Fiber materials: In selection of materials ~~based on~~ for optical fibers, a number of requirements must be satisfied:

(1) It must be possible to make long, thin, flexible fibers from the materials.

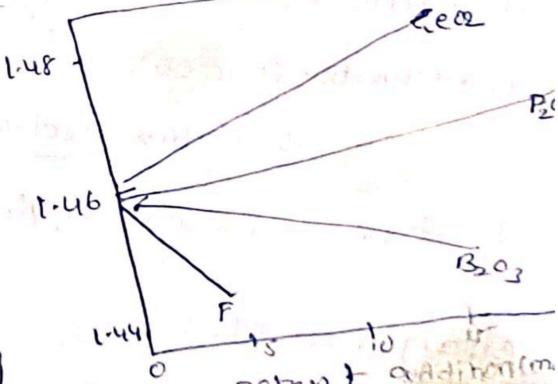
(2) The material must be transparent at a particular optical wavelength in order for the fiber to guide light efficiently.

(3) physically compatible materials that have slightly different refractive indices for the core and cladding must be available.

Materials that satisfy these requirements are glasses & plastics

Glass fibers: Most of the fibers are made up of glass consisting of either silica (SiO_2) or silicate. High loss glass fibers are used for short-transmission distance and Low-loss glass fibers are used for long distance applications. plastic fibers are less used because of their higher attenuation than glass fibers.

Glass fiber: The glass fibers are made from oxides, sulfides or selenides. The most common oxide is silica whose refractive index is 1.458 at 850nm. To get different index fibers the dopants such as GeO_2, P_2O_5 are added to silica. GeO_2 & P_2O_5 increases the refractive index



few fiber compositions are

1. GeO_2 - SiO_2 core ; SiO_2 cladding
2. P_2O_5 - SiO_2 core ; SiO_2 cladding
3. SiO_2 core B_2O_3 - SiO_2 cladding.
4. GeO_2 - B_2O_3 - SiO_2 core ; B_2O_3 - SiO_2 cladding

The principle raw material for silica is sand. Glass composed of pure silica is referred to as either silica glass, fused silica (or) vitreous silica. Some desirable properties of silica are: (i) Resistance to ~~deformance~~ deformation at temperature as high as 1000°C (ii) High resistance to breakage from thermal shock. (iii) Good chemical durability (iv) High transparency in both the visible & infrared re[gion] [for optical fiber communication]. its high melting temperature is a disadvantage. avoid in vapor deposition te

Halide glass fibers: Halide glass fibers are formed by adding different materials to the glass fibers.

Molecular composition of a ZBLAN fluoride glass

Material	Molecular percentage
ZrF_4	54
BaF_2	20
LaF_3	4.5
AlF_3	3.5
NaF	18

* In 1975 discovered that fluoride glasses have extremely low transmission losses at mid-infrared wavelengths (0.2 – 8 μm, with the lowest loss around 2.55 μm). Fluoride glasses belongs to a general family of halide glass & in group VII of the periodic table, the elements are fluorine, chlorine, bromine & iodine.

ZBLAN (after its element ZrF_4, BaF_2, LaF_3, AlF_3 and NaF.)

The above material increases the refractive index of core. To reduce the refractive index, ~~ZF~~ ZrF_4 is replaced by HaF_4 to get a ZHBLAN cladding (lower-refractive index glass). Long length of these fibers are difficult.

Active Glass fibers:

[Two commonly used for fiber lasers are] erbium & neodymium are commonly used for fiber LASER. ~~The ionic concentrations of the~~ By examining the absorption and fluorescence spectra of these materials, an optical source emits an absorption wavelength to excite electrons to higher energy levels in the rare-earth dopant (The ionic concentration is 0.005 – 0.05 mole percent).

When these excited electrons drop to lower energy levels from higher level, they emit light in a narrow optical spectrum at the fluorescence wavelength.

chalgenide glass fibers: In addition to allowing the creation of optical amplifier ~~fiber~~ the nonlinear properties of glass fibers other application, such as all-optical switches and fiber lasers. chalgenide glass ~~is~~ used because of its high optical nonlinearity & long interaction length. These glasses contain at least one chalcogen element (S, Se, or Te) and one other elements as P, I, Cl, Br, Cd, Ba, Si or Tl for tailoring thermal mechanical, and optical properties of the glass. Among the various chalgenide glasses, As_2S_3 is one of the well known materials. Single mode fibers using $As_{40}S_{58}Se_2$ and As_2S_3 for the core and cladding materials, respectively. Losses in these glasses is 1dB/m.

plastic optical fibers:

For delivering high-speed services directly to the workstation has led fiber developers to creat high-Bandwidth graded-index polymer (plastic) optical fiber (POF) for.

The core of these fibers is either polymethylmethacrylate (or) a perfluorinated polymer. These fibers are referred to as PMMA POF and PFP POF, w.r.t

Although they exhibit considerably greater optical signal attenuation than glass fibers, they are tough and durable.

Inexpensive plastic injection-molding technologies can be used to fabricate connectors, splices and transceivers.

Signal degradation in optical fibers:

Attenuation: (fiber loss) the basic attenuation mechanisms in a fiber are absorption, scattering, and radiative losses of the optical energy. Absorption is related to the fiber material, whereas scattering is associated with both the fiber material & structural imperfections in the optical waveguide. Attenuation owing (giving) to radiative effects originates from perturbations (both microscopic & macroscopic) of the fiber geometry.

Attenuation units: As light travels through a fiber, its power decreases exponentially with distance. if $P(0)$ is the optical power in a fiber at the origin (at $z=0$) then the power $P(z)$ at a distance z is

$$P(z) = P(0)\, e^{-\alpha_p z} \Rightarrow \alpha_p = \frac{1}{z}\log\left[\frac{P(0)}{P(z)}\right].$$

α = nepers.

α_p is the fiber attenuation coefficient & [dB/km].

optical powers are commonly expressed in dBm, is dB power level ...

Attenuation: (Fiberloss) 1

The basic attenuation mechanisims in a fiber are Absorption, Scattering and radiation losses of the optical energy.

Absorption due to the fiber material,

Scattering is due to both the fiber material & structural imperfections

Radiation losses due to perturbation (both microscopic & macroscopic) of the fiber geometry.

Attenuation units: As light travels through a fiber, its power decreases exponentially with distance.

if $P(0)$ is optical power in a fiber at the origin $(z=0)$.

Then the power $P(z)$ at a distance z is

$$P(z) = P(0)\, e^{-\alpha_p z} \Rightarrow \frac{P(z)}{P(0)} = e^{-\alpha_p z} \Rightarrow \frac{P(0)}{P(z)} = e^{\alpha_p z}$$

$$\Rightarrow \log\left[\frac{P(0)}{P(z)}\right] = \log_e e^{\alpha_p z}$$

$$\Rightarrow \alpha_p = \frac{1}{z} \log P(0)/P(z)$$

$$\Rightarrow \alpha_p = \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right].$$

α_p is the fiber attenuation coefficient [dB/km].

optical power are commonly expressed in dBm. is the dB. power level to 1m

1. Absorption: 3 types of Absorption.

1. Absorption by atomic defects in the fiber material
2. Extrinsic absorption by impurity atoms in the fiber material.
3. Intrinsic absorption by basic constituent atoms of fiber material

1. Absorption by atomic effects: Atomic defects such as vacancy, imperfections of the atomic structure of the fiber material and clusters (group) of atoms produce a small absorption loss.

By careful preparation of perform & then fiber fabrication will reduce atomic defects.

2. Extrinsic Absorption by impurity atoms:

Impurity absorption results from (i) transition metal ions

Eg: iron, chromium, copper, magnesium and nickel.

In ultra low loss fiber, the impurity ranges from 1 to 5 parts billion. The loss is produced at $\lambda = 0.8 \mu m$

(ii) Impurity Absorption results from (ii) OH ions.

Eg: $SiCl_4$, $GeCl_4$ & $POCl_3$.

The fundamental Absorption by molecular vibration of OH impurity at $\lambda = 2.7 \mu m$

This absorption is reduced by water content in the fiber below 1PPb (parts per billions) as in MCVD method

MCVD [Modified Chemical Vapour Deposition].

3. Intrinsic Absorption due to (i) basic fiber material (SiO_2).

(ii) due to Electronic Absorption bands in UV region ~~& fi~~

(iii) due to Atomic Vibration bands in the infrared region.

The Rayleigh scattering loss is ...

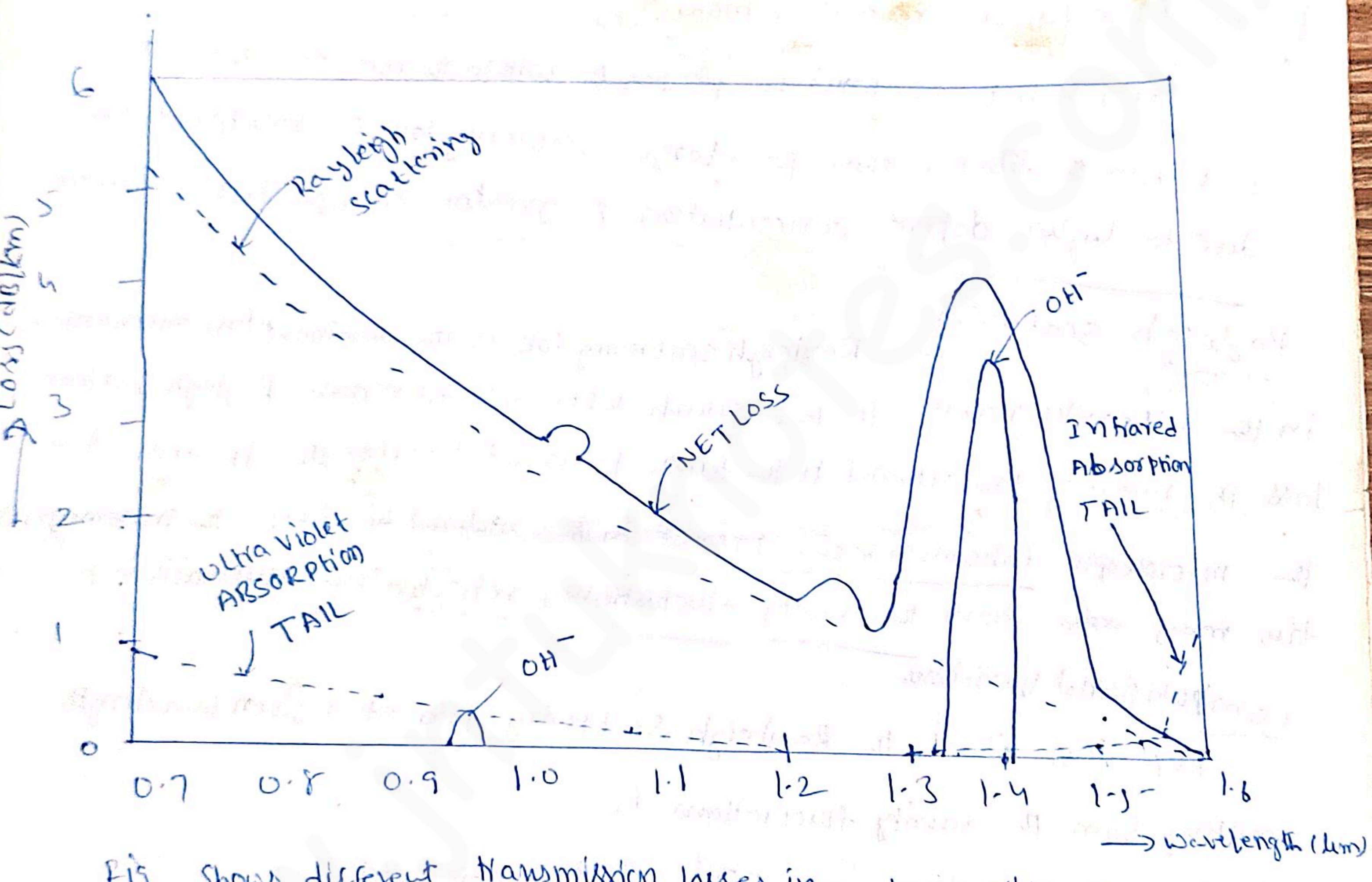


Fig shows different transmission losses in a pure silica fiber. it is found that at 1.3 μm & 1.55 μm, the losses are minimum.

Scattering loss: Due to microscopic variations in material density, compositional fluctuations, structural inhomogeneities in fiber manufacture

Scattering losses are 2 types:

(i) linear scattering
- (a) Rayleigh scattering.
- (b) Mie scattering.

(ii) nonlinear scattering
- (a) Stimulated Brillouin scattering.
- (b) Stimulated Raman scattering.

linear scattering loss: linear scattering transfers linearly the optical power in one propagating mode to a different mode. in a leaky mode (or) radiation mode.

Large scattering loss in multimode fibers due to higher dopant concentration & creates compositional changes.

Rayleigh scattering is: This loss is the dominant loss in UV region. Due to inhomogenities in material (fiber), density fluctuation, Δ & composition changes. Rayleigh scattering (α_{scat}) is inversely proportional to the 4th power of λ (wavelength).

i.e $\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \; m^{-1}$.

n & p are refractive index & photo elastic coefficient for silica.

β_c is the isothermal compressibility.

T_F : Fictive temperature (at which solidification of glass takes place.

The transmission loss due to Rayleigh scattering $\alpha = \exp(-\alpha_{scat} L)$

L = length of fiber.

The Rayleigh scattering loss is reduced by operating at higher wavelength

Rayleigh scattering is as elastic scattering because there is no change in frequency.

Mie scattering: (i) due to inhomogeneities are comparable in size to guided wavelength

(ii) imperfect cylindrical structure of waveguide [OFC]

(iii) Irregularities in core-cladding interface

(iv) core cladding refractive index difference (Δ)

(v) diameter fluctuations

Nonlinear scattering: At high optical power ($\simeq$ 100 mW)

(i) Stimulated Brillouin scattering: is defined as the modulation of light through thermal molecular vibrations within the fiber.

The scattered light contains a upper & lower sidebands along light (frequency)

An incident photon produces a scattered photon as well as a phonon of acoustic frequency.

The frequency shift is maximum in backward direction & reduced to zero in the forward direction.

The threshold optical power for Brillouin scattering is proportiontional to $d^2\lambda^2\alpha_B$ where d is fiber core diameter, λ = operating wavelength | α_B = Brillouin scattering loss coefficient

(ii) Stimulated Raman scattering:- scattered light consists of a scattered photon & a high frequency optical phonon. Raman scattering occurs both in the forward direction & backward direction in the optical fiber.

The threshold optical power for Raman scattering is proportional to $d^2\lambda\alpha_R$. where d = core diameter ; λ = operating wavelength

α_R = Raman scattering loss coefficient

Generally the scattering losses are max in multimode fiber than single mode fiber due to higher larger diameter & large compositional variation.

At $\lambda = 1.55\mu m$

Bending loss :- if optical fiber contains bends, then bends produce radiation losses. 2 types of Bending losses:

(a) Macroscopic bending losses : Radius of curvature of bend is greater than fiber diameter. Fiber cable turns a corner.

(b) Microscopic bending losses : Bends in the fiber axis.

Macroscopic bending losses :-

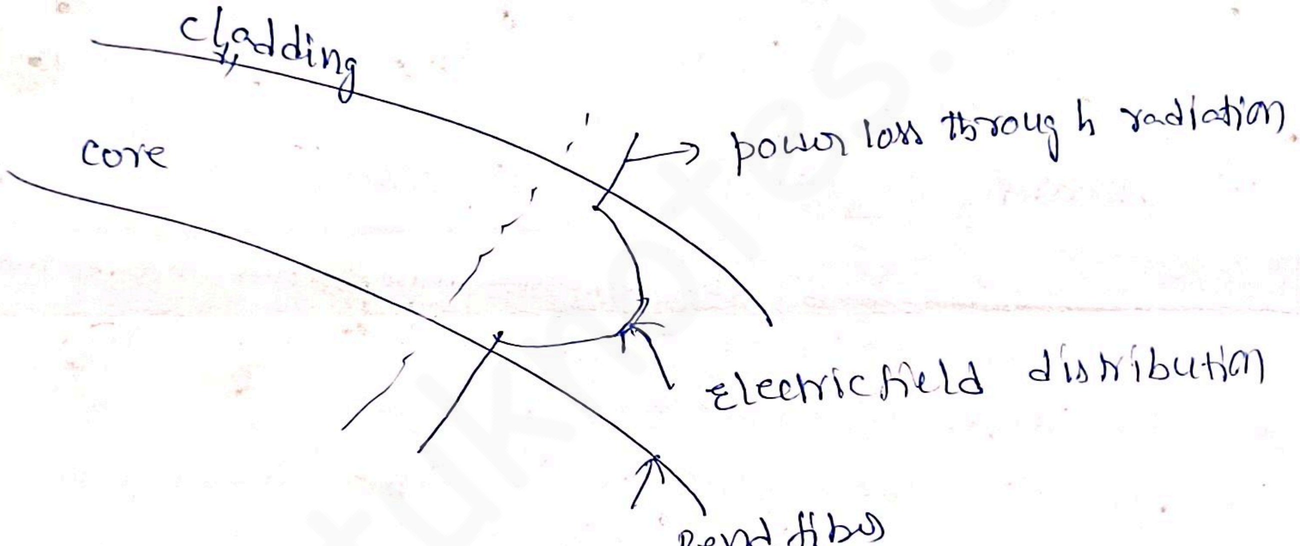


fig: Radiation loss at a fiber bend.

when radius of curvature of bend is large, the loss is small.

curvature of fiber increases, the radius of curvature of bend decreases on curvature of fiber increases. The loss increases exponentially up to a critical radius of curvature.

For multimode fiber the critical radius of curvature of bend

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

The attenuation coefficient (by macrobends) $\alpha_b = A\exp(-BR_c)$

A & B are constants are independent of R_c

In the case of single mode fiber

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

$$\lambda_c = \text{cut-off wavelength} = \frac{2\pi a\, n_1(2\Delta)^{1/2}}{2.405}$$

$$\lambda_c = \frac{2\pi a\,(NA)}{V_c}$$

where $V_c = 2.405$ for singlemode fiber,
V_c = normalized cut-off frequency.

Micro Bending loss (mode coupling losses)

Due to (1) Slight surface imperfection due to mode coupling b/n adjacent modes(or) coupling of the guided modes & leaky modes (non guided modes) is also called Radiative loss. The amount of loss depends on the fiber deformation.

→ Micro bending losses proportional to the no. of modes propagating through the fiber & inversely proportional to wavelength.

→ due to small scale fluctuations in the radius of curvature of the fiber axis,

→ non-uniform lateral pressures created during the cladding of the fiber,

→ manufacturing of fiber.

core and cladding losses:

The core & cladding have different refractive indices. Therefore they differ in composition. So core and cladding have different attenuation coefficients α_1 & α_2 respectively.

For stepindex fiber, the loss for a mode of order (m, l)

$$\alpha_{m,l} = \alpha_1 \frac{P_{core}}{P} - \alpha_2 \frac{P_{clad}}{P}$$

Where $\frac{P_{core}}{P}$ & $\frac{P_{clad}}{P}$ are the fractional power in core and cladding is.

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

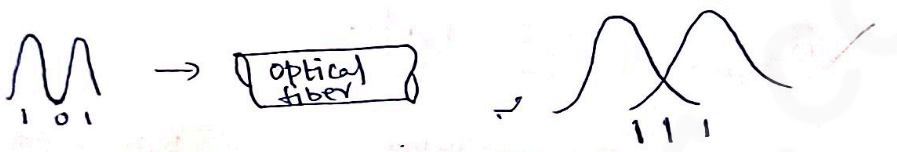
In the case of single mode fibers, $\Delta << 1$. Hence the core-cladding loss is very minimum. But in the case of multimode fibers the relative refractive index difference is large and the core - cladding loss is more

3. Information capacity, Dispersion and optical fiber connectors.

Introduction:

Since, the signal attenuation limits the information carrying capacity of an optical fiber. The other transmission characteristic of optical communication system is Bandwith of the fiber. This is limited by the signal dispersion within the fiber.

Dispersion is defined as the spreading of the optical pulses propagating through the fiber. is shown in fig.



NOTE: Dispersion — spreads the pulse.

Information Capacity Determination

Dispersion induced signal distortion results in broadening of light pulses as propagating through the fiber. fig below shows the pulse broadening cause a pulse to overlap with neighbouring pulses.

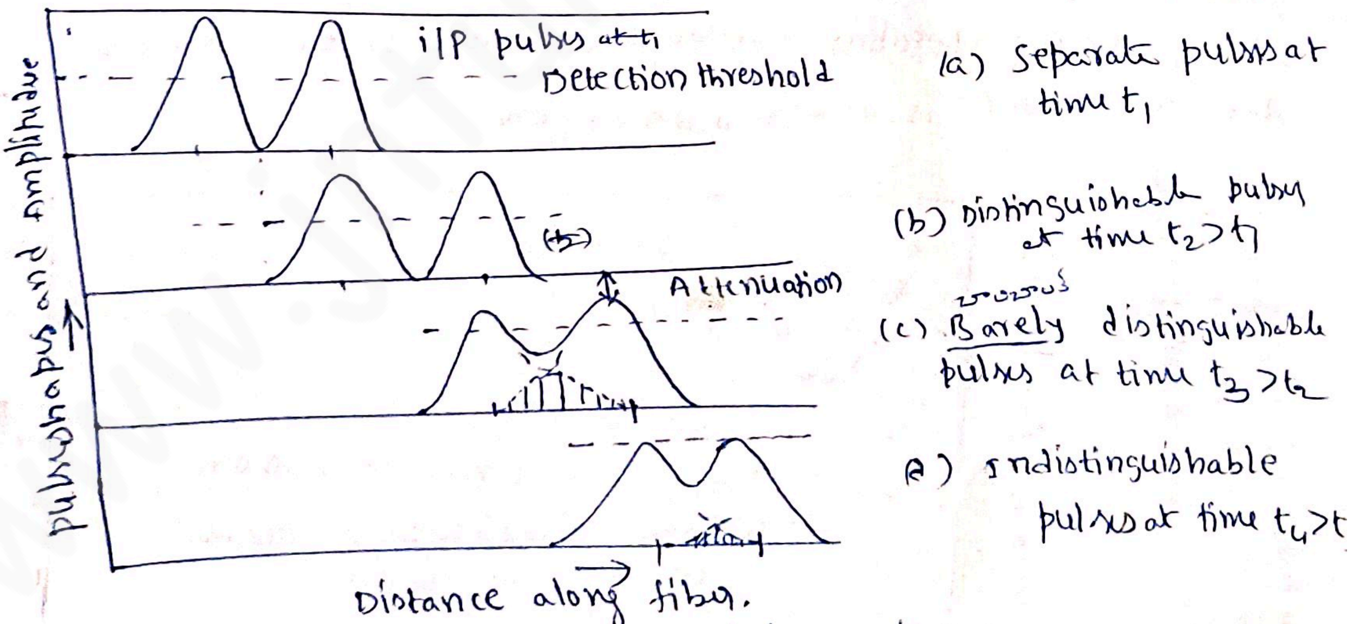


fig: Broadening of pulses if they travel along a fiber

If the neighbouring pulses get overlapped, then adjacent pulses (can no longer be individually) not distinguished at the receiver and errors will occur. Thus, the dispersive properties determines the limit of the information capacity of the fiber.

In diagram, The effect of overlapping of pulses is called Inter Symbol Interference (ISI), Thus, ISI becomes more pronounced when increasing no. of errors are encountered on the digital optical channel.

For no overlapping (overlapping) pulses down on an optical fiber link, the digital bit rate $B_T \leq \frac{1}{2\tau}$ → 1

where 2τ = Broadened pulse duration through dispersion

Eq (1) indicates the max. transmission rate in order to avoid dispersion.

The maximum bit rate approximated by Gaussian shape is

$$B_{T,max} \simeq \frac{0.2}{\sigma} \text{ bit/sec} \rightarrow 2.$$

σ = The rms value of light pulse width. [Gaussian shape]

Information capacity of an optical fiber can be measured by Bandwidth - distance product. it is expressed in MHz - km. The BW-distance product for a step index fiber is 20 MHz km.

Since the radial refractive index profile of a graded index fiber can be selected, hence, the pulse broadening in it can be reduced at a specific operating wavelength, Because to this, The value of BW distance product is as high as 8.5 GHz km.

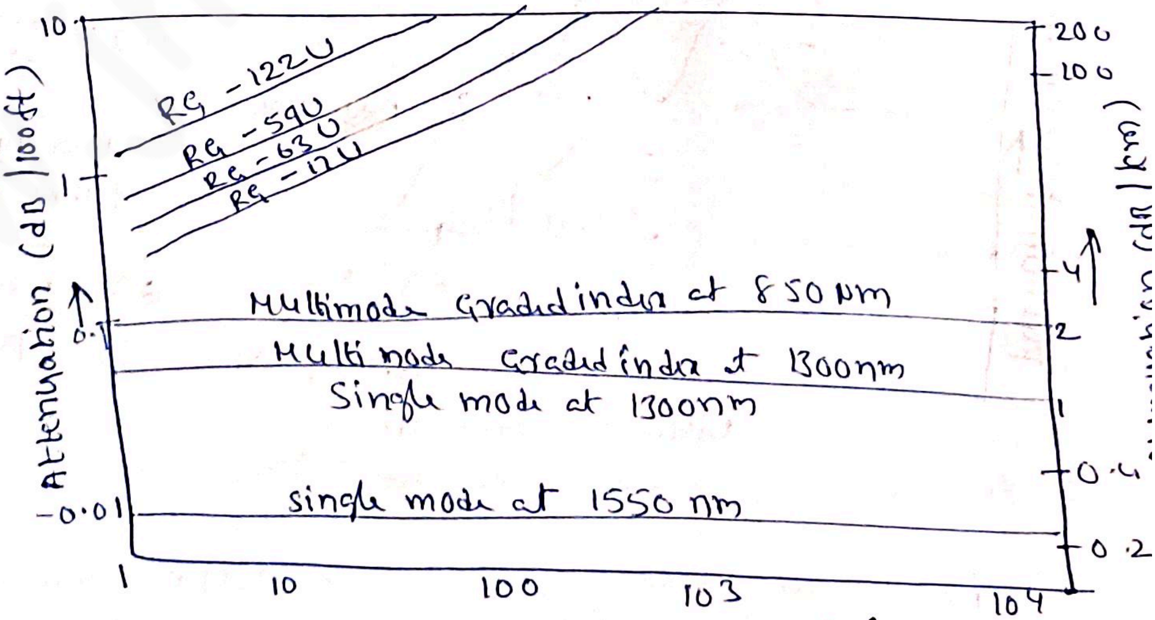


fig: comparison of various information capacities with coaxial cable used for UHF & VHF transmission.

Fig shows the comparison of various information capacities with the cables used for UHF & VHF Tx. The important factor used the calculation of Information transmission capacity is short pulse propagating along fiber.

* Group delay / Time delay gives amount of pulse spreading that sustained due to different amounts of time taken by spectral components of any particular mode to travel a certain distance along the fiber

$$V_g = \frac{D}{T_g}$$

$$\frac{1}{V_g} = \frac{T_g}{D}$$

$$\frac{1}{V_g} = \frac{1}{c}\frac{d\beta}{dK}$$

$$= \frac{1}{c}\frac{d\beta}{d\left[\frac{2\pi}{\lambda}\right]}$$

$$= \frac{\lambda}{2\pi c}\frac{d\beta}{d\left[\lambda/\lambda\right]}$$

$$\frac{1}{V_g} = \frac{T_g}{D} = -\frac{\lambda^2}{2\pi c}\cdot\frac{d\beta}{d\lambda} \rightarrow 1$$

$$V_g = \frac{d\omega}{d\beta} = \frac{1}{\sqrt{\mu\epsilon}} = \frac{1}{\sqrt{\mu_0\epsilon_0}\sqrt{\mu\epsilon}} = c\frac{1}{\sqrt{\mu\epsilon}} = c\frac{\omega}{\beta}$$

$$\frac{1}{V_g} = \frac{1}{c}\frac{\beta}{K}$$

$\omega = K$

D : Distance travelled by the pulse

β : propagation constant in a medium.

V_g = group velocity ; T_g = Time/group delay.

$$V_g = c\left[\frac{d\beta}{dK}\right]^{-1} = \left(\frac{d\beta}{d\omega}\right)^{-1} \rightarrow 2$$

total delay

The delay difference per unit wavelength over the propagation path is $\frac{dT_g}{d\lambda}$

The total delay δT over a Distance 'D' for the spectral components (which are $d\lambda$ apart and $\frac{\delta\lambda}{2}$ above & below a central wavelength).

$$\frac{T_g}{D} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

$$\frac{T_g}{\lambda} = -\frac{D\lambda}{2\pi c}\frac{d\beta}{d\lambda}$$

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

$$\delta T = \frac{dT_g}{d\lambda}\delta\lambda$$

$$=$$

$$= \frac{-D}{2\pi c}\left[2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right]\delta\lambda \rightarrow 3.$$

Equ (3) can be expressed in terms of angular velocity 'ω' as,

$$\delta T = \frac{dT_g}{d\omega}\cdot\delta\omega = \frac{d}{d\omega}\left(\frac{D}{V_g}\right)\delta\omega \qquad \left[\frac{1}{V_g} = \frac{T_g}{D}\right]$$

Total Delay

$$\delta T = \frac{d}{d\omega}\left(\frac{D}{V_g}\right)\cdot\delta\omega$$

$$= \frac{d}{d\omega}\left(\frac{D}{\frac{d\omega}{d\beta}}\right)\cdot\delta\omega$$

$$= \frac{d}{d\omega}\left(\frac{d\beta}{d\omega}\right)\delta\omega\cdot D$$

$$= D\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega \rightarrow 4.$$

$\frac{d^2\beta}{d\omega^2}$ = GVD factor. which determines the pulse broadening of travelling along the fiber.
(Group velocity Dispersion)

$\beta_2 = \frac{d^2\beta}{d\omega^2}$ = GVD factor (β_2)

if the spectral width $(\delta\lambda)$, is characterized by its r.m.s value then the spreading of pulse

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

$$\sigma_g = \frac{D}{2\pi C}\left[2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right|\Big]\sigma\lambda$$

$$= \frac{D\sigma_\lambda}{2\pi C}\left[\left|2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right|\right].$$

The Dispersion factor $B = \frac{1}{D}\cdot\frac{d\tau_g}{d\lambda}$

$$= \frac{d}{d\lambda}\left[\frac{\tau_g}{D}\right]$$

$$\Rightarrow B = \frac{d}{d\lambda}\left[\frac{1}{V_g}\right]$$

[Dispersion is defined as pulse spreading as a function of wavelength]

$\therefore B = \frac{-2\pi C}{\lambda^2}\beta_2$ is termed as dispersion $\rightarrow 5$

Types of Dispersion : The different times taken by different rays propagation through the fiber, The dispersion of signal due to following 2 types.

1) ~~Intern~~ Intramodal dispersion
2) Intermodal dispersion

Intramodal dispersion: Due to the dispersive properties of the waveguide material as a function of wavelength(λ) : 2 types ; 1. Material Dispersion
2. Waveguide Dispersion.

Material Dispersion: due to variations in the refractive index of core material as a function of wavelength(λ).

Fiber is said to exhibit material dispersion when $\frac{d^2 n}{d\lambda^2} \neq 0 \rightarrow 1$

if $n_1(\lambda)$ is the refractive index of fiber core. the propagation constant

$$\beta = \frac{2\pi}{\lambda} n_1 \quad \rightarrow 2$$

∴ The group velocity per unit length is

$$\frac{T_g}{D} = \frac{1}{V_g} = \frac{1}{c}\left(\frac{d\beta}{dk}\right) = \frac{-\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \quad \rightarrow 3.$$

put the value of β in (3)

$$\frac{T_{mat}}{D} = \frac{-\lambda^2}{2\pi c}\frac{d}{d\lambda}\left[\frac{2\pi}{\lambda} n_1\right]$$

$$\Rightarrow \frac{T_{mat}}{D} = \frac{-\lambda^2}{2\pi c}\left[\left(-\frac{2\pi}{\lambda^2}\right)n_1 + \frac{2\pi}{\lambda}\frac{dn_1}{d\lambda}\right]$$

$$\Rightarrow \frac{T_{mat}}{D} = \frac{+\cancel{\lambda^2}}{\cancel{2\pi} c}\cdot\frac{\cancel{2\pi}}{\cancel{\lambda^2}}\left[n_1 - \lambda\frac{dn_1}{d\lambda}\right]$$

$$\therefore T_{mat} = \frac{D}{c}\left[n_1 - \lambda\frac{dn_1}{d\lambda}\right]$$

material Dispersion

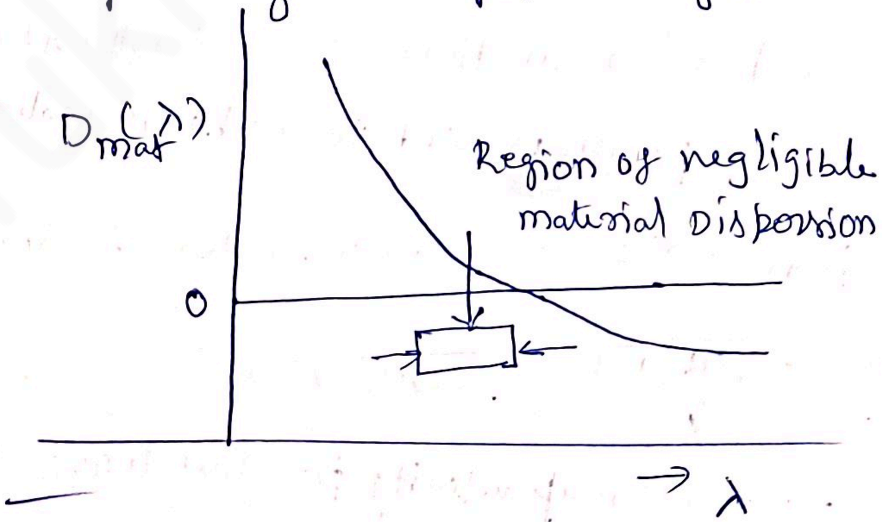
$$\sigma_{mat} = \frac{d\,T_{mat}}{d\lambda}\sigma_{\lambda} \qquad \text{where } \sigma_{\lambda} = \text{Spectral width}$$

$$= \frac{D}{c}\left|\lambda\frac{d^2 n_1}{d\lambda^2}\right|\sigma_{\lambda}$$

$$\sigma_{mat} = D_{mat}(\lambda)\,D\sigma_{\lambda}$$

where $D_{mat}(\lambda)$ = material Dispersion parameter $= \frac{\lambda}{c}\frac{d^2 n_1}{d\lambda^2}$

Material Dispersion Can be reduced by optical sources with narrow spectral o/p (or operating at longer wavelengths.



Waveguide Dispersion : due to variation in group velocity as a function of wavelength for a particular mode.

Fiber is said to be waveguide Dispersio ; $\frac{d^2\beta}{d\lambda^2} \neq 0$

The waveguide dispersion is less when compared to material Dispersion.

∴ The normalized propagation constant $b = 1 - \left(\frac{ua}{V}\right)^2 \rightarrow 5$.

where u = Radial propagation constant ; $u = (n_1^2k^2 - \beta^2)^{1/2}$

V = Normalized frequency ; $V = \frac{2\pi}{\lambda} a\,(NA)$

$$V = a\left(\frac{2\pi}{\lambda}\right)\sqrt{n_1^2 - n_2^2}$$

$$= ak\sqrt{n_1^2 - n_2^2}$$

put u, V in (5) ; $b = 1 - \frac{a^2(n_1^2k^2 - \beta^2)}{a^2k^2(n_1^2 - n_2^2)}$

$$b = 1 - \frac{a^2k^2\left(n_1^2 - \frac{\beta^2}{k^2}\right)}{a^2k^2(n_1^2 - n_2^2)} = \frac{n_1^2 - n_2^2 - n_1^2 + \frac{\beta^2}{k^2}}{n_1^2 - n_2^2}$$

$$b = \frac{\left(\frac{\beta}{k}\right)^2 - n_2^2}{n_1^2 - n_2^2} \longrightarrow 6.$$

Δ = relative refractive index difference, $\Delta = \frac{n_1 - n_2}{n_1}$

$$b \simeq \frac{\beta / k - n_2}{n_1 - n_2} \rightarrow 7$$

solving Eqn(7) for β ; $\beta = kn_2(1 + b\Delta) \longrightarrow 8$.

from (3), group delay $\frac{T}{D} = \frac{1}{c}\left(\frac{d\beta}{dk}\right) \longrightarrow 9$.

$$\Rightarrow T = \frac{D}{c}\frac{d\beta}{dk}.$$

∴ waveguide dispersion $T_{w.g} = \frac{D}{c}\frac{d}{dk}[kn_2(1 + b\Delta)]$ ..

$$\Rightarrow T_{w.g} = \frac{D}{c}\frac{d}{dk}\left[k n_2 (1 + b\Delta)\right].$$

$$= \frac{D}{c}\left[n_2 + n_2\Delta \frac{d}{dk}(kb)\right]. \rightarrow 10$$

For small values of Δ, $V \equiv k$

$\Rightarrow dV = dk$

Eq (10) modifies as : $T_{wg} = \frac{D}{c}\left[n_2 + n_2\Delta \frac{d}{dV}(Vb)\right].$

The pulse spreading σ_{wg} due to waveguide Dispersion (σ_{wg})

$$\sigma_{wg} = \sigma_\lambda \left|\frac{dT_{wg}}{d\lambda}\right|$$

$$= D\,|D_{wg}(\lambda)|\,\sigma_\lambda \rightarrow 11$$

where $D_{wg}(\lambda)$ = waveguide dispersion parameter

$$D_{w.g}(\lambda) = \left(\frac{n_2\Delta}{\lambda c}\right)\left[\frac{V\, d^2(Vb)}{dV^2}\right] \rightarrow 12$$

Intermodal Dispersion :- (modal or mode dispersion)

- pulse broadening due to intermodal dispersion results from the propagation delay differences between modes within a multi fiber. (As the different modes constitute a pulse in a multimode fiber travel along the channel at different group velocities the pulse width at the o/p is dependent upon the transmission times of slowest and fastest modes.

Intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile is provided by the near parabolic profile of graded index fibers. Hence, the overall pulse broadening in multimode graded index fibers is far less than multimode step index fiber (by a factor of 100). Thus graded index fibers used with a multimode source give a tremendous Bandwidth advantage over multimode step index fiber.

Intermodal Dispersion in multimode step index fiber

consider two rays propagating through the fiber shown in fig.

The time taken for the axial ray to travel along a fiber of length L gives the minimum delay time Tmin

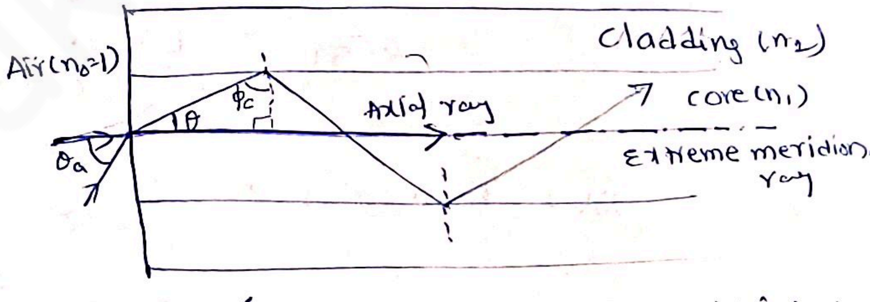


fig: Intermodal dispersion in step index fiber Using Ray model.

$$T_{min} = \frac{distance}{velocity} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c} \rightarrow 13$$

where $n_1 \rightarrow$ refractive index of core
$c \rightarrow$ velocity of light in vacuum.
$n_2 \rightarrow$ refractive index of cladding.

The Extreme meridional ray exhibits the maximum delay time,

$$T_{max} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta} \rightarrow 14$$

Using snell's law of refraction at the core - cladding interface,

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

put $\cos\theta$ value in (14) $\quad T_{max} = \frac{Ln_1}{c(n_2/n_1)} = \frac{Ln_1^2}{cn_2} \rightarrow 15$

The delay difference, δT_s b/n the extreme meridional ray and axial ray is obtained by subtracting the Eqn 13 from 15. Hence,

$$\delta T_S = T_{max} - T_{min} \qquad \frac{Ln_1}{c}\left[\frac{n_1}{n_2} - 1\right]$$

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

$$= \frac{Ln_1}{c}\left[\frac{n_1 - n_2}{n_2}\right] = \left(\frac{Ln_1}{c}\right)\Delta \quad \rightarrow 16$$

Δ = relative refractive index difference.

Numerical aperture is $NA = n_1\sqrt{2\Delta}$

$$(NA)^2 = n_1^2(2\Delta) \Rightarrow \Delta = \frac{(NA)^2}{2n_1^2} \quad \rightarrow 17$$

put for Δ in 16.

$$\delta T_S = \frac{Ln_1}{c}\frac{(NA)^2}{2n_1^2}$$

Delay difference $\delta T_S = \frac{L}{2n_1 c}(NA)^2 \quad \rightarrow 18$

Further rms pulse broadening due to intermodal dispersion is

$$\sigma_{SI} = \frac{Ln_1\Delta}{2\sqrt{3}\,c}$$

But from 17, $\Delta = \frac{(NA)^2}{2n_1^2}$

$$\therefore \sigma_{SI} = \frac{L}{4\sqrt{3}\,n_1}(NA)^2 \quad \rightarrow 19.$$

Intermodal Dispersion in Multimode Graded index fiber

Intermodal dispersion in multimode fibers is minimized with use of graded index fibers. By using multimode graded index fibers, Bandwidth is improved as compared to multimode step index fibers. The reason for improved performance of graded index fibers is explained in ray diagram

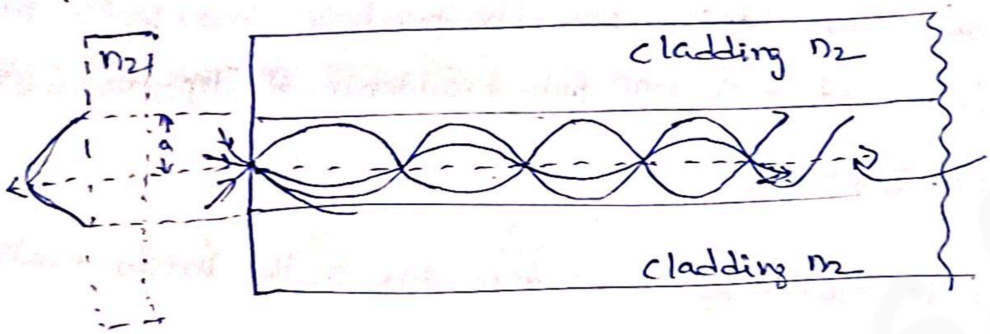


Fig: Intermodal Dispersion in graded index using parabolic profile.

The index profile is $n(r) = n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right]^{1/2}$ $\quad r < a$ (core)

$= n_1(1-2\Delta)^{1/2} = n_2$ $\quad r \geq a$ cladding

From fig. apart from the axial ray, the meridional rays following sinusoidal trajectories of different path lengths results from index grading. As the group velocity is inversely proportional to the Local refractive index and therefore longer sinusoidal paths are compensated for by higher speeds in the lower index medium away from the axis. Hence there is an equalization of the transmission times for the various trajectories.

Multimode fiber BW is improved by using a parabolic refractive index profile. This can be explained by reduced delay difference δT_G between the fastest & slowest modes for this graded index fibre.

Ray theory gives an expression for delay difference as:

$$\delta T_G = \frac{Ln_1\Delta^2}{2c} = \frac{Ln_1}{2c}\left(\frac{[NA]^2}{2n_1^2}\right)^2 = \frac{Ln_1(NA)^4}{2c(4n_1^4)}$$

$$= \frac{Ln_1(NA)^4}{8n_1^4 c} = \frac{L(NA)^4}{8n_1^3 c}$$

$$= (NA)^4/8n_1^3 c \quad \to 20 \quad (\text{if } L=1)$$

$NA = n_1\sqrt{2\Delta}$

$NA^2 = n_1^2 2\Delta$

$n_1^2 = \frac{NA^2}{2\Delta}$

However, Electromagnetic mode theory gives an expression as:

$$\delta T_g = \frac{L n_1 \Delta^2}{8C} \rightarrow 21$$

The two Expressions 20 & 21 are not same. Hence, the rms pulse broadening is a useful ~~is a useful~~ parameter for assessment of intermodal dispersion in multimode graded index fiber.

The rms pulse broadening of a near parabolic index profile graded index fiber (σ_{GI}) is related to the rms pulse broadening of step-index fiber (σ_{GI}) by the following expression:

$$\sigma_{GI} = \frac{\Delta}{D} \sigma_S$$

Where D is constant, value in the range of 4 & 10 depending on the precise evaluation and exact optimum profile chosen.

The best theoretical intermodal rms pulse broadening for a graded index fiber is

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

Polarization Mode Dispersion : polarization means the Electric field orientation of a light signal, polarization varies along the length of fiber. The maintenance of the state of polarization is explained interms of phenomenon known as modal birefringence.

Single-mode fibers allow two degenerate modes with orthogonal polarizations to propagate, the modes have different propagation constant due to the difference in the effective refractive indices (Δ) and the phase velocities.

When the fiber-cross-section is independent of the fiber length L in the z-direction, then the modal birefringence B_F for the fiber is

$$B_F = \frac{\beta_x - \beta_y}{2\pi/\lambda} \rightarrow 1$$

$\beta_x, \beta_y \rightarrow$ propagation constant of two modes in X & Y direction w.r.t

λ – optical wavelength.

The difference in phase velocities causes the fiber to exhibit a linear retardation $\phi(z)$ (assuming the phase coherence of two mode components is maintained is given by)

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

* The condition for the birefringent coherence to be maintained over a length of fiber L_c known as coherence length, is

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

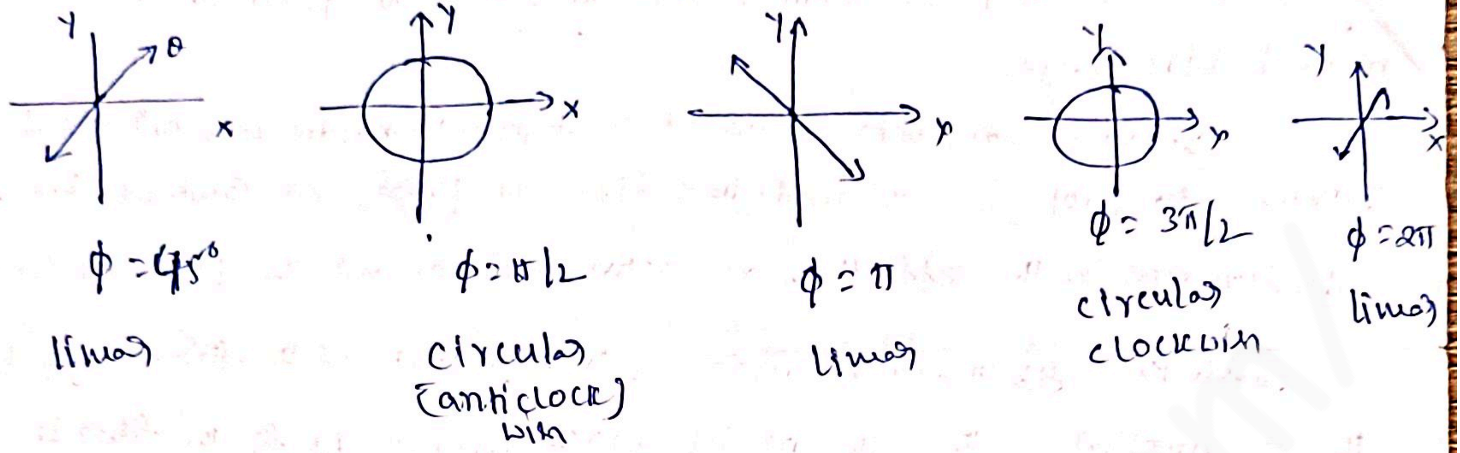
where δf = source frequency width

c = velocity of light in a vacuum

$\delta\lambda$ = source line width.

When the phase coherence is maintained, $\beta = kn_1 [1 - 2\Delta(1-b)]^{1/2}$ is an elliptical polarization. but varies periodically along the fiber. ~~in elliptical polarization~~. This is shown in diagrams below., where the incident linear polarization is at $\phi(z) = 45^\circ$ w.r.t x-axis becomes circular polarization at $\phi(z) = \pi/2$ and linear again at $\phi(z) = \pi$. The process continues through the another circular polarization at $\phi(z) = 3\pi/2$ before returning to the initial linear polarization $\phi(z) = 2\pi$.

The characteristics length corresponding to this process is known as the beat length $L_B = \frac{\lambda}{B_F}$ → 2



From 1 & 2. $L_B = \frac{\lambda}{\frac{(B_x - B_y)}{2\pi/\lambda}} = \frac{2\pi\lambda}{(B_x - B_y)\lambda} = \frac{2\pi}{B_x - B_y}$

Single mode fibers have beat length of a few centimeters.

polarization dispersion in optical fibers

polarization mode dispersion in a optical fiber is shown in figure above. The signal energy at a given wavelength occupies two orthogonal polarization modes. A varying birefringence along its length will cause each polarization mode to travel at a slightly different velocity. The resulting difference in propagation times, ΔT_{PMD}, between the two orthogonal polarization modes gives ~~result in~~ pulse spreading. This is the polarization mode dispersion T_{PMD}.

if the group velocities of the two orthogonal polarization modes are V_{gx} & V_{gy}, then the differential time delay, ΔT_{PMD} between the two polarization components during propagation of pulse over a distance L is

polarization mode dispersion $\Delta T_{PMD} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right|$

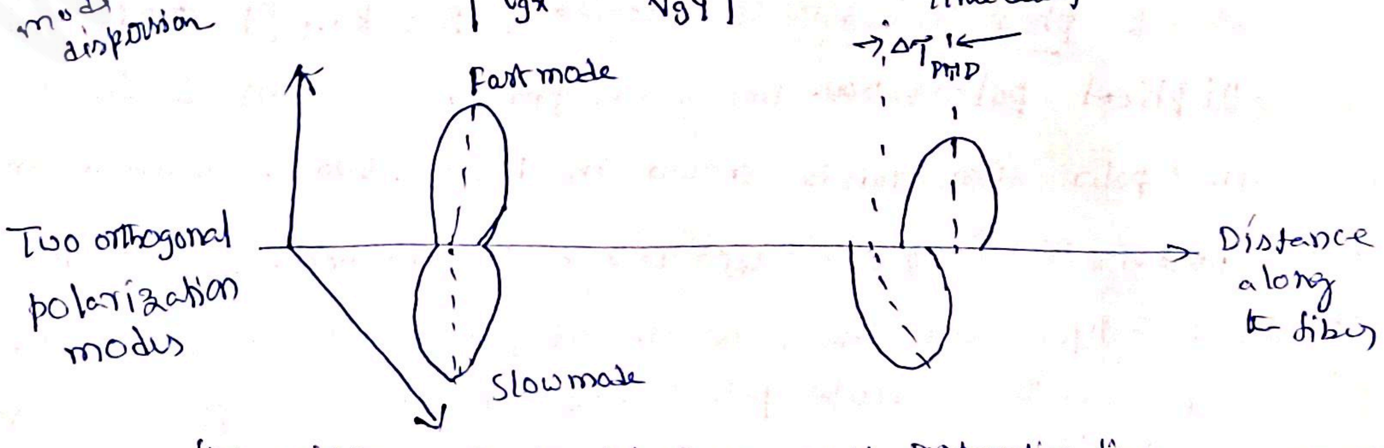


fig: Difference in the polarization model propagation times.

Overall fiber Dispersion

The pulse broadening in multimode fiber results from intermodal dispersion and intramodal dispersion. The total rms pulse broadening, σ_T

$$\sigma_T = \sqrt{\sigma^2_{intra} + \sigma^2_{inter}} \rightarrow 1$$

where $\sigma_{intra} \rightarrow$ Intramodal dispersion

$\sigma_{inter} \rightarrow$ Intermodal dispersion.

The intramodal term, σ_{intra} includes dispersion due to both material & waveguide dispersion. Since the waveguide dispersion is generally negligible when compared with material dispersion in multimode fibers, so $\sigma_{intra} = \sigma_{mat}$. The Intermodal term $\sigma_{inter} = \sigma_{SI}$ (for multimode step index fibers)

and $\sigma_{inter} = \sigma_{GI}$ (for multimode graded index fiber).

Overall Dispersion in single mode fiber

The dispersion (pulse broadening) in single mode fibers occurs entirely from intermodal dispersion.

The transit-time or group delay T_g for a light pulse propagating along a unit length is $T_g = \frac{1}{c}\frac{d\beta}{dk}$ where c = velocity of light in vacuum

β = propagation constant for a mode in the fiber core.

K = propagation constant for the mode in vacuum.

The total first order dispersion parameter (or) chromatic dispersion of a single mode fiber is $D_T = \frac{dT_g}{d\lambda}$

The total dispersion parameter, when λ variable is replaced with 'ω'

$$D_T = \frac{-\omega}{\lambda}\frac{dT_g}{d\omega} = \frac{-\omega}{\lambda}\frac{d^2\beta}{d\omega^2}$$

But, when β varies non-linearly with wavelength, the fiber exhibits intramodal dispersion, then 'β' can be expressed as: $\beta = kn_1(1-2\Delta[1-b])^{1/2}$

Where b = normalized frequency ; Δ = Relative refractive index difference.

Total r.m.s pulse broadening = $\sigma_\lambda L \left|\frac{dT_g}{d\lambda}\right| = \frac{\sigma_\lambda L 2\pi}{c\lambda^2}\frac{d^2\beta}{dK^2}$

where L = Length of fiber.

σ_λ = source r.m.s spectral line width centered at a wavelength λ.

The ~~pulse~~ [dependency of] pulse broadening & normalized propagation constant 'b' carry three interrelated effects involving complicated cross product terms and

1) Material Dispersion parameter:

$$D_{mat} = \frac{\lambda}{c}\left|\frac{d^2n}{d\lambda^2}\right|$$

where $n = n_1$ (or) n_2 for core or cladding w.r.t

2) Waveguide dispersion parameter:

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

3) profile dispersion parameter, D_p is proportional to $\frac{d\Delta}{d\lambda}$

i.e $D_p \propto \frac{d\Delta}{d\lambda}$

The total first order dispersion parameter can be written as

$$D_T = D_{Mat} + D_W + D_p$$

The dispersion behaviour varies with wavelength and also with fiber type.

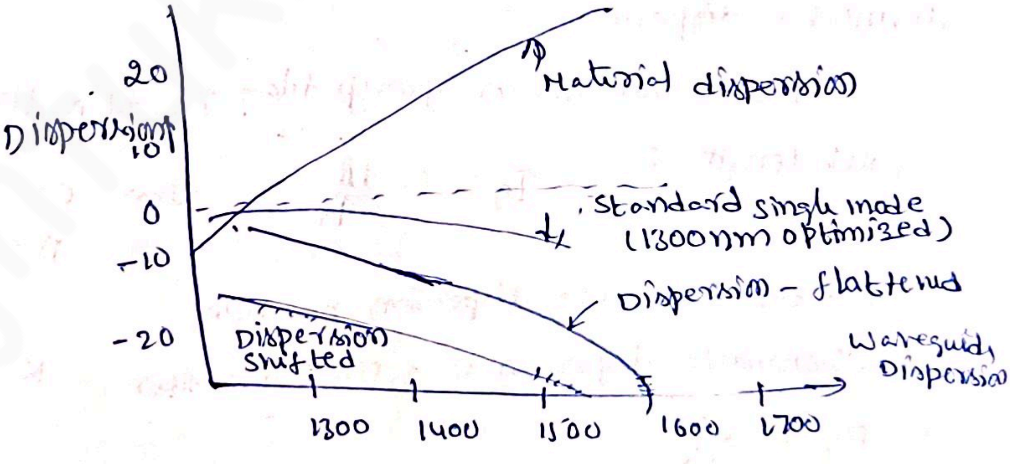


fig (a) Typical waveguide dispersion and common material dispersion of three different single mode fiber designs.

[P.T.O]

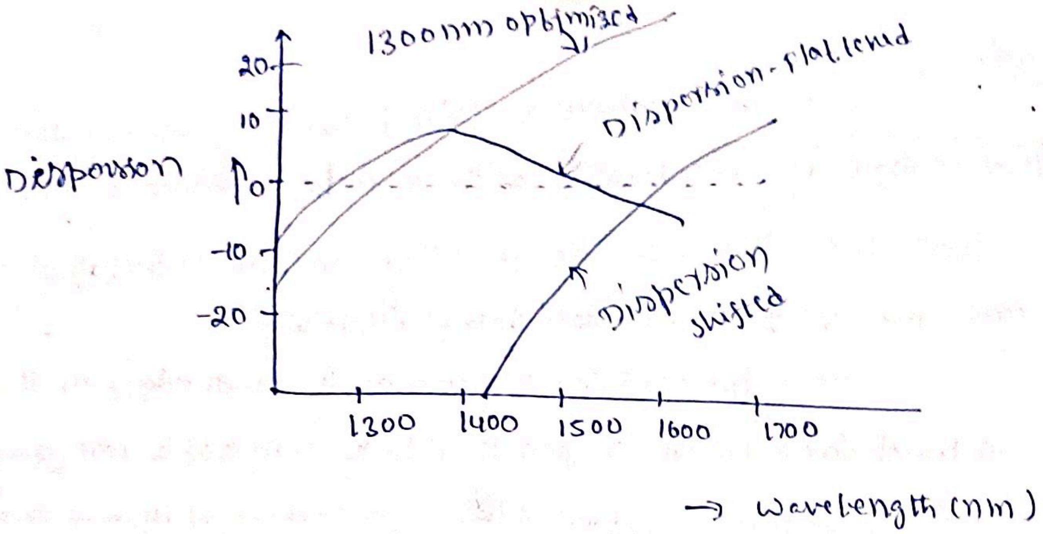


fig (b) : Resultant total Dispersions.

To calculate the dispersion for a non – dispersion shifted fiber in 1270nm to 1340nm region, the standard, group delay per unit length of a three – term sellmeier equation of the form,

$$\tau = A + B\lambda^2 + C\lambda^{-2}$$

A, B & C are the curve-fitting parameters.

An Equivalent expression is $\tau = \tau_0 + \frac{S_0}{8}\left(\lambda - \frac{\lambda_0^2}{\lambda}\right)^2$

where τ_0 = The relative delay minimum at zero-dispersion

λ_0 = wavelength

S_0 = The value of dispersion slope $S(\lambda) = \frac{dD}{d\lambda}$ at λ_0

As $D_T(\lambda) = \frac{d\tau}{d\lambda}$ hence the dispersion for a non-dispersion-shifted fiber is

$$D_T(\lambda) = \frac{\lambda S_0}{4}\left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

To calculate the dispersion for a dispersion-shifted fiber in the 1500 nm to 1600nm region, the standards recommended using the quadratic expression.

$$\tau = \tau_0 + \frac{S_0}{2}(\lambda - \lambda_0)^2$$

which results in the dispersion expression.

$$D_T(\lambda) = (\lambda - \lambda_0)S_0$$

S_0 = 0.092 ps (nm²-km) (nondispersion shifted fibers

S_0 = 0.06 – 0.08 ps (nm²-km) (dispersion shifted fiber

Consider a 30 km long optical fiber that has an attenuation of 0.8 dB/km at 1300 nm. If 200 μW of optical power is launched into the fiber, find the optical output power P_{out}.

Sol. : Given Data : Length of the optical fiber (L) = 30 km

Optical power launched into the fiber (P_{in}) = 200 μW

Attenuation constant ($\alpha_{dB/km}$) = 0.8 dB/km.

The most common derived units for calculating power level in optical communication is the dBm. This is given as

$$\text{Power level (dBm)} = 10 \log \frac{P(\text{Walts})}{1 \text{ mW}}$$

In this case,

$$P_{in}\,(\text{dBm}) = 10 \log\left[\frac{P_{in}\,(W)}{1\text{ mW}}\right]$$

$$= 10 \log\left[\frac{200 \times 10^{-6}\ \ }{1 \times 10^{-3}\ W}\right]$$

$$= -7.0\text{ dBm}$$

$$P_{out}\,(\text{dBm}) = 10 \log\left[\frac{P_{out}\,(W)}{1\text{ mW}}\right] = 10 \log\left[\frac{P_{in}\,e^{-\alpha L}}{1\text{ mW}}\right]$$

$$= 10 \log\left[\frac{P_{in}\,(W)}{1\text{ mW}}\right] - \alpha L$$

$$= -7.0\text{ dBm} - \left(0.8\,\frac{\text{dB}}{\text{km}}\right)(30\text{ km})$$

$$= -31.0\text{ dBm.}$$

In units of watts, the output power is

$P\,(30\text{ km}) = 10^{-31.0/10}\,(1\text{mW}) = 0.79 \times 10^{-3}\text{ mW} = 0.79\ \mu\text{W}$.

Example Problem 2.3

Suppose if the mean optical power launched into an 10 km length of fiber is 150 μW, the mean optical power at the fiber output is 5 μW. Calculate

1) **The overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices.**

2) **The signal attenuation per kilometer for the fiber.**

3) **The overall signal attenuation for a 15 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB.**

4) **The numerical input/output power ratio in (3).**

Sol. : 1) From Eq. (2.4.1), Signal attenuation in decibles is given by

$$\alpha_{dB} = 10 \log_{10}\frac{P_{in}}{P_{out}} = 10 \log_{10}\frac{150 \times 10^{-6}}{5 \times 10^{-6}}.$$

$$= 10 \log_{10}(30)$$

$$= 14.7\text{ dB.}$$

2) From Eq. (2.4.3), attenuation in dB/km is given by,

$$\alpha_{dB/km} = \frac{\left(10 \log_{10} \frac{P_{in}}{P_{out}}\right)}{L}$$

$$\Rightarrow \alpha_{dB/km} = \frac{14.7\ dB}{10\ km}$$

$$\therefore \alpha_{dB/km} = 1.47\ dB\,/\,km.$$

3) As α = 1.47 dB/km, the loss incurred along 15 km length of the fiber is given by,

$$\alpha L = 1.47 \frac{dB}{km} \times 15\ km = 22\ dB.$$

However, the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 14 dB.

Hence, the overall signal attenuation for the link is signal attenuation = 22 + 14 = 36 dB.

4) From Eq. (2.4.2), Numerical value for the input/output power ratio is given by,

$$\frac{P_{in}}{P_{out}} = 10^{36/10} = 3981.$$

[May/June – 09]

Example Problem 2.4

A $K_2O - SiO_2$ glass core optical fiber has an attenuation resulting from Rayleigh scattering of 0.46 dB/km at a wavelength of 1 μm. The glass has an estimated fictive temperature of 758 K, isothermal compressibility of 8.4 × 10^{-11} $m^2 N^{-1}$ and a photoelastic coefficient of 0.245. Determine from theoretical considerations the refractive index of the glass.

Sol. : Given Data : Operative wavelength (λ) = 1 μm

Fictive temperature (T_F) = 758 K

Isothermal compressibility (β_c) = 8.4×10^{-11} m^2N^{-1}

Photoelastic co-efficient (ρ) = 0.245

Using Eq. (2.6.1) Rayleigh scattering coefficient is given as :

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_T K_B T_F$$

$$= \frac{8 \times (3.14)^3 \times n^8 \times (0.245)^2 \times 8.4 \times 10^{-11} \times 1.38 \times 10^{-23} \times 758}{3 \times (10^{-6})^4}$$

$$= 4.35 \times 10^{-6}\ n^8.$$

$$\text{Attenuation}(\text{dB/km}) = 10 \log_{10}\left(\frac{1}{T_{km}}\right)$$

$$\Rightarrow 0.46 = 10 \log_{10}(e^{\alpha_{scat} L}) \qquad (\because T = e^{-\alpha_{scat} \cdot L})$$

$$\Rightarrow 0.46 = 4.34\ (\alpha_{scat}\ L)$$

$$\Rightarrow 0.46 = 4.34 \times 4.35 \times 10^{-6}\ n^8 \times 1000$$

$$\Rightarrow n^8 = \frac{0.46}{4.34 \times 4.35 \times 1000 \times 10^{-6}}$$

$$\Rightarrow n^8 = 24.365$$

$$\therefore n = (24.365)^{1/8} = 1.49.$$

The threshold optical powers for stimulated Brillouin and Raman Scattering in a long 10μm core diameter single mode fiber are found to be 150mW and 1.50W respectively, when using an injection LASER source with a bandwidth of 1GHz. calculate the operating wavelength of the LASER and the attenuation in dB/km of the fiber at this wavelength.

sol: source bandwidth $= 1GHz$

threshold optical power for stimulated Brillouin (P_{SBS}) $= 150$ mW

threshold optical power for stimulated Raman (P_{SRS}) $= 1.50$ W

core diameter (d) $= 10$ μm

threshold power for Brillouin scattering $P_{SBS} = \cancel{4.4 \times 10^{-3} d^2 \lambda^2 \alpha_i}$

$$= 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_B BW \rightarrow 1$$

threshold power for Raman scattering is

$$P_{SRS} = 5.9 \times 10^{-2} d^2 \lambda \alpha_R \rightarrow 2$$

$$\Rightarrow \frac{P_{SBS}}{P_{SRS}} = \frac{4.4 \times 10^{-3} d^2 \lambda^2 \alpha_B BW}{5.9 \times 10^{-2} d^2 \lambda \alpha_R}$$

$$\Rightarrow \frac{150 \times 10^{-3}}{1.5} = 0.074 \times 10^{-1} \lambda BW$$

$$\Rightarrow \cancel{\lambda =} 100 \times 10^{-3} = 0.074 \lambda BW$$

$$\Rightarrow \lambda = \frac{100 \times 10^{-3}}{0.074 \times 1} \quad [BW = 1GHz]$$

$\lambda = 1.35$ μ

put the value of λ in (2)

$$1.50 = 5.9 \times 10^{-2} \times (10)^2 \alpha_R$$

$$\Rightarrow \alpha_R = \frac{1.50}{5.9 \times 10^{-2} \times 100} = 0.254 \text{ dB/km}$$

A multimode graded index fiber exhibits the pulse broadening of 0.2 μs over a distance of 15 km. Estimate

i) optimum BW of fiber.

ii) Dispersion per unit length.

iii) BW length product.

Sol:

Total pulse broadening $(\tau) = 0.2\ \mu sec$

Distance $L = 15\ km$

i) The max. possible BW ~~aft~~ assuming no Inter symbol Interference (ISI) given by $B_T = \frac{1}{2\tau} = \frac{1}{2 \times 0.2 \times 10^{-6}} = 2.5\ MHz$

ii) The dispersion per unit length be acquired dividing the total dispersion by the total length of the fiber

i.e Dispersion per unit length $= \frac{\text{Total dispersion}}{\text{Total length of the fiber}}$

$$= \frac{\tau}{L} = \frac{0.2 \times 10^{-6}}{15}$$

$$= 13.33\ ns/km$$

∴ Dispersion per unit length

iii) The BW-length product of the link is $B_T L$

$$= 2.5 \times 10^{6} \times 15$$

$$= 37.5\ MHz\text{-}km$$

$$\therefore B_T L = 37.5\ MHz\_km$$

Alternately, the BW-length product is obtained by from dispersion per unit length as

$$B_T L = \frac{1}{2 \times \text{Dispersion per unit length}} = \frac{1}{2 \times 13.33 \times 10^{-6}}$$

$$= 37.5\ MHz\text{-}km$$

A Single mode fiber operating at the wavelength of 1.3 μm is found to have a total material dispersion of 2.81 ns and a total waveguide dispersion of 0.495 ns. Determine the received pulse width and approximate bit-rate of the fiber if the transmitted pulse has a width of 0.5 ns.

sol: $D_{mat} = 2.81 ns$, $D_{wg} = 0.495 ns$

$\lambda = 1.3 \mu m$; $T_0 = 5 ns$

∴ r.m.s value $T_0 = \frac{5}{\sqrt{2}} ns$

$$T_{0rms} = 3.535 ns$$

$$T_{0r.ms} = \sigma_0$$

when σ_0 is the rms value i/p pulse ~~with~~ width.

Total dispersion $D = D_{mat} + D_{wg}$

$$= (2.81 + 0.495) ns$$

$$= 3.305 ns$$

$$\beta_2 = \frac{-D\lambda^2}{2\pi c} = \frac{3.305 \times 10^{-9} \times (1.3 \times 10^{-6})^2}{2\pi \times 3 \times 10^8}$$

$$\beta_2 = -2.28 \times 10^{-30}$$

The factor $\sigma_D = DL\sigma_\lambda$

$$= 3.305 \times 10^{-9} \times 1 \times 10^3 \times \frac{1.3}{\sqrt{2}} \times 10^{-6}$$

$$= 3.038 \times 10^{-12}$$

∴ The o/p pulse width $\sigma = (\sigma_0^2 + \sigma_D^2)^{1/2}$

$$= \sqrt{(3.535 \times 10^{-9})^2 + (3.038 \times 10^{-12})^2}$$

$$= 3.~~5350 \times 10^{-9}~~ s \quad 3.535001306 \times 10^{-9} s$$

For the fiber it is given that, at $\lambda = 850nm$, $\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right| = 0.015$ the R.M.S spectral width of the light sources is 20 nm at this wavelength, Determine

i) Material dispersion parameter

ii) R.M.S pulse broadening / km due to material dispersion.

Soln $\lambda = 850 \times 10^{-9} m$

$\lambda^2 \left(\frac{d^2 n_1}{d\lambda^2} \right) = 0.015$

spectral width : $\sigma_\lambda = 20 \times 10^{-9} m$

1) Material dispersion parameter $D_{mat}(\lambda)$

$$D_{mat}(\lambda) = \frac{\lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right|$$

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

$$= \frac{0.015}{3 \times 10^8 \times 850 \times 10^{-9}}$$

$$= 58.8 \text{ ps nm}^{-1} / km$$

$\therefore D_{mat}(\lambda)$

ii) The R.M.S pulse broadening due to material dispersion

$$\sigma_{mat} \simeq \frac{\sigma_\lambda D}{c} \left| \lambda \frac{d^2 n_1}{d\lambda^2} \right| \simeq \sigma_\lambda D_{mat}(\lambda) D$$

Hence, R.M.S pulse broadening per km

$$\sigma_{mat}(1km) = \sigma_\lambda D_{mat}(\lambda)$$

$$= 20 \times 58.8 \times 10^{-12}$$

$$= 1.17 \text{ ns km}^{-1}$$

The broadening factor

$$\frac{\tau}{\tau_0} = \frac{3.5350 \times 10^{-9}}{3.535 \times 10^{-9}} = 1$$

O/P pulse time period = 4.992 ns

The bit rate $T_b = \frac{1}{2T} = \frac{1}{2 \times 4.992 \times 10^{-9}}$

$= 100 \times 10^{6}$

$T_b = 100\, MHz$

A single mode ~~fiber~~ step-index fiber gives a total pulse broadening of 95 ns over a 5 km length. Estimate the BW length product for the fiber when a non-return to zero digital code (NRZ) is used.

sol: Total pulse broadening (T) = 95 ns

Length of optical fiber (L) = 5 km

When a NRZ is used then the transmission BW

1) $B_T = \frac{1}{2T} = \frac{1}{2 \times 95 \times 10^{-9}} = 5.25\, MHz$

Dispersion defined as, $B_T L = \frac{1}{2 \times 95 \times 10^{-9}} =$

$= 5.25\, MHz \times 5\, km$

$= 26.25\, MHz\, km$

KEY FORMULAE

1) The cut-off wavelenth for step index fiber is :

$$\lambda_c = \frac{V\lambda}{2.405}$$

2) Effective refractive index for single mode fiber is :

$$n_{eff} = \frac{\beta}{k}$$

3) Rayleigh scattering :

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 \rho^2 \beta_c k T_F$$

4) Stimulated Brillouin scattering :

$$P_{SBS} = 4.4 \times 10^{-3}\ d^2 \lambda^2\ \alpha_{dB}\ V \text{ watts.}$$

5) Stimulated raman scattering :

$$P_{SRS} = 5.9 \times 10^{-2}\ d^2\ \lambda\ \alpha_{dB} \text{ watts.}$$

6) Critical value of radii of curvature R_C for macroscopic bending losses.

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

7) The effective number of modes for curved multimode fiber :

$$N_{eff} = N_{\infty}\left\{1 - \frac{\alpha + 2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2kR}\right)^{2/3}\right]\right\}$$

Fill in the Blanks

1) In single mode fibers, only the mode exists is ________.

2) Single mode of propagation of LP_{11} mode is possible over the range ________.

3) Mode field diameter, MFD related to spot size ω_0 by ________.

4) The mode field diameter depends upon the ________.

5) Glass fibers are made up of ________.

6) Doping silica with ________ increases the refractive index.

7) Doping silica with ________ decreases the refractive index.

8) Plastic fibers have higher ________ than the glass fibers, so they are mainly used in ________ communications.

9) The effective refractive index varies over the range ________.

10) Signal attenuation is OFC is due to ________, ________ and ________.

11) Attenuation in optical fiber is a function of ________.

12) Fiber bending is divided into ________ and ________.

13) Blue sky in the scattering means ________.

14) ________ scattering is due to inhomogenieties occurring in the fiber material.

15) Mie scattering is due to ________.

16) Mie scattering can be reduced by ________.

17) Non-linear scattering losses, usually happens at a ________.

18) Two types of non-linear scattering losses are ________ and ________.

19) Bending losses are also known as ________.

20) Microbending losses can be minimized by ________.

Q6) **Higher the radiation, the attenuation is** **Ans. [b]**

a) Larger
b) Smaller
c) Both
d) None

Q7) **Attenuation is an function of** **Ans. [a]**

a) Wavelength
b) Dispersion
c) Bending
d) None

Q8) **Attenuation coefficient unit is** **Ans. [a]**

a) Km^{-1}
b) Km^{-2}
c) Km/Sec^2
d) None

Q9) **Attenuation is increased due to** **Ans. [a]**

a) Ionizing radiation
b) Ionizing absorption
c) Ionizing penetration
d) Ionizing pattern

Q10) **Extrinsic absorption is due to** **Ans. [a]**

a) Transit metal impurities
b) transit metal purities
c) Both
d) None

Q11) **The loss in power during the propagation of a light through the fiber is known as** **Ans. [b]**

a) Absorption
b) Attenuation
c) Dispersion
d) Scattering

Q12) **Absorption in optical fiber is due to** **Ans. [d]**

a) Atomic defects in the glass composition
b) Density variations
c) Material inhomogenieties
d) All of the above

Q13) **Which of the following corresponds to the basic transmission window wavelength** **Ans. [c]**

a) 725 nm

b) 1400 nm

c) Both (a) and (b)

d) None of the above

Q14) **The typical attenuation encountered in the 1550 nm wavelength is** **Ans. [a]**

a) 0.3 dB km^{-1}

b) 0.5 dBkm^{-1}

c) 4 dB km^{-1}

d) 0.6 dB km^{-1}

Q15) **Which of the following occurs due to the inhomogenieties occurring in the fiber material?**

Ans. [a]

a) Rayleigh scattering

b) Mie scattering

c) Stimulated Brillouin scattering

d) Stimulated raman scattering

16) **The microbending losses can be reduced by** **Ans. [c]**

a) Designing fibers with large relative refractive index difference

b) Operating at the shortest wavelength possible

c) Both (a) and (b)

d) None.

Q17) **The core and cladding have** **Ans. [b]**

a) Same attenuation coefficients

b) Different attenuation coefficients

c) One is double of the other

d) One is one third of other

18) **The relation between the total power p, the power in the cladding P_{clad} and total power in core P_{core} is** **Ans. [d]**

a) $\frac{P_{cladd}}{P} = 1 + \frac{P_{core}}{P}$

b) $\frac{P_{core}}{P} = 1 - \frac{P_{cladd}}{P}$

c) $\frac{P_{core}}{P} = 1 + \frac{P_{cladd}}{P}$

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

Q19) **The attenuation in dB/km is given by multiplying factor with _____ nepers/km** **Ans. [b]**

a) 10 b) 4.343

c) 2.343 d) 0.273

Q20) **The peaks and valleys in the attenuation curve resulted in the designation of various _____ to optical fibers.** **Ans. [a]**

a) Transmission window b) Untransmission window

c) Both d) None

Unit-3

3.7 OPTICAL FIBER CONNECTORS

Just like any channel communication system, optical fiber links have a requirement for joining and termination of the medium. The number of optical fiber connection or joints depends upon the length of the optical link. Splicing and connectorizing are the two ways of joining the fibers. The primary task of both these techniques is to precisely match the core of one optical fibers with that of another in order to produce a smooth junction through which light signals can continue without any interruption.

1) **Splices**

These are semi-permanent or permanent joints between two optical fibers.

2) **Connectors**

These are removable joints which allow easy, fast, manual coupling and uncoupling of fibers.

Splicing techniques are studied in detail in unit 4 in this chapter, we emphasize on optical fiber connectors. Optical fiber connectors are the means by which fiber optic cable is usually connected to peripheral equipments and to other fibers.

3.7.1 Requirements of a Good Connector Design [May-10]

There are many different types of optical connectors in use today. Their uses range from simple single-channel fiber-to-fiber connectors in a simple location to multichannel connectors used in harsh military field environments. Some of the principal requirements of a good connector design are as follows :

1) **Low Coupling Losses**

The connector assembly must maintain stringent alignment tolerances to assure low mating losses. These low losses must not change significantly during operation or after numerous connects and disconnects.

2) **Compatibility**

Connectors of the same type must be compatible from one manufacturer to another.

3) **Ease of Assembly**

The installation of the connector should be easy in a field environment rather in the connector factory.

4) **Low Environment Sensitivity**

There must be very little effect of environmental conditions such as temperature, dust and moisture.

5) **Low Cost and Reliable Construction**

The connector must have a precision suitable to the application, but its cost must not be a major factor in the fiber system.

6) **Ease of Connection**

Generally, one should be able to mate and demate the connector, simply, by hand.

7) **Load Capability**

Optical connector must cope with tensile load on the cable.

8) **Coupling Efficiency**

The coupling efficiency should not change much with repeated matings.

3.7.2 Connector Types

The two basic types of fiber optic connectors used are :

1) Butt-jointed connectors.
2) Expanded-beam connectors.

3.7.2.1 Butt - Joined Connectors

Fiber optic butt-jointed connectors align and bring the prepared ends of two fibers into close contact. There are two most widely accepted designs of butt jointed alignment. They are explained as follows,

1) **Cylindrial Ferrule Connectors or Straight Sleeve Connectors**

cylindrical

The basic ferrule connector or straight sleeve connector is the simplest optical fiber connector design as shown in Fig. 3.7.1. In this design, the two fibers to be connected are permanently bounded with epoxy resin in metal plugs known as ferrules which have an accurately drilled hole in their end faces where the stripped fiber is located. Within the connector, two ferrules are placed in an alignment sleeve, which allows the two fibers to be butt jointed.

With this type of connector, it is essential that the fiber end faces are smooth and square.

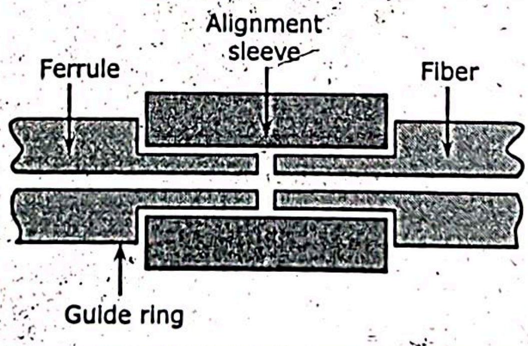


Fig. 3.7.1 Straight Sleeve Connectors

2) Biconical Ferrule Connector or Tapered Sleeve Connector

Tapered sleeve connector is the most widely used part of jumper cables in a variety of applications. The plugs in a tapered sleeve connector are either moulded directly on to fiber or cast around the fiber using a silica-loaded epoxy resin ensuring concentricity to within 5μm. After plug attachment, the fiber end faces are polished before the plugs are inserted and aligned in the biconical moulded centre sleeve, as shown in Fig. 3.7.2.

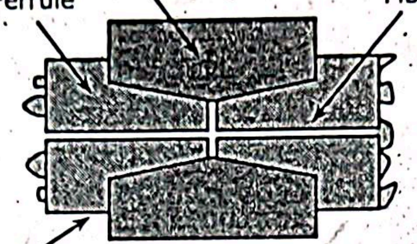


Fig. 3.7.2 Tapered Sleeve Connector

The tapered sleeve connector has a mean insertion loss of 0.21 dB when using with a 50μm core diameter graded index fibers. This type of connector can also be used with single mode fibers by reducing the eccentricity of the tapered cone and also the fiber core eccentricity to 0.33 μm or less, while the tilt angle of fibers to 0.35^0 or less.

3.7.2.2 Expanded Beam Connectors

Fiber optic expanded-beam connectors use two lenses to first expand and then refocus the light from the transmitting fiber into the receiving fiber.

An expanded - beam connector, illustrated in Fig. 3.7.3, employs lenses at the end of the fibers. These lenses either collimate the light emerging from the transmitting fiber, or focus the expanded beam onto the core of the receiving fiber. The fiber to lens distance is equal to the focal length of the lens. The advantage of this schema is that, since the beam is collimated, separation of the fiber ends may take place within the connector. Thus, the connector is less dependent on lateral alignments. In addition, optical processing elements, such as beam splitters and switches, can easily be inserted into the expanded beam between the fiber ends.

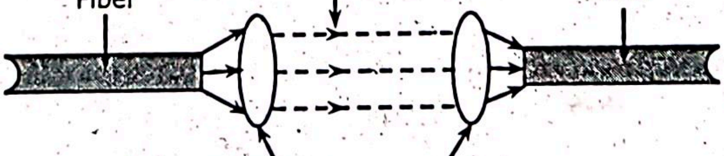


Fig. 3.7.3 Schematic Representation of an Expanded-beam Fiber Optic Connector

Due to the wide usage of single mode fiber optic links and also due to its greater alignment precision required for the system, it pays a very important note to calculate the connector coupling losses for this fiber. Based on the Gaussian-beam model of single mode fiber fields, the coupling loss between the single mode fibers have been derived, which have unequal mode-field diameters; lateral, longitudinal and angular offsets and reflections.

$$\boxed{L_{SM.ff} = -10\log\left[\frac{16n_1^2 n_3^2}{(n_1 + n_3)}\,\frac{4\sigma}{q}\exp\left(\frac{-\varsigma\mu}{q}\right)\right]} \qquad ...(3.7.1)$$

Where,

$$\varsigma = (kw_1)^2$$

$$q = G^2 + (\sigma + 1)^2$$

$$\mu = (\sigma + 1)F^2 + 2\sigma FG\sin\theta + \sigma(G^2 + \sigma + 1)\sin^2\theta$$

$$F = \frac{d}{kw_1^2}$$

$$G = \frac{s}{kw_1^2}$$

$$\sigma = \left(\frac{w_2}{w_1}\right)^2$$

$$k = \frac{2\pi n_3}{\lambda}$$

n_1 = core refractive index of fibers

n_3 = refractive index of medium between fibers

λ = wavelength of source

d = lateral offset

s = longitudinal offset

θ = angular misalignment

$w_1 = \frac{1}{e}$ mode field radius of transmitting fiber

$w_2 = \frac{1}{e}$ mode field radius of receiving fiber.

3.7.4 Connector Return Loss

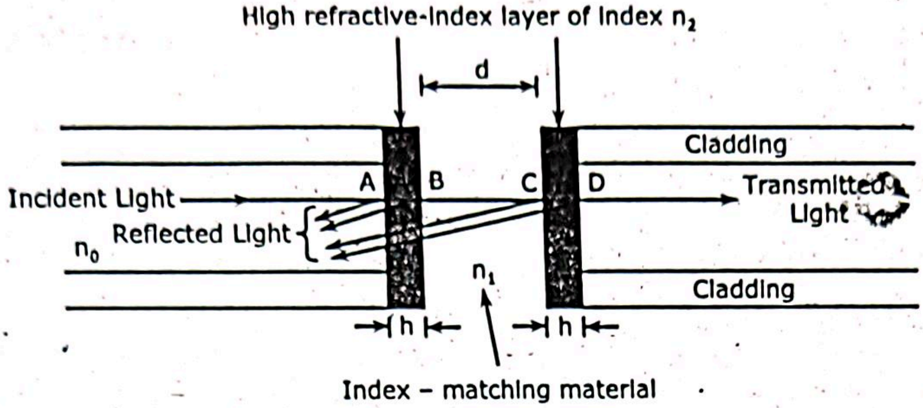


Fig. 3.7.4 Model of an Index-matched Connection with Perpendicular Fiber End Faces

Fig. 3.7.4 shows a model of an index-matched connection with perpendicular fiber end faces. In this figure and in the following analysis, offsets and angular mis alignments are not taken into consideration. The connection model shows that the fiber end faces have a thin surface layer of thickness h, having a high refractive index, n_2, relative to the core index, which is a result of fiber polishing. The fiber core has an index n_0 and the gap width between the end faces is filled with index matching material having a refractive index, n_1. The return loss, RL_{Im}, in decibels for the index matched gap region is given by,

$$RL_{Im} = -10 \log \left\{2R_1 \left[1 - \cos\left(\frac{4\pi n_1 d}{\lambda}\right)\right]\right\}$$

where,

R_1 → Reflectivity at a single-material coated end face and is given by,

$$R_1 = \left[\frac{r_1^2 + r_2^2 + 2r_1r_2\cos\delta}{1 + r_1^2 r_2^2 + 2r_1r_2\cos\delta}\right]$$

Here,

$$r_1 = \left(\frac{n_0 - n_2}{n_0 + n_2}\right) \text{ and } r_2 = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)$$

are the reflection coefficients through the core from higher-index layer and through the high-index layer from the core, respectively.

When the perpendicular end faces are in direct physical contact, then the return loss, RL_{PC}, in decibels is given by,

$$RL_{PC} = -10 \log \left\{2R_2 \left(1 - \cos\frac{4\pi n_2}{\lambda} 2h\right)\right\}$$

where, R_2 is the reflectivity at the discontinuity between the refractive indices of the fiber core and high-index surface layer and is given by,

$$R_2 = \left(\frac{n_0 - n_2}{n_0 + n_2}\right)^2$$

Fiber Splicing and Optical Sources

Syllabus

Fiber Splicing, Splicing Techniques, Splicing Single Mode Fibers, Fiber Alignment and Joint Loss, Multimode Fiber Joints, Single Mode Fiber Joints, Optical Sources, LEDs, Structures, Materials, Quantum Efficiency, Power, Modulation, Power Bandwidth Product, Injection Laser Diodes, Modes, Threshold Conditions, External Quantum Efficiency, Laser Diode Rate Equations, Resonant Frequencies, Reliability of LED and ILD.

4.1 FIBER SPLICING

A fiber splice is a permanent joint or a semi-permanent joint between two fibers. These are typically used to create long optical links or used in situations where frequent connection and disconnection are not needed. In making and evaluating such splices, one must taken into account the geometrical differences in the two fibers, fiber misalignments at the joint and the mechanical strength of the splice.

4.2 SPLICING TECHNIQUES

Depending on the splicing techniques used, splices are broadly categorized as two types. They are :

1) Fusion Splices.

2) Mechanical Splices.

4.2.1 Fusion Splices

Fusion Splices are made by thermally bonding together prepared fiber ends, as shown in Fig. 4.2.1

1) In this method, the fiber ends are first prealigned and butted together. This is done either in a grooved fiber holder or under a microscope with micromanipulators.

2) The butt joint is then heated with an electric arc or a laser pulse so that the fiber ends are momentarily melted and hence bonded together.

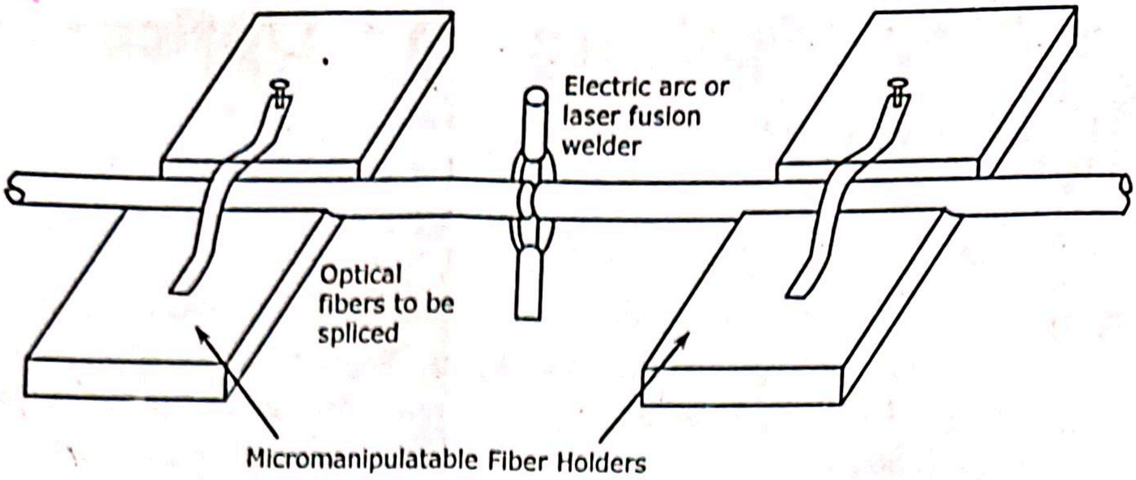


Fig. 4.2.1 Fusion Splicing of Optical Fibers

Fig. 4.2.2 illustrates the step-by-step process for accurately splicing optical fibers. Firstly, the broken fiber edges are aligned and then an adequate buffing pressure is applied, as per exact requirement. Next, heat is applied to based fiber by an electric arc. When the fiber ends are fused, they unite as a single fiber.

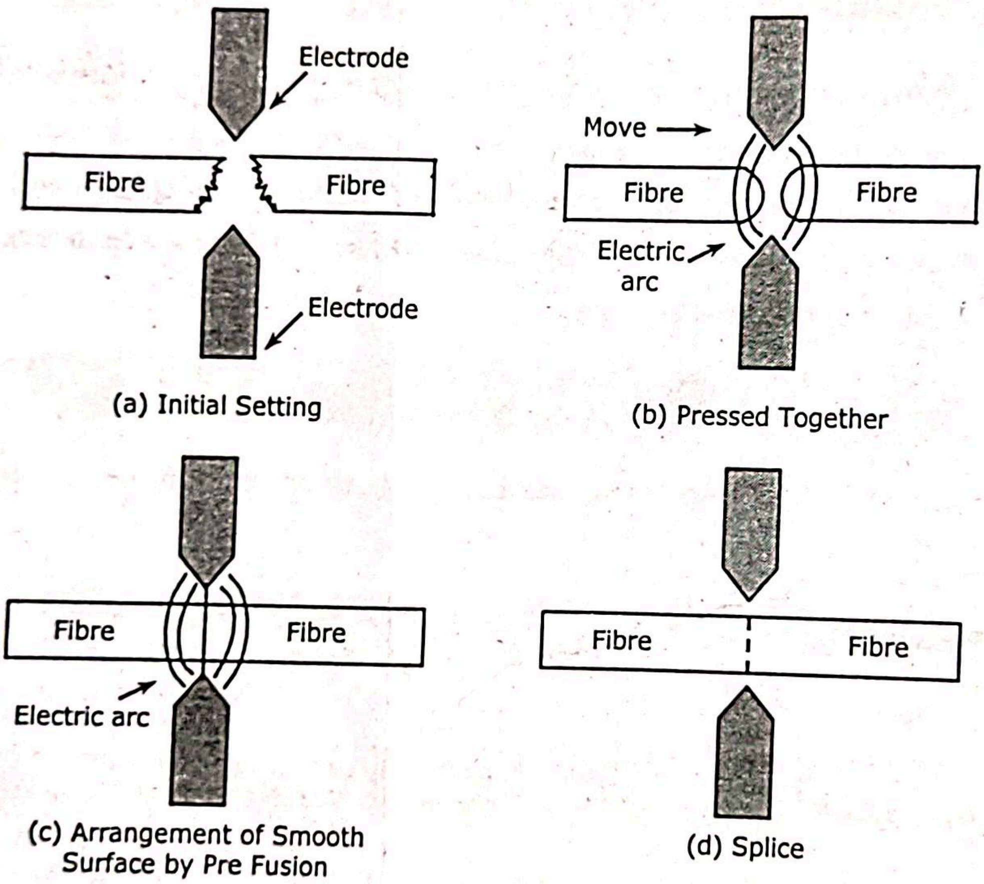


Fig. 4.2.2 Schematic Illustration of Step-by-step Process for Accurately Splicing Optical Fibers.

Fusion splicing of single mode fibers with typical core diameters between 5 μm and 10μm presents problems of more critical fiber alignment. However, splice insertion losses below 0.3dB may be achieved due to a self alignment phenomenon which partially compensates for any lateral offset.

Self alignment, as illustrated in Fig. 4.2.3, is caused by surface tension effects between the two fiber ends during fusing. The possible drawback with fusion splicing is that the heat necessary to fuse the fibers may weaken the fiber in the vicinity of the splice. It is been found that out of utmost care, the tensile strength of the fused fiber may be as low as 30% of that of the uncoated fiber joint. The fiber fracture generally occurs in the heat affected zone adjacent to the fused joint. It is therefore, necessary that the completed splice is packaged so as to reduce tensile loading upon the fiber in the vicinity of the splice.

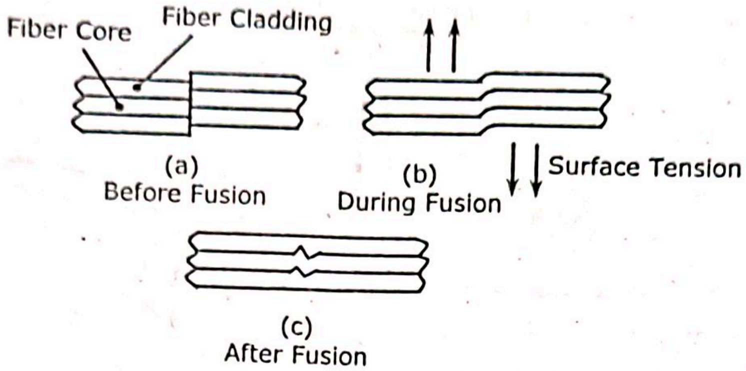


Fig. 4.2.3 Self-alignment phenomenon which takes place during fusion splicing.

.2.2 Mechanical Splices

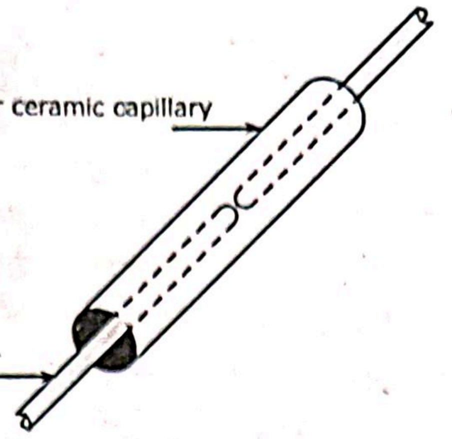
The basis of splicing techniques used in mechanical splicing are to align the broken fiber edges and lock them in position with the help of various positioning devices and optical cement. A number of mechanical techniques are used for splicing individual optical fibers and they are :

1) Snug tube splice.
2) V-Groove splice.
3) Elastomeric or elastic tube splice.
4) Springroove splice.

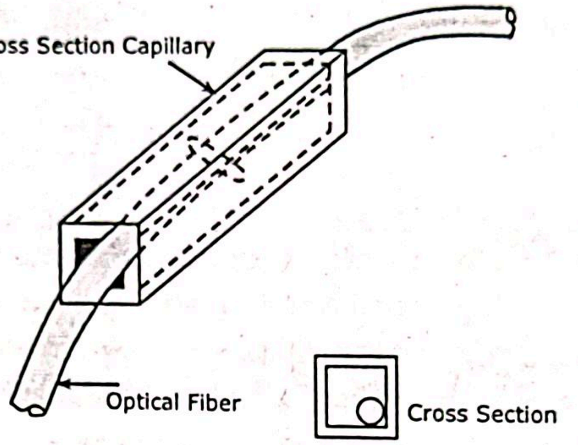
2.1 Snug Tube Splices

Snug tube splice involves the use of an accurately produced rigid alignment tube into which the prepared fiber ends are permanently bonded. This snug tube splice is illustrated in Fig. 4.2.4 (a), which may also utilize a glass or ceramic capillary with an inner diameter just large enough to accept the optical fibers. Transparent adhesive is injected through a transverse bore in the capillary to give mechanical sealing and index matching of the splice.

A mechanical splicing technique which avoids the critical tolerance requirements of the snug tube splice is shown in Fig. 4.2.4(b). This loose tube splice uses an oversized square section metal tube which easily accepts the prepared fiber ends. Transparent adhesive is first inserted into the tube followed by the fibers. The splice is self aligning when the fibers are curved in the same plane, forcing the fiber ends simultaneously into the same plane and into the same corner of the tube.



(a) Snug Tube Splice

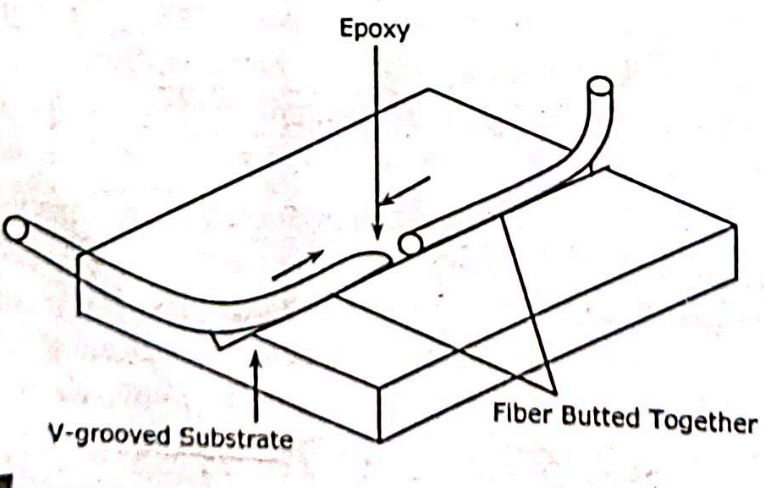


(b) Loose Tube Splice

Fig. 4.2.4 Techniques for Tube Splicing of Optical Fibers

4.2.2.2 Groove Splicing

In this mechanical splicing technique, the grooves are used to make the fibers secure, which are to be joined. This simple method uses a V-groove into which the two prepared fiber ends are pressed. They are then bonded together with an adhesive or are held in place by means of a cover plate. The V-shaped channel can be either a grooved silicon, plastic, ceramic or metal substrate. The splice loss in this method depends strongly on the fiber size and eccentricity. A typical V-groove splice is shown in Fig. 4.2.5.



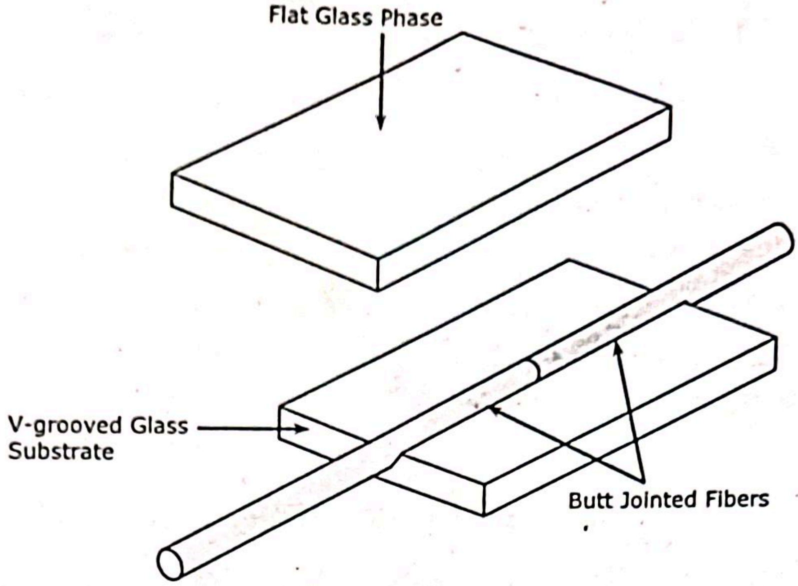


Fig. 4.2.5 V-groove Splices

V-groove can also be formed by sandwiching the butted fiber ends splices between V-groove glass substrate and a flat glass retainer plate. Splice insertion loss of less than 0.01dB when coupling single mode fibers were recorded using this technique.

4.2.2.3 Elastic Tube Splice

The cross-sectional view of an elastic tube splice is shown in Fig. 4.2.6. It is a unique device that automatically performs lateral, longitudinal and angular misalignment. It splices the multimode fibers to give losses in the same range as commercial fusion splices, but much less equipment and labour skill are needed. This splice mechanism basically uses a tube made of an elastic material. The central hole diameter is slightly smaller than that of the fiber to be spliced and is tapered on each end for easy fiber insertion. When a fiber is inserted, it expands the hole diameter so that the elastic material exerts a symmetric force on the fiber. This symmetry feature allows an accurate and automatic alignment of the axes of the two fibers to be joined. A wide range of fiber diameters can be inserted into the elastic tube. Thus, the fibers to be spliced do not have to be equal in diameter, since each fiber moves into position independently relative to the tube axis.

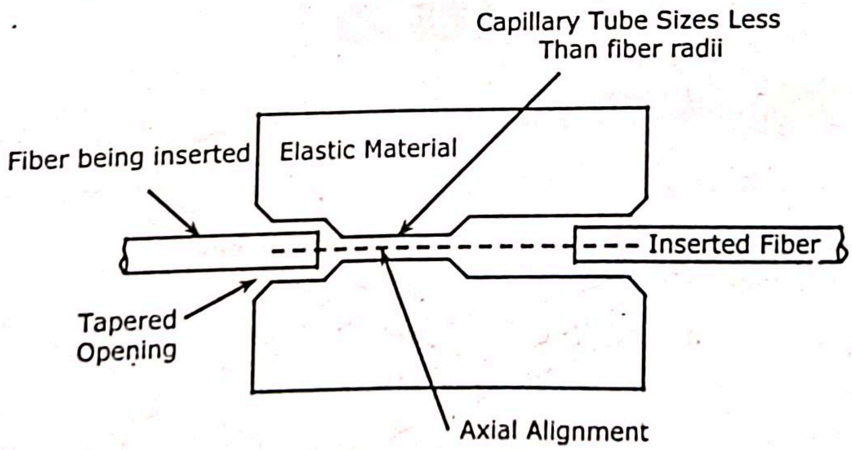


Fig. 4.2.6 Schematic Illustration of an Elastic Tube Splice

4.2.2.4 Springroove Splice

Springroove is relatively a more complex groove splice technique. It utilizes a jacket containing two cylindrical pins which serve as an alignment guide for the two prepared fiber ends. The cylindrical pin diameter is chosen such that it allows the fibers to protrude above the cylinders as shown in Fig. 4.2.7. An elastic element, i.e., a spring is used to press the fibers into the groove and maintain the fiber end alignment, as shown in Fig. 4.2.7. The complete structure is obtained using a drop of epoxy resin. Mean splice insertion losses of 0.05dB have been obtained using multimode graded index fibers with the spring groove splice.

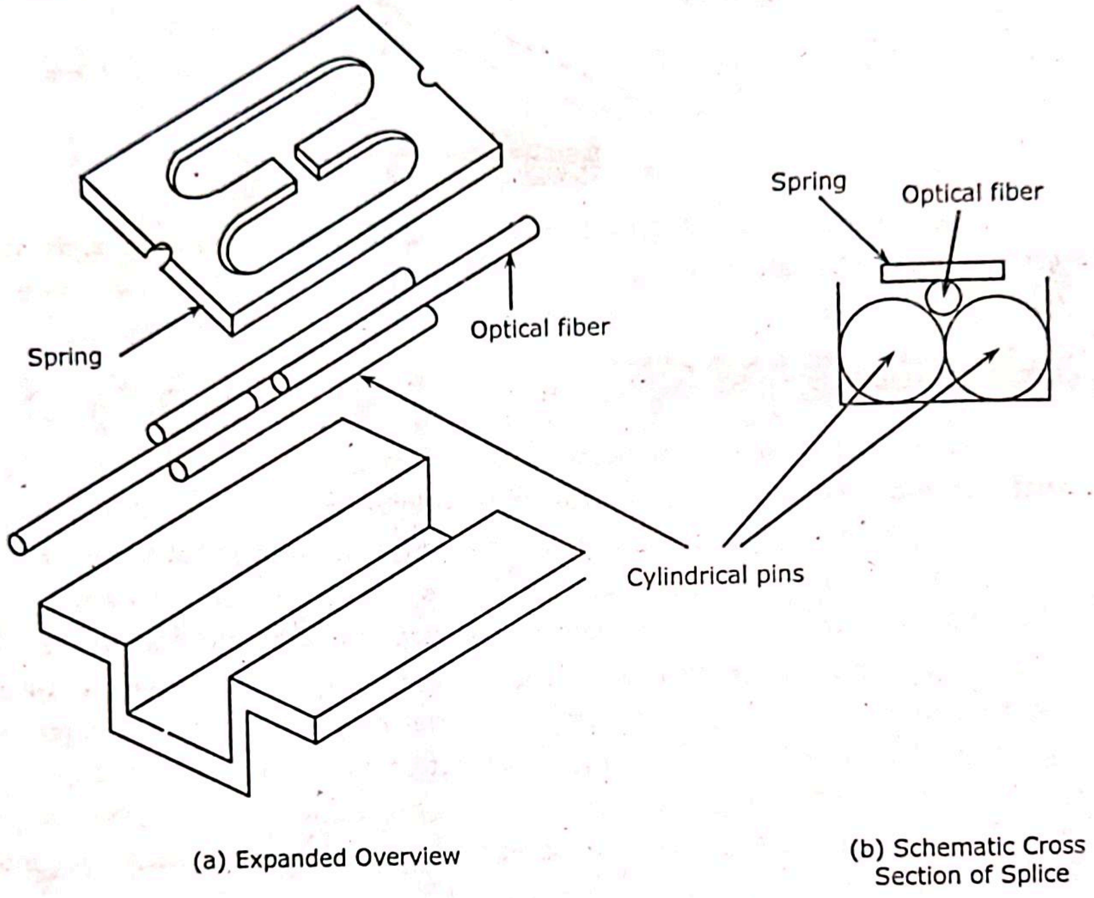


Fig. 4.2.7 The Springroove Splice

4.3 FIBER ALIGNMENT AND JOINT LOSS

The design of fiber optic systems depends on how much light is launched into an optical fiber from an optical source and how much light is coupled between fiber optic components, such as from one fiber to another. Even with the utmost care there will be always some type of imperfections present at fiber optic connections that causes some loss of light. Fiber-to-fiber connection loss is affected by intrinsic and extrinsic coupling losses. Intrinsic coupling losses are caused by inherent fiber characteristics, whereas, extrinsic coupling losses are caused by jointing techniques.

Fiber-to-fiber connection loss is increased by the following sources of intrinsic and extrinsic coupling loss. They are :

1) Reflection losses.
2) Longitudinal Misalignment (fiber separation).
3) Lateral misalignment.
4) Angular misalignment.

4.3.1 Fresnel Reflection

When optical fibers are connected, optical power may be reflected back into the source fiber. Light that is reflected back into the source fiber is lost. This reflection loss called Fresnel reflection, occurs at every fiber interface.

Fresnel reflection is because of a step-change in the refractive index that occurs at the fiber joint i.e., at glass–air–glass.

The magnitude of the partial reflection of the light transmitted through interface is estimated by using the Fresnel's Formula given by :

$$\boxed{R = \left(\frac{n_1 - n}{n_1 + n}\right)^2} \quad \text{... (4.3.1)}$$

where,

R → Fraction of light reflected at the fiber joint.

n_1 → Refractive index of the fiber core.

n → Refractive index of the medium between two fibers (For Air, n = 1).

The fiber-to-fiber coupling loss in decibels due to Fresnel reflection at a single interface is given as,

$$\boxed{Loss_F = -10\log(1-R)} \quad \text{... (4.3.2)}$$

The fiber-to-fiber coupling loss can also be given in terms of coupling efficiency η_F as given by,

$$Loss_F = -10\log\eta_F \quad \text{... (4.3.3)}$$

Where,

$$\boxed{\eta_F = \frac{M_{comm}}{M_E}} \quad \text{... (4.3.4)}$$

M_{comm} → Common mode volume.

M_E → Number of modes in the emitting fiber.

Even when all the other aspects of connections are made ideal, the losses due to Fresnel reflection can be significant. However, this effect of Fresnel reflection at a fiber-fiber connection can be reduced to a very low level through the use of an index matching fluid in the gap between the joined fibers.

Example Problem 4.1

The Fresnel reflection at a butt joint with an air gap in a multimode step index fiber is 0.46 dB. Determine the refractive index of the fiber core.

Sol. : From Eq. (4.3.2), the optical loss in dB at the single interface is given by,

$$\text{Loss}_F = -10\log_{10}(1-R)$$

$$0.18 \text{ dB} = -10 \log_{10}(1-R)$$

$$\therefore R = 0.05$$

From Eq. (4.3.1), Fresnels reflection is given by,

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

$$\Rightarrow 0.05 = \left(\frac{n_1 - 1}{n_1 + 1}\right)^2 \quad (\because \text{ For air, } n = 1)$$

$$\Rightarrow \frac{n_1 - 1}{n_1 + 1} = \sqrt{0.05} = 0.0227$$

$$\Rightarrow n_1 - 1 = 0.227\, n_1 + 0.227$$

$$\Rightarrow n_1[1 - 0.227] = 1.227$$

$$\therefore n_1 = \frac{1.227}{0.772} = 1.588.$$

Example Problem 4.2

A silica multimode step index fiber has a core refractive index of 1.46. Determine the optical loss in decibels due to Fresnèl reflection at a fiber joint with :

1) **A small air gap.**
2) **An index matching epoxy which has a refractive index of 1.40.**

Sol. : 1) From Eq. (4.3.1) Fresnel reflection at a fiber joint is given by,

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

Given, $n_1 = 1.46$, n (air gap) = 1.0

$$\Rightarrow R = \left(\frac{1.46 - 1.0}{1.46 + 1.0}\right)^2$$

$$\therefore R = \left(\frac{0.46}{2.46}\right)^2 = 0.035$$

From Eq. (4.3.2), Optical loss in dB at the fiber joint is given by,

$$\text{Loss}_F = -10\log_{10}(1 - R)$$

$$= -10\log_{10}(1 - 0.035)$$

$$= -10\log_{10}(0.965)$$

$$= 0.15 \text{ dB}$$

2) Fresnel reflection due to index matching fluid having refractive index, n = 1.40 is calculated as,

$$R = \left(\frac{1.46 - 1.40}{1.46 + 1.40}\right)^2 = \left(\frac{0.06}{2.86}\right)^2$$

$$= 4.4 \times 10^{-4}$$

Loss in dB is calculated as;

$$\text{Loss}_F = -10\log_{10}(1 - 4.4 \times 10^{-4})$$

$$= -10\log_{10}(0.9995)$$

$$= (1.9 \times 10^{-3}) \text{ dB}$$

Comment on Result : *From both results, it can be observed that fresnel reflection loss can be reduced by 0.1481 dB using index matching fluid between interface.*

4.3.2 Fiber Misalignment Losses

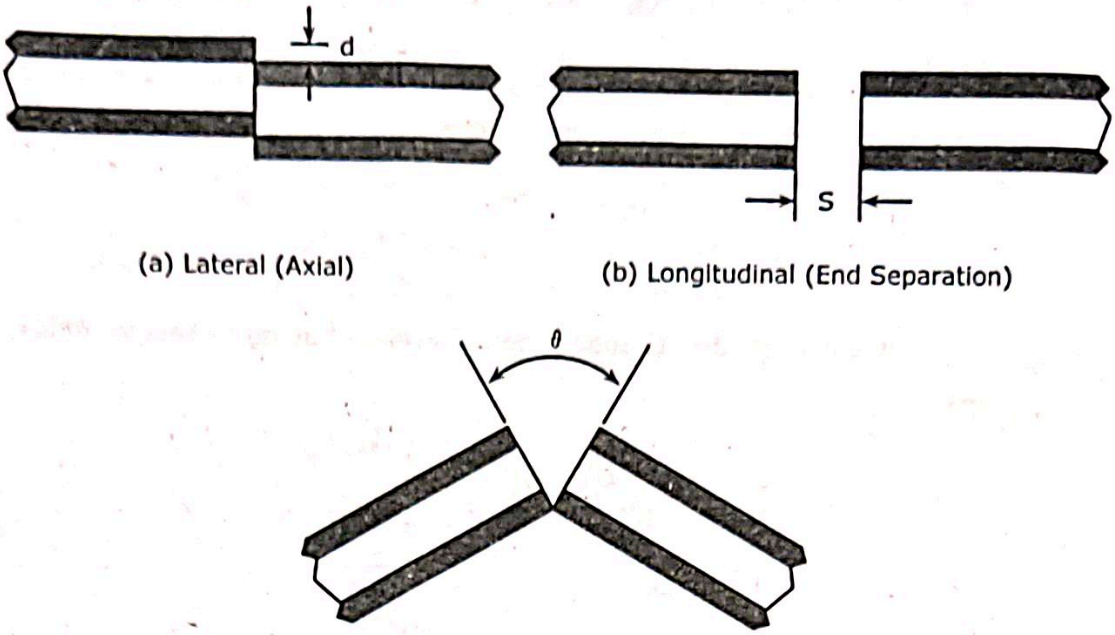
In the earlier section we have seen radiation loss due to Fresnels reflection. Besides Fresnels reflection, the magnitude of the radiation losses also depends on the degree of misalignment of optical fiber cores. Generally there are three fundamental types of misalignment between fibers, they are :

1) Longitudinal misalignment.
2) Angular misalignment.
3) Axial/lateral misalignment.

Radiation (optical output) losses due to these three misalignment depend upon.

1) Type of fiber used (single or multimode).
2) Diameter of core.
3) Distribution of optical power between the propagating modes.

Fig. 4.3.1 illustrates the three types of mechanical misalignments that occurs at the joint o the optical fibers.



(a) Lateral (Axial)

(b) Longitudinal (End Separation)

(c) Angular

Fig. 4.3.1 Three Types of Mechanical Misalignments

4.3.2.1 Longitudinal Misalignment

With longitudinal misalignment (fiber end separation), a small gap('s'), remains between fibre-end faces after completing the fiber connection as shown in Fig. 4.3.1(b). When a gap is present, some of the transmitted rays are not intercepted by the receiving fiber. As the gap increases, larger amounts of the transmitted power miss the receiving core because of the beam divergence. Fibres with larger numerical apertures will have greater separation losses simply because their beams diverge quicker.

4.3.2.2 Lateral Misalignment

Lateral misalignment occurs when the axes of the two fibers are separated by a distance 'd' as shown in Fig 4.3.1(a). Experimental observations proved that the lateral misalignments gives significantly greater losses per unit displacement than the longitudinal misalignment. For example, lateral misalignment of 10 μm gives insertion loss of about 1 dB while similar longitudinal misalignment gives insertion loss of about 0.1 dB.

4.3.2.3 Angular Misalignment

The angular misalignment occurs when the two axes form an angle so that the fiber end faces are no longer parallel. Fig. 4.3.1(c) illustrates the angular misalignment between the core axes. Due to angular misalignment the optical power leaving from emitting fiber falls outside the solid acceptance angle of the receiving fiber. Hence the power outside the solid acceptance angle of the receiving fiber is lost, reducing the power coupling between two fibers. Theoretical a[nd] experimental studies of fiber misalignment in optical fiber connectors allow approxim[ate] determination of the losses encountered with the various misalignments of different fiber typ[es]

4.3.3 Misalignments of Multimode Fiber Joints

Obtaining exact calculation of coupling loss between different multimode fibers which takes into consideration a non-uniform distribution of optical power among the modes and propagation effects in the second fiber is quite difficult and a lengthy process. Hence, we assume the uniform excitation of all the optical modes in a multimode step-index fiber.

1) Lateral misalignment reduces the overlap region between the two fiber cores and hence the lateral coupling efficiency, η_{lat} between two multimode step-index fibers is given by,

$$\boxed{\eta_{lat} = \frac{16\left(\frac{n_1}{n_2}\right)^2}{\left(1+\frac{n_1}{n_2}\right)^4}\frac{1}{\pi}\left[2\cos^{-1}\left(\frac{y}{2a}\right)-\left(\frac{y}{a}\right)\left[\left(1-\left(\frac{y}{2a}\right)^2\right)\right]^{1/2}\right]} \quad ...(4.3.5)$$

where,

n_1 → Refractive index of the core

n_2 → Refractive index of the medium

y → Lateral offset of the fiber core axis

a → Core radius

The lateral misalignment loss in dB may be found using

$$\boxed{\text{Loss : Lat} = -10\log_{10}\eta_{lat}} \text{ dB} \quad ...(4.3.6$$

The losses predicted by these equations are slightly higher than the measured value as it was assumed that all modes are equally excited.

2) Based on the assumption of uniform power distribution, Gloge has calculated the later misalignment loss for the multimode graded index fibers having only guided modes is give by,

$$\boxed{L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right)} \text{ for } 0 \le y \le 0.2a \quad ...(4.3.7$$

The lateral coupling efficiency between two multimode graded index fibers is given by

$$\eta_{lat} = 1 - L_t$$

With a parabolic refractive index profile $\alpha = 2$, Eq. (4.3.7) reduces to :

$$L_t = \frac{8}{3\pi}\left(\frac{y}{a}\right) = 0.85\left(\frac{y}{a}\right) \quad ...(4.3.$$

Eq. (4.3.8) is lateral misalignment loss by considering only guided modes.

Lateral misalignment losses transformed into another expression by including bo the leaky modes and guided modes is given by,

$$\boxed{L_t = 0.75\left(\frac{y}{a}\right)} \quad ...(4.$$

3) Assuming uniform power distribution, the loss for small separation (longitudinal misalignment) between two multimode step index optical fibers is given by,

$$\boxed{\text{Loss : Long} = -10\log_{10}\left[1.\frac{dNA}{4an_0}\right]} \text{ dB} \quad \text{... (4.3.10)}$$

where,

n_0 → Refractive index of the matching fluid.

d → Separation of fibers.

4) Angular misalignment losses at joints in multimode step index fibers may be predicted with reasonable accuracy using an expression for the angular coupling efficiency given by :

$$\boxed{\eta_{ang} = \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\left[1-\frac{n\theta}{\pi n_1(2\Delta)^{1/2}}\right]} \quad \text{...(4.3.11)}$$

where,

θ → Angular displacement (radians)

Δ → Relative refractive index difference for the fiber.

Hence, angular misalignment loss in dB can be determined as :

$$\boxed{\text{Loss : ang} = -10\log_{10}\eta_{ang}} \text{ (dB)} \quad \text{...(4.3.12)}$$

From Eq. (4.3.11) and (4.3.12) we can predict that the smaller the values of Δ, the larger will be the coupling loss due to angular misalignment.

Example Problem 4.3

A graded index fiber with a parabolic refractive index profile (α = 2) has a core diameter of 40 μm. Determine the difference in the estimated insertion losses at an index matched fiber joint with a lateral offset of 1 μm (no longitudinal or angular misalignment). When performing the calculation assume (a) the uniform illumination of only the guided modes and (b) the uniform illumination of both guided and leaky modes.

Sol. : a) Assuming uniform illumination of only the guided modes from Eq. (4.3.8) the lateral misalignment loss is given as :

$$L_t = 0.85\left(\frac{y}{a}\right)$$

$$= 0.85\left(\frac{1\times10^{-6}}{20\times10^{-6}}\right) \quad (\because \text{ Given } d = 40\ \mu m, \Rightarrow a = 20\ \mu m)$$

$$\therefore L_t = 0.0425$$

The lateral coupling efficiency is given by,

$$\eta_{lat} = 1 - L_t$$
$$= 1 - 0.0415 = 0.9575$$

∴ Insertion loss due to the lateral misalignment is given by,

$$\text{Loss:lat} = -10\log_{10}(0.9575)$$
$$= 0.19 \text{ dB}$$

b) Assuming the uniform illumination of both guided and leaky modes, Gloge's formula Eq. (4.3.9) is given by,

$$L_t = 0.75\left(\frac{y}{a}\right)$$

$$= 0.75\left(\frac{1 \times 10^{-6}}{20 \times 10^{-6}}\right)$$

$$= 0.0375$$

Therefore the lateral coupling efficiency is given by,

$$\eta_{lat} = 1 - 0.0375$$
$$= 0.9625$$

And, hence the insertion loss is given by,

$$\text{Loss:Lat} = -10\log_{10}(0.9625)$$
$$= 0.165 \text{ dB}$$

∴ Difference in the estimated is 0.19 - 0.165 = 0.025 dB.

Example Problem 4.4

A step index fiber has a core refractive index of 1.5 and a core diameter of 50 μm. The fiber is jointed with a lateral misalignment between the core axes of 5 μm. Estimate the insertion loss at the joint due to the lateral misalignment assuming a uniform distribution of power between all guided modes when :

a) There is a small air gap at the joint.

b) The joint is considered index matched.

Sol. : a) Assuming from Eq. (4.3.5), the coupling efficiency for a multimode step index fiber (uniform illumination of all propagating modes) is given by,

$$\eta_{lat} = \frac{16(n_1/n_2)^2}{[1+(n_1/n_4)]^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{y}{2a}\right) - \left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{1/2}\right\}$$

$$= \frac{16(1.5)^2}{(1+1.5)^4 \times 3.14}\left\{2\cos^{-1}\left(\frac{5}{50}\right) - \left(\frac{5}{25}\right)\left[1-\left(\frac{5}{50}\right)^2\right]^{1/2}\right\} \quad [\because \text{ for air } n = 1]$$

$$= \frac{36}{122.65}(2 \times 1.47 - 0.2\,[1 - 0.01]^{1/2})$$

$$= 0.293(2.94 - 0.2 \times (0.99)^{1/2})$$

$$= 0.293\ (2.94 - 0.199)$$

$$= 0.293 \times 2.74 = 0.803.$$

Total insertion loss due to lateral misalignment is given by,

$$\text{Loss:lat} = -10\log_{10}(\eta_{lat})$$

$$= -10\log_{10}\ (0.803)$$

$$= -10(-0.09528) = (0.9528)\ \text{dB}.$$

Hence assuming a small air gap at the fibers joint the insertion loss is approximately 1 dB when the offset is 10% of the fiber diameter.

b) When the joint is considered index matched (i.e., air gap = zero) the coupling efficiency may be obtained by using Eq. (4.3.5).

In this case, $n_1 = n$.

$$\eta_{lat} = \frac{16(1)^2}{[1+1]^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{5}{50}\right) - \left(\frac{5}{25}\right)\left[1-\left(\frac{5}{50}\right)^2\right]^{1/2}\right\}$$

$$= \frac{16}{2^4} \times \frac{1}{3.14}[2 \times 1.47 - 0.2[1 - 0.01]^{1/2}]$$

$$= 0.318 \times 2.74 = 0.872$$

Therefore the insertion loss is given by,

$$\text{Loss:lat} = -10\log_{10}(0.872)$$

$$= 0.59\ \text{dB}.$$

Example Problem 4.5 **[May / June - 09], [Nov. - 08]**

Two multimode step index fibers have numerical apertures of 0.15 and 0.35 respectively and both have the same core refractive index which is 1.45. Estimate the insertion loss at a joint in each fiber caused by a 5° angular misalignment of the fiber core axes. It may be assumed that the medium between the fibers is air.

Sol. : From Eq. (4.3.11), the angular coupling efficiency is given by,

$$\eta_{ang} \simeq \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\left[1 - \frac{n\theta}{\pi n_1(2\Delta)^{1/2}}\right]$$

Since, NA = $n_1(2\Delta)^{1/2}$, using this in η_{ang}, we get

$$\eta_{ang} \cong \frac{16(n_1 / n)^2}{[1 + (n_1 / n)]^4}\left[1 - \frac{n\theta}{\pi NA}\right]$$

For the 0.15 NA fiber :

$$\eta_{ang} \cong \frac{16(1.45)^2}{(1 + 1.45)^4}\left[1 - \frac{5 \times \pi / 180}{\pi \times 0.15}\right] \qquad (\because \text{ For air, } n = 1)$$

$$= \frac{33.64}{36.03}[1 - 0.185] = \frac{27.41}{36.03} = 0.761$$

Hence insertion loss due to the angular misalignment may be obtained as,

$$\text{Loss:ang} = -10\log_{10}(\eta_{ang})$$

$$= -10\log_{10}(0.761) = 1.186 \text{ dB.}$$

For the 0.35 NA fiber :

$$\eta_{ang} = \frac{33.64}{36.03}\left[1 - \frac{5\pi / 180}{\pi \times 0.35}\right] = 0.86$$

$$\text{Loss:ang} = -10\log_{10}(\eta_{ang})$$

$$= -10\log_{10}(0.86) = -10(-0.065)$$

$$= 0.65 \text{ dB.}$$

4.3.4 Misalignments of Single Mode Fiber Joints

1) Similar to that of the multimode fibers, single mode fibers also present the more serious misalignment due to the lateral offset loss. This loss basically depends upon the shape of the propagating mode. In the absence of angular misalignment, Marcuse calculated that the loss due to lateral offset y given by

$$\boxed{L_T = 2.17(y / \omega)^2} \text{ dB} \qquad \dots (4.3.13)$$

where,

ω → Normalized spot size of fundamental mode.

y → Lateral offset

Marcuse estimated normalized spot size of the fundamental mode (LP_{01}) (corresponds to HE mode) by the empirical formula given by,

$$\omega = a\frac{(0.65 + 1.62V^{-3/2} + 2.88V^{-6})}{\sqrt{2}} \qquad \dots (4.3.14)$$

where,

ω → Spot size in μm

a → Fiber core radius

V → Normalized frequency number for the fiber

2) Insertion loss, $T_{angular}$ caused by an angular misalignment θ (radian) at a joint in the single mode fiber is given by

$$\boxed{T_{angular} = 2.17\left(\frac{\theta \omega n_1 V}{aNA}\right)^2 \text{ dB}} \quad \text{... (4.3.15)}$$

where,

n_1 → Refractive index of the core

NA → Numerical aperture.

3) For a gap 'S' with material of index n_3, where $G = \frac{S}{kW^2}$, the longitudinal misalignment loss is given as,

$$\boxed{L_{SMlong} = -10\log\frac{64n_1^2 n_3^2}{(n_1+n_3)^4(G^2+4)} \text{ dB}} \quad \text{... (4.3.16)}$$

Example Problem 4.6

A 10 μm core diameter single-mode fiber has a normalized frequency number of 1.7. A fusion splice at a point along its length exhibits an insertion loss of 0.15 dB. Assuming only lateral misalignment contributes to the splice insertion loss, estimate the magnitude of the lateral misalignment.

Sol. : Given Data : Core diameter (2a) = 5 μm

Normalized frequency (V) = 1.7

Core refractive index, (n_1) = 1.48

Insertion loss = 0.15 dB.

As given only lateral misalignment contributes to fiber insertion loss, hence using Eq. (4.3.13), insertion loss due to lateral misalignment is given by,

$$L_T = 2.17\left(\frac{y}{\omega}\right)^2$$

Here, $\omega = \dfrac{a(0.65 + 1.6V^{-3/2}\ 2.88V^{-6})}{2^{1/2}}$

$$= \frac{2.5\times10^{-6}(0.65+1.6(1.7)^{-1.5}+2.88(1.7)^{-6})}{2^{1/2}}$$

$$= \frac{2.5\times10^{-6}(0.65+0.73+0.12)}{1.414}$$

$$= \frac{3.75\times10^{-6}}{1.414} = 2.65\ \mu m$$

Using the value of ω, in L_T, we have,

$$L_T = 2.17\left(\frac{y}{2.65\ \mu m}\right)$$

$$\Rightarrow 0.15 \text{ dB} = 2.17\left(\frac{y}{2.65\ \mu m}\right)^2$$

$$\Rightarrow \frac{0.15}{2.17} = \left(\frac{y}{2.65\times10^{-6}}\right)^2$$

$$\Rightarrow \frac{y}{2.65\times10^{-6}} = \sqrt{0.069} = 0.2629$$

$\therefore$ y = 0.696 μm.

Example Problem 4.7

Given the following parameters for a single-mode step index fiber with a fusion splice estimate :

1) The fiber core diameter.

2) The numerical aperture for the fiber.

Fiber normalized frequency = 1.9

Fiber core refractive index = 1.46

Splice lateral offset = 0.5 μm

Splice lateral offset loss = 0.05 dB

Splice angular misalignment = 0.3°

Splice angular misalignment loss = 0.04 dB.

Sol. : 1) The loss due to the lateral offset is given by,

$$L_T = 2.17\left(\frac{y}{\omega}\right)^2 \quad \text{...(i)}$$

$$\Rightarrow 0.05 = 2.17\left(\frac{0.5\times10^{-6}}{\omega}\right)^2$$

We have mode field radius (ω), given by,

$$\omega = \frac{a(0.65+1.6V^{-3/2}+2.88V^{-9})}{2^{1/2}}$$