Signal Degradation in Fibers

The fiber is acting as a transmission medium in optical communication.

The signal passes through this transmission medium, is affected by Attenuation and Dispersion.

Both the parameters will determine the transmission characteristics of the fiber.

Attenuation – The light intensity decreases over a distance.

Dispersion – The width of the pulse is broadening.

2.1 ATTENUATION

Transmission loss (or) Attenuation is one of the important characteristics of a fiber.

It is a measure of decay of signal strength or loss of light power that occurs through the length of the fiber. This characteristic is taking major role in determining the maximum distance between the transmitter and receiver without repeaters. The basic attenuation mechanisms are

i) Absorbtion loss

ii) Scattering loss

iii) Radiative loss

`The unit of attenuation is expressed in terms of logarithmic unit of the decibel. The decibel is defined as the ratio of the input optical power P_i to the output optical power P_o.

$$\text{Number of decibels (db)} = 10\log_{10}\frac{P_i}{P_o}$$

When the light is travel along the fiber, its power decreases exponentially with distance. Let us take the origin process is P(o) and the power at the distance 'z' is P(z) then P(z) is expressed

$$P(z) = P(o)\ e^{-\alpha_p z}$$

$$\text{Where} \qquad \alpha_p = \frac{1}{z}\ln\left[\frac{P(o)}{P(z)}\right]$$

α_p is the fiber attenuation co-efficient, which is having the unit of km^{-1}.

Some times attenuation can be expressed in terms of neper. If P_1 and P_2 are two power levels, with $P_2 > P_1$, then the power ratio in nepers is given as the natural logarithmic unit.

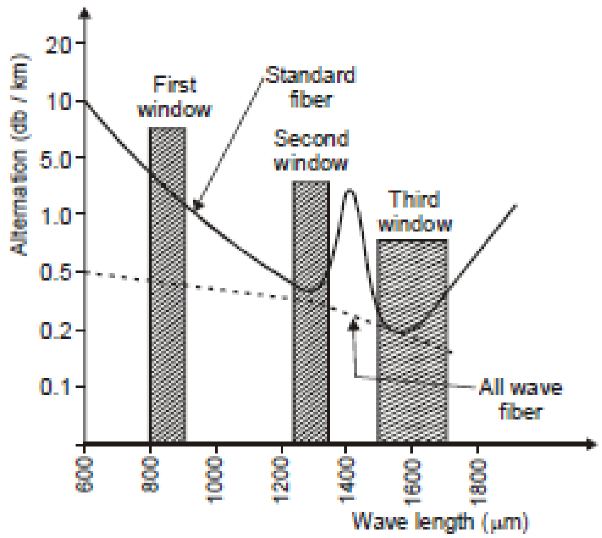


Figure 2.1: Illustration of attenuation as the function of wavelength in Optical Communication

The above figure shows the attenuation variation with respect to wavelength in optical communication. It shows the nominal value of 0.5 db/km at 1300 nm and 0.3 db at 1550 nm for standard single mode fiber (solid line). Dashed line is showing characteristic for all wave fiber.

Three basic attenuation mechanisms:

1. Absorption loss- It is related to the fiber material.

2. Scattering loss – It is due to fiber structure imperfections.

3. Radiative loss- It occurs due to bend of the cable.

2.2 ABSORPTION / MATERIAL ABSORPTION LOSS

It is caused by absorption of photons within the fiber. The photons move the valence electrons to higher energy levels. Hence photons are destroyed and the radiant energy is transferred into electric potential energy.

Absorption is caused by three mechanisms.

i) Absorption by atomic defects in the fiber materials.

ii) Intrinsic absorption by the basic constituent atoms of the fiber material.

iii) Extrinsic absorption by impurity atoms in the fiber material.

2.2.1 Absorption by Atomic Defects

These type of absorption is caused by atomic defects (i.e. improper atomic structure) like missing molecules, clusters of atoms, imperfection of the atomic structure of the fiber material. This type of absorption having very small value, the value is mostly negligible when comparing with instrinsic and extrinsic absorption.

In some places, for example nuclear reactor environment, medical absorption, space mission that pass through the earth's van allen belts, accelerator instrumentation, fiber is exposed to ionizing radiation. This radiation will change the internal structure of the fiber. The total radiation energy received by the fiber is expressed in units of rad (si), which is a measure of radiation absorbed by a silicon.

$$1 \text{ rad (si)} = 0.01 \text{ J/kg}$$

When the radiation level increases, attenuation will get increase. At the time of radiation, radiation particles will be produced. The particles or rays such as electrons, neutrons, gamma rays are affect the structure of fiber.

2.2.2 Intrinsic Absorption

Intrinsic absorption occurs when the material is in absolutely pure state with no impurities.

Electronic absorption – It occurs when a light particle (photon) interacts with an electron and excites it to a higher energy level.

The intrinsic absorption having two type

i) Intrinsic absorption due to ultra violet fail.

i) Intrinsic absorption due to infrared absorption fail

The optical communication wavelength range in terms of μm is 0.8 μm to 1.7 μm. In silica fibers, intrinsic absorption will occur above 1.5 μm. The photons of light energy are converted into random mechanical vibration infrared absorption. Maximum IR peak value at 0.8 μm and minimum peak value at 3.2, 3.8 and 4.4 μm.

In the visible region losses at 1.5 μm are lesser than 0.5 db/km. The optical loss is determined by calculating the presence of OH ions and the inherent infrared absorption of the constitutent material. The inherent absorption will occur because of the interaction between the vibrating bond and the EM field of the optical signal results the transfer of energy between vibrating bond and field,giving rise to absorption. The emperical expression for the infrared absorption for $GeO_2 - SiO_2$ glass isgiven by

$$\alpha\,(\mathrm{IR}) = 7.81 \times 10^{11} \times \mathrm{e}\left(\frac{48.48}{\lambda}\right)$$

Intrinsic absorption also depends upon the electronic absorption bands in the ultraviolet region. Ultraviolet absorption decays exponentially with increasing wavelength at 0.8 μm the ultra violet absorption having the value of 0.3 db/km. Thus in the case of silica fiber, it will act as a transmission window from 1 μm to 1.6 μm.

2.2.3 Extrinsic Absorption by Impurity Atoms

Extrinsic absorption is due to transition metal ions such as iron, chromium, copper, maganese and nickel. This type of absorption is more pronounce in direct melt methods because in that type of fabrication method, the dopants are added directly to the silica. In the case of Vapour Axial Deposition (VAD) the impurity level ranges from 1 to 5 parts per billion. The transision metal ions produce loss at $\mu = 0.8$ μm.

Impurity absorption also results from OHions. TheseOH impurity results from the oxyhydrogen flame used for the hydrolysis reaction of the $SiCl_4$, $GeCl_4$ and $PoCl_3$. This type of absorption is reduced by reducing the water content in the fiber below one ppb (parts per billion).

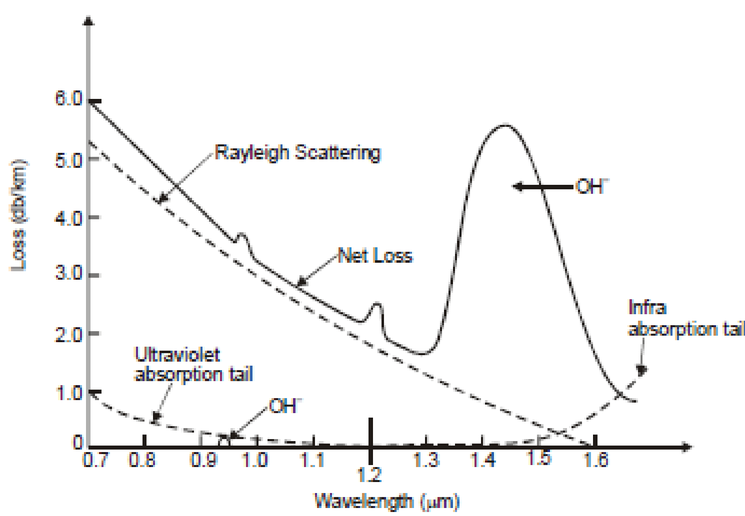


Figure 2.2: Illustrate of types of losses in a pure silica fiber

2.3 SCATTERING LOSSES

Scattering losses arise due to following factors

1. Compositional Fluctuations
2. Structural Inhomogeneties
3. Microscopic variations in the material density
4. Structural defects occuring during fiber fabrication

A glass is composed by randomly connected network of molecules and several oxides. These added molecules and oxides are the major cause of compositional structure fluctuation.

Scattering losses having two types

i) Linear scattering loss

a) Rayleigh Scattering

b). Mie Scattering

ii) Non linear scattering loss

a) Stimulated Brillouin Scattering
b) Stimulated Raman Scattering

2.3.1 Linear Scattering Losses

Linear scattering transfers linearly the optical power in one propagating mode to a different mode. This losses will occurs as a leaky mode or as radiation mode. This mode does not continue to propagate within the fiber core but it is radiated from the fiber. Since there is no change in frequency of the signal, it is said to be linear scattering. Scattering loss will be more in multimode fibers due to higher dopant concentration and greater compositional fluctuations.

2.3.1.1 Rayleigh Scattering

This loss occurs in the Ultra violet region. Its tail extends upto infrared region. It arises from the microscopic inhomogeneities present in the material of fiber. Inhomogeneities may arise from the density fluctuations, reflective fluctuations and compositional variations.

For SiO_2 fiber, Rayleigh loss is given by

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c k T_F m^{-1}$$

where, n - Refractive index of silica

p- Photoelastic co-efficient of silica

β_c - Isothermal compressibility

T_F - Fictive temperature at which solidification of glass takes place or simply annealing temperature.

The transmission loss due to Rayleigh scattering

$$\alpha_{Trans.scatt} = \exp(-\alpha_{scat} L).$$

where, L - length of fiber

At high wavelength Rayleigh scattering loss will be reduced. It is an elastic scattering because there is no change in frequency.

2.3.1.2 Mie Scattering

Mie Scattering arises due to the imperfect structure of the wave guide, irregularities in the core-cladding interface, core-cladding refractive index difference along the fiber and diameter fluctuations.

When the scattering in homogeneities size is greater than $\lambda/10$, angular dependence.

By achieving high relative refractive index difference and doing perfect fabrication Mie scattering get reduced.

2.3.2 Non-linear Scattering Losses

Non linear scattering losses occurs at high power levels. It causes the optical power to be transferred in either forward or backward direction to the same, or other modes at a different frequency.

When the refractive index of the medium depends on the optical intensity of the signal, then these non linear scattering occurs. It becomes significant above threshold power levels. It can also be used to give optical amplification of integrated optical techniques.

Non-linear scattering losses will occur at high power levels. When the transferring of one mode to other mode taking place the output will be forward on reverse direction. This is inelastic scattering due to shift in the frequency when the refractive index of the medium depends on the optical intensity of the signal, then these non linear scatterings are occured.

2.3.2.1 Stimulated Brillouin Scattering

Stimulated Brillouin scattering is a loss mechanism due to thermal molecular vibrations within the fiber. This type of scattered light contains upper side band and lower side band along with the incident light frequency.

The incident photon in the scattering process produces a photon of acoustic frequency as well as a scattered photon.

The frequency shift varies with the scattering angle.

The frequency shift is shift is maximum in the backward direction and reducing to zero in the forward direction.

The Brillouin scattering is only significant above threshold power density.

$$P_{SBS} = 4.4 \times 10^{-3}\, d^2\, \lambda^2 \alpha_B\, B \text{ Watts.}$$

The threshold optical power form Brillouin Scattering is proportional to $d^2\lambda^2\alpha_B$

where d - Fiber core diameter

λ - Operating wavelength

α_B - Brillouin scatteringloss co-efficient

B- Source Bandwidth.

In stimulated Brillouin scattering an incident light will produce scattered photon as well as a photon of acoustic frequency.

2.3.2.2 Stimulated Raman Scattering

The scattered light consist of a scattered photon and a high frequency optical photon. In contrast to Brillouim scattering, Raman scattering is having three orders of high magnitude. The threshold optical power for Raman Scattering is given by.

$$P_{SRS} = 5.9 \times 10^{-2}\, d^2\, \lambda \alpha_B \text{ Watts.}$$

where d - Core diameter

λ - Operatingwave length

α_R - Raman scattering loss co-efficient

2.4 RADIATIVE LOSSES (OR) BENDING LOSSES

Whenever the bends and curves will be in the path of optical ray radiative losses will occur.

There are two types of bending losses,

a) Macroscopic bending bsses

b) Microscopic bending losses

2.4.1 Macroscopic Bending Losses (or) Large Radius Losses

These occur when the radius of curvature of bend is greater than the fiber diameter. When the radius of curvature of bend decreases (or) curvature of fiber increases, the loss increases exponentially upto a critical radius of curvature.

To maintain a wave front perpendicular to the direction of propagation, the part of the mode which is on the cladding may be required to travel faster than that on the inside. This is not possible, so the energy associated with this part of the mode is lost through radiation.

The higher order modes are bound less tightly to the fibre core than lower order modes, the higher order modes will radiate out of the fiber first.

The total number of modes that can be supported by a curved fiber is less than in a straight fiber.

For multimode fiber the critical radius of curvature of bend $'R_c' = \frac{3 n_1^2 \lambda}{4\pi\left(n_1^2 - n_2^2\right)^{3/2}}$.

The attenuation co-efficient by the macrobends $\alpha_b = A \exp(-B R_c)$

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

Where λ_c = cutoff wavelength

$$= \frac{2\pi a n_1 \sqrt{2\Delta}}{2.405}$$

$$= \frac{2\pi a (NA)}{2.405}$$

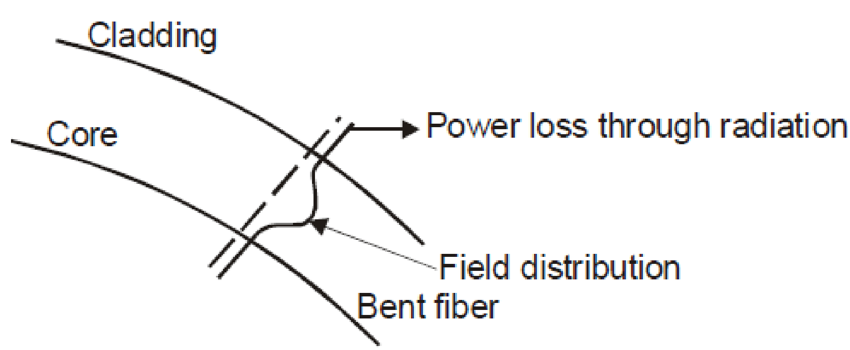


Figure 2.3: Radiation loss at a fiber bend

Minimization of this type of losses is done by

i) Fibers with large relative refractive index difference.

ii) Operating at the shortest wavelength possible

2.4.2 Microbending (Mode Coupling Losses)

Microbending introduces from the fiber when it is incorporated into cables. This type of bending introduces slight surface imperfections which can cause mode coupling between adjacent modes or coupling of energy between the guided modes and the leaky modes (non guided modes) in the fiber which inturn creates a radiative loss. The losses due to non uniform pressure during cabling is referred as cabling or packaging losses. The loss is depends on the fiber deformation, length of fiber and the optical power distribution. Microbending losses proportional to the number of modes propagating through the fiber and inversely proportionalto wavelength.

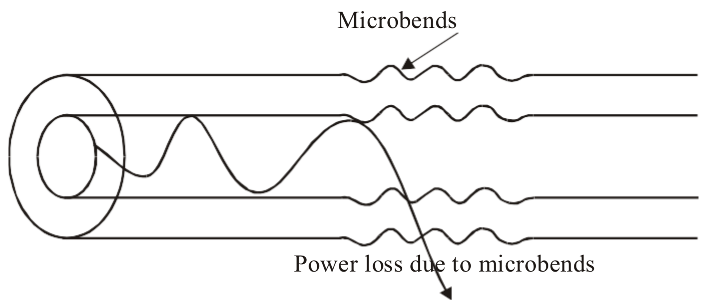


Figure 2.4

Minimization of this microbending loss is done by

1. Introducing compressible jacket over the fiber.

2. When external forces are applied, the jacket will be deformed but the fiberwill tend to stay relatively straight.

2.5 CORE-CLADDING LOSS

The core and cladding have different refractive indices because they are having different composition. Therefore core and cladding have different attenuation co-efficients α_1 and α_2 respectively.

For step index fiber, the loss for a mode of order (v, m) is given by

$$\alpha_{(v,m)} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P}$$

We know that

$$\frac{P_{core}}{P} = 1 - \frac{P_{clad}}{P}$$

Therefore the above equation becomes

$$\alpha_{(v,m)} = \alpha_1 \left(1 - \frac{P_{clad}}{P}\right) + \alpha_2 \frac{P_{clad}}{P}$$

$$\alpha_{(v,m)} = \alpha_1 + (\alpha_2 - \alpha_1) \frac{P_{clad}}{P}$$

The total loss of the fiber can be found by summing over all modes weighted by the fractional power in that mode

Graded-Index Fiber

The attenuation coefficients and modal power are functions of radial coordinates. The loss at radial distance *r* from core axis is expressed as

$$\alpha\,(r) = \alpha_1 + (\alpha_1 - \alpha_2) \frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2}$$

Where α_1 and α_2 are the axial and cladding attenuation coefficients respectively. The loss increases with increasing mode number.

2.6 DISPERSION IN FIBERS

Dispersion causes the spreading of pulse width in the fiber. This broadening or spreading of the pulse determines how close (in time) two adjacent output pulses are. There should be a minimum spacing required between the output pulses, then only the receiver can able to resolve the two separate pulses.

So the amount of pulse spreading in the fiber limits the maximum rate at which data can be sent. Otherwise we can say if the data rate is fixed, the amount of spreading determines the maximum length of the fiber. The dispersion degrades the input signal, at the output side overlapping between the pulses will introduce the Inter

Symbol Interference.

2.8 INFORMATION CAPACITY DETERMINATION

Due to dispersion, pulse broadening will occur in signal, causes signal distortion along the fiber. So overlap between the pulses will occur at the receiver side yieds error. Thus, the dispersive properties determine the limit of the information capacity of the fiber. A measure of the information capacity of an optical waveguide is generally represented by the bandwidth distance product in MHz km.

As the length of an optical cable increases, the bandwidth decreases in proportion.

For step index the bandwidth distance product is 20 MHz km and for graded index it is 2.5 GHz. km.

Input Pulse

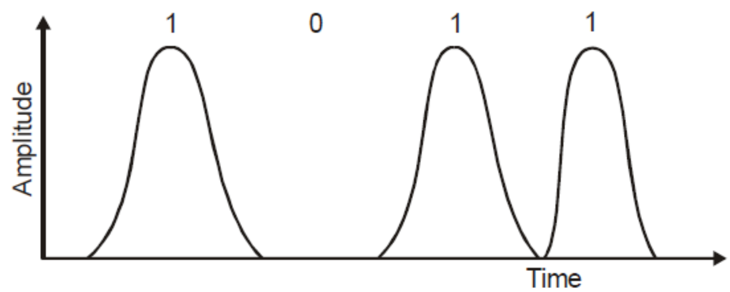


Figure 2.6

Fiber output with Intersymbol Interference

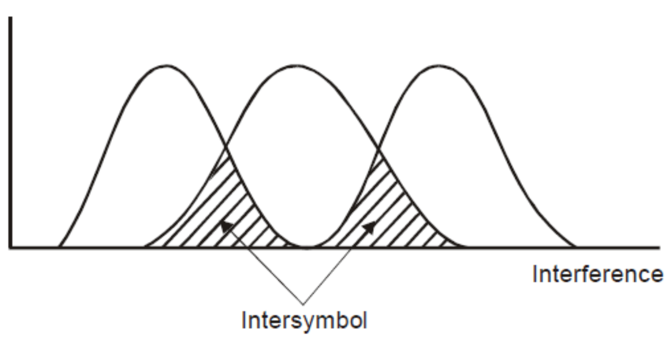


Figure 2.7

2.14 RELATION BETWEEN DISPERSION AND BANDWIDTH

Dispersion is directly affect the bandwidth. Bandwidth is expressed interms of bandwidth length product. Broadening of light pulses occur in the output side when light ray travels along the fiber. This will reduce the maximum bit rate. Let us take the pulse duration as τ and the pulse broadening due to dispersion in the fiber optic link as τ.

The maximum bit rate = $\frac{1}{2\tau}$.

Due to pulse broadening, bandwidth of fiber (B_T) get reduced and it is inversely proportional to 2τ.

$$B_T \leq \frac{1}{2\tau}$$

Optimum value is given by

$$B_{opt} = \frac{1}{2\tau}$$

Due to dispersion,
Bandwidth length product is becomes

$$B_{opt} L = \frac{0.44}{\tau} \text{ ns km}^{-1} \qquad \text{(or)}$$

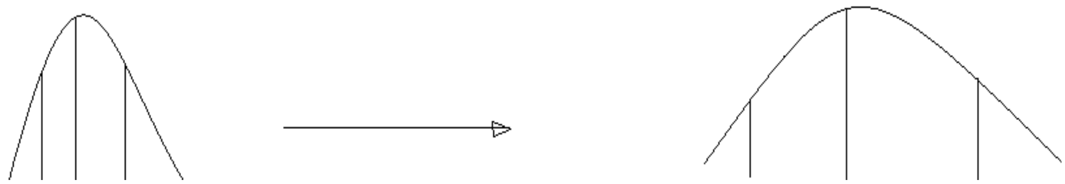
$$B_{opt} = \frac{0.44}{L\tau}$$

Dispersion :

- ❖ Pulse broadening in optical fiber.
- ❖ Occurs due to group velocity and group delay.

Group delay :

Delay that occurs between two spectral components travelling with different wavelengths at the receiving end.
Corresponding velocity is called group velocity.
When the signal enters the optical fiber, the signal will be narrow but when it is received at the other end, it gets broadened.



Narrow pulse Broadened pulse

As wavelength increases, propagation delay increases which in turn increases the pulse width. This broadening of pulse is called dispersion.

<u>To find Dispersion parameter</u>

1. **<u>Find the relationship between group delay and group velocity.</u>**

Phase velocity $V_p = \omega / \beta$

Group velocity $V_g = d\omega / d\beta$

Group delay $\tau_g = L / V_g$

$$\tau_g = \frac{L}{d\omega / d\beta} = L.\frac{d\beta}{d\omega}$$

$$\boxed{\tau_g = L.\frac{d\beta}{d\omega}} \longrightarrow 1$$

Where, L- length of fiber

2. **Substitute $\omega = 2\pi f$ in eqn.1 and simplify**

$$\tau_g = L.\frac{d\beta}{d(2\pi f)} = L.\frac{d\beta}{d\left(\frac{2\pi c}{\lambda}\right)} = \frac{L}{2\pi c}.\frac{d\beta}{d\lambda^{-1}}\left(\frac{d\lambda}{d\lambda}\right)$$

$$\boxed{\tau_g = \frac{L}{2\pi c}.\frac{d\beta}{d\lambda}.\frac{d\lambda}{d\lambda^{-1}}} \longrightarrow 2$$

To find $\frac{d\lambda}{d\lambda^{-1}}$

$$\frac{d(\lambda^{-1})}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{\lambda}\right) = \frac{-1}{\lambda^2} \qquad \frac{d(\lambda)}{d\lambda^{-1}} = -\lambda^{-2}$$

From eq. 2

$$\boxed{\tau_g = \frac{-\lambda^2 L}{2\pi c} \cdot \frac{d\beta}{d\lambda}} \longrightarrow 3$$

3. **Calculate delay difference per unit wavelength**

$$\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left[\frac{-\lambda^2 L}{2\pi c} \cdot \frac{d\beta}{d\lambda}\right]$$

$$= \frac{-L}{2\pi c}\left[\frac{\lambda^2 . d^2\beta}{d\lambda^2} + 2\lambda\frac{d\beta}{d\lambda}\right]$$

Dispersion is due to the first term $\frac{\lambda^2 . d^2\beta}{d\lambda^2}$ and the second term is neglected.

$$\frac{d\tau_g}{d\lambda} = \frac{-L}{2\pi c}\left[\frac{\lambda^2 . d^2\beta}{d\lambda^2}\right]$$

4. **Find rms pulse width broadening parameter**

$$\sigma_g = \left|\frac{d\tau_g}{d\lambda}\right| . \sigma_\lambda$$

$$= \left|\frac{-L}{2\pi c}\left[\frac{\lambda^2 . d^2\beta}{d\lambda^2}\right]\right| . \sigma_\lambda$$

Where, σ_λ is the spectral width of light source.

$$\boxed{\sigma_g = \frac{L}{2\pi c}\left|\frac{\lambda^2 d^2\beta}{d\lambda^2}\right| . \sigma_\lambda} \longrightarrow 4$$

Dispersion parameter $D = \left|\frac{\lambda^2 d^2\beta}{d\lambda^2}\right|$ ps/Km/nm.

$D = D_{material} + D_{waveguide}$

This dispersion is called Intra modal dispersion.

.**TYPES OF DISPERSION:**

DISPERSION

Material dispersion

INTRAMODAL (OR) CHROMATIC DISPERSION → Waveguide dispersion

→ INTERMODAL DISPERSION

INTRAMODAL DISPERSION:

- Occurs in all types of fibers.
- Optical source emits band of frequencies.
- Due to this there may be propagation delay differences b/w the different spectral components of the transmitted signal.
- Cause pulse broadening of each mode leads to intramodal dispersion.
- The delay differences caused by

- Properties of material → Material dispersion.
- Guidance effects in fiber structure → Waveguide dispersion

1. Expressions for Material Dispersion:

Material dispersion:

Material dispersion occurs due to variation of refractive index of the medium depending on wavelength.

In dispersion medium, 'n' is a function of 'λ'.

Propagation constant , β = $\frac{2\pi n(\lambda)}{\lambda}$ for dispersion medium.

Group delay , $\tau_g = \frac{-\lambda^2 L}{2\pi c} \cdot \frac{d\beta}{d\lambda}$ from eqn. 3

Group delay due to material dispersion is

$$\tau_g = \tau_{mat} = \frac{-\lambda^2 L}{2\pi c} \cdot \frac{d}{d\lambda}\left[\frac{2\pi n(\lambda)}{\lambda}\right]$$

$$= \frac{-\lambda^2 L}{2\pi c} .2\pi \frac{d}{d\lambda}\left[\frac{n(\lambda)}{\lambda}\right]$$

$$= \frac{-\lambda^2 L}{c} \cdot \frac{d}{d\lambda}\left[n(\lambda).\lambda^{-1}\right]$$

$$= \frac{-\lambda^2 L}{c}\left[\lambda^{-1}.\frac{dn(\lambda)}{d\lambda} + n(\lambda).(-\lambda^{-2})\right]$$

$$\boxed{\tau_{mat} = \frac{-L}{c}\left[\lambda.\frac{dn(\lambda)}{d\lambda} - n(\lambda)\right]} \longrightarrow 5$$

Material dispersion delay per unit wavelength

$$\frac{d\tau_{mat}}{d\lambda} = \frac{d}{d\lambda}\left[\frac{-L}{C}\left\{\frac{\lambda dn(\lambda)}{d\lambda} - n(\lambda)\right\}\right]$$

$$= \frac{-L}{C}\left[\lambda.\frac{d^2n(\lambda)}{d(\lambda^2)} + \cancel{\frac{dn(\lambda)}{d\lambda}} - \cancel{\frac{dn(\lambda)}{d\lambda}}\right]$$

$$\frac{d\tau_{mat}}{d\lambda} = \frac{-L}{C}\left[\lambda.\frac{d^2n(\lambda)}{d(\lambda^2)}\right]$$

The rms pulse width broadening is given by

$$\tau_{mat} = \left|\frac{d\tau_{mat}}{d\lambda}\right| . \sigma_\lambda$$

where σ_λ is the spectral width of light source.

$$\sigma_{mat} = \left|\frac{-L}{C}\left(\frac{\lambda.d^2n(\lambda)}{d\lambda^2}\right)\right| . \sigma_\lambda$$

$$= \frac{L}{C}\left|\frac{\lambda.d^2n(\lambda)}{d\lambda^2}\right| . \sigma_\lambda \qquad \text{ps or ns.}$$

Material dispersion parameter

$$D_{mat} = \frac{1}{C}\left(\frac{\lambda.d^2n(\lambda)}{d\lambda^2}\right) \text{ ps. Nm}^{-1}\text{.km}^{-1}$$

Minimization

Material dispersion can be reduced by using

i) Using narrow spectral width light source like LASER.

ii) Using longer wavelength operation since refractive index difference is small or negligible.

2. Expressions for waveguide dispersion:

Waveguide dispersion is a type of intramodal dispersion which occurs due to variation of group velocity as a function of wavelength for a particular mode.It is wavelength independent.

Group delay can be expressed in terms of normalized propagation constant 'b' defined as

$$\boxed{b = \frac{\frac{\beta^2}{k^2} - n_2^2}{n_1^2 - n_2^2}} \longrightarrow 1$$

For small values of index difference $\Delta = \frac{n_1 - n_2}{n_1}$, eqn. 1 can be approximated by

$$b = \frac{\frac{\beta}{k} - n_2}{n_1 - n_2}$$

$$\frac{\beta}{k} = n_2 + b\,(n_1 - n_2)$$

$$\boxed{\beta = k\,(n_2 + b\,(n_1 - n_2))} \longrightarrow 2$$

Differentiate eqn. 2 wrt 'k'

$$\frac{d\beta}{dk} = n_2 + b\,(n_1 - n_2)$$

$$= n_2 + b\,(n_1 - n_2).\frac{dk}{dk}$$

$$\boxed{\frac{d\beta}{dk} = n_2 + (n_1 - n_2).\frac{d(bk)}{dk}}$$

Group delay for waveguide dispersion

$$\tau_{wg} = \frac{L}{C}.\frac{d\beta}{dk}$$

$$= \frac{L}{C}\left[n_2 + (n_1 - n_2).\frac{d(bk)}{dk}\right]$$

$$= \frac{Ln_2}{C}\left[\frac{n_2}{n_2} + \frac{n_1 - n_2}{n_2}.\frac{d(bk)}{dk}\right]$$

$$\tau_{wg} = \frac{Ln_2}{C}\left[1 + \Delta.\frac{d(bk)}{dk}\right] \qquad (\because n_2 \approx n_1)$$

The normalized frequency V is given by

$$V = k\,a\sqrt{n_1^2 - n_2^2}$$

$$V \approx kan_2\sqrt{2\Delta} \qquad (\because n_2 \approx n_1)$$

The approximation of V is valid for small values of Δ and hence group delay can be expressed in terms of V instead of k.

$$V \approx k$$

$$\boxed{\therefore \quad \tau_{wg} = \frac{L}{C}\left[n_2 + n_2\Delta.\frac{d(bV)}{dV}\right]} \longrightarrow 3$$

The first term is a constant and second term represents the group delay arising from waveguide dispersion.

<u>The rms pulse broadening due to waveguide dispersion is</u>

$$\sigma_{wg} = \left|\frac{d\tau_{wg}}{d\lambda}\right|.\sigma_\lambda \qquad ps\ km^{-1}\ nm^{-1}$$

To find $\frac{d\tau_{wg}}{d\lambda}$

$$\boxed{\frac{d\tau_{wg}}{d\lambda} = \frac{d\tau_{wg}}{dv}.\frac{dv}{d\lambda}} \longrightarrow 4$$

$$\frac{d\tau_{wg}}{dv} = \frac{d}{dv}\left[\frac{L}{C}(n_2 + n_2\Delta\frac{d(bv)}{dv}\right]$$

$$\boxed{\frac{d\tau_{wg}}{dv} = \frac{Ln_2\Delta}{C}.\frac{d^2(bv)}{dv^2}} \longrightarrow 5$$

$$\frac{dv}{d\lambda} = \frac{d}{d\lambda}\left[\frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}\right] \qquad \left(\because V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}\right.$$

Or

$$= \frac{d}{d\lambda}\left[2\pi a\sqrt{n_1^2 - n_2^2}.(\lambda^{-1})\right] \qquad V = k\,a\sqrt{n_1^2 - n_2^2}$$

where $k = 2\pi/\lambda$

$$= -2\pi a\sqrt{n_1^2 - n_2^2}.(\lambda^{-2})$$

$$\boxed{\frac{dv}{d\lambda} = \frac{-2\pi a\sqrt{n_1^2 - n_2^2}}{\lambda^2}} \longrightarrow 6$$

Substitute eqn. 5 and 6 in 4

$$\frac{d\tau_{wg}}{d\lambda} = \frac{Ln_2\Delta}{C}.\frac{d^2(bv)}{dv^2} \text{ x } \frac{-2\pi a\sqrt{n_1^2-n_2^2}}{\lambda^2}$$

$$= \frac{Ln_2\Delta}{C}.\frac{d^2(bv)}{dv^2} \text{ x } \frac{-V\cancel{\lambda}}{\cancel{\lambda}^2}$$

$$\boxed{\frac{d\tau_{wg}}{d\lambda} = \frac{-Ln_2\Delta V}{C\lambda}.\frac{d^2(bv)}{dv^2}} \longrightarrow \quad 7$$

$$\therefore \sigma_{wg} = \left|\frac{-Ln_2\Delta V}{C\lambda}.\frac{d^2(bv)}{dV^2}\right|.\sigma_\lambda$$

$$\sigma_{wg} = \left[\frac{L.n_2\Delta V}{C\lambda}.\frac{d^2(bv)}{dv^2}\right].\sigma_\lambda \quad \text{ps or ns.}$$

Waveguide dispersion parameter

$$D_{wg} = \frac{1}{L}\left(\frac{d\tau_{wg}}{d\lambda}\right)$$

$$= \frac{1}{\cancel{L}}\left(\frac{-\cancel{L}n_2\Delta V}{C\lambda}.\frac{d^2(bv)}{dv^2}\right)$$

$$\boxed{D_{wg} = \frac{-n_2\Delta V}{C\lambda}.\frac{d^2(bv)}{dv^2} \quad \text{ps.km}^{-1}.\text{nm}^{-1}} \longrightarrow 8$$

$$\boxed{\therefore \quad \sigma_{wg} = L\,|\,D_{wg}\,|\,\sigma_\lambda \quad (\text{ps or ns})} \longrightarrow 9$$

Minimization :

Wavelength dispersion can be reduced by

i) Using large index difference.

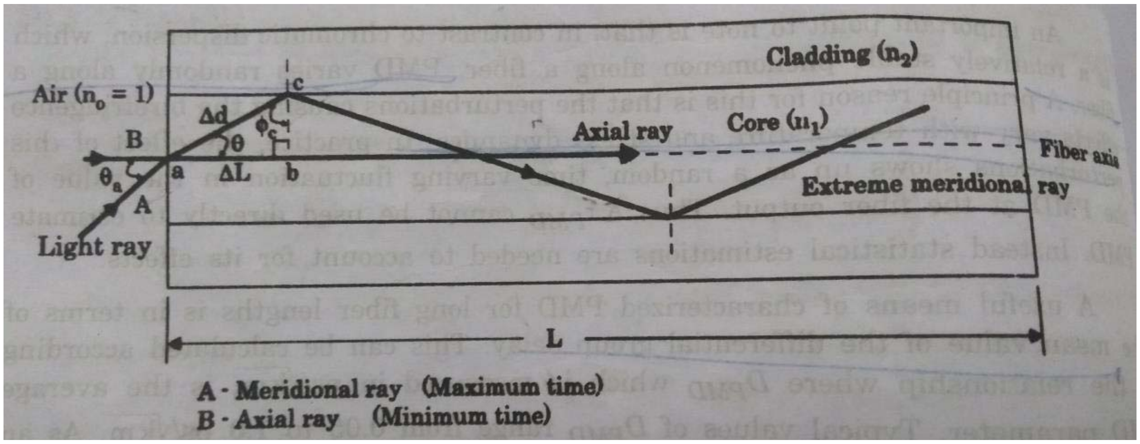
ii) Using short wavelength operation.

INTERMODAL DISPERSION (OR) MODAL DELAY.

→In multimode fibers many modes propagate along the fiber at a time.

→Different modes take different ray path and they reach at different time at the output end of the fiber, so a time delay is experienced between modes. This is called intermodal delay.

→Pulse broadening occurs due to intermodal delay is called intermodal dispersion.



A	→	Meridionel Ray	→	Travels maximum Time
B	→	Axial Ray	→	Travels minimum Time

The time required for axial ray to travel over fiber is

$$T_{min} = \frac{Distance}{Velocity} = \frac{L}{C/n_1} = \frac{n_1 . L}{C}$$

By applying snell's law in Δ abc, we get

$$\text{Sin}\phi_c = \frac{n_2}{n_1},$$

From the above figure Δ abc, $\phi_c = 90^\circ - \theta$.

$$\therefore \ \text{Sin}(90 - \theta) = \frac{n_2}{n_1} = \text{Cos}\,\theta = \frac{n_2}{n_1},$$

From Δ abc, consider a small length ab = ΔL

$$\therefore \ \text{Cos}\,\theta = \frac{\Delta L}{\Delta d}$$

When $\Delta \rightarrow \infty$; $\text{Cos}\,\theta = \frac{L}{d} \Longrightarrow \boxed{d = \frac{L}{Cos\theta}}$

The time required for meridionel Ray to travel over the fiber is

$$T_{max} = \frac{Distance}{Velocity} = \frac{L/Cos\theta}{C/n_1} = \frac{n_1.L}{C.Cos\theta} = \frac{n_1.L}{C.n_2/n_1} = \frac{L.n_1^2}{C.n_2}$$

$$\boxed{T_{max} = \frac{L.n_1^2}{C.n_2}}$$

The delay between meridionel and axial ray at the output end of the fiber is

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

$$= \frac{Ln_1^2}{Cn_2} - \frac{Ln_1}{C} = \frac{Ln_1^2 - Ln_1 n_2}{Cn_2}$$

$$= \frac{Ln_1^2}{Cn_2}\left[1 - \frac{n_2}{n_1}\right] = \frac{Ln_1^2}{Cn_2}\left[\frac{n_1 - n_2}{n_1}\right]$$

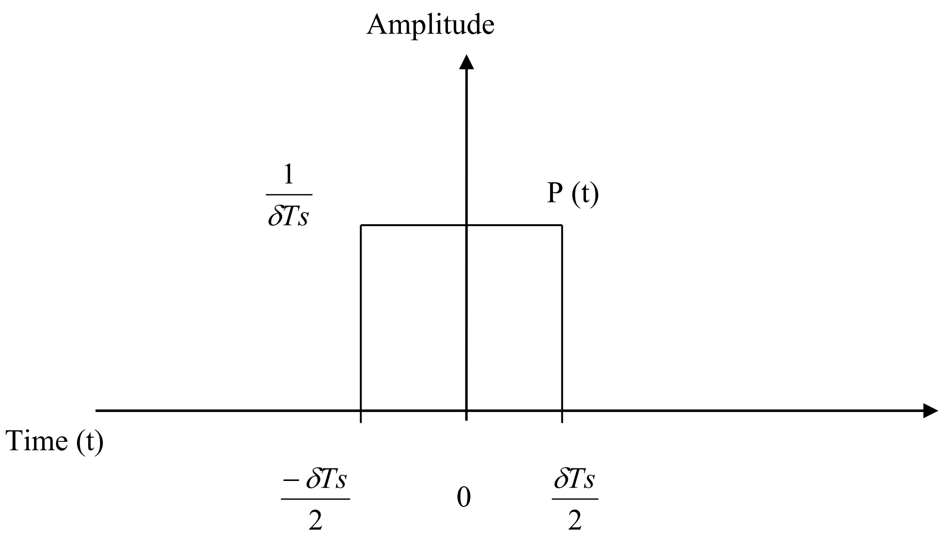
$$\delta T_s = \frac{Ln_1^2.\Delta}{C.n_2}$$

When $n_1 \approx n_2$; then

$$\boxed{\delta T_s = \frac{Ln_1 .\Delta}{C}}$$

<u>RMS pulse broadening;-</u>

Time Delay as rectangular function with unit area.



The variance for the pulse P (t) is

$$\sigma_s^2 = \int_{\frac{-\delta Ts}{2}}^{\frac{\delta Ts}{2}} P(t).t^2.dt = \int_{\frac{-\delta Ts}{2}}^{\frac{\delta Ts}{2}} \frac{1}{\delta Ts}.t^2.dt$$

$$= \frac{1}{\delta Ts}\left[\frac{t^3}{3}\right]_{\frac{-\delta Ts}{2}}^{\frac{\delta Ts}{2}} = \frac{1}{3\delta Ts}\left[\left(\frac{\delta Ts}{2}\right)^3 + \left(\frac{\delta Ts}{2}\right)^3\right]$$

$$\sigma_s^2 = \frac{1}{3\delta Ts} X 2.\left(\frac{\delta Ts}{2}\right)^3 = \frac{2.\delta Ts^3}{3X8X\delta Ts} = \frac{\delta Ts^2}{12}$$

$$\boxed{\sigma_s^{\,2} \quad = \quad \frac{\delta Ts^2}{12}}$$

The rms Pulse broadening due to intermodal dispersion is $\sigma_s = \dfrac{\delta Ts}{2\sqrt{3}}$

Substitute $\delta T_s = \dfrac{Ln_1 \,.\Delta}{C}$

$$\boxed{\therefore \quad \sigma_s \quad = \quad \frac{Ln_1 \,.\Delta}{2\sqrt{3}.C}}$$

The maximum Bit rate is $B_{T\,(\max)} = \dfrac{1}{2\tau} = \dfrac{1}{2\delta Ts}$

Maximum optical Bandwith is $B_{opt\,(\max)} = \dfrac{0.2}{\sigma_s}$ and the bandwidth length product is B_{opt} x L.

- Intermodal dispersion is mimimized by using parabolic Index profile in multimode fiber.

Overall Fiber dispersion:

The overall dispersion in multimode fiber comprises both chromatic and intermodal terms. The total rms pulse broadening is

$$\sigma_T = \left[\sigma_C^{\;2} + \sigma_S^{\;2}\right]^{1/2}.$$

Where

σ_c = rms pulse broadening of intramodal dispersion

and

σ_s = rms pulse broadening of intermodal dispersion.

$\sigma_c \longrightarrow$ chromatic dispersion consists of material and waveguide dispersion.

- Waveguide dispersion is negligible compared to material dispersion. $\therefore (\sigma_c = \sigma_{mat}) \qquad \sigma_T = \left(\sigma_{mtc}^{\;2} + \sigma_s^{\;2}\right)^{1/2}$

Minimization

- Intermodal dispersion - Reduced when using parabolic index profile in MM fiber.
- Material dispersion - Narrow spectral width light source like laser.
  - For MM laser diode, σ_λ and 10^2 nm.
  - For SM laser diode, σ_λ and 10^{-2} nm.
  - Longer wavelength operation, since refractive index difference is small or negligible.
- Waveguide dispersion - Index difference should be large.
  - Short wavelength operation.

- ❖ PMD - The distance between two polarization modes must be Less than both beat length and coupling of birefringence.

Polarization Mode dispersion (PMD)

- ❖ Different frequency component of a pulse acquires different polarization states (such as linear polarization and circular polarization). This results in pulse broadening is known as polarization mode dispersion (PMD).
- ❖ PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Fiber Birefringence

- ❖ The algebraic difference of the index of refraction of the fiber for plane polarized light vibrating parallel to the longitudinal axis of the fiber and the index of refraction for light vibrating perpendicular to the long axis is called fiber birefringence.
- ❖ Can occur due to internal and external stress or fiber bending.
- ❖ Two orthogonal polarization modes make difference in effective refractive indices (n_x - n_y) and this difference is called as birefringence.

- ❖ The modes have different propagation constants

  β_x → for slow mode

  β_y → for fast mode
- ❖ Modal Birefringence B_f

$$B_f = n_x - n_y = \frac{\beta_x \lambda}{2\pi} - \frac{\beta_y \lambda}{2\pi} = \frac{(\beta_x - \beta_y)\lambda}{2\pi}$$

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

- ❖ Linear retardation $\phi(z)$ occurred due to difference in phase velocities which depends on fiber length L

$$\boxed{\phi(z) = (\beta_x - \beta_y)L}$$

→Phase coherence of two mode components is achieved when the delay between two transit times is less than the coherence time of the source.

→The coherence time for the source is equal to the reciprocal of the un correlated source frequency width ($1/\delta$ f).

Fiber Beat length: It is a characteristic of optical fiber used to calculate the fiber's ability to maintain polarization. The beat length describes the length required for the polarization to rotate 360 degrees. For a given wavelength, it is inversely proportional to the fiber's birefringence

The propagation distance for which a 2π phase difference accumulates between the two polarization modes is known as beat length.

$$\boxed{L_B = \frac{\lambda}{B_f}} \qquad \boxed{L_B = \frac{2\pi}{\beta_x - \beta_y}}$$

Polarization Maintaining fibers:

- Symmetrical cylindrical fiber structure should be maintained.
- It is unsymmetrical then the fast & slow modes of polarization will be obtained.
- Which causes delay b/w the modes.
- The unsymmetrical condition of the fiber occurs due the birefringence effect.
- Birefringence has two effects - Geometric effect

  \- Stress effect.
- Geometric effect occurs during manufacturing process.
- Stress effect occurs due to external force.
- Different types Stresses cause birefringence effect.
  - → bow-tie fiber → elliptical cladding
  - → twisted fiber → flat cladding
  - → circular fiber
- Birefringence effect can be reduced by modern fabrication technique.
- Fabrication techniques such as CVD, MCVD → PCVD can reduced this effect.
- PCVD reduces the pulse broadening and dispersion will also get reduced.
- Characteristics of PM fibers are described not only by the modal birefringence or beat length but also by the modes coupling parameter or polarization crosstalk.
- The mode coupling parameter or coefficient h, which characterizes the PM ability of fibers based on random mode coupling, useful in the comparison of different length of the fiber. It is related to polarization crosstalk. (CT)

$$CT = 10\log_{10}\frac{P_y}{P_x} = 10\log_{10}\tan.h(hl)$$

Where l – fiber length.

P_x & P_y – represent optical power in the excided mode and coupled mode.

Mode Coupling

After certain initial length, the **pulse distortion increases** less rapidly because of **mode coupling**. The energy from one mode is coupled to other modes because of:

1. Structural imperfections.
2. Fiber diameter variations.
3. Refractive index variations.
4. Microbends in cable.

Due to mode coupling, average propagation delay becomes less and intermodal distortion reduces.

2.9 SIGNAL DISTORTION IN SINGLE MODE FIBERS

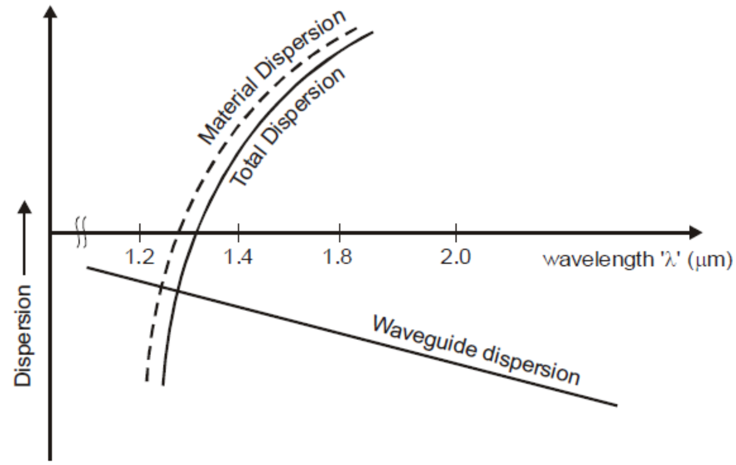


Figure 2.8: Signal distortion in single mode fibers

We can make the total dispersion value to zero by the cancellation of positive material dispersion and negative waveguide dispersion.

2.11 REFRACTIVE INDEX PROFILE DISPERSION

The wavelength of the carrier light and the nature of the dopant material will decide the optimum value of attenuation.

$$\text{Optimum value of } \alpha = 2 - \frac{12\Delta}{5}$$

This type of dispersion due to different dispersive properties of dopant material and host material. This can be reduced by shaping the refractive index profile of the core in a parabolic manner where $\alpha = 2$.

2.12 BROADERNING OF PULSE DUE TO LIGHT SOURCE

Dispersion for LED sources is more and for single mode laser diode, the value of the dispersion is very small.

Dispersion in Different Fibers

i) Multimode Step Index Fiber

Due to large amount of pulse broadening. Multimode step index fiber exhibit a large value of dispersion. Multimode step index fiber having intermodal dispersion of high value and smaller waveguide dispersion.

ii) Multimode Graded Index Fiber

In multimode graded index fiber only material dispersion will dominate and intermodal dispersion is minimum. It exhibits an overall dispersion which is 100 times lesser than the multimode step index fibers dispersion. This is due to shaping the refractive index profile in a parabolic manner.

iii) Single Mode Step Index Fiber

The material and waveguide dispersion will exist $\frac{d^2\beta}{d\lambda^2} \neq 0$. There is no intermodal distortion. For longer wavelength $\sigma_{wg} > \sigma_m$ and with the wavelength less than 1 μm $\sigma_m > \sigma_{wg}$.

2.13 DESIGN OPTIMIZATION OF SINGLE MODE FIBERS AND REFRACTIVE INDEX PROFILES

Single mode fibers are used in the telecommunication applications and optical networks, the dispersion produced in single mode fiber must be reduce. This can be achived by the suitable design of refractive index profile and making the addition of material and waveguide dispersion is equal to zero.

There are three ways of shaping the refractive index profile

1. 1300 nm optimized fiber
2. Dispersion shifted fiber
3. Dispersion flattened fiber
4. Large-effective core area fibers

1. 1300 nm Optimized Fiber

At 1300 nm, single mode fiber is having two types,

i) Matched cladding refractive index profile,

ii) Dispressed cladding refractive index profile.

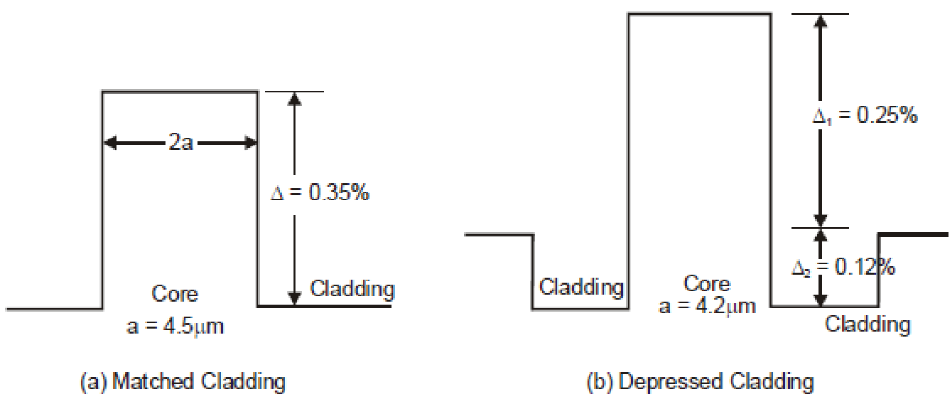


Figure 2.10

Matched cladding fibers having uniform index profile throughout the cladding. In this type mode field diameters are 9.5 μm and relative refractive index difference is about 0.35%. In the dispersed cladding fibers, the cladding region surrounding the core has a lower refractive index than the outer cladding region.

Thus its refractive index is in the form of a depressed manner surrounding with high refractive index regions. This is the type in which the waveguide dispersion value will be zero at 1.3 μm or 1300nm.

2. Dispersion Shifted Single Mode Fibers

Even though there is no waveguide dispersion at 1.3 μm, there will be some finite loss. Therefore now a days the single mode fibers are designed such that zero dispersion at 1.55 μm with a minimum loss. At 1.55 μm, the material dispersion having positive and large value, the same time waveguide dispersion is having negative and small value.

To make the total dispersion value is equal to zero, the relative refractive index different is slightly increased by adding more GeO_2 in core, a triangular refractive index profile can be designed. Thus the dispersion shifted fibers have minimum loss and zero dispersion at 1.55 μm.

3. Dispersion Flattened Fibers

This type fibers having minimum dispersion over a range of wavelengths from 1.3 μm to 1.55 μm. Such that zero dispersion points lie at 1.3 μm and 1.55 μm. These fibers can also be used for wavelength division multiplexing. The refractive index profile is modified, so the dispersion value is shifted to zero.

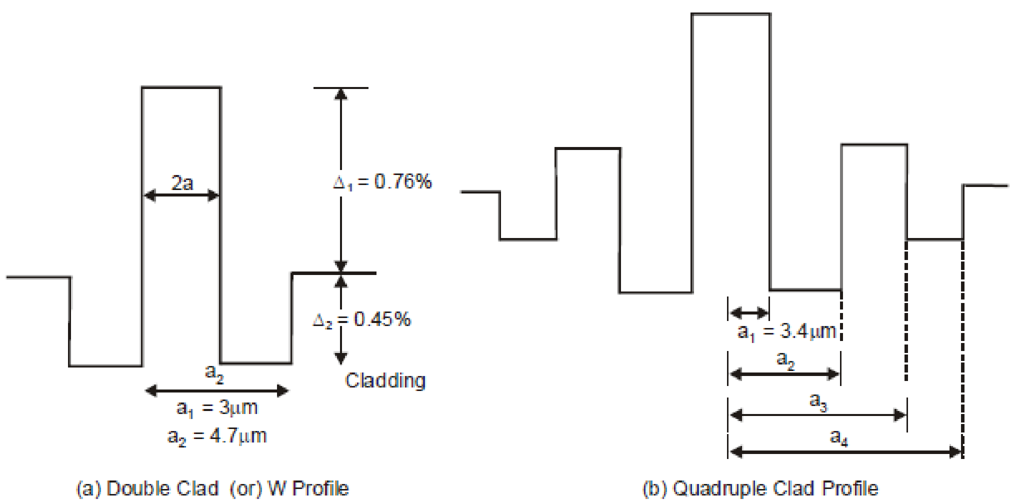


Figure 2.11: Dispersion flattened fibers

There is two type

i) Double clad or w profile ii) Quadrupole clad profile

w profile type with steeper maximum refractive at the center of the core and the quadrupole cladd is the improved version of w profile. All these refractive index profile designs are making zero dispersion at 1.55 μm by adjusting the magnitude of waveguide dispersion.

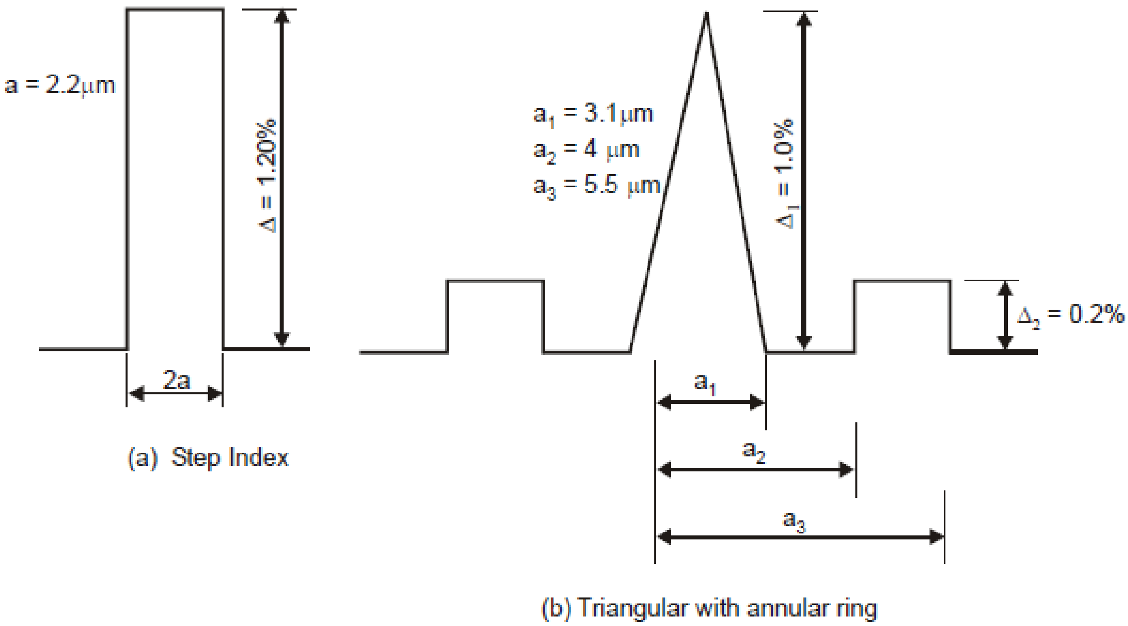


Figure 2.12: Dispersion shifted single mode fiber

4. Large Effective Core Area Fibers

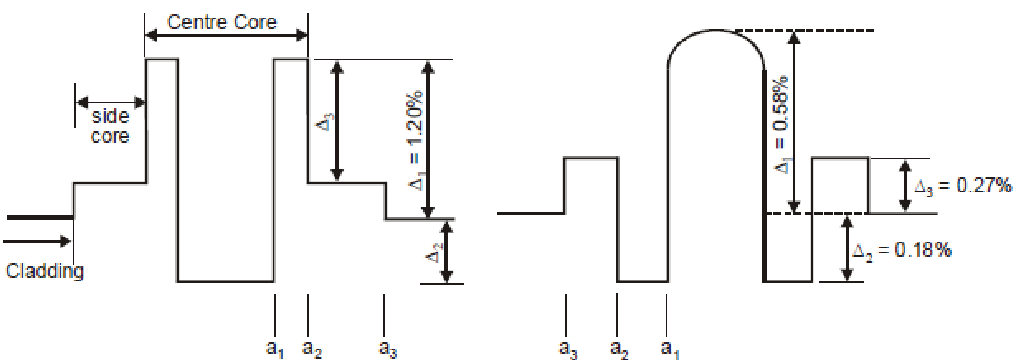


Figure 2.13: Large effective core area fibers

Large core area is the need to reduce the effects of fiber non linearity. Two examples of the index profile is

a) Large area dispersion shifted b) Large area dispersion shifted

2.16 MODE COUPLING

The pulse distortion increases, after a certain initial length of fiber because of mode coupling and different mode loss. Initially coupling of energy from one mode to another arises because of structural imperfections, fiber diameter and refractive index variations and cabling induced microbends.

The pulse spreading caused by mode coupling over the distance z < Lc is related to the excess loss hz is given

$$hz\left(\frac{\sigma_c}{\sigma_0}\right)^2 = C$$

where, $C \rightarrow$ constant

$\sigma_0 \rightarrow$ pulse broadening in the absence of mode coupling

$\sigma_c \rightarrow$ pulse broadening in the presence of mode coupling

$hz \rightarrow$ excess attenuation resulting from mode coupling

C is independent of all dimensional quantities.

The mode coupling is used to average out the propagation delays associated with the modes and thereby reduce the intermodal dispersion.

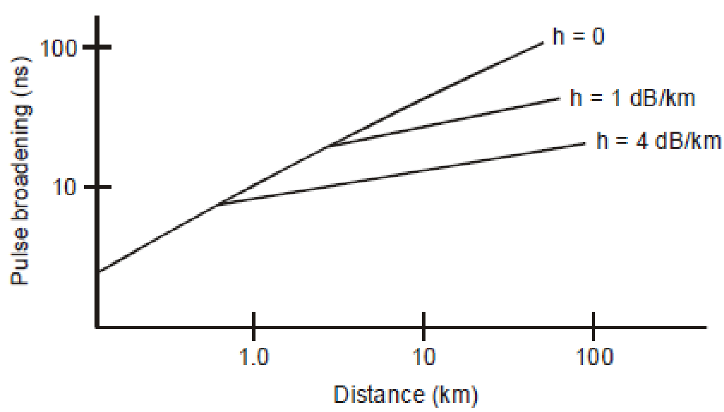


Figure 2.14: Mode -coupling effects on pulse distortion in long fibers for various coupling losses

The mode coupling and power distribution can occur at connectors, splices and other passive components. The transmission bandwidth is affected by mode coupling

2.17 CUTOFF WAVELENGTH

Cutoff wavelength is an important parameter which separates single mode from multimode region. Cutoff of wavelength is given by

$$\lambda_{cutoff} = \frac{2\pi a}{V}\left(n_1^2 - n_2^2\right)^{1/2}$$

$$= \frac{2\pi n}{V}(\text{Numerical Aperture})$$

$$\text{at cutoff } V = 2.405$$

$$\lambda_{cutoff} = \frac{2\pi a}{2.405}\left(n_1^2 - n_2^2\right)^{1/2} \text{ for step index fibers.}$$

For step index fiber the cutoff normalized frequency

$$V_c = 2.405.$$

The cutoff wavelength is $\lambda_c = \dfrac{2\pi a\, n_1}{V_c}(2\Delta)^{\frac{1}{2}}$

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

At this wavelength, only the LP_{01} mode should propagate in the fiber. The cutoff wavelength is an important parameter, when we estimate the radius of curvature for a single mode fiber.

$$R_{CS} = \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left[2.748 - 0.996\frac{\lambda}{\lambda_c}\right]^{-3}$$

Effective Cutoff Wavelength (λ_c)

It is defined as the largest wavelength at which higher order LP_{11} mode power is reduced to 0.1 dB that is when $R(\lambda) = 0.1$ db

$$R(\lambda) = 10 \log \left[\frac{P_1(\lambda)}{P_2(\lambda)} \right]$$

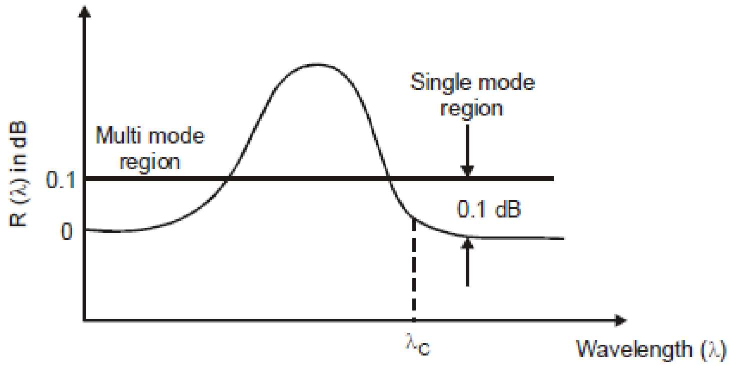


Figure 2.15: R(λ) versus wavelength plot

Recommended value of λ_c range from 1100 to 1280 nm, to avoid modal noise and dispersion problems.

2.15 PULSE BROADENING IN GRADED INDEX WAVEGUIDE

In graded index fibers, intermodal dispersion is dominant. The root mean square (rms) pulse broadening σ in a graded - index fiber can be obtained from the sum

$$\sigma = \left(\sigma^2_{\text{intermodal}} + \sigma^2_{\text{intramodal}} \right)^{1/2}$$

where $\sigma_{\text{intermodal}} \rightarrow$ rms pulse width resulting from intermodal dispersion

$\sigma_{\text{intramodal}} \rightarrow$ rms pulse width resulting from intramodal dispersion

To find the intermodal delay distortion, the relation between intermodal delay and pulse broadening is given by

$$\sigma_{\text{intermodal}} = \left(\left\langle \tau_g^2 \right\rangle - \left\langle \tau_g \right\rangle^2\right)^{1/2}$$

where τ_g is the group delay for a particular mode having the order (V,m).

$$\tau_g(V, m) = \frac{L}{C} \qquad \frac{\partial \beta_{vm}}{\partial k}$$

$$\frac{\tau_g(V, m)}{L} = \frac{1}{C} \qquad \frac{\partial \beta_{vm}}{\partial k}$$

The value of $<\tau_g>^2$ and $<\tau_g>$ is taken as the averages of τ_g^2 and τ_g.

$$\left\langle \tau_g \right\rangle^2 = \sum_{V,m} \frac{P_{vm} \tau_g^2(V, m)}{m}$$

and $$\left\langle \tau_g \right\rangle = \sum_{V,m} \frac{P_{vm} \tau_g(V, m)}{m}$$

where

$P_{vm} \rightarrow$ Optical power contained in the mode of order (V,m)

$m \rightarrow$ Number of fiber modes

By omitting the subscripts for simpilicity, the group delay is given by

$$\tau_g = \frac{L}{C} \cdot \frac{\partial \beta}{\partial k}$$

β is the proportional constant, given by

$$\beta = \left[k^2 n_1^2 - 2\left(\frac{\alpha + 2}{\alpha} \frac{m}{a^2}\right)^{\frac{\alpha}{\alpha+2}} \left(n_1^2 k^2 \Delta\right)^{\frac{\alpha}{\alpha+2}} \right]^{1/2}$$

$$\beta = \left(k^2 n_1^2\right)^{1/2}\left[1-2\left(\frac{\alpha+2}{\alpha}\frac{m}{a^2}\right)^{\frac{\alpha}{\alpha+2}}\Delta^{\frac{\alpha}{\alpha+2}}\right]^{1/2}$$

$$\beta = kn_1\left[1-2\Delta\left(\frac{m}{M}\right)^{\frac{\alpha}{\alpha+2}}\right]^{1/2}$$

m is the total number of possible guided modes, m is the number of guided modes having propagation constants between n_1k and β.

$$\frac{\partial\beta}{\partial k} = \frac{kn_1}{\beta}\left[N_1-\frac{4\Delta}{\alpha+2}\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}\left(N_1+\frac{n_1k}{2\Delta}\frac{\partial\Delta}{\partial k}\right)\right]$$

$$\therefore \qquad \tau_g = \frac{L}{C}\frac{kn_1}{\beta}\left[N_1-\frac{4\Delta}{\alpha+2}\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}\left(N_1+\frac{n_1k}{2\Delta}\frac{\partial\Delta}{\partial k}\right)\right]$$

$$= \frac{LN_1}{C}\frac{kn_1}{\beta}\left[1-\frac{\Delta}{\alpha+2}\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}(4+\varepsilon)\right]$$

For graded index fiber number of modes M is given by

$$m = \frac{\alpha}{\alpha+2}\alpha^2 k^2 n_1^2 \Delta$$

and $$N_1 = n_1 + k\frac{\partial n_1}{\partial k}$$

$$\varepsilon = \frac{2n_1 k\partial\Delta}{N_1\Delta\partial k}$$

Let us assume the core cladding index difference $\Delta << 1$ and take

$$y = \Delta\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)} << 1$$

We know that

$$\beta = kn_1\left[1-2\Delta\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}\right]^{1/2}$$

$$\frac{kn_1}{\beta} = \frac{1}{\left[1-2\Delta\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}\right]^{1/2}}$$

$$\frac{kn_1}{\beta} = \frac{1}{(1-2y)^{1/2}}$$

$$\frac{kn_1}{\beta} = (1-2y)^{1/2}$$

By approximating

$$\frac{kn_1}{\beta} = 1+y+\frac{3y^2}{2}$$

$$\therefore \qquad \tau_g = \left[1+\frac{d-2-\varepsilon}{d+2}\Delta\left(\frac{m}{M}\right)^{\left(\frac{\alpha}{\alpha+2}\right)}+\frac{3a-2-2\varepsilon}{2(a+2)}\Delta^2\left(\frac{m}{M}\right)^{\left(\frac{2\alpha}{\alpha+2}\right)}+0\left(\Delta^3\right)\right]$$

The above equation shows to first order in Δ, the group delay difference between the modes is zero if $a = 2+\varepsilon$. If all the modes are equally excited.

$$\sigma_{\text{intermodel}} = L\frac{N_1\Delta}{2C}\frac{a}{a+1}\left(\frac{a+2}{3a+2}\right)^{\frac{1}{2}}\times\left[C_1^2+\frac{4C_1C_2(a+1)\Delta}{2a+1}+\frac{16\Delta^2C_2^2(a+1)^2}{(5a+2)(3a+2)}\right]^{1/2}$$

Where $C_1 = \dfrac{a-2-\varepsilon}{a+2}$;

$$C_2 = \frac{3a-2-2\varepsilon}{2(a+2)}$$

$$\sigma_{\text{intramodel}} = \left(\frac{\sigma\lambda}{\lambda}\right)^2\left\langle\left(\frac{\lambda d\tau_g}{d\lambda}\right)^2\right\rangle$$

If the effect of material dispersion is ignored (i.e., $\frac{d\,u_1}{d\lambda} = 0$), the optimum index profile is given by,

$$\sigma_{opt} = \frac{n_1 \Delta^2 L}{20\sqrt{3\,C}}$$

This can be compared with the dispersion in a step index fiber by setting a = ∞ and e = 0.

$$\sigma_{step} = \frac{n_1 \Delta L}{C} \frac{1}{2\sqrt{3}} \left(1 + 3\Delta + \frac{12\Delta^2}{5}\right)^{1/2} \simeq \frac{n_1 \Delta L}{2\sqrt{3}\,C}$$

$$\therefore \quad \frac{\sigma_{step}}{\sigma_{opt}} = \frac{10}{\Delta}$$

Typical value of $\Delta = 0.01$ indicates that the capacity of a graded index fiber is about three orders of magnitude larger than that of a step index fiber.

UNIT-2.

SIGNAL DISTORTION OPTICAL FIBER.

PROBLEMS.

① A multimode step index fiber has a Numerical Aperture of 0.3 and a core refractive index of 1.45. The material dispersion parameter for the fiber is 250 ps nm^{-1} km^{-1} which makes material dispersion the totally dominating intramodal dispersion mechanism. Calculate (a) the total rms pulse broadening per km when the fiber is used with an LED source of rms spectral width 50 nm. (b) corresponding Bandwidth-length product for the fiber.

Solution.

Given $NA = 0.3$, $n_1 = 1.45$

Material dispersion $M = 250$ ps nm^{-1} km^{-1}

Spectral width $\sigma_\lambda = 50$ nm.

ⓐ rms pulse broadening per km due to material dispersion.

$$\sigma_m(1km) = \frac{\sigma_\lambda L \lambda}{c} \left| \frac{d^2 n_i}{d\lambda^2} \right|$$

$$= \sigma_\lambda \cdot LM.$$

$$= 50 \times 1 \times 250 \text{ ps km}^{-1}$$

$$\sigma_{m(1km)} = 12.5 \text{ ns km}^{-1}.$$

rms pulse broadening per km due to intermodal dispersion

$$\sigma_s(1km) = \frac{L(NA)^2}{4\sqrt{3}\, n_1 c} = \frac{10^3 \times (0.3)^2}{4 \times \sqrt{3} \times (1.45)(3 \times 10^8)}$$

$$= \frac{10^3 \times 0.09}{3013768405} = 2.99 \times 10^{-8}$$

$$\sigma_s = 29.9 \text{ ns km}^{-1}.$$

$$\sigma_T = \sigma_m + \sigma_s$$

$$= 12.5 + 29.9$$

(b) Bandwidth distance product

$$B \times L = \frac{0.2}{\sigma_T} = \frac{0.2}{32.4 \times 10^{-9}}$$

BL product = 6.2 MHz.km.

(2) When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. Determine (a) the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices. (b) signal attenuation per km for the fiber (c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB. (d) the numerical input/output power ratio in (c).

Solution.

Given.

Length of fiber $L = 8$ km.

Input power $P_i = 120\,\mu W$

output power $P_o = 3\,\mu W$.

(a) overall signal attenuation $= 10 \log \frac{P_i}{P_o} = 10 \log \frac{120 \times 10^{-6}}{3 \times 10^{-6}}$

$$= 10 \log 40 = 16 \text{ dB}.$$

(b) Signal attenuation per km $\alpha_{dB} L = 10 \log_{10} \frac{P_i}{P_o}$

$$\alpha_{dB} L = 16 \text{ dB}$$

$$\alpha_{dB} = \frac{16}{8} \quad \boxed{\alpha_{dB} = 2 \text{ dB.km}^{-1}}$$

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

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

9 → splices (1 km interval) → attenuation 1 dB.

loss due to splices = 9 dB

overall signal attenuation = 20 dB + 9 dB = 29 dB.

(d) Numerical value for input/output power ratio $= \frac{P_i}{P_o} = 10^{(dB/10)}$

$$= 10^{(29/10)} = 794.3$$

$$\boxed{P_i/P_o = 794.3}$$

Part – A

1. What is Rayleigh scattering**?(May-June 2013)(R)**
2. What are bending losses? Name any two types. **(Apr-May 2015) (R)**
3. What are the types of fiber losses which are given per unit distance?**(Nov-Dec 2014) (R)**
4. List the factors that cause intrinsic joint losses in a fiber. **(NOv-Dec 2014) (R)**
5. A fiber has an attenuation of 0.5dB/Km at 1500nm. If 0.5mW of optical power is initially launched into the fibre, what is the power level in after 25Km? **(Nov—Dec 2015, Apr-May 2017) (U)**
6. What do you mean by Polarization dispersion in a fiber and write the expression for it? **(Nov—Dec 2015,Apr-May 2017, Apr-May 2018) (U)**
7. A continuous 12 kms-long optical fiber link has a loss of 1.5dB/km. What is the minimum optical power that must be launched into the fiber to maintain an optical power level of 0.3 μW at the receiving end?**(Nov-Dec 2013) (AZ)**
8. Define dispersion in multimode fibers. What is its effect? **(Nov-Dec 2013) (R)**
9. What are the two reasons for Chromatic Dispersion? **(Nov-Dec 2012) (R)**
10. What are the most important non-linear effects of optical fibre communication? **(Nov-Dec 2012) (R)**
11. What is chromatic dispersion?**(May - June 2016) (R)**
12. What are the causes of absorption? **(Nov-Dec 2016) (R)**
13. Define attenuation. **(Nov-Dec 2017) (R)**
14. A manufacturer's data sheet lists the material dispersion Dmat = 110ps/nm.km at a wavelength of 860nm. Find the rms pulse broadening per km due to material dispersion if the optical source has a spectral width = 40nm at an output wavelength of 860 nm. **(Nov-Dec 2017) (A)**
15. What is elastic and inelastic scattering? Give examples.**(Apr-May 2018) (R)**

Part – B

1. Discuss about the design optimization of single mode fiber.**(Nov-Dec 2016) (U)**
2. What is waveguide dispersion? Derive and expression for time delay produced due to waveguide dispersion.**(Nov-Dec 2016) (A)**
3. With necessary diagrams, explain the causes and types of fiber attenuation loss. **(Nov-Dec 2015) (U)**
4. With diagram, derive the expression for intra modal dispersion. **(Nov-Dec 2015) (AZ)**
5. What are the loss or signal attenuation mechanism in a fibre? Explain. **(Apr-May 2015, May-June 2016, Apr-May 2017) (U)**
6. Discuss the pulse broadening in graded index fibers. **(U)**
7. Explain in detail about polarization mode dispersion and intermodal dispersion in SM fibers. **(U)**
8. Distinguish between intermodal and intramodal dispersions. Explain

them with necessary equations and diagrams. **(Nov-Dec 2013) (AZ)**

9. Describe the linear and non-linear scattering losses in optical fibers. **(Nov-Dec 2012) (U)**
10. Derive expressions for material dispersion and waveguide dispersion and explain them. **(May-June 2013 Apr-May 2018) (AZ)**
11. What is meant by critical bending radius of optical fibers? Explain. **(Nov- Dec 2014) (U)**
12. Explain the following in single mode fiber : Modal birefringence and beat length. **(Nov-Dec 2014) (U)**
13. An LED operating at 850nm has a spectral width of 45nm. What is the pulse spreading is ns/km due to material dispersion? What is the pulse spreading when a laser diode having a 2nm spectral width is used? **(Nov-Dec 2012) (U)**
14. Discuss the attenuation encountered in optical fiber communication due to: 1.Bending 2. Scattering 3.Absorption. **(Nov-Dec 2013, Apr-May 2018) (U)**
15. In detail, explain linear scattering losses. **(Nov-Dec 2017) (U)**