UNIT-II

TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

SIGNAL ATTENUATION:

Signal attenuation in an optical fiber is defined as the decrease in light power during light propagation along an optical fiber. It is also known as fiber loss or signal loss in an optical fiber. It results in a reduction of power of light wave as it travels down the optical fiber, It determines the maximum repeater less separation between the transmitter and the receiver.

Due to attenuation, the power of light wave decreases exponentially with distance.

Let

\[ P(0) = \text{optical power in an optical fiber at the origin} \]
\[ P(z) = \text{optical power in a fiber at a distance } z \]

\[ P(z) = P(0) e^{-\alpha_p z} \]

where, \( \alpha_p = \frac{1}{z} \log \left( \frac{P(0)}{P(z)} \right) \)

Signal attenuation within optical fiber is usually measured in terms of decibel/km,
also known as attenuation coefficient or attenuation rate.

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

Types of losses in optical fiber cable are:

(i) Absorption losses
(ii) Bending losses
(iii) Scattering losses

(i) Absorption losses : (Material Absorption losses)

The composition of the material and the fabrication process of the fiber gives rise to material absorption. This results in the mechanism where optical power transmitted is lost as heat in the waveguide. The material absorption is of two types:

(a) Intrinsic absorption
(b) Extrinsic absorption.

(a) **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 results from electronic absorption bands in ultra violet region and from atomic vibration bands in the near infrared region. Absorption occurs when a photon
interacts with an electron in the valence band and excites it to higher energy level. These intrinsic losses are mostly insignificant in a wide region where fiber can operate but these inhibit the extension of fiber systems towards ultraviolet as well as infrared regions. Intrinsic absorption is very strong in the short wavelength ultraviolet portion of electromagnetic spectrum.

(b) **Extrinsic absorption**: Extrinsic absorption is caused by the presence of impurities in fiber like iron, cobalt, chromium, copper and OH ions in glass material. These impurities are incorporated during the fabrication process and it is very hard to eliminate. 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) band. This band has a fundamental absorption at 2700 nm. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonic increases extrinsic absorption at 1383nm, 1250 nm and 950 nm.

(ii) **Bending losses**: (Radiative losses)

Bending losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. This is one of the major causes of total attenuation that light experiences while propagating through an optical fiber. Fibers can be subject to two types of bends, so, there are mainly two types of bending losses.

(a) Macro bending losses

(b) Micro bending losses

(a) Macro bending losses : Micro bends are the bends having radii that are large compared to the fiber diameter e.g. such bends occur when a fiber cable turns a corner.

Whenever an optical fiber cable is bent, then the ray of light forms a propagation angle that is more than critical angle when it strikes the fiber. Due to this total internal reflection is not achieved in bent fiber. Some portion of the light beam escapes from the core of the fiber and the power of the light at its receiving end is less than the power of the light emitted into the fiber from a light source.

(b) **Microbending losses**: Microbending loss is caused by the micro deformation of the fiber axis. Microbends do not have regular shapes or distributions along the fiber. These may have different radii over small sections and are distributed randomly over the length of the fiber. Although light travels along straight segment of a fiber, light beam meets these imperfections and gets deflected. The beam that initially travels at the critical propagation angle changes its angle of propagation after reflection at these imperfections. So, condition of total internal reflection is not met and a
portion of the beam will be refracted and will leak out of the core. Fig. shows mechanism of micro bending losses.

![Mechanism of microbending loss](image1.png)

(iii) Scattering losses

Scattering losses are due to microscopic variations in the material density from compositional fluctuations and from structural defects occurring during manufacture. Molecular density is not uniform since glass is made up of several oxides such as GeO2, SiO2 and P2O5. Even very small changes in the values of the core refractive index will be seen by a traveling beam as an optical obstacle and this obstacle will change the direction of original beam. This effect will inhibit attainment of the condition of total internal reflection at core-cladding boundary, resulting in power loss. Since some light will pass out of the core. Rayleigh scattering accounts for about 96 percent of attenuation in optical fiber. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs. If the light is scattered at an angle that does not support forward travel, however, the light is directed out of the core then attenuation occurs.

**Rayleigh scattering** is a fundamental loss mechanism arising from microscopic fluctuations in density. It is a dominant loss in low absorption window between the ultraviolet and infrared absorption tails. When light strikes an object, it is reflected in different directions which is called light scattering. In the optical fiber, due to impurity particle, scattering occurs in the core or cladding. If there is any impurity particle in the path of light in the core, the particle will scatter the light in another direction and affect the total internal reflection at the boundary of core-cladding. When the fiber material are prepared, there may be some in homogeneities or imperfections in the core layer Due to in homogeneity, light beam propagating at an angle close to or more than critic angle will hit the obstacle and bend its direction because of scattering. The beam will be refracted into cladding layer as shown in Fig.

![Scattering loss](image2.png)

The in homogeneity can result into variation of refractive index and the variation in refractive index may be such that the particular location with large refraction index will act as an obstacle
and cause scattering loss. This type of loss is called Rayleigh scattering loss. Rayleigh scattering loss occurs whenever a light wave travels through a medium having scattering objects smaller than a wavelength. Rayleigh scattering coefficient. It is given by

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

where,
- $\lambda$ = Optical wavelength
- $n$ = Refractive index of medium
- $p$ = Average photo elastic coefficient
- $\beta_c$ = Isothermal compressibility
- $T_F$ = Fictive temperature
- $k$ = Boltzmann constant

The transmission loss factor or transmissivity of the fiber $T_L$ is related to Rayleigh scattering coefficient by:

$$T_L = \exp (-Y_R L)$$

where, $L$ = length of the fiber in m.

**Mie Scattering:** Linear scattering occur at in homogeneities which are comparable to in size with the guided wavelength. When the size of scattering in homogeneities is greater than $\lambda/10$ the scattered intensity has an angular dependence and can be quite large. The scattering occurring due to such in homogeneities is mainly in forward direction and this type of scattering is known as Mie scattering. Depending on the fiber material, design and manufacture, Mie scattering can cause considerable power loss. The in homogeneities can be minimized by reducing imperfection during glass manufacturing process and by carefully controlled extrusion and coating on the fiber.

Non linear scattering cause disproportionate attenuation at high optical power levels. This causes the transfer of optical power from one mode either in forward or backward direction to the same or other modes at a different frequency. The important types of non linear scattering within optical fibers are

(i) Stimulated Brillouin Scattering (SBS)
(ii) Stimulated Raman Scattering (SRS)
(i) Stimulated Brillouin Scattering (SBS)

**Stimulated Brillouin scattering** is the modulation of light through thermal vibrations within the fiber Modulation frequency for the scattered light separates the incident light into upper and lower side bands. The incident photon produces a photon of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with scattering angle because the frequency of the sound wave varies with acoustic wavelength. The frequency shift is maximum in backward direction reducing to zero in forward direction making SBS a mainly backward process.
The optical power level at which Brillouin scattering becomes significant in a single mode fiber is given by an empirical formula. The threshold power level \( B \) is given by

\[
P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{\text{dB}} \Delta T \text{ watts}
\]

\( d \) = Fiber core diameter
\( \lambda \) = operating wavelength
\( \alpha_{\text{dB}} \) = fiber attenuation in dB/km
\( \Delta T \) = source bandwidth.

In current systems SBS has not been much of the problem for the following reasons:

(i) Direct modulation of the transmit laser’s injections current produces a chirp and broadens the signal. This significantly reduces the effect of SBS.

(ii) The SBS effect is less in 1300 nm systems than 1550 nm systems due to the higher attenuation of the fiber.

(iii) SBS effect decreases with increase in speed because of the signal broadening affect of the modulation;

But SBS can be a major problem in three situations.

(i) In long distance systems where the span between amplifiers is great and the bit rate low.

(ii) In WDM systems (upto 10 Gbps) where the spectral width of the signal is very normal.

(iii) In remote pumping of an erbium doped fiber amplifier (EDFA) through a separate fiber.

(ii) Stimulated Raman Scattering (SRS)

Stimulated Raman Scattering (SRS) generates a high frequency optical phonon in the scattering process and is similar to SBS except that acoustic phonon is generated in SBS rather than optical phonon. SRS occurs in both the forward and backward direction in the optical fiber and has an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber. So the stimulated Raman scattering is an interaction between the light wave and the vibration modes of silica molecules. SRS generates scattered light at a wavelength larger than that of the incident light.

Dispersion: “Spreading of optical pulses as they travel down the fiber” is known as dispersion. It is the time distortion of an optical signal that results from many discrete wavelength components travelling at different rates. The dispersion leads to the degradation of the signal quality at the output end. It spreads the output pulse in the time domain and changes its shape so that it may merge into the succeeding or previous pulses. In a fiber three distinct types of dispersions are observed

(i) Inter modal dispersion

(ii) Intra modal dispersion

(iii) Polarization mode dispersion.
Dispersion the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier is called dispersion. The dispersion leads to the degradation of the signal. Quality at the output end due to overlapping of the pulses. There are three kinds of dispersion mechanisms in the fiber.

(1) Intermodal Dispersion

(ii) Intermodal Dispersion

(iii) Polarization Mode Dispersion

(i) Intermodal Dispersion

Pulse widening caused by the mode structure of a light beam inside the fiber is called inter modal (modal) dispersion; This type of dispersion occurs due to the fact that the light inside the fiber propagates in different modes. The higher order modes travel a longer distance and arrive at the receiver end later than the lower order modes. Thus one mode travels more slowly than another mode. So, intermodal dispersion is a result of different values of the group delay for each individual mode at a single frequency. It mainly occurs in multimode fibers. Intermodal dispersion limits both the bandwidth as well as the distance. The maximum pulse broadening arising from intermodal dispersion is the difference between the travel time $T_{\text{max}}$ of the higher order mode and the travel time $T_{\text{min}}$ of the fundamental mode

$$\delta T_{\text{mod}} = T_{\text{max}} - T_{\text{min}} = \frac{n_1 \Delta L}{c}$$

(ii) Intramodal dispersion

It is a pulse spreading that occurs within single mode fiber. It is also known as chromatic dispersion. It is caused by the dependence of the optical properties on wavelength. It limits both the bandwidth and the distance that information can be transmitted. Chromatic dispersion consists of two mechanisms:

(a) Material Dispersion

(b) Wave guide Dispersion
(a) **Material Dispersion:** It is the pulse spreading due to dispersive properties of the material. Material dispersion is caused by the wavelength dependence of the silica’s refractive index. An information carrying light pulse contains different wavelengths because a light source radiates light of a spectral width. So, the components of the pulse with different wavelengths will travel within the fiber at different velocities and will arrive at the fiber end at different times, causing the spread of the pulse. The amount of pulse spreading caused by material dispersion per length is given by:

\[
\frac{\Delta t_{\text{mat}}}{L} \left( \frac{\text{Ps}}{\text{Km}} \right) = D_{\text{mat}}(\lambda) \Delta \lambda
\]

where,

\[ D_{\text{mat}}(\lambda) = \text{Material dispersion parameter} \]

\[ \Delta \lambda = \text{spectral width of light source} \]

\[ L = \text{fiber length}. \]

(b) **Waveguide Dispersion:** Waveguide dispersion is most significant in single mode fibers. An information carrying light pulse after entering in a single mode fiber is distributed between the core and cladding. Its major portion travels within the core, the rest within the cladding. Both portions propagate at different velocities. Since core and cladding have different refractive indexes, the pulse will spread because light is confined within the structure having different refractive indexes. The amount of pulse spreading caused by waveguide. Dispersion per unit time is given by:

\[
\frac{\Delta t_{\text{wg}}}{L} = D_{\text{wg}}(\lambda) \Delta \lambda
\]

\[ D_{\text{wg}} = \text{waveguide dispersion parameter} \]

\[ \Delta \lambda = \text{spectral width of light source} \]

Intermodal dispersion is the sum of material and waveguide dispersion.

**Dispersion units**

Modal dispersion in an optical fiber is specified by the characteristics pulse spread per kilometer length in the units of ns/km as it is independent of the linewidth of the source. Material and waveguide dispersion depend on the source linewidth, so these are expressed as ns/km.nm.

**Intermodal dispersion in multimode step index fiber.**

Pulse widening caused by the mode structure of light beam inside the fiber is called intermodal (modal) dispersion. It mainly occurs in multimode fibers. Intermodal dispersion occurs because each mode travels a different distance over the same time span as shown in Fig.
The autocorrelation function of $i_s(t)$ is related to spectral density $S_s(F)$ by Wiener-Khinchin theorem.

$$< i_s(t) i_s(t + \tau) > = \int_{-\infty}^{\infty} S_s(F) \exp(2\pi i ft) \, df \quad \text{... (1)}$$

where angle brackets denote an ensemble average over and fluctuations.

The spectral density of shot noise is constant and is given by $S_s(F) = q I_p$, where $S_s(F)$ is two sided spectral density +ve and -ve frequencies are included in above $= n(1)$. If only + ye frequencies are considered by changing the lower limit of integration to zeros, one sided spectral density becomes $2q I_p$.

Noise variance is obtained by setting $r = 0$ in equation (1),

$$\sigma_s^2 = <i_s^2(t)>$$

$$= \int_{-\infty}^{\infty} S_s(f) \, df = 2q I_p \Delta_f$$

where $\Delta_f = \text{effective noise bandwidth of receives}$.

If we consider current fluctuations and include total transfer for two HT $(F)$.

$$\sigma_s^2 = 2q I_p \int_{0}^{\infty} |H_T(f)|^2 \, df$$

$$= 2q I_p \Delta_f$$

where, $\Delta_f = \int_{0}^{\infty} |H_T(f)|^2 \, df$.
Since, dark current $I_d$ also generates shot noise. Its contribution is included by replacing $I_p$ by $I_p + I_d$

$$\therefore \quad \text{Total shot noise} = \sigma_s^2$$
$$= 2q (I_p + I_d) \Delta_f$$

where, $\sigma_s = \text{Root mean square value of noise current induced by shot noise.}$

where, $n_2 = \text{refractive index of the cladding}$

$$\therefore \quad T_{\text{max}} = \frac{L n_1}{c \left( \frac{n_2}{n_1} \right)} = \frac{L n_1^2}{c n_2}$$

The difference in time taken by axial ray and the meridional ray

$$\delta T = T_{\text{max}} - T_{\text{min}} = \frac{L n_1^2}{c n_2} - \frac{L n_1}{c}$$

$$= \frac{L n_1}{c} \left[ \frac{n_1}{n_2} - 1 \right] = \frac{L n_1}{c} \left[ \frac{n_1 - n_2}{n_2} \right]$$

$$= \frac{L n_1}{c} \Delta$$

- where, $\Delta = \frac{n_1 - n_2}{n_2}$ relative refractive index difference between the core and the cladding.

But $\quad \text{NA} = n_1 (2\Delta)^{1/2}$

$$\Rightarrow \quad \left( \frac{\text{NA}}{n_1} \right)^2 = 2\Delta \Rightarrow \Delta = \frac{1}{2} \left( \frac{\text{NA}}{n_1} \right)^2$$

$$\therefore \quad \delta T = \frac{L n_1}{c} \times \frac{1}{2} \left( \frac{\text{NA}}{n_1} \right)^2$$

This equation represents the maximum pulse broadening in time due to intermodal dispersion in multimode step index fiber.

**Polarization Mode Dispersion (PMD):**
Pulse spreading caused by a change of fiber polarization properties is called PMD. PMD is a serious limitation for fiber optic communication systems operating 40Gb/s per channel. It occurs in single mode fibers when fibers are not cylindrical symmetrical. Single mode fibers support one mode which consists of two orthogonal polarization modes. Ideally, the core of an optical fiber has an index of refraction that is uniform over the entire cross-section. Mechanical stresses and external environmental effects can cause slight changes in the core of the fiber which causes a change in index of refraction. This can cause one of orthogonal modes to travel faster than the other, causing dispersion of optical pulse, so PMD is the result of birefringence which is the difference in refractive indices along perpendicular axis in the fiber. Birefringence arises due to intrinsic and extrinsic non-homogeneity of fiber core diameter.

Causes of PMD

In single mode fiber, PMD is random. It varies from fiber to fiber because of the randomness of the underlying geometric stress irregularities. The birefringence which causes PMD is due to intrinsic and extrinsic factors.

(i) Intrinsic Factors: Intrinsic factors are those that are present in the fiber during manufacturing stage. It can include elliptical core, elliptical cladding, internal stresses, etc. During manufacturing of fiber, the fiber drawing process can induce some asymmetry that cause birefringence.

(ii) Extrinsic Factors: Extrinsic factors are those that induce birefringence after manufacture. Birefringence occurs when external forces act on the fiber. These external forces can be radial compressive forces when fiber lies against each other, compressive and tensile forces when fiber is bent, and shear forces when fiber is twisted. Cabling of fiber after manufacture can cause stresses that induce birefringence. It also occurs due to seasonal heating and cooling of optical fiber.

Group velocity dispersion.

Ans. Group Velocity Dispersion: GVD is the phenomenon that the group velocity of light in a transparent medium depends on the optical frequency or wavelength. The group velocity dispersion is the group delay dispersion per unit length. The basic units are $\text{S}^2/\text{m}$.

For optical fibers, the group velocity dispersion usually defined as a derivative w.r.t. wavelength. This can be calculated as

$$\frac{\partial}{\partial \omega} \left( \frac{1}{v_g} \right) = \frac{\partial}{\partial \omega} \left( \frac{\partial k}{\partial \omega} \right) = \frac{\partial^2 k}{\partial \omega^2}$$

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This is usually specified with units of ps/nm km. GVD is responsible for dispersive effects in fiber optic communication systems.
broadening of pulses as well as for the group velocity mismatch of different waves in parametric nonlinear interactions.

GVD causes a short pulse of light to spread in time as a result of different frequency components of pulse travelling at different velocities

**FIBER CONNECTORS AND SPLICES:**

**Ans.** Good connector should have following requirements:

(i) Low coupling losses
(ii) Ease of assembly
(iii) Low environmental sensitivity
(iv) Low cost
(v) Reliable construction
(vi) Ease of connection

Fiber splice: it is a permanent or semi-permanent joint between two fibers. It is used to create long optical links. Fiber splice is used in situations where frequent connection and disconnection is not needed. Splices are of two types: midspan splice in which two cables are connected and pigtail splice in which there is a connector at one end of the fiber and other end is free for splicing to a cable.

Fiber Connector: It is a detachable connection between two fibers. Connectors are used to link fiber cable with the transmitter or the receiver. Fiber connectors are classified into two broad categories: the butt connector and the Expanded beam connector. In the butt connectors two fiber ends are aligned in such a way that the fiber core axis coincide and are then butted to each other. In the expanded beam connector, lenses are used on the ends of the fibers. This collimates the light emerging from transmitter fiber to be focused on to the core of the receiving fiber.