Unit -2: Optical Communication

Signal loss and system bandwidth describe the amount of data transmitted over a specified length of fiber. Many optical fiber properties increase signal loss and reduce system bandwidth. **The most important properties that affect system performance are:**

- Fiber attenuation
- Dispersion

In addition to fiber attenuation and dispersion, other optical properties are there which can affect the system performance such as:

- Modal noise
- Pulse broadening
- polarization

They can reduce the system performance. Modal noise, pulse broading and polarization are too complex to discuss at introductory level.

ATTENUAATION IN OPTICAL FIBER

Attenuation is the loss of power of the light signal that occurs during its propagation through the optical fiber.

Attenuation reduces the amount of optical power transmitted by the fiber. Attenuation controls the distance an optical signal can travel. Once the power of an optical pulse is reduced to a point where the receiver is unable to detect the pulse. An error occurs. Attenuation is mainly a result of light absorption, scattering and bending losses. Attenuation is shown in fig. (1)

Therefore attenuation is the loss of optical power as light travels along the fiber.

- Signal attenuation is defined as the ratio of optical input power (P_i) to the optical output power P_o.
- Optical input power is the power injected into the fiber 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:

Attenuation

$$(\alpha) = \left(\frac{10}{L}\right)\log_{10}\left(\frac{p_i}{p_o}\right) ------(1)$$

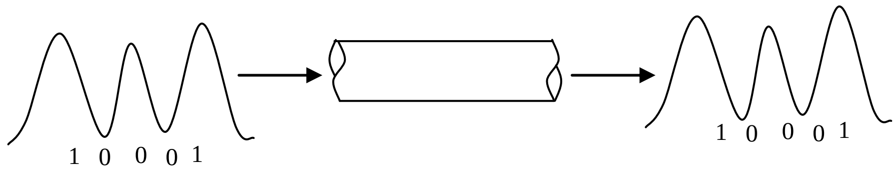

Fig (1) Attenuation reduced power

Since the length (L) is expressed in kilometers, therefore the unit of attenuation is decibels/ kilometers (dB/Km)as.

$$\alpha_{dB} L = 10\log_{10}\left(\frac{p_i}{p_o}\right) ------2$$

Where, α_{dB} L= Signal attenuation per unit length.

ABSORPTION LOSSES

Absorption: Absorption is a major cause of signal loss in an optical fiber. Absorption is defined as the portion of attenuation resulting form the conversion of optical power into another energy form, such as eat. Absorption in optical fibers is explained by there factors:

- Imperfections in the atomic structure of the fiber material
- The intrinsic or basic fiber- material properties
- The extrinsic (presence of impurities) fiber-material properties

Imperfections in the atomic structure induces absorption by the presence of missing molecules or oxygen defects. Absorption is also inducted by the diffusion of hydrogen molecules into the glass fiber. Since intrinsic and extrinsic material properties are the main cause of absorption, they are discussed further.

Intrinsic absorption

Intrinsic Absorption is caused by basic fiber-material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption sets the minimum level of absorption. In fiber optics, silica (pure glass) fibers are used predominantly. Silica fibers are used because of their low intrinsic material absorption at the wavelengths of operation.

In silica glass, the wavelengths of operation range from 700 nanometers (nm) to 1600 nm. Figure 2 shows the level of attenuation at the wavelengths of operation. This wavelength of operation is between two intrinsic absorption regions.

- The first region is the ultraviolet region (below 400-nm wavelength).
- The second region is the infrared region (above 2000-nm wavelength).

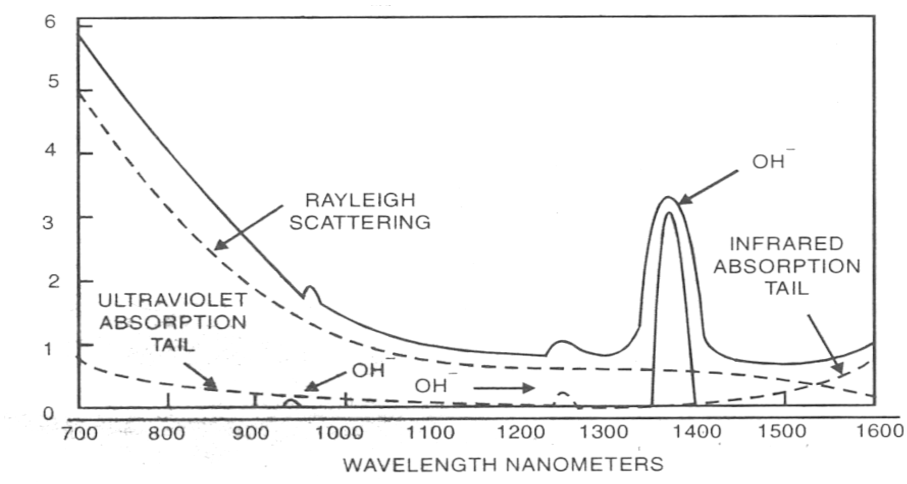

Figure 2 Fiber losses

Intrinsic absorption in the ultraviolet region is caused by electronic absorption bands. Basically, absorption occurs when a light particle (photon) interacts with an electron and excites it to a higher energy level tail of the ultraviolet absorption band is shown in fig. 2

The main cause of intrinsic absorption in the infrared region is the characteristic vibration frequency of atomic bonds, in silica glass; absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond. The tail of the infrared absorption band is shown in fig 2

Extrinsic absorption

Extrinsic absorption is caused by impurities introduced into the fiber material. Trace 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.

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. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonics increase extrinsic absorption at 1383nm, 1250 nm, and 950nm, figure 2 shows the presence of the three OH^- harmonics. The level of the OH harmonic absorption is also indicated.

These absorption peaks define three regions or windows of preferred operation. The first window is centered at 850nm. The second window is centered at 1300 nm. The third window is centered at 1550 nm, fiber optic systems operate at wavelengths defined by one of these windows.

The amount of water (OH^-) impurities present in a fiber should be less than a few parts per billion. Fiber attenuation caused by extrinsic absorption is affected by the level of impurities

(OH^-) present in the fiber. If the amount of impurities in a fiber is reduced, then fiber attenuation is reduced.

BENDING LOSSES

Bending losses takes place when even an optical fiber undergoes a bend of finite radius of curvature. Bending the fiber also causes attenuation, bending loss is classified according to the bend radius of curvature:

- Microbend loss
- Macrobend loss

Microbands are small microscopic bends and the fiber axis that occur mainly when a fiber is cabled. Macrobends are bends having a large radius of curvature relative to the fiber diameter. Microbend and macrobend losses are very important loss mechanisms. Fiber loss caused by microbending can still occur even if the fiber is cabled correctly. During installation, if fibers are bent too sharply, macrobend losses will occur.

Microbend Loss

Microbend losses are caused by small discontinuities or imperfections in the fiber. Uneven coating

applications and improper cabling procedure increases microbend loss. Extenal forces are also a source of microbends. An external force deforms the cabled

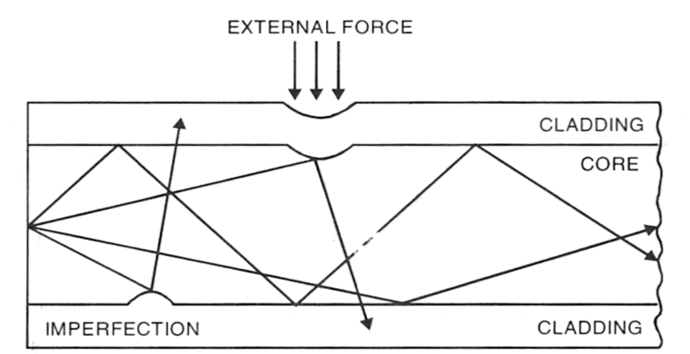

Figure 3 Microbend Loss

Jacket surrounding the fiber but causes only a small bend in the fiber. Microbends change the path that propagation modes take, as shown fig 3 microbend loss increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy.

Macrobend Loss

Macrobend losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter as shown in fig 4. Theses bends become a great source of loss when the radius of curvature is less than several centimeters.

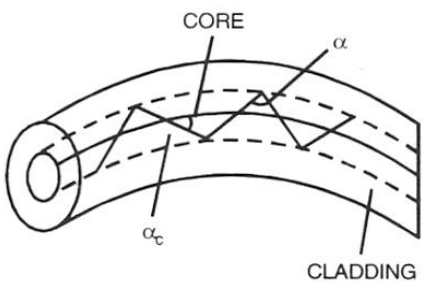

Figure. 4

The loss can be represented by a radiation attenuation coefficient, which has the form

$$\alpha_r = C_1 \exp(-C_2 R) \text{--------} (3)$$

Where, C_1, C_2 = constants which are independent of R.

R = Radius of curvature of the fiber bend.

Large bending losses occur in multimode fibers at a critical radius of curvature R_C, given by the equation

$$RC \cong \frac{3n_1^2 \lambda}{4\pi \left(n_1^2 - n_2^2\right)^{1/2}} \text{---------} (4)$$

From the eq. (4) it is clear that microbending losses may be reduced by

- Operating at the shortest wavelength.
- Designing fiber with large relative refractive index differences.

For a **single quasi guided mode**, bending loss is given by

$$RC \cong \frac{20\lambda}{(n_1 - n_2)^{1/2}} \left[2.748 - 0.996 \frac{\lambda}{\lambda c}\right]^{-3} \text{--------} (5)$$

.

Where, $\lambda c =$ cutoff wavelength for the single mode fiber.

LINEAR SCATTERING LOSSES

Linear scattering mechanism is transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode. This process results in attenuation but with all linear process there is no change in frequency or scattering.

Linear scattering may be categorized into two main types:

- Rayleigh scattering.
- Mie scattering.

Rayleigh Scattering

Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas as shown in fig. 5 light is then partially scattered in all directions.

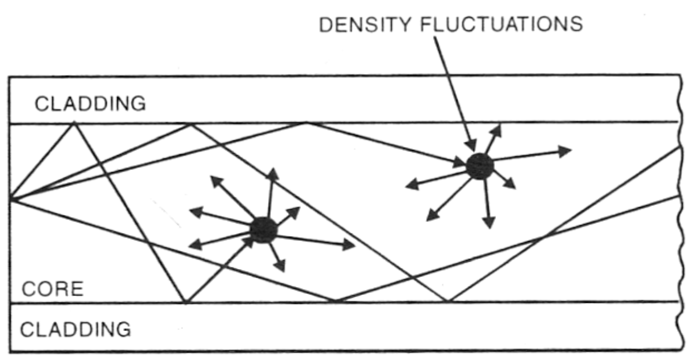

Figure 5: Light Scattering

In commercial fibers operating between 700-nm and 1600-nm wavelength, the main source of loss is called **Rayleigh scattering**. Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions as shown in fig.4 Rayleigh scattering occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light. Loss caused by Rayleigh scattering is proportional to the fourth power of the wavelength ($1/\lambda^4$) . As the wavelength increases, the loss caused by Rayleigh scattering decreases.

For a single component glass, it is given by

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \quad \text{-----------------}(6)$$

Where, γ_R = Rayleigh scattering coefficient

λ = Optical wavelength

n = Refractive index of medium

p = Average photoelastic coefficient

β_c = Isothermal compressibility

T_F = Fictive temperature

K = Boltmann's constant

The fictive temperature T_F is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature and is closely related to the anneal temperature

The Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber £ following the relation:

$$£ = \exp(-\gamma_R L) \text{-------------} (7)$$

Where, £= length of the fiber

It is clear from the eq. 7 that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

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**. Mie scattering, caused by these large defects in the fiber core, scatters light out of the fiber core. However, in commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects.

Linear scattering may also occur at inhomogeneties and they are comparable in size to the guided wavelength. **This type of scattering is because of fiber imperfections such as**:

- Irregularities in the core-cladding interface
- Core cladding refractive index differences along the fiber length
- Diameter fluctuation
- Strains and bubbles.

Scattering intensity can be very large if the scattering inhomogeneties size is grater than $\frac{\lambda}{10}$

Such inhomogeneities creates scattering in forward direction and is known as Mie scattering. Mie scattering may cause significant losses. **The inhomogeneities may be reduced by**

- Removing imperfections because of glass manufacturing process.
- Coating of the fiber
- Carefully controlled extrusion.
- Increasing the fiber guidance by increasing the relative refractive index difference.

NON-SCATTERING LOSSES

Optical waveguides do not always behave as linear channels where output optical power is directly proportional to the input optical power. Several nonlinear effects occur which causes scattering.

Nonlinear scattering is the transfer of optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes at different frequency. There are two types of nonlinear scattering.

- Stimulated brillouin scattering
- Stimulated raman scattering.

Stimulated Brillouin Scattering (SBS)

It can be considered as the modulation of light through molecular vibrations within the fiber. The scattered light appears as upper and lower side bands which are separated from the incident light by the modulation frequency. In this process, the incident photon produces a photon of acoustic frequency as well as scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic Wavelength.

The stimulated Brillouin Sccattering is nonlinear and in practical system requires a power level of something above 3 m W for any serious effect to be observable. It also requires a long interaction length and a very narrow line width signal. In general the signal line width must be less than about 100MHz (around 0.1 nm) for SBS. The effect in the forward direction is experienced as an increase in attenuation. This is repaid and adds noise to the signal. For narrow line width signals SBS imposes an upper limit on the usable transmit power.

In most systems SBS is not a major problem for the following reasons:

- Direct modulation of the transmit laser's injection current produces a chirp and broadens the signal. This significantly reduces the impact of SBS.
- The effect is less in 1300nm Systems than in 1550 nm systems due to the higher attenuation of the fiber.
- Lasers capable of producing the necessary power level have become available and amplifiers are also a recent innovation.

- At speeds of below 2.4 GHz it not necessary to use either very high power or very narrow line width lasers.
- SBS effects decrease with increase in speed because of the signal broadening affect of the modulation.

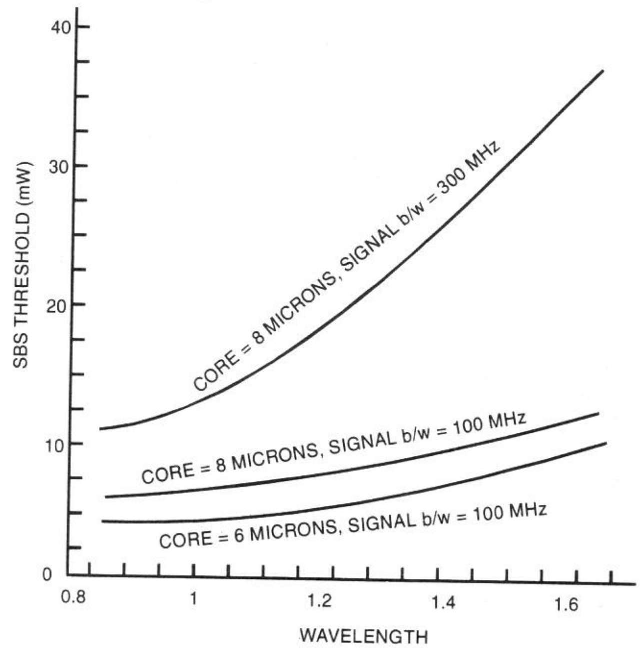

Figure 6. SBS threshold variation with wavelength.

In several cases where SBS could be a problem, the line width is often intentionally broadened. This can be done by using an additional RF modulation on the laser injection current, by using an external phase modulator or by using a self pulsating laser. The increasing line width may creates a problem against long distance transmission because it increases the effect of chromatic dispersion. However **SBS can be a major problem** in three situations :

- In long distance systems where the span between amplifiers is long and the bit rate is low (below about 2.5 Gbps).
- In WDM systems (up to about 10 Gbps)where the spectral width of the signal is very narrow.
- In remote pumping of an erbium doped fiber amplifier (EDFA) through a separated fiber.

Brillouin scattering is significant above a threshold power density. Threshold power P_B is given by

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} v Watts ----------- (8)$$

Where, d=fiber core diameter in µm

λ = Operating wavelength in µm

α_{dB} = fiber attenuation in dB

v = source bandwidth in GHz.

P_B is the threshold optical power launched into a single mode optical fiber berore SBs occurs.

Stimulated Raman Scattering

Stimulate raman scattering (SRS) is similar to stimulated brillouin scattering (SBS) except that a high frequency optical photon is generated in process rather than acoustic photon.

In a single-channel system the Raman Threshold (the power level at which Raman Scattering begins to take effect) is very high. Other effects (such as SBS) limit the signal power to much less than the Raman Threshold in single- channel systems.

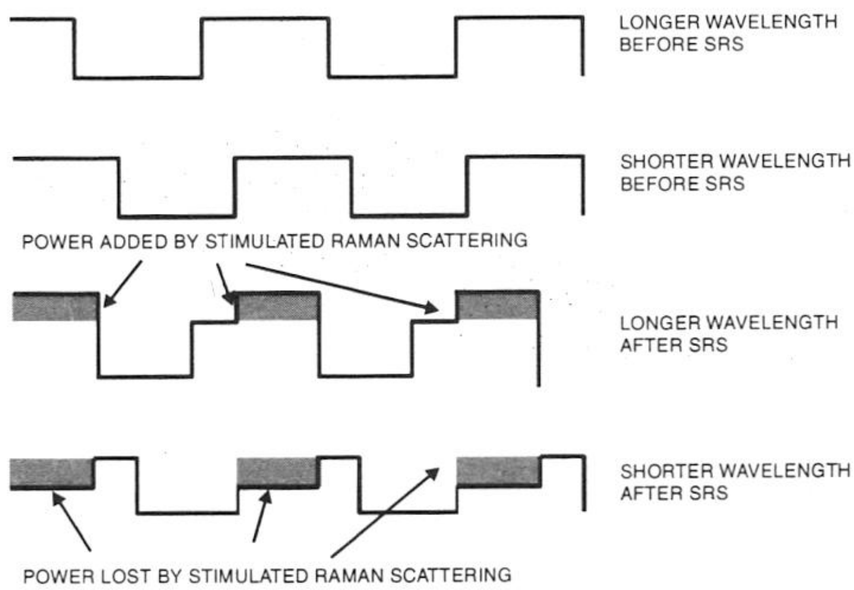

Figure 7. Stimulated raman scattering.

Stimulated Raman Scattering is not a major problem in single-channel systems while it can be a significant problem in WDM systems. When multiple channel are present, power is transferred from shorter wavelengths to longer ones. This can be a useful effect in that and it is possible to build an optical amplifier based on SRS. But in the transmission system it is a source of noise.

Figure. 7 shows the principle. Two wavelengths are shown before and after SRS. Notice that power has been transferred from the shorter wavelength to the longer one (from the higher energy wave to the lover energy one). This power transfer is because of the interactions of the light with vibrating molecules. Optical power so transferred is known as **stokes Wave.**

Important characteristics of SRS are:

1. The effect of SRS because higher as the signals are moved further and further apart. This is a problem because we would like to separate the signals as much as we can avoid four-wave mixing effects and when we do, we get SRS.
2. SRS increases exponentially with increased power. At very high power it is possible that all of the signal poser cab be transferred to the Stock Wave.

A SRS can occur in both forward and backward direction in optical fiber, and optical power threshold is of three orders of magnitude higher than brillouin threshold.

The threshold optical power (P_R) for SRS in a long single mode fiber is given by

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} ----------(9)$$

Where, $\lambda =$ Operating wavelength in μm

$d =$ Fiber core diameter in μm

$\alpha_{dB} =$ Fiber attenuation in dB.

CORE AND CLADDING LOSSES

The refractive indices of core and cladding are different and because of this they have different compositions. Therefore the attenuation coefficients for core and cladding will be different. The attenuation coefficients for core anf cladding may be denoted by α_1 and α_2 respectively.

If we ignore the effect of mode coupling, the loss for mode or order (υ, m) for a step index waveguide is expressed as:

$$\alpha_{vm} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P} --------(10)$$

Where , $\frac{P_{core}}{P}$ and $\frac{P_{clad}}{P}$ are fractional powers.

Therefore above Eq. (10) can be rewritten as :

$$\alpha_{vm} = \alpha_1 + (\alpha_1 - \alpha_2) \frac{P_{clad}}{P} --------(11)$$

DISPERSION AND PULSE BROADENING

Dispersion spreads the optical pulse as it travels among the fiber. This spreading of the sigal pulse reduces the system bandwidth or the information carrying capacity of the fiber. Dispersion limits how fast information is transferred as shown in fig. 8

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers.

- In digital transmission dispersion limits the maximum data rate, the maximum distance or the information carry capacity of a single mode fiber link.
- In analog transmission, dispersion can cause a waveform to become significantly distorted and can result in unacceptable levels of composite second order distortion (CSO).

An error occurs when the receiver is unable to distinguish between input pulses caused by the spreading of each pulse. The dispersion increases as the pulse travels the length of the fiber.

Therefore dispersion in optical fiber results in a broadening in time domain of the information signal which modulates the intensity of light propagating through the fiber. Dispersion of the transmitted optical signal cause distortion for both digital and analog transmission along optical fibers. When optical pulses injected into the fiber spread in time domain, they can interfere with the adjacent pulses resulting in what is commonly known as **Inter Symbol Interference or ISI** in digital communication. Figure (8). Shows the diagrammatic representation of the consequences of dispersion.

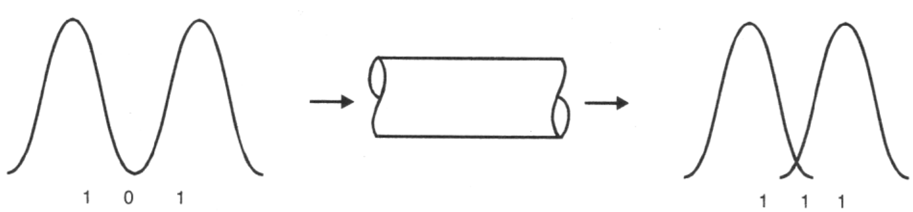

Figure 8. Dispersion (Spreads the Pulse)

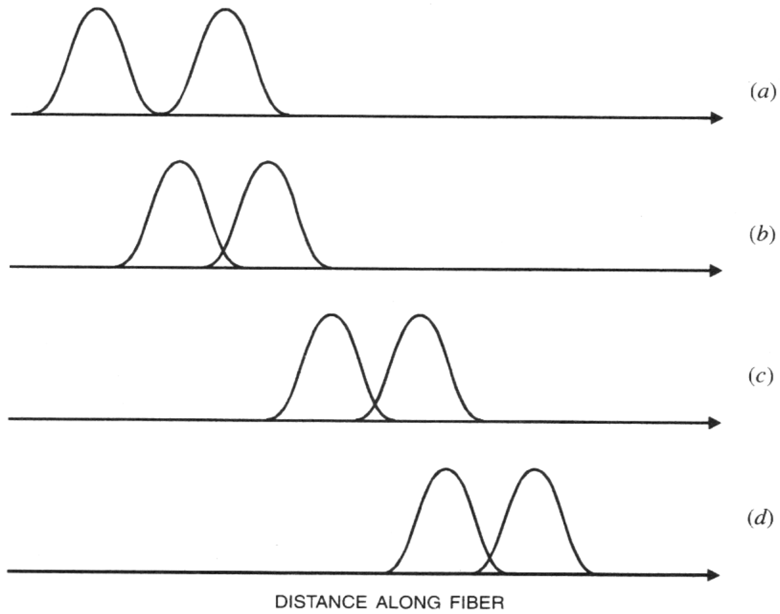

Figure 9. Consequences of dispersion and overlapping result in severe ISI is shown in (d).

An increasing number of errors may occur on the digital optical channel as the ISI becomes more pronounced. The error rate is function of

- Signal attenuation on the ling.
- Signal to noise ratio (SNR) at the receiver.

Signal dispersion limits the maximum possible bandwidth. For no overlapping of light pulses, digital bit rate must be less than the reciprocal of pulse duration (2τ).

Hence,

$$BT \leq \frac{1}{2\tau} ---------(12)$$

Where, τ = Input pulse duration.

If the light pulse at the output is of Gaussian shape with an rms width of σ, it allows certain amount of signal overlap on the channel. The maximum bit rate is given by

$$B_{\tau(\max)} = \frac{0.2}{\sigma} bit/\sec ----------(13)$$

Pulse broadening is associated with the three common optional fiber structures.

1. Multimode step index fiber.
2. Multimode graded index fiber.
3. Single mode step index fiber.

Multimode step index fiber shows the greatest dispersion of a transmitted light pulse and the multimode graded index fiber gives improved performance. While the single mode fiber gives minimum pulse broadening and is capable of greatest transmission bandwidths.

The amount of pulse broadening is dependent upon the distance the pulse ravels within the fiber and hence for a optical fiber ling the restriction on used bandwidth is dictated by the distance between regenerative repeaters.

NTERAMODAL DISPERSIONS

Intramodal, or chromatic, dispersion depends primarily on fiber materials and results from the finite spectral line width of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies, then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion:

- Material dispersion
- Waveguide dispersion

Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds.

In multimode fibers, waveguide dispersion and material dispersion are basically separate properties. Multimode waveguide dispersion is generally small compared to material dispersion. Waveguide dispersion is usually neglected. However, in single mode fibers, material and waveguide dispersion are interrelated. The total dispersion present in single mode fibers may be minimized by trading material and waveguide properties depending on the wavelength of operation.

Material Dispersion:

Material dispersion occurs because the speeding of a light pulse is dependent on the wavelengths interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times.

Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths.

A material will exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

i.e. $$\frac{d^2n}{d\lambda^2} \neq 0$$

the pulse spreading due to material dispersion may be obtained by the group delay τ_g in the optical fiber which is the reciprocal of the group velocity v_g

$$\tau_g = \frac{dB}{dw}$$

$$\tau_g = \frac{1}{C}\left[n_1 - \lambda.\frac{dn_1}{d\lambda}\right] ------------(14)$$

Where, n_1= Refractive index of the core material.

The pulse delay τ_m due to material dispersion in a fiber of length L is

$$\tau_m = \frac{L}{C}\left[n_1 - \lambda.\frac{dn_1}{d\lambda}\right] --------(15)$$

For a source with rms spectral width σ_λ and a mean wavelength λ the rms pulse broadening due to material dispersion σ_m may be obtained by the Tyalor series expansion about λ. Where,

$$\sigma_m = \sigma_\lambda.\frac{d\tau_m}{d\lambda} + \sigma_\lambda.-\frac{2d^2\tau_m}{d\lambda^2} + -------(16)$$

For the source operating over the 0.8 to 0.9 μm wavelength, usually the first term dominates. Then,

$$\sigma_m \cong \sigma_\lambda.\frac{d\tau_m}{d\lambda} ------17$$

Therefore pulse spreading may be calculated by considering the dependence of τ_m on λ Form Eq. (13) we get

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{C}\left[\frac{dn_1}{d\lambda} - \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right]$$

$$= -\frac{L\lambda}{C}\left[\frac{d^2n_1}{d\lambda^2}\right] --------(18)$$

Substituting he value of $\frac{d\tau_m}{d\lambda}$ form eq. (1)5 into (16) we get.

$$\sigma_m \cong \frac{\sigma_\lambda . L}{C} . |\lambda \frac{d^2 n_1}{d\lambda^2} ------(19)$$

Therefore the material dispersion parameter M is defined as

$$M = \frac{1}{L} . \frac{d\tau_m}{d\lambda}$$

or

$$M = \frac{\lambda}{L} \left| \frac{d^2 n_1}{d\lambda^2} \right| --------(20)$$

Sometimes which is expressed in units of P_s $nm^{-1}km^{-1}$

Waveguide Dispersion

Waveguide dispersion occurs because the mode propagation constant (β) is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

If a fiber can be operated so that intermodal dispersion and material dispersion both disappear (as for a single mode fiber operated near 1.3µm), then a third dispersion medium will predominate. This is known as waveguide dispersion and results only from the guiding characteristics of the fiber.

All practical light sources contain light components of different wavelength distributed over a spectral bandwidth. A slight spectral shift to higher wavelength will slightly changes the path length between successive reflection points and increases the corresponding incidence angle for each supported mode. This will increase the corresponding group velocity. Therefore each supported mode will suffer a dispersion effect dependent on spectral width of the source so that, even if the other effects cancel, this could still remain. It will also disappear if a truly monochromatic light source could be developed, but that is not possible.

For an ideal single mode step index fiber the dispersion coefficient due to the waveguide dispersion mechanism has a peak value to about $\Delta_w = 6.6 ps/nm/km$.

Dispersion when, $\left(\frac{d^2\beta}{d\lambda^2} \right) \neq 0$.

For multimode fibers, the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and generally it is negligible compared with material dispersion($\cong 0.1$ to 0.2 ns km^{-1}).

INTERMODEL DISPERSION

Intermodal or modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. As the modes propagate along the fiber, light energy distributed among the modes is delayed by different amounts. The pulse spreads because each mode propagates along the fiber at different speeds. Since modes travel in different direction, some modes ravel longer distances. Modal dispersion occurs because each mode travels a different distance over the same time span, as shown in fig. 11. The modes of a light pulse that enter the fiber at one time exit the fiber a different time. This condition causes the light pulse to spread. As the length of the fiber increases, modal dispersion increases.

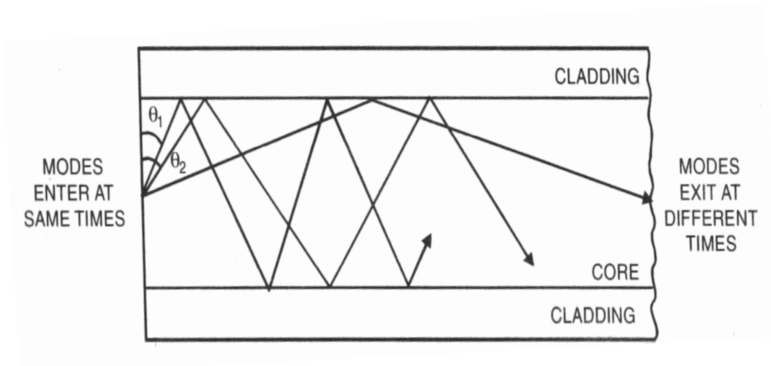

Fig. 10 Distance traveled by each mode over the same time span.

Modal dispersion is the dominant source of dispersion in multimode fibers. Modal dispersion does not exist in single mode fibers. Single mode fibers propagate only the fundamental mode. Therefore,

- Single mode amplifiers exhibit the lowest amount of total dispersion.
- Single mode fibers also exhibit the highest possible bandwidth.

Let the total fiber length be Z. Since it is convenient to state losses and delays in terms of a standard unit length. Figure 9 show different meridional rays of different modes following their zigzag paths down as fiber is incident at an angle ϕ. The total zigzag path length for each ray is found as

$$Z_t = \frac{Z}{\sin\phi} ------(21)$$

In the lowest order mode, the maximum angle of incidence is 90° and in the highest order mode it is almost critical.

$$\phi(\max) = \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) ------(22)$$

Now the shortest path is found to be

$$Z_t(\min) = \frac{Z}{\sin\phi(\max)} = \frac{Z}{\sin 90^\circ} = Z ------(23)$$

And the longest path is

The maximum time dispersion now becomes

$$\Delta Z = Z_t(\max) - Z_t(\min)$$

$$\Delta Z = Z\left(\frac{n_1}{n_2} - 1\right)$$

$$Z_t(\max) = \frac{Z}{\sin\phi(\min)} = Z.\frac{n_1}{n_2} -------(25)$$

In terms of normalized index of refraction difference as

$$\Delta Z = Z\left(\frac{\Delta}{1-\Delta}\right) --------(24)$$

Multimode Step Index Fiber

According to the Ray theory in step index fiber

- Fastest mode is represented by axial ray.
- Slowest mode is represented y extreme meridional ray.

Figure 12 shows the path take by these two rays in a structured step index fiber.

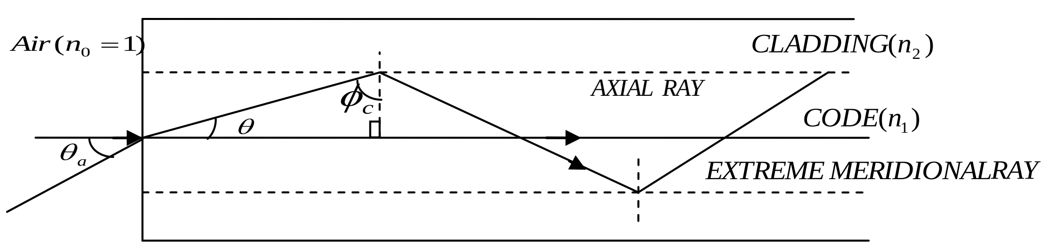

Figure 11 Path taken by axial and meridional ray.

The delay difference between these two rays given estimation of the pulse broadening resulting from intermodal dispersion within the fiber. When both rays are travelling with same velocity with in the constant refractive index fiber core, then the delay difference is directly related to their path length.

Therefore **minimum delay time** is given by

$$T_{\min} = \frac{Distence}{Velocity} = \left(\frac{L}{\frac{C}{n_1}} \right) = \frac{L.n_1}{C} ----------------(26)$$

Where, n_1 = Refractive index of core.

C = Velocity of right in vacuum.

L = Length along the fiber.

The extreme meridional ray show the **maximum delay time , T_{max}** where

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

$$= \frac{L.n_1}{C.\cos\theta} ------(27)$$

According to the Senll's law at core-cladding interface we ge

$$\sin\phi_c = \frac{n_2}{n_1}$$

$$= \cos\theta --------(28)$$

Where n_2= Refractive index of cladding

Putting the value of cos θ in Eq. (27) we get

$$T_{\min} = \frac{L.n_1^{\;2}}{C.n_2} ---------(29)$$

The delay difference δTs between the extreme meridional Ray and the axial ray may be obtained by subtracting Eqs. (28) and (29)

$$\delta T_s = T_{max} - T_{min}$$

$$= \frac{L.n_1^2}{C.n_2} - \frac{L.n_1}{C}$$

$$\frac{L.n_1}{C}\left[\frac{n_1}{n_2} - 1\right]$$

$$\frac{L.n_1}{C}\left[\frac{n_1 - n_2}{n_2}\right]$$

$$\delta T \cong \frac{L.n_1}{C}\Delta ----------(30)$$

Where, Δ= Relative refractive index difference.

Where $\Delta \cong \left(\frac{n_1 - n_2}{n_1}\right)$

In terms of numerical aperture,

$$NA = n_1(2\Delta)^{1/2} --------(31)$$

Substituting the value of Δfrom Eq. (31) to Eq. (30)

$$\delta T_s \cong \frac{L.(NA)^2}{2n_1 C} --------(32)$$

This analysis is based on the pulse broadening due to meridional rays and totally ignores skew rays with acceptance angles $\theta_{as} > \theta_a$

Another consideration with **perfect step index fiber**, useful quantity with intermodal desperation is the rms pulse broadening results from dispersion mechanism. If the optical input to the fiber is a pulse $P_i(t)$ of unit area, as shown in Fig.12

$$\int_{-\infty}^{\infty} P_i(t).dt = 1----------(33)$$

$P_i(t)$has a constant amplitude of $\frac{1}{\delta T_s}$, over the range

$$-\frac{\delta T_s}{2} \leq P(t) \leq \frac{\delta T_s}{2} --------(34)$$

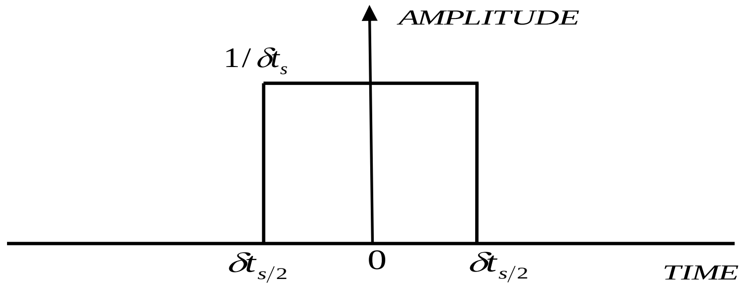

Figure 12. Light input to the fiber.

At the fiber output, the rms pulse for the multimode step index fiber may be given in terms of the variance, $\sigma^2{}_s$ as

$$\sigma^2{}_s = M_2 - M_1{}^2 --------(35)$$

Where, M_1 = first temporal moment, it is equivalent to mean value of pulse.

M_2 = Second temporal moment it is equivalent to mean squire value of pulse.

Hence, $$M_1 = \int_{-\infty}^{\infty} tP_i(t).dt ----------(36)$$

And $$M_2 = \int_{-\infty}^{\infty} t^2 P_i(t).dt ----------(37)$$

The mean value $M_1$for the unit input pulse is zero and assuming that it is maintained for the output pulse.

Then $$\sigma^2{}_s = M_2 = \int_{-\infty}^{\infty} t^2 P_i(t).dt -------(38)$$

Integrating over the limits of input pulse and putting the value of $P_i(t)$, we get

$$\sigma^2{}_s = \int_{-sT_s/2}^{st_s/2} \frac{1}{\delta T_s}.dt$$

$$= \frac{1}{\delta T_s}\left[\frac{t^3}{3}\right]_{-\delta T_s/2}^{\delta T_s/2}$$

$$= \frac{1}{3}\left[\frac{\delta T_s}{2}\right]^2 --------(39)$$

$$\sigma^2{}_s = \frac{1}{\sqrt{3}}.\left[\frac{\delta T_s}{2}\right] ---------(40)$$

Putting the value of σ_{Ts} in Eq. (30) we get

$$\sigma_s = \frac{1}{\sqrt{3}}.\left[\frac{L.n_1\Delta}{2C}\right] ---------(41)$$

$$\sigma_s = \frac{L.(NA)^2}{4\sqrt{3}.n_1 C}. ---------(42)$$

It gives the estimation of the rms impulse response of a multimode step index fiber.

Multimode Graded Index Fiber

Intermodal dispersion is multimode fiber is reduced with the use of graded index fibers. Therefore it gives substantial bandwidth over multimode step index fibers.

Analytically, multimode graded index profile is given by

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right]^{1/2} \\ n_1(1-2\Delta)^{1/2} = n_2 \end{cases} ----------(43)$$

Graded profile reduces the disparity in the mode transit time. According to the ray theory the delay difference is given by

$$\delta T_g \cong \frac{Ln_1\Delta^2}{2C} -----------(44)$$

$$\delta T_g \cong \frac{(NA)^4}{8n_1{}^3C} ----------(45)$$

Electromagnetic mode theory analysis gives an absolute temporal width at fiber output

$$\delta T_g \cong \frac{L.n_1\Delta^2}{8C} ----------(46)$$

Which indicates an increase in transmission time for the slowest mode of $\frac{\Delta^2}{8}$ over the fastest mode.

The rms pulse broadening is given by

$$\sigma_g \cong \frac{\Delta}{D}\sigma_s ----------(47)$$

Where, D= constant between 4 and 10 depending upon the evaluation and exact optimum profile.

The best minimum theoretical intermodal rms pulse broadening for a graded index fiber with an optimum characteristic refractive index profile for the core α_{op} is

$$\alpha_{op} = 2 - \frac{12\Delta}{5} --------(48)$$

Therefore by combining Eq. 30and Eq. 47 we get

$$\sigma_g = 2 - \frac{L.n_1\Delta^2}{20\sqrt{3}C}$$

OVERALL FIBER DISPERSION

Multimode Fibers:-

The overall dispersion in multimode fibers comprises both chromatic and intermodal terms. The total rms pulse broadening σ_T is given by:

$$\sigma_T = \left(\sigma_C{}^2 + \sigma_n{}^2\right)^{1/2} --------(49)$$

Where, σ_C =Intermodal or chromatic broadening

σ_C = Intermodal broadening caused by delay differences between the modes. Waveguide dispersion. But in multimode fibers, generally waveguide dispersion is negligible as compared to material dispersion, then

$$\sigma_C = \sigma_m$$

Single Mode Fibers:-

The pulse broadening in single mode fibers is mainly because of intramodal or chromatic dispersion as only a single mode is allowed to propagate. Therefore, the bandwidth is limited by the finite spectral width or the source.

The group delay τ_g or transit time for a light pulse propagating along a unit length of single mode fiber, may be given as:

$$\boxed{\tau_g = \frac{1}{C}\frac{d\beta}{dk}}$$

Where, C = Velocity of light in a Vacuum

β = Propagation constant for a mode within the fiber

n_1 = Refractive index

k = Propagation constant for the mode in a vacuum

the total first order dispersion parameter or the chromatic dispersion of a single mode fiber, D_T is given by the derivative of specific group delay w.r.t. the vacuum length, λ as :

$$D_T = \frac{d\tau_g}{d\lambda} ----------(50)$$

With material dispersion parameter, usually it is expressed in units of ps $nm^{-1}km^{-1}$ when the variable λ is replaced by ω, the total dispersion parameter will we:

$$D_T = \frac{-\omega}{\lambda}\left(\frac{d\tau_g}{d\lambda}\right)$$

$$D_T = \frac{-\omega}{\lambda}\left(\frac{d^2\beta}{dw^2}\right) ----------(51)$$

When β varies nonlinearly with wavelength, the fiber exhibits intramodal dispersion. β may be expressed in terms of relative refractive index Δ and the normalized propagation constant b as :

$$b=\left[\frac{\left(\frac{\beta}{k}\right)^2-n_2^{\,2}}{2n_1^{\,2}\Delta}\right]----------(52)$$

$$\beta=kn_1\left[1-2\Delta(1-b)\right]^{1/2}--------(53)$$

The **rms pulse broadening** because of intramodal dispersion down a fiber of gength L is given by the derivative of the group delay w.r.t. wavelength:

Total rms pulse broadening $=\sigma_\lambda L\left|\frac{d\tau_g}{d\lambda}\right|$

$$=\frac{\sigma_\lambda L2\pi}{c\lambda^2}\left|\frac{d^2\beta}{dk^2}\right|$$

Where, $\sigma_\lambda =$ Source rms spectral line width centred at a wavelength λ.

The dependence of the pulse broadening on the fiber material's properties and the normalized propagation constant. This gives rise to three inter-related effects which are as following

(1) The waveguide dispersion parameter D_m defined by,

$$D_M=\frac{\lambda}{C}\left|\frac{d^2n}{d\lambda^2}\right|--------(54)$$

Where , n = n_1 or n_2 for the core or cladding respectively.

(2) The waveguide dispersion parameter D_w defined by,

$$D_w=\left(\frac{n_1-n_2}{\lambda C}\right)V\frac{d^2(Vb)}{dV^2}------(55)$$

Where, V= Normalized frequency for the fiber
Since normalized propagation constant b for a specific fiber is any dependent on V.

Then the normalized waveguide dispersion coefficient $\frac{Vd^2(Vb)}{dV^2}$ also depends on V.

(3) A profile dispersion parameter D_P which is proportional to $\frac{d\Delta}{d\lambda}$.

Then the normalized waveguide dispersion D_T in a practical single mode fiber is given by :

$$D_T = D_M + D_W + D_P (ps/nm/km) -------- (56)$$

Where, D_M = Material dispersion

D_w = Waveguide dispersion

D_P = Profile dispersion component

But in **standard single mode fibers the** total dispersion tends to be dominated by the material dispersion of the fused silica.

POLARIZATION MODE DISPERSION

Polarization mode dispersion (PMD) is pulse spreading caused by a change of fiber polarization properties. It can become a limiting factor for optical fiber communication at high transmission rates. It is a random effect because of both:

- Intrinsic circular fiber core geometry and residual stresses in the glass material near the core.
- Extrinsic factors which results in group velocity variation with polarization state.

The pulse spreading is denoted by Δt_{PMD} and can be calculated as:

$$\Delta t_{PMD} = D_{PMD}\sqrt{L}$$

Where D_{PMD} = Coefficient of polarization mode dispersion measure in $Ps/\sqrt{Km}$.

L= Length in km.

Tow key factors are there regarding the polarization mode dispersion:

- D_{PMD} does not depend on wavelength.
- It does not depend on the square root of fiber length.

Modal Birefringence:-

Single model fibers which are having nominal circular symmetry about the core axis allow the propagation of two nearly degenerate models with orthogonal polarizations. Therefore they are bimodal supporting HE_{11}^x and HE_{11}^y modes where the principle axes x and y are determined by the symmetry element of the fiber cross-section. Thus the fiber behaves as a birefringent medium due to the difference in effective refractive indices, and hence phase velocities for these two orthogonally polarized modes.

Therefore the modes have different propagation constants β_x and β_y . when the fiber cross-section is independent of the fiber length L in the Z- direction, then the model birefringence B_F for the fiber is given by:

$$B_F = \frac{\beta_x - \beta_y}{(2\pi/\lambda)} ------(57)$$

Where, λ = optical wavelength

Light polarized along one of the principle axes will retain its polarization for all L.

The fiber exhibit a linear retardation $\phi(z)$ because of the difference in phase velocities. It depends on the fiber length L in the z-direction and is given by: (assuming that the phase coherence of the two mode components is maintained)

$$\phi(z) = (\beta_x - \beta_y)L ------(58)$$

The phase coherence of the two mode components is achieved when,

The delay between the two transit times < Coherence time of the source --------(59)

Coherence time for the source = $\frac{1}{\delta f}$

Where, $\frac{1}{\delta f}$ = Uncorrelated source frequency width

The birefringent coherence is maintained over a length of fiber L_{bc} when:

$$L_{bc} \cong \frac{C}{B_F \delta f}$$

$$L_{bc} = \frac{\lambda^2}{B_F \delta f} --------(60)$$

Where, C = Velocity of light in a vacuum.

$\delta\lambda$ = Source line width

When phase coherence is maintained, it leads to a polarization state which is generally elliptical but which varies periodically long the fiber. This situation is shown in Figure(13).

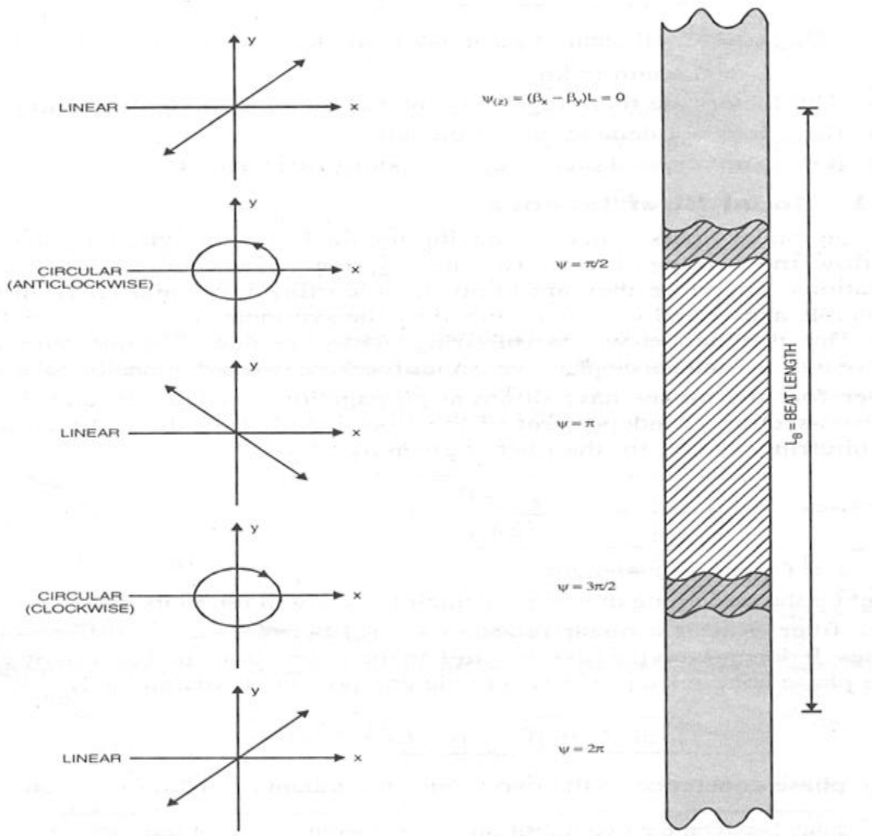

Figure 13. An illustration of the beat length in a single mode optical fiber.

Here the incident linear polarization which is at 45° w.r.t. the x-axis becomes circular polarization at $\phi = \frac{\pi}{2}$ and linear again at $\phi = \pi$. The process continues through another circular polarization at $\phi = \frac{3\pi}{2}$ before returning to the initial linear polarization at $\phi = 2\pi$. The characteristic length corresponding to this process is known as the beat length, which is given by

$$L_B = \frac{\lambda}{B_F} ----------(61)$$

Substituting the value of B_F form Eq. (55) we get

$$L_B = \frac{2\pi}{(\beta_x - \beta_y)} ------(62)$$

Above equation may be obtained directly from Eq. (58) where

$\phi(L_B) = (\beta_x - \beta_y)L_B = 2\pi$

$$\therefore \qquad L_B = \frac{2\pi}{(\beta_x - \beta_y)} --------(63)$$

The beat length of a typical single mode fiber is of a few centimeters and its effect may be observed directly within a fiber via Rayleigh scattering with the use of a suitable visible source (Example He-Ne laser).

In a non perfect fiber various perturbations along the fiber length such as train or variations in the fiber geometry and composition lead to coupling of energy from one polarization to the other. These perturbations are difficult to avoid as they may easily occur in the fiber manufacture and cabling.

The energy transfer is maximum when the perturbations have a period A, corresponding to the wavelength, defined by:

$$\wedge = \frac{\lambda}{B_F} ---------(64)$$

However, the cross-polarization effect may be minimized, when .

The period of perturbations <Cutoff period $(\wedge_c)$

There are two ways by which the polarization maintaining fibers may be designed:

(1) **High (large) birefringence**: The maximization of the model birefringence may be achieved by reducing the beat length L_B to around 1 mm or less.
(2) **Low (small) birefringence**: The minimization of the polarization coupling perturbations with a period of $\wedge$. This may be achieved by increasing $\wedge_c$ giving a large beat length of around 50m or more.

In a uniformly birefringent fiber, the orthogonal fundamental modes have different phase propagation constants β_x and β_y. Hence the two modes exhibit different specific group delays of t τ_{gx} and τ_{gy}. A delay difference $\delta\tau_g$ therefore occurs between the two orthogonally polarized wave such that.

$$\delta\tau_g = \tau_{gx} - \tau_{gy} ---------(65)$$

Where, $\delta\tau_g$ = Polarization mode dispersion

Its range from significantly less than 1 ps km^{-1} conventional single mode fibers to greater than 1 ns km^{-1}in high birefringence polarization maintaining fibers. To greater than 1 ns km-[1] in high birefringence polarization maintaining fibers.

Since the two fundamental modes launched into single mode fiber have different group velocities, the output from the fiber length L will comprise two elements separted by a time interval $\delta\tau_g$ L. For high birefringence fibers, the product $\delta\tau_g$ L provides good estimate of pulse spreading in long fiber lengths. In this case the bandwidth B is given by

$$B = \frac{0.9}{\delta\tau_g L} --------- (66)$$

But for short fiber lengths and fiber lengths longer than a characteristics coupling length L_c the

$$Pulsespreading \propto (LL_c)^{1/2} -------- (67)$$

Instead of simply L

The maximum bit rate $B_{T(max)}$ for digital transmission in relation to polarization mode dispersion is given by

$$B_{T(\max.)} = \frac{B}{0.55} ------ (68)$$

Polarization Maintaining Fibers

Interference and delay difference between the orthogonally polarized modes in a birefringent fibers may cause polarization modal noise and polarization mode dispersion respectively. Polarization is also of concern when a single mode fiber is coupled to a modulator or other waveguide device that can require the light to be linearly polarized for efficient operation . Hence there are several reasons to be considered for the use of fibers that will permit light to pass through with the retention of its state of polarization. Such polarization maintaining (PM) fibers can be classified into:

- High birefringence (HB) fibers
- Low birefringence (LB) fibers

The range of the birefringence of conventional single mode fiber is $B_F = 10^{-6}$ to 10^{-5} . A HB fiber requires $B_F > 10^{-5}$and a value better than 10^{-4} is a minimum for polarization maintenance. HB fibers are classified into :

- Tow polarization (TP) fibers

- Single polarization (SP) fibers

Figure 15 shows the various types of PM fiber, classified in terms of their linear polarization maintenance.

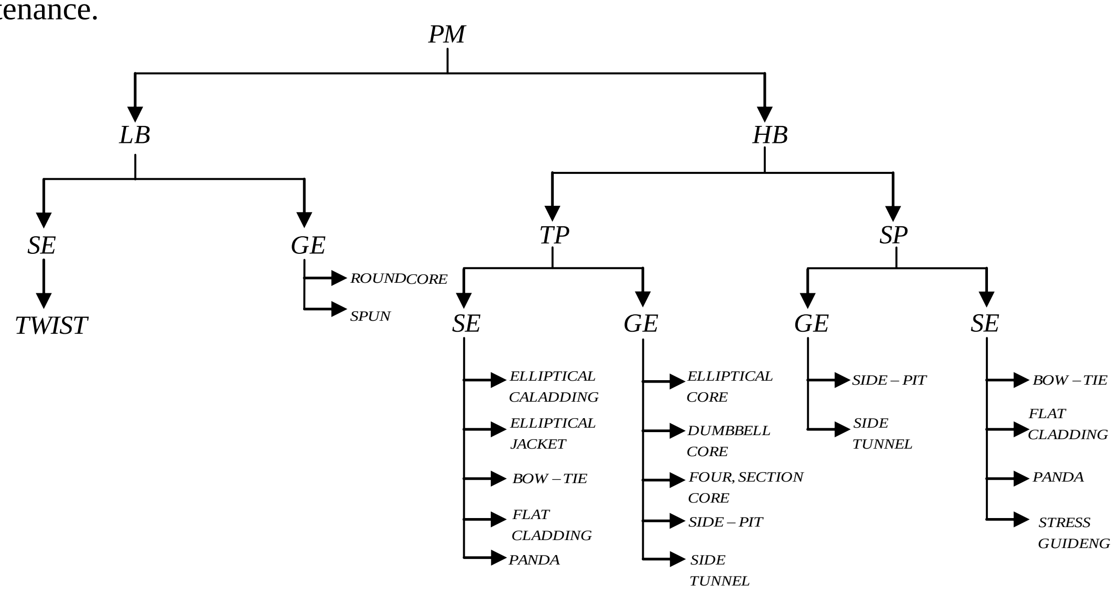

Figure 14.Classification of Polarization Maintaining Fibers.

PM= Polarization maintaining
HB= High birfreingent
LB= Low birefreingent
SP= Single polarization
TP= Two polarization modes
GE= Geometrical effect
SE= Stress effect

The most common polarization maintaining fiber structures are shown in Fig.14

- Fig. 15(a) and (b) employs geometrical shape birefrience. Geometrical birefringen is a weak effect and a large relative refractive index difference between the core and cladding is required to produce high birefringence.
- The ellipitical core fiber of Fig. 15(a) has high doping levels which can increase the optical losses as well as well as the polarization cross coupling.
- Deep low refractive index side pits as shown in Fig. 15(b) can be employed to produce HB fibers.
- Stress birefringence may be induced using an elliptical cladding fig. 15(C) with a high thermal expansion coefficient.
- The HB fibers shown in fig. 15(d) and (e) employ tow distinct stress regions and are often known as **the bow-tie** and **PANDA fibers** because of the shape of these regions.

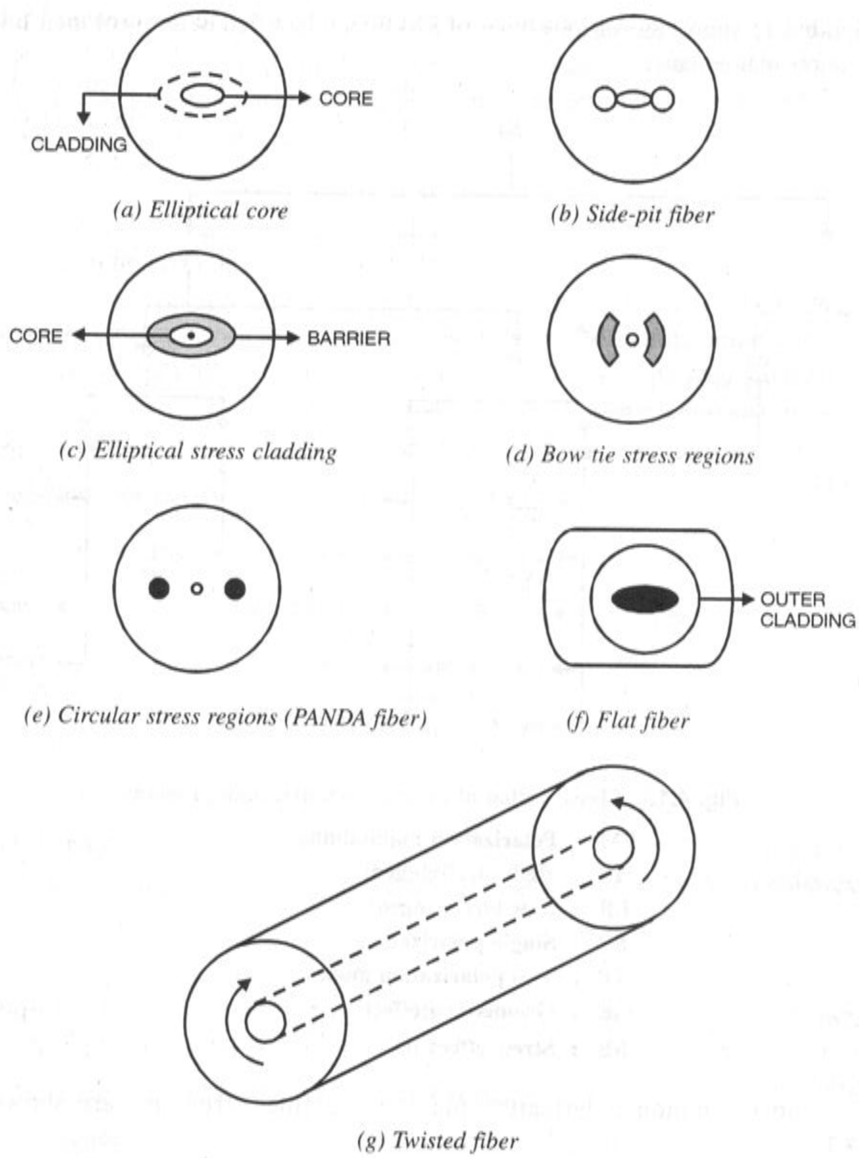

Figure 15. Polarization maintaining fiber structure