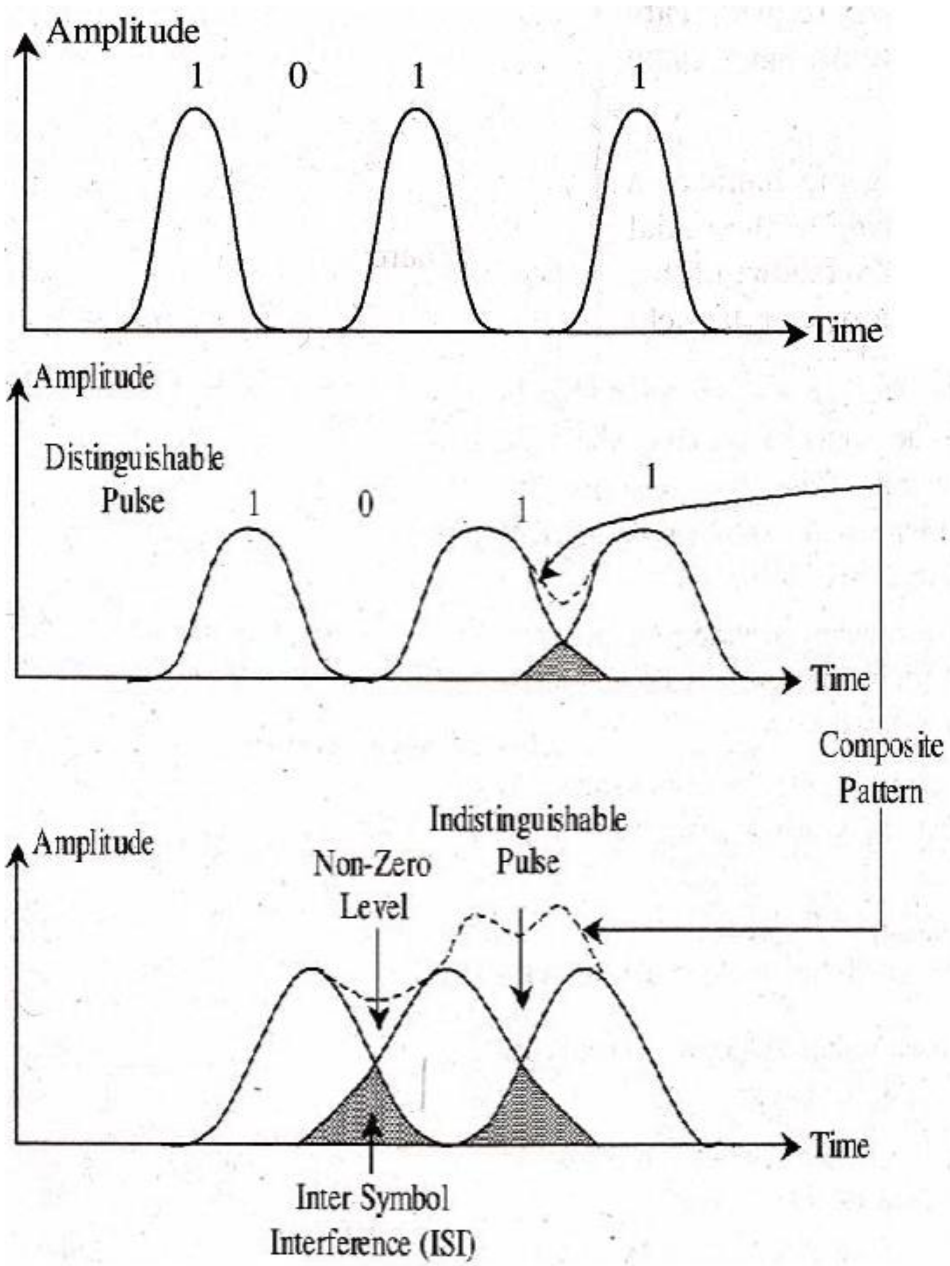


Illustration Of pulse Broading using Digital Bit Pattern 1011

GROUP DELAY OR TIME DELAY IN FIBER OPTICS:

Modulating signal of an optical source enhances all the modes of fiber equally. This results in carrying of equal amount of energy by each and every mode of fiber. Since each mode contains all the spectral components in the wavelength band over which the source emits, hence the modulating signal modulates every spectral component equally. The signals propagating through these spectral components experience a time delay or group delay per unit length in the direction of propagation and it is given as,

$$\frac{\tau_g}{D} = \frac{1}{V_g} = \frac{1}{C}\frac{d\beta}{dk} = \frac{-\lambda^2}{2\Pi C}\frac{d\beta}{d\lambda}$$

------------------- Equation (2)

Here D = Distance travelled by the pulse

β = Propagation constant along fiber axis

k = 2Π/λ

V_g= Velocity with which the energy in a pulse travels along a fiber

$$V_g = C\left(\frac{d\beta}{dk}\right)^{-1} = \left(\frac{d\beta}{d\omega}\right)^{-1}$$

From equation (2) we can say that group delay is a function of wavelength 'λ', therefore each spectral component of any particular mode takes different time to travel a particular distance. This causes difference in time delays and spreading of pulse with time as it travels along the fiber.

The variations in group delay causes pulse spreading. If the spectral width of the optical source is quite wide, then the delay difference per unit wavelength over the propagation path is given as

$\frac{d\tau_g}{d\lambda}$ The total delay 8x over a distance 'D' for the spectral components which are $\delta\lambda$ apart and $\delta\lambda/2$ above and below a central wavelength 'λ_c' is,

$$\delta\tau = \frac{d\tau_g}{d\lambda} d\lambda = \frac{-D}{2\Pi C}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\delta\lambda$$