UNIT II - Signal Degradation Optical Fibers:
Attenuation,
Absorption losses,
Scattering losses,
Bending Losses,
Core and Cladding losses,
Signal Distortion in Optical Wave guides,
Information Capacity determination,
Group Delay,
Material Dispersion,
Wave guide Dispersion,
Signal distortion in SM fibers
Polarization Mode dispersion,
Intermodal dispersion,
Pulse Broadening in GI fibers,
Mode Coupling,
Design Optimization of SM fibers-RI profile and cut-off wavelength.

ATTENUATION:

It place major role in determining the maximum transmission distance between a transmitter and receiver. As a light travels along a fiber, its power decreases exponentially with distance.

The attenuation in db/km $\alpha = [10/L] \log10[Pin/Pout]$.

It is defined as ratio of optical i/p power Pin to optical o/p power Pout propagating from a fiber of length 'L'.

PROBLEM NO:2.1

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) the signal attenuation per kilometer for the fiber.

Ans:

(a) The overall signal attenuation in decibels through the fiber is:

Signal attenuation $= 10 \log_{10} [P_i/P_o] = 10 \log_{10}[120\mu/3\mu]$

$= 10 \log_{10} 40 = 16.0$ dB

(b) The signal attenuation per kilo meter for the fiber may be simply obtained by dividing the result in (a) by the fiber length which corresponds to it using Eq.

$\alpha = [10/L] \log10[Pin/Pout]$.

where: $\alpha dB\, L = 16.0$ dB

hence: $\alpha dB = 16/8$

$= 2.0$ dB km^{-1}

MATERIAL ABSORPTION LOSSES IN SILICA GLASS FIBERS:

Material absorption is a loss mechanism related to the material composition and fabrication process for the fiber, which results in dissipation of transmitted optical power as heat in the wave guide.

Absorption is caused by 3 different mechanisms. 1] Absorption by atomic defects in the glass composition. 2] Extrinsic absorption by impurity atom in glass materials. 3] Intrinsic absorption by basic atoms of the material.

Atomic defects are due to imperfections of the atomic structures of the fiber material such as missing molecules, high density clusters of atom groups or oxygen defects in the glass structure.

Atomic defects losses are negligible compare to extrinsic losses & intrinsic losses. But significant when atomic defect fiber placed at ionizing radiation such as nuclear reactor environment, in medical radiation therapies etc.,

High radiation may accumulate several years. Radiation damages the internal structure of optical fiber. Damage effect caused by energy of ionization rays can be measured in dose rate. The total does received by material is expressed in units of rad(Si)

1 rad(Si)=0.01 J/Kg

If ionizing radiation increases then atomic defects or attenuation centres increases & attenuation increases.

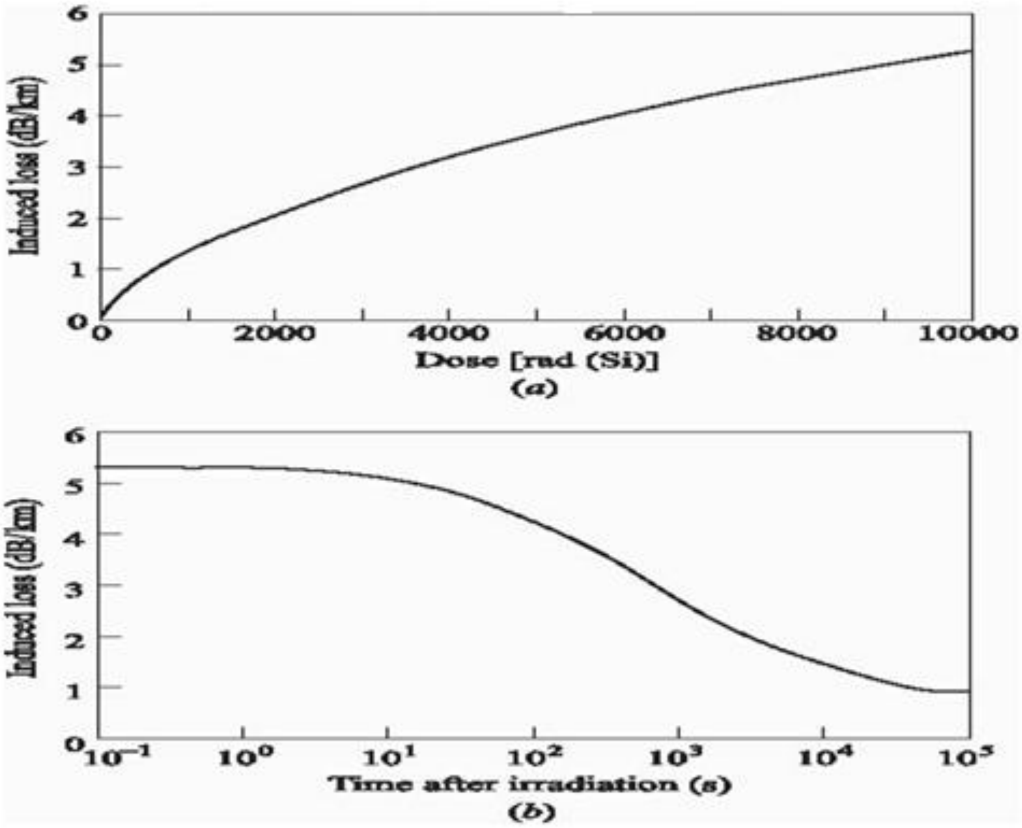


Fig.2.1: Effects of ionizing radiation

EXTRINSIC ABSORPTION LOSSES:

Fibers are prepared by direct melt method in the presence of impurities. Impurity absorption results from transition metal ions such as iron, chromium, cobalt, copper and OH [water] ions. These transition metal impurities cause losses from 1 to 10db/km.

Transition metal impurity levels were around 1part per million [ppm] in fiber made in the 1970's which resulted in losses ranging from 1 to 4db/km

These losses occur due to electron transitions between the energy levels within these ions.

- **Table :** Absorption losses caused by some of the more common metallic ion impurities in glasses, together with the absorption peak wavelength

	Peak wavelength (nm)	One part in 109 (dB km−1)
Cr3+	625	1.6
C2+	685	0.1
Cu2+	850	1.1
Fe2+	1100	0.68
Fe3+	400	0.15
Ni2+	650	0.1
Mn3+	460	0.2
V4+	725	2.7

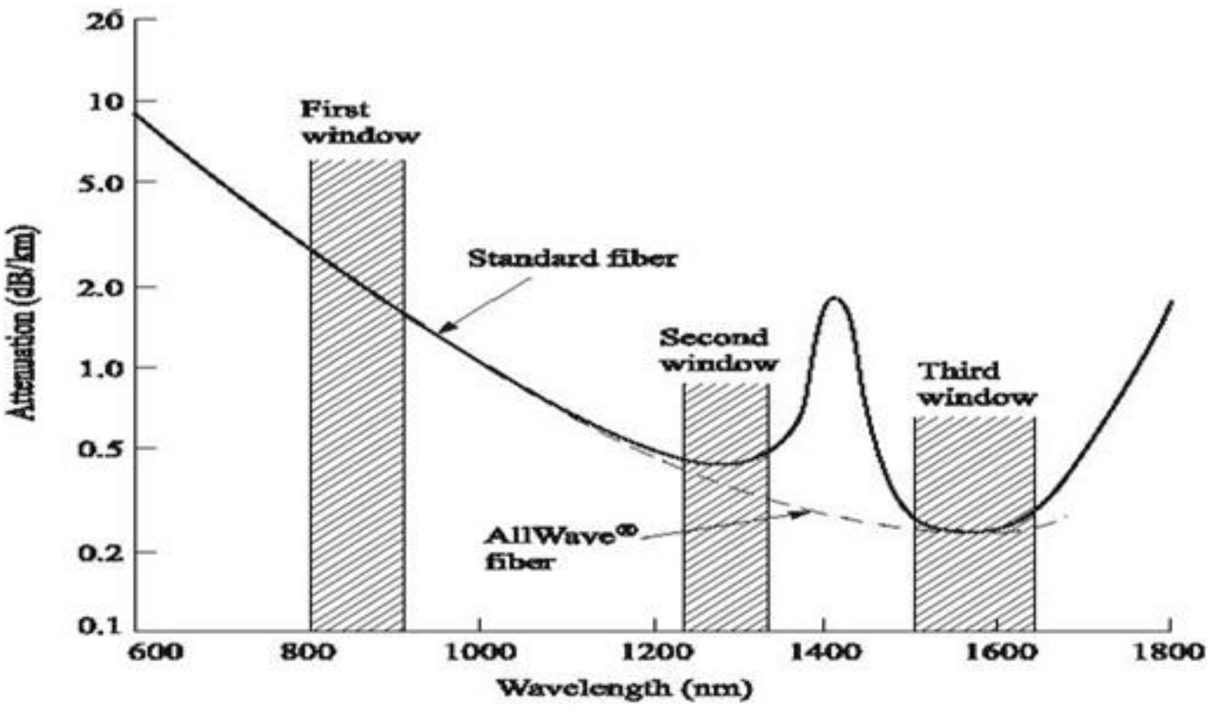


Fig.2.2: Optical fiber attenuation – the peak & valleys in attenuation curve- transition windows

By reducing OH content of fiber to below 1ppm, single mode fibers have nominal attenuation of 0.4db/km at 1310nm – o-band. Less than 0.25 db/km at 1550nm – c-band. Low-water-peak at 1440 nm – E-band

INTRINSIC ABSORBTION LOSSES:

Intrinsic absorption is associated with the basic fiber material [pure SiO2]. It occurs when the material is in a perfect state with no density variations, impurities etc,. It results from electronic bands in near uv region & atomic vibration bands in near infrared region.

Electronic absorption bands – absorption occurs when a photon interacts with an electron in v-band and exited it to a higher energy level

$$\alpha_{uv} = \frac{154.2x}{46.6x + 60} \times 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)$$

- Where x = doping %
- λ = wave length
  - Atomic vibration band – chemical bonds between atoms in fiber causes an interaction between vibrating bond and the EM field of the optical signal results in transfer of energy from field to bond – near infrared region. The attenuation due to this is

$$\alpha_{IR} = 7.81 \times 10^{11} \times \exp\left(\frac{-48.48}{\lambda}\right)$$

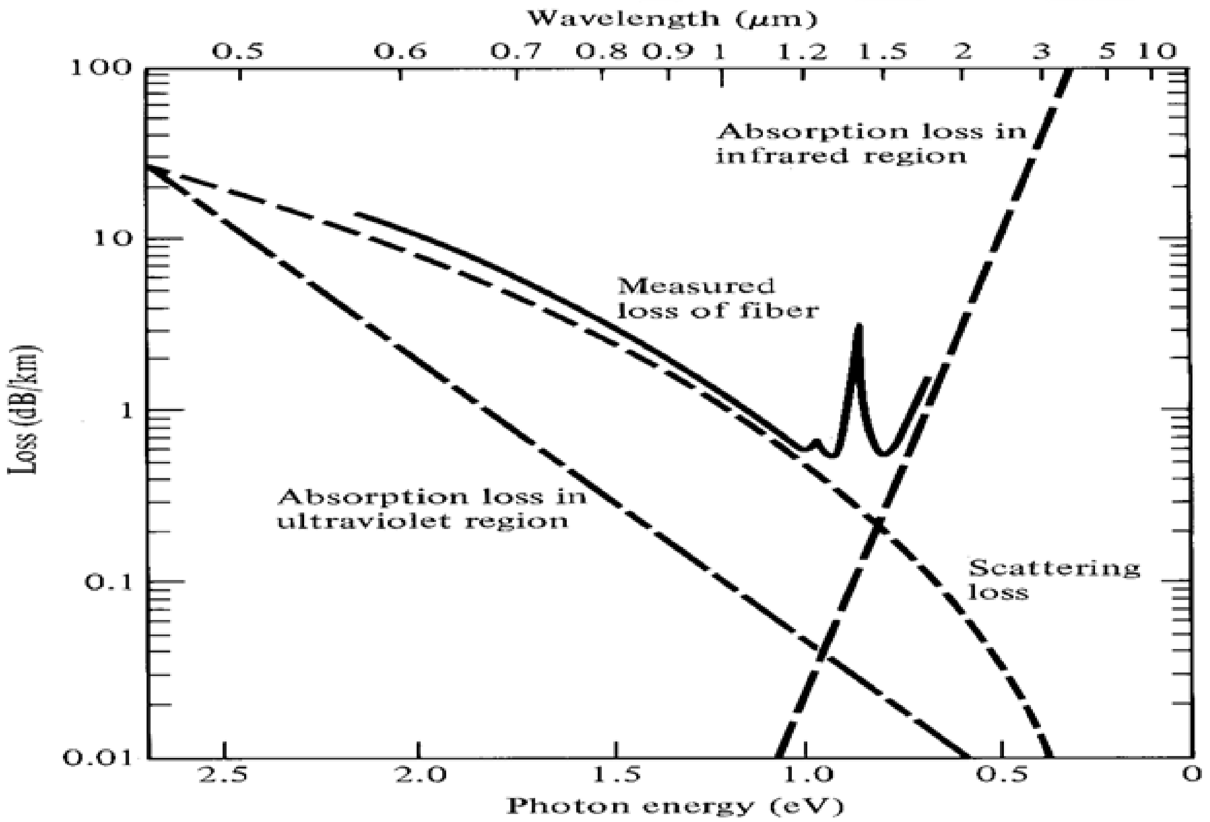


Fig.2.3: Attenuation characteristics

LINEAR SCATTERING LOSSES:

Scattering losses in glass arise from microscopic variations in material density, from compositional fluctuations & from structural in-homogeneities of defects occurring during fiber manufacture. This linear scattering mechanism causes the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode.

That transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. Linear scattering may be categorized in to 2 types. 1] Rayleigh scattering 2] Mie scattering.

RAYLEIGH SCATTERING:

The glass is composed of a randomly connected n/w of molecules. Such a structure normally contains either higher or lower density in glass.

The glass is made up of several Oxides, such as SiO_2, GeO_2 & P_2O_5 causes compositional fluctuations.

These 2 effects [density fluctuations & compositional fluctuations] cause RI variations which occur within the glass over distance which causes Rayleigh scattering.

For single component glass the scattering loss at a wave length λ resulting from density fluctuations can be given as

$\gamma R = \alpha SCAT = [8\pi^3/3\lambda^4]\,[n^2 - 1]^2 kBT_f\, \beta_T$

where n = RI, kB=Boltzmann's constant, β_T=isothermal compressibility of material, T_f=fictive temperature.

αSCAT can also expressed in term of P as

$\alpha SCAT = [8\pi^3/3\lambda^4] n^8 P^2 kBT_f\, \beta_T$

where P=photo elastic co-efficient.

For multi component glasses the scattering is given by

$\alpha SCAT = [8\pi^3/3\lambda^4]\,[\Delta n^2]^2\, \Delta v$

where $[\Delta n^2]^2$ is square of mean square RI fluctuation over a volume Δv.

γR relation with transmission loss factor [transmissivity] of the fiber is

Ł=exp[-γR L] where L = length of fiber .

Attenuation due to Rayleigh scattering in db/km= 10 log10 [1/ Ł].

PROBLEM 2.1:

Silica has an estimated fictive temperature of 1400k with an isothermal compressibility of $7 \times 10^{-11}\ m^2N^{-1}$. The RI & photo elastic co-efficient for silica are 1.46 & 0.286 respectively. Determine theoretical attenuation in db/km due to fundamental Rayleigh scattering in silica at WL of 0.63, 1.00 & 1.30μm. Boltzmann's constant is $1.381 \times 10^{-23} JK^{-1}$.

MIE SCATTERING:

Linear scattering may also occur at in-homogeneities from non-perfect cylindrical structure of WG, irregularities in core & cladding interface, core-cladding RI difference along the fiber length, diameter fluctuations, strains & bubbles.

When in-homogeneity size is greater than $\lambda/10$, scatter intensity can be very large & such type of scatter is called as Mie scatter. It is mainly in forward direction.

The in-homogeneity may be reduced by [a] removing imperfection due to glass manufacturing process [b] carefully controlled intrusion & coating of fiber [c] increasing fiber guidance by increasing RRID.

BENDING LOSSES:

Radiative losses occur whenever an OF undergoes a bend of finite radius of curvature.

Fibers are subjected to 2 types of bends.

MACROSCOPIC: Macroscopic bends have radius that are large compare to fiber diameter. MICROSCOPIC: These bends arises when the fibers are incorporated into cables. MACROSCOPIC BENDING LOSSES:

For slight bends the excess loss is extremely small. As the radius of curvature decreases, the loss increases exponentially. Curvature loss effects can be explained with mode field distribution.

In mode field distribution, field tail in cladding decays exponentially as a function of distance from core. When a fiber is bent, the field tail on the far side of the center of curvature must move faster to keep up with the field in the core.

At a certain critical distance from the center of fiber the field tail would have to move faster than the speed of light & radiates away. The amount of optical radiation from a bent fiber depends on the field strength at XC & on radius of curvature R. Thus the total no. of modes can be supported by curved fiber is less than the straight fiber.

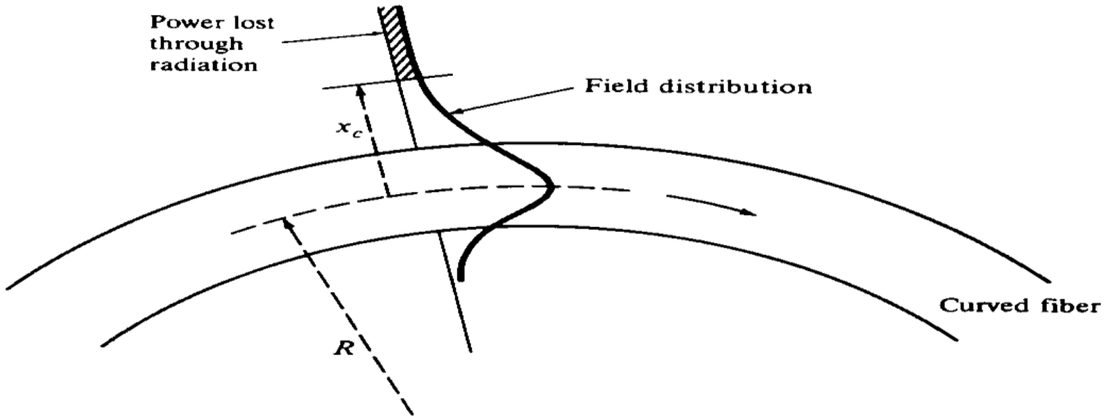


Fig2.4: sketch of the fundamental mode field in a curved optical waveguide.

The effective no. of modes that are guided by a curved multimode fiber of radius 'a'

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

where α = graded index profile, n_2=RI of cladding, k=2π/λ wave propagation constant, N_∞=[α/α+2][$n_1$ka]^{2}Δ=total no. of modes in straight fiber.

<u>MICRO BENDING LOSSES</u>:

Micro bends are repetitive small scale fluctuations in radius of curvature of the fiber axis. They are caused either by non-uniformities in manufacturing of the fiber or by non-uniform lateral pressures created during the cabling of the fiber, which is known as cabling losses or packaging losses.

An increase in attenuation results from micro bending which causes repetitive coupling of energy between guided modes & leaky modes in the fiber.

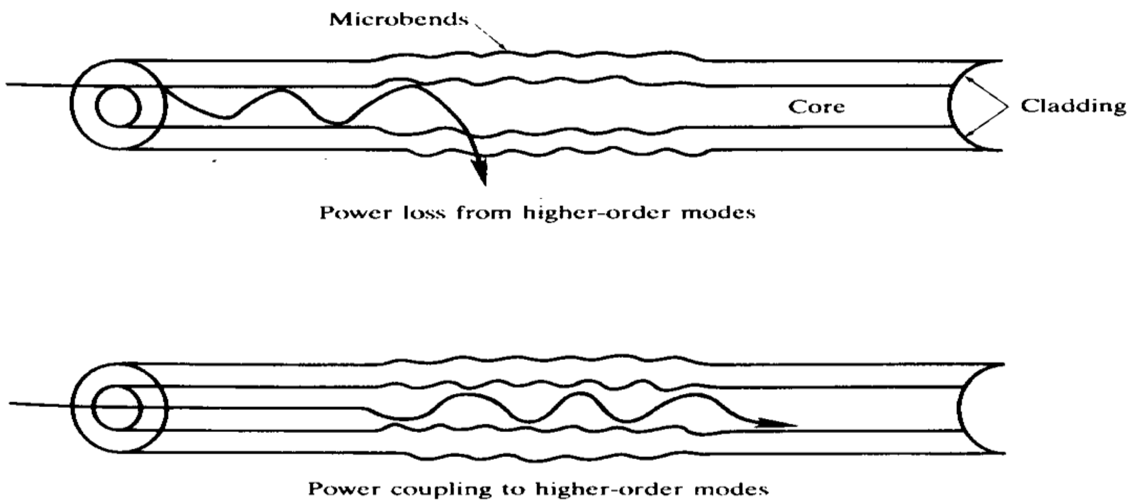


Fig 2.5: Micro bends on an optical fiber

Small scale fluctuation in the radius of curvature of the fiber axis leads to microbending losses. Microbends can shed higher order modes and can cause power from low-order modes to couple to higher order modes

One method of minimizing micro bending losses is by extruding a compressible jacket over the fiber. When external forces are applied to this configuration, the jacket will be deformed but the fiber will tend to stay relatively straight.

For a multimode graded index fiber having a core radius 'a', outer radius 'b'[excluding jacket], RRID Δ, then micro bending loss α_M of a jacket fiber is reduced from that of an unjacketed fiber by a factor

$$F(\alpha_M) = \left[1 + \pi\Delta^2\left(\frac{b}{a}\right)^4 \frac{E_f}{E_j}\right]^{-2}$$

where E_j, E_f are young's modulus of jacket & fiber.

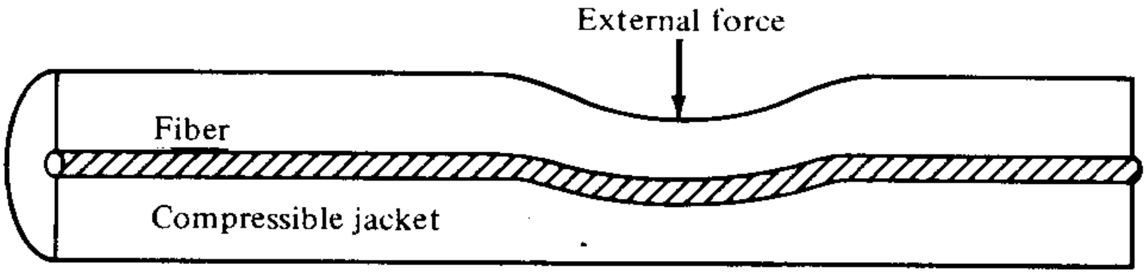


Fig 2.6: Acompressible jacket extruded over a fiber reduces microbending resulting from external forces.

CORE & CLADDING LOSSES:

The core & cladding have different RI's & differ in composition. They have different attenuation coefficients, denoted as α1 & α2 respectively.

The loss for a mode of order [v,m] for a step index fiber is

$\alpha_{VM} = \alpha_1[\text{Pcore} / P] + \alpha_2[\text{Pclad} / P]$

where P=total power in mode v & [Pcore / P], [Pclad / P] are fractional power in core and cladding for Pv,m mode.

We know that, $[\text{Pcore} / P]+[\text{Pclad} / P]=1$

$[\text{Pcore} / P]= 1-[\text{Pclad} / P]$

Therefore $\alpha_{VM} = \alpha_1[1-[\text{Pclad} / P]]+ \alpha_2[\text{Pclad} / P]$

$=\alpha_1- \alpha_1 [\text{Pclad} / P]+ \alpha_2[\text{Pclad} / P]$

$= \alpha_1+ [\alpha_2 - \alpha_1][\text{Pclad} / P]$

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

For the case of graded index fiber: at a distance 'r' from core axis, the loss is

$$\alpha[r]= \alpha_1+ [\alpha_2 - \alpha_1] * [n^2(0)-n^2(r)] / [n^2(0)-n_2{}^2]$$

DISPERSION:

The dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. This causes a pulse to overlap with neighboring pulses.

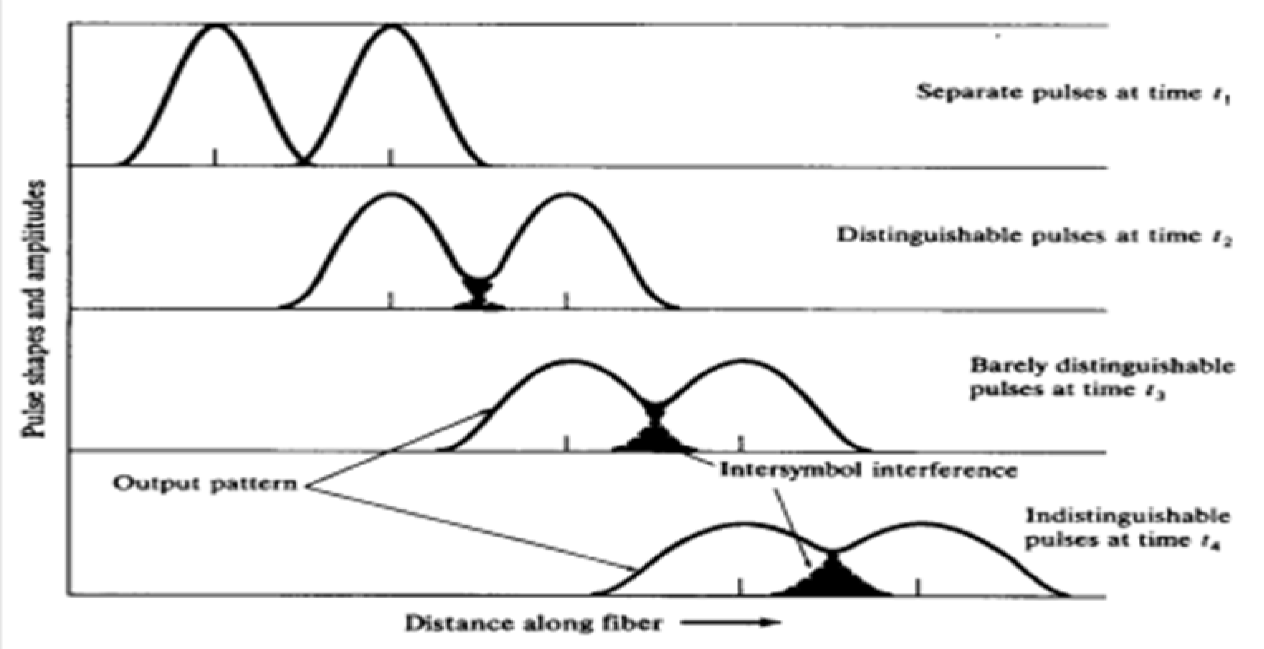


Fig2.6: Broadening & attenuation of 2 adjacent pulses as they travel along a fiber

INFORMATION CAPACITY DETERMINATION:

As a result of Dispersion after certain amount of overlap has occurred, adjacent pulses can no longer be individually distinguished at the receiver and error will occur. This dispersive property determines the limit of the information capacity of the fiber which can be specified by bandwidth distance product in MHz.Km.

For SIF the various distortion effects tend to limit the BW-distance product to about 20MHz.Km. In GIF the radial RI profile can be carefully selected so that pulse broadening is minimized at a specific operating wavelength. This led to BW-distance product as high as 2.5GHz.Km.

Single mode fibers can have capacities well in excess of this. A comparison of information capacities of various optical fibers with the capacities of coaxial cables used for UHF & VHF transmission is shown in fig2.7. The curves are shown in terms of signal attenuation versus data rate. The flatness of the attenuation curves for the fiber extend up to the microwave spectrum.

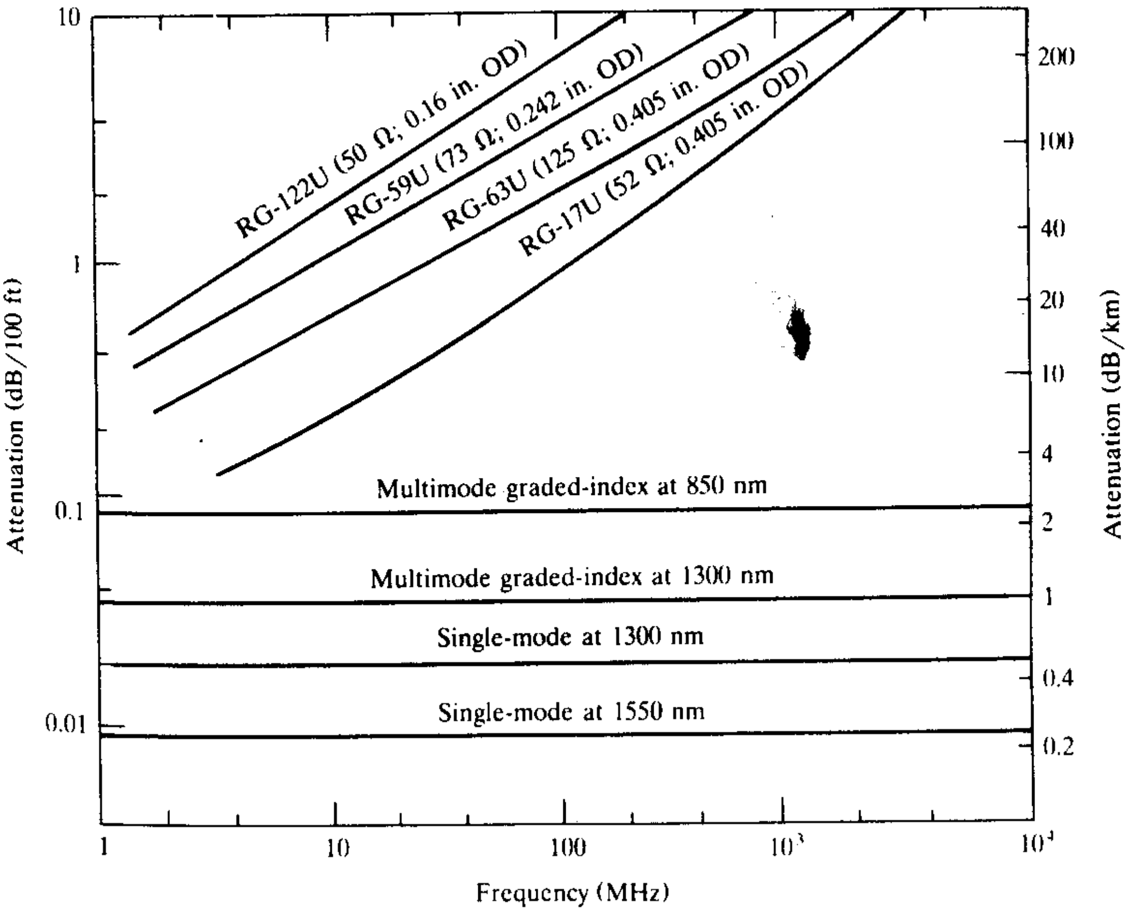


Fig.2.7: A comparison of information capacities of various optical fibers with the capacities of coaxial cables

GROUP DELAY:

The modulated optical signal excites all modes equally at the input end of the fiber. Each mode carries an equal amount of energy through the fiber. Each mode contains all of the spectrum components in the wave length band over which the source emits.

As the signal propagates along the fiber, each spectral component can be assumed to travel independently and to undergo a time delay or group delay per unit length in the direction of propagation which is given by

$$\frac{\tau_g}{L} = \frac{1}{V_g} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

Where L= distance traveled by the pulse, β = propagation constant,
k = [2π/λ] Vg= C[dβ/dk]$^{-1}$ = group velocity.

GROUP VELOCITY: is the velocity at which the energy in a pulse travels along a fiber. Since the group delay depends on the wavelength, each spectral component of any particular mode takes a different amount of time to travel a certain distance. As a result of this difference in time delays, the optical signal pulse spreads out with time as it is transmitted over the fiber.

There fore group delay causes the pulse spreading .

If the spectral width of the optical sourece is not too wide, the delay difference per unit wavelength along the propagation path is approximately $d\tau g/d\lambda$. The total delay difference $\delta\tau = [d\tau g/d\lambda]\ \delta\lambda$

If the spectral width $\delta\lambda$ of an optical source is characterized by its root-mean square (rms) value σ_A, then the pulse spreading can be approximated by rms pulse width as σg=

$$\sigma_g = \frac{d\tau_g}{d\lambda}\sigma_\lambda = -\frac{L\sigma_\lambda}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)$$

The factor $D = [1/L]\ [d\tau g/d\lambda]$ is designated as the dispersion. It defines the pulse spread as a function of wavelength.

TYPES OF DISPERSIONS: There are 3 types of dispersions.
1] Intramodal dispersion [Material dispersion, Wave guide dispersion
2] Intermodal dispersion
3] Polarization mode dispersion.

MATERIAL DISPERSION:

It occurs because of 1] RI varies as a function of optical wavelength 2] various spectral components of a given mode will travel at different speeds, depends on wavelength.

Material dispersion is an Intramodal dispersion effect in single mode wave guide and LED systems which has a broader o/p spectrum than a laser diode.

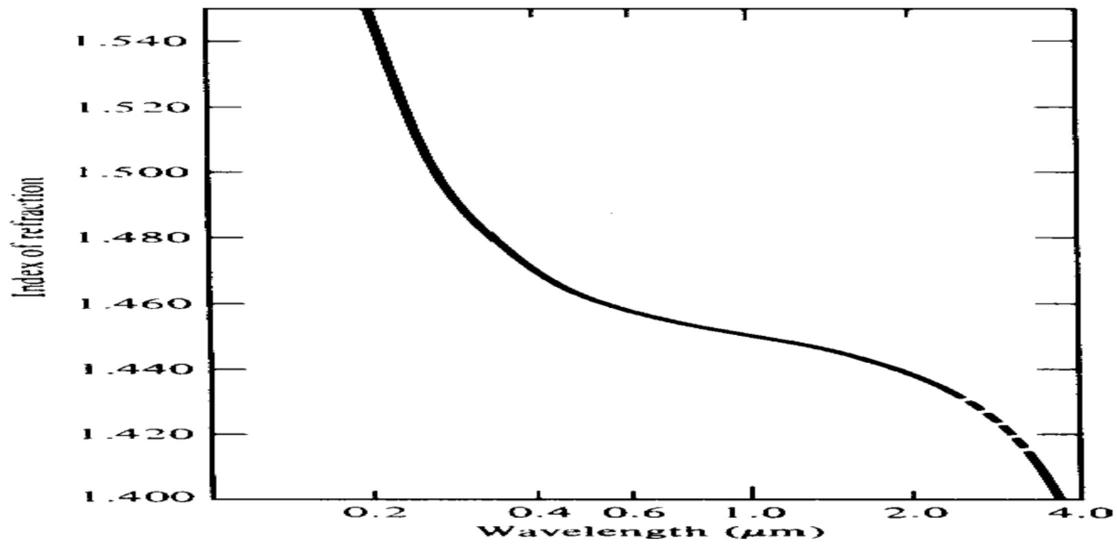


Fig.2.8: Variations in the index of refraction as a function of the optical wavelength for silica

- To calculate MD, consider a plane wave propagating in an infinitely extended dielectric medium that has a RI n(λ) equal to that of fiber core. The propagation constant $\beta=[2\pi n(\lambda)/\lambda]$.
- $\frac{d\beta}{d\lambda} = 2\pi[\frac{-n}{\lambda^2} + \frac{1}{\lambda}\frac{dn}{d\lambda}]$
- $= \frac{-2\pi}{\lambda^2}[n - \lambda\frac{dn}{d\lambda}] = \frac{-2\pi}{\lambda^2} N$
- Wkt $V_g = [\frac{d\beta}{d\omega}]^{-1}$
- $= [\frac{d\beta}{d\lambda} * \frac{d\lambda}{d\omega}]^{-1}$
- $\omega = 2\pi f = 2\pi c/\lambda$
- $\frac{d\omega}{d\lambda} = -[2\pi c/\lambda^2]$
- $\frac{d\lambda}{d\omega} = -[\lambda^2 / 2\pi c]$
- $V_g = [\frac{d\beta}{d\lambda} * \frac{d\lambda}{d\omega}]^{-1} = [\frac{-2\pi}{\lambda^2} N * \frac{\lambda^2}{2\pi c}]^{-1} = [\frac{N}{c}]^{-1} = [\frac{c}{N}]$

- $T_{Mat} = \frac{L}{Vg} = \frac{L}{c} N = \frac{L}{c} [n - \lambda \frac{dn}{d\lambda}]$
- Group delay due to MD is $\tau_{MAT} = [L/C][n\text{-}\lambda dn/d\lambda]$
- Pulse spreading due to MD is $\sigma_{MAT} = [d\, \tau_{MAT}/d\lambda]\sigma_A$
- $= \frac{L}{c} [\frac{dn}{d\lambda} - \lambda[d^2n/d\lambda^2] - \frac{dn}{d\lambda}]$
- $= - \frac{L\lambda}{c} [d^2n/d\lambda^2]\ \sigma_A$ $= \sigma_A\, L\, D_{MAT}(\lambda)$ where $D_{MAT}(\lambda)$ is material dispersion.
- $D_{MAT}(\lambda) = [\lambda/Lc][d^2n/d\lambda^2]$

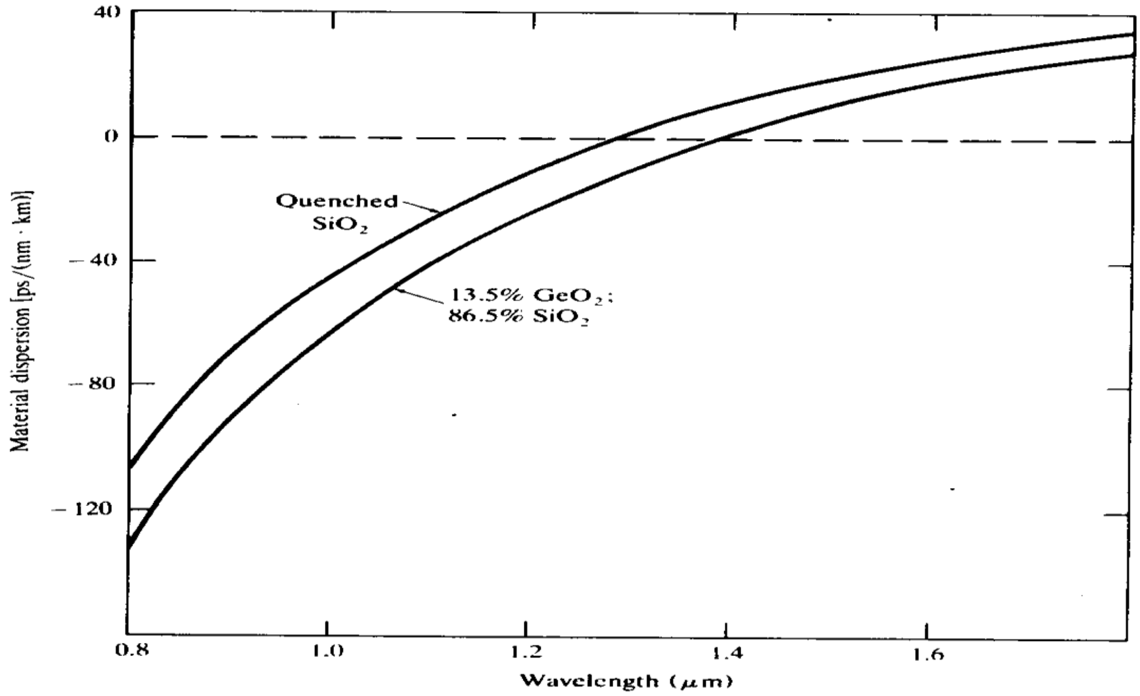


Fig.2.9: Material dispersion as a function of optical wavelength for pure silica and 13.5% GeO2/86.5% SiO2

WAVEGUIDE DISPERSION:

The effect of WGD on pulse spreading can calculated by assuming RI of material is independent of wavelength. Consider the group delay in terms of normalized propagation constant 'b'.

We know that $b=[[\beta/k]^2\text{-}n2^2]/[n1^2\text{-}n2^2]$

$= [[\beta/k]\text{-}n2]/[n1\text{-}n2]$

$=[[\beta/k\ n2]\text{-}1]/[n1\text{-}n2]\ /n2$

$b = [[\beta/k\ n2]\text{-}1]/\Delta$

$\beta= n2k[b\Delta+1]$

Group delay arising from WGD is
$\tau_{WG} = [L/C]d\beta/dk = [L/C][n_2 + n_2\Delta[d(kb)/dk]$
Wkt normalized frequency $V=kan2[2\Delta]^{1/2}$
The τWG in terms of V instead of k is $\tau WG = [L/C][n2 + n2\Delta[d(Vb)/dV]$
The first term is constant and second term represents group delay arising from WGD.

When a light pulse is launched into a fiber, it is distributed among many guided modes. These various modes arrive at the fiber end at different times depending on their group delay, so that a pulse spreading results. For MM fibers the WGD is very small compared with MD and can be neglected.

WAVEGUIDE DISPERSION IN SM FIBERS

WGD can be of same order of magnitude as a MD. Pulse spreading factor due to wave guide dispersion is

$$\sigma_{wg} = \sigma_\lambda \frac{d\tau_{wg}}{d\lambda} = \sigma_\lambda L D_{wg}(\lambda)$$

$$= -\frac{V}{\lambda}\sigma_\lambda \frac{d\tau_{wg}}{dV} = -\frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

INTERMODAL DISPERSION:

It is a result of different values of group delay for each individual mode at a single frequency. Consider a meridional ray in step index fiber. If mode no. is high consequently slower the axial group velocity. This variation in group velocities of different modes results in a group delay spared or internal mode dispersion.

This dispersion mechanism can be eliminated by single mode operations but important in multimode operations.

The pulse broadening arising from intermodal dispersion is difference between travel time Tmax of longest ray paths and travel time Tmin of shortest ray paths.

$$\sigma MOD = Tmax - Tmin = [n1\Delta L]/C$$

POLARIZATION MODE DISPERSION:

It results from fact that light-signal energy at a given wave length in a single mode fiber occupies 2 orthogonal polarization states or modes.

At the input of fiber 2 polarization modes are aligned. Since fiber material is not perfectly uniform throughout its length, each polarization mode encounters slightly different refractive indexes. Therefore each mode will travel at slightly different velocities.

The modes propagating with different phase velocities at different RI's are called FIBER BIRE FRINGENCE.

$BF = [\beta x - \beta y]/[2\pi/\lambda]$

where βx , βy are propagation constants for slow & fast mode respectively.

The propagation distance for which a 2π phase difference accumulates between 2 modes is known as BEAT LENGTH.

$LB = \lambda / BF = 2\pi / [\beta x - \beta y]$

$BF = \lambda / LB$

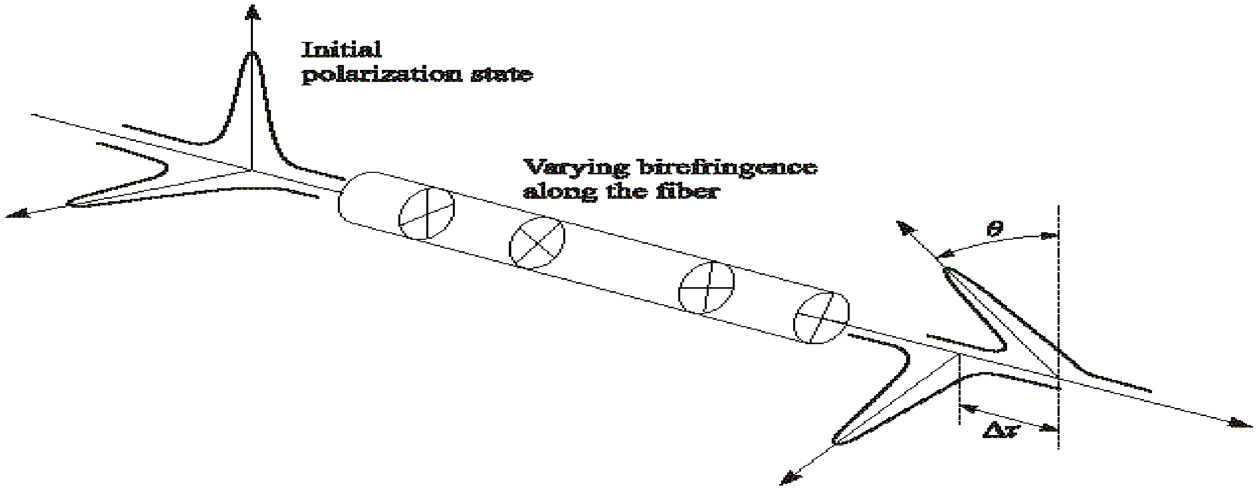


Fig.2.10: Polarization mode dispersion

The resulting difference in propagation time's τ_{PMD} between 2 orthogonal polarization modes causes pulse spreading.

If the group velocities of 2 orthogonal polarization modes are V_{gx} & V_{gy} then differential time delay $\Delta\tau_{PMD}$ between 2 polarization modes over a distance L is

$\Delta\tau_{PMD} = | [L/V_{gx}]-[L/V_{gy}] | \approx DPMD[L]^{1/2}$ where DPMD is dispersion due to polarization modes measured in $PSec/[Km]^{1/2}$, ranges from 0.05 to 1.0 $PS/[Km]^{1/2}$.

OVERALL DISPERSION:

The overall dispersion in multimode fibers comprises both Intramodal and intermodal terms. The total rms pulse broadening $\sigma T = [\sigma c^2 + \sigma n^2]^{1/2}$ where σc = Intramodal or chromatic broadening [material & wave guide dispersions] & σn = intermodal broadening caused by delay differences between the modes.

The pulse broadening in single mode fibers is solely due to Intramodal dispersion as only a single mode is allowed to propagate. The mechanisms giving Intramodal dispersion in single mode fibers tend to be interrelated in a complex manner.

PULSE BRODANING IN GIF:

The analysis of pulse broadening in GIF waveguide is more involved due to the radial variation in core RI. The feature of this grading of RI profile is that it offers multimode propagation of very low intermodal delay distortion. This combination allows the transmission of high data rates over long distances.

The index of refraction is lower at the outer edges of the core, light rays will travel faster in this region than in the center of the core where the RI is higher.

The root mean square [rms] pulse broadening in GIF can be obtained from

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

The group delay

$$\tau_g = \frac{L}{c}\frac{\partial \beta}{\partial k}$$

The group delay is the time it takes energy in a mode having a propagation constant β to travel distance L.

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

Therefore the group delay

$$\tau = \frac{N_1 L}{c}\left[1 + \frac{\alpha - 2 - \epsilon}{\alpha + 2}\Delta\left(\frac{m}{M}\right)^{\alpha/(\alpha+2)} + \frac{3\alpha - 2 - 2\epsilon}{2(\alpha + 2)}\Delta^2\left(\frac{m}{M}\right)^{2\alpha/(\alpha+2)} + O(\Delta^3)\right]$$

Where

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

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

If all the modes are equally excited then

$$\sigma_{\text{intermodal}} = \frac{LN_1\Delta}{2c}\frac{\alpha}{\alpha+1}\left(\frac{\alpha+2}{3\alpha+2}\right)^{1/2} \times\left[c_1^2 + \frac{4c_1c_2(\alpha+1)\Delta}{2\alpha+1} + \frac{16\Delta^2c_2^2(\alpha+1)^2}{(5\alpha+2)(3\alpha+2)}\right]^{1/2}$$

'here we have used the abbreviations

$$c_1 = \frac{\alpha-2-\epsilon}{\alpha+2}$$

$$c_2 = \frac{3\alpha-2-2\epsilon}{2(\alpha+2)}$$

The Intramodal pulse broadening can be written as

$$\sigma_{\text{intramodal}} = \frac{L}{c}\frac{\sigma_\lambda}{\lambda}\left[\left(-\lambda^2\frac{d^2n_1}{d\lambda^2}\right)^2 - N_1c_1\Delta\left(2\lambda^2\frac{d^2n_1}{d\lambda^2}\frac{\alpha}{\alpha+1} - N_1c_1\Delta\frac{4\alpha^2}{(\alpha+2)(3\alpha+2)}\right)\right]^{1/2}$$

MODE COUPLING:

In real systems pulse distortion will increases less rapidly after certain initial length of fiber because of mode coupling. In this initial length of fiber, coupling of energy from one mode to another arises due to imperfection of fiber structure, variation in RI & fiber diameter, micro bends. The mode coupling tends to average out the propagation delay thereby reducing intermodal dispersion.

Associated with this coupling is an additional loss, which is designated by 'h' and which has units db/km. the result of this phenomenon is that, after a certain coupling length Lc, the pulse distortion will change from an L dependence to $[L\ Lc]^{1/2}$ dependence.

The improvement of pulse spreading caused by mode coupling over the distance Z < Lc is

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

Where σ_o = pulse width increases in the absence of mode coupling, σ_c = pulse width in the presence of mode coupling

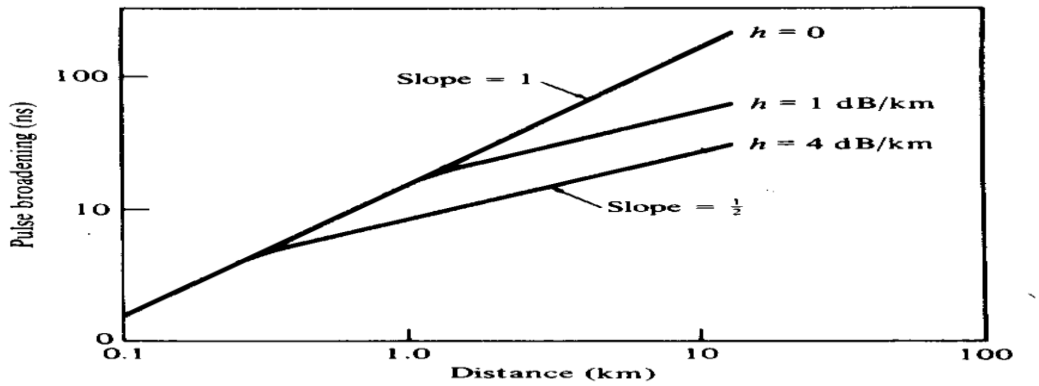


Fig.2.11: Mode coupling effect on pulse distortion in long fibers.

CUTOFF WAVE LENGTH:

The single mode operation occurs above the theoretical cutoff wavelength given by

$$\lambda_c = \frac{2\pi a}{V}(2\Delta)^{1/2}$$

At this wavelength only LP_{01} mode should propagate in the fiber. The cutoff wavelength of the first higher order mode [LP11] is an important transmission parameter for single mode fiber from the multimode regions.

Since in the cutoff region the field of the LP11 mode is widely spread across the fiber cross section, its attenuation is strongly affected by fiber bends, length and cabling.

As λ_c is stabilizing in short fiber lengths, it decreases as

$$d\lambda_c = -m \log \frac{L}{2}$$

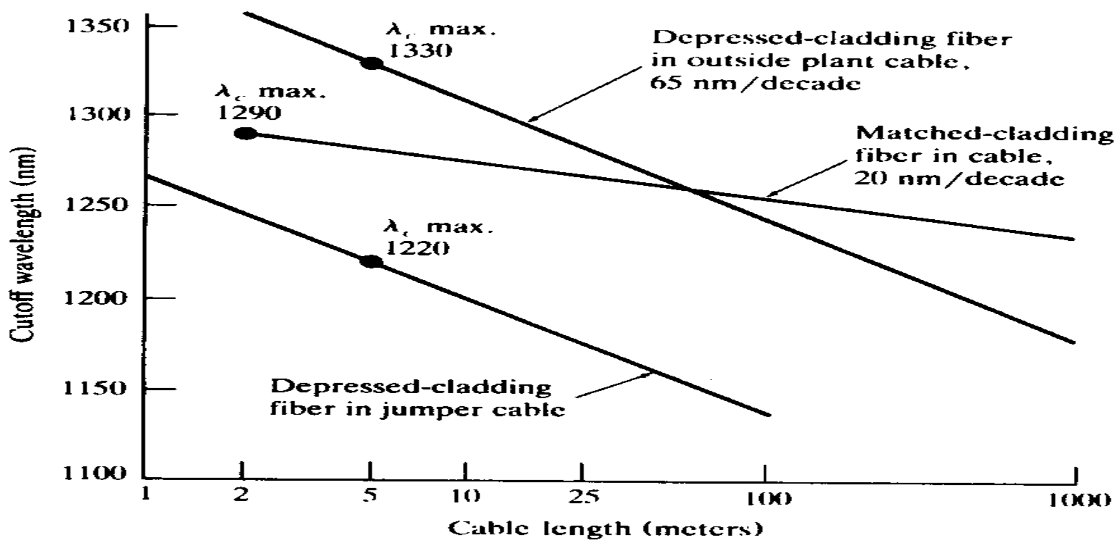


Fig.2.12: Cutoff wavelength as a function of fiber length for depressed cladding and matched cladding single mode fibers.

SINGLE MODE FIBER DESIGN OPTIMIZATION: RI PROFILE

The dispersion occurs in MMF is due to Intermodal dispersion & Intramodal dispersion. The dispersion occurs in SMF is due to Intramodal dispersion only. Therefore Dispersion is low in SMF compare to MMF.

Material Dispersion is hard to alter significantly. However, it is possible to modify the WGD. The WGD is mainly depends upon structure of OF, core diameter, RRID & RI PROFILE. It is possible to modify the WGD by changing from a simple SIF design to more complex index profiles for the cladding.

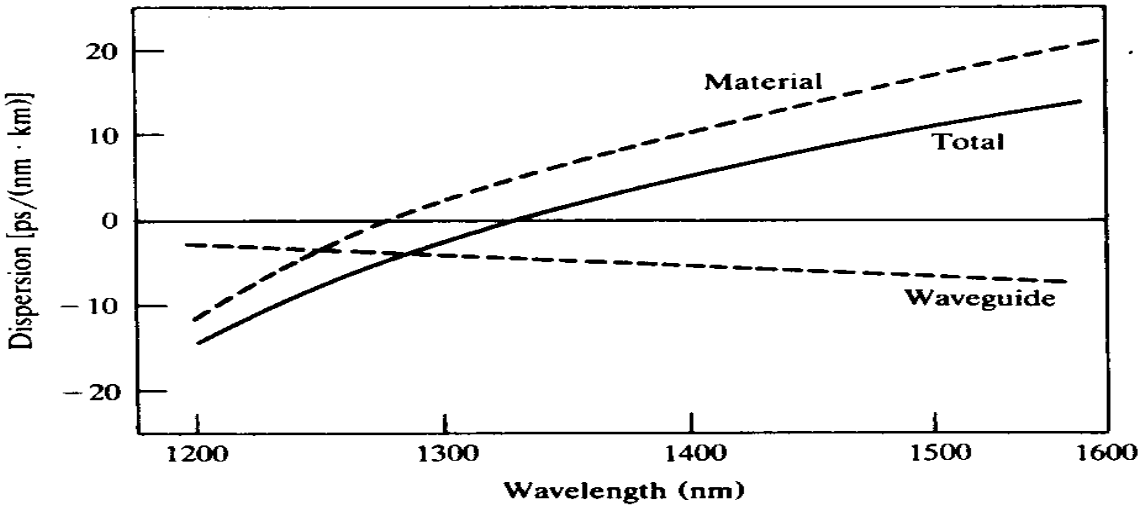


Fig.2.13: Dispersion as a function of optical WL in SMF

In SMF dispersion is due to Intramodal dispersion [MD + WGD]. SMF are suitable for short distance communications only. To use in long distance applications, some optimization techniques have to adopt in SMF design. It is possible to modify the dispersion characteristics of single-mode fibers by the tailoring of specific fiber parameters.

It is possible to modify the WGD by changing from a simple step index core profile design to more complicated index profiles.

The most popular single mode fibers used in telecommunication networks are near step index fiber, which are dispersion optimized for operation at 1300nm. These 1300-nm-opticized SMFs are either of the matched-cladding or the depressed-cladding design shown in below figure.

Matched-cladding fibers have a uniform RI throughout the cladding. Typical MFDs are 9.5µm and core to cladding index differences are around 0.35% . In depressed cladding fibers the cladding portion next to the core has a lower index than the outer cladding region. MFDs around 9µm and typical positive and negative index differences are around 0.25 and 0.12% respectively.

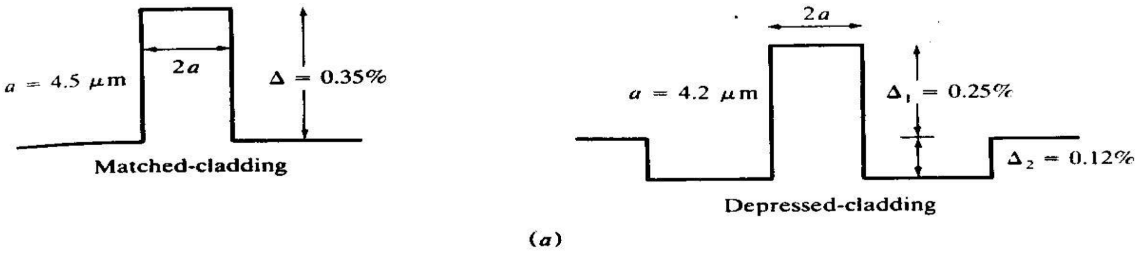
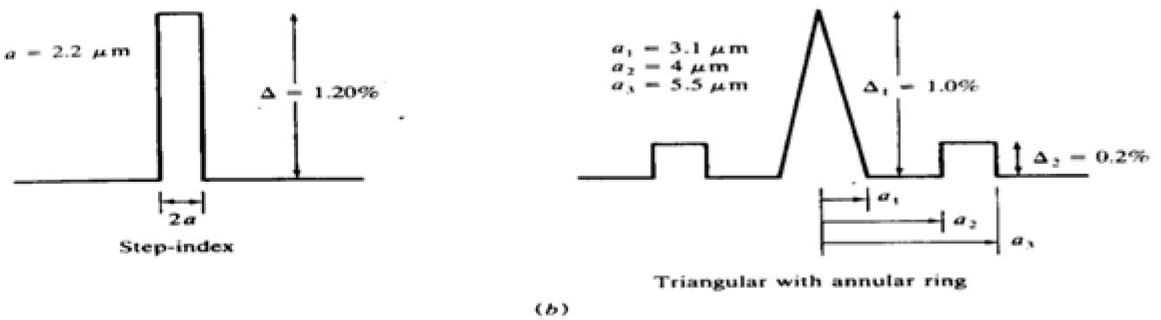


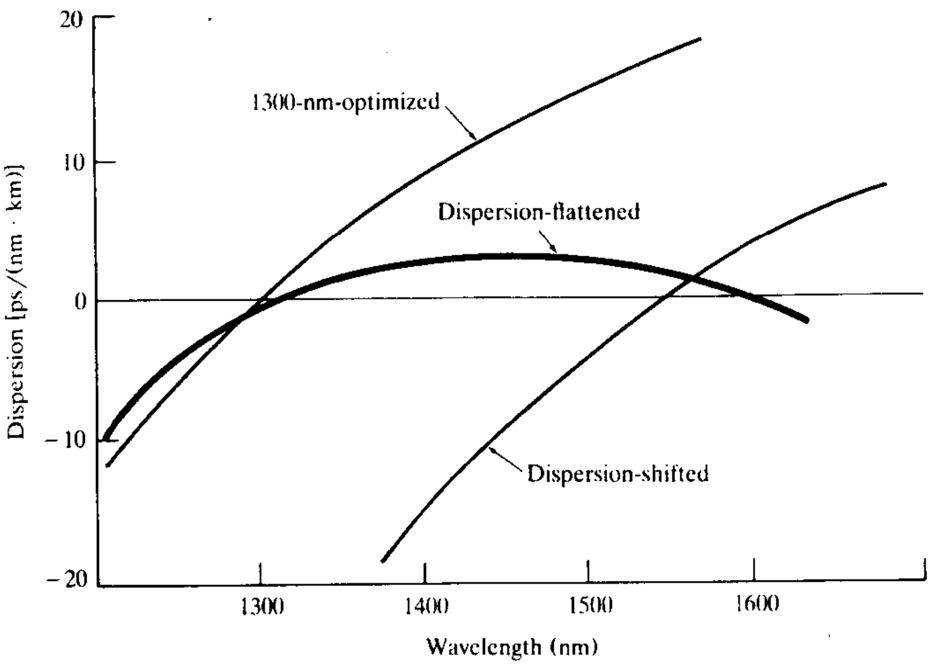
Fig. 2.14: 1300 nm Optimized SMF

DISPERSION SHIFTED FIBER

Dispersion is low at 1330nm. Attenuation is low at 1550nm but dispersion is high. To improve information capacity we have to operate SMF at 1550nm by shifting ZDP to long wavelengths. Such type of fibers are known as DISPERSION SHIFTED FIBERS[DSF]

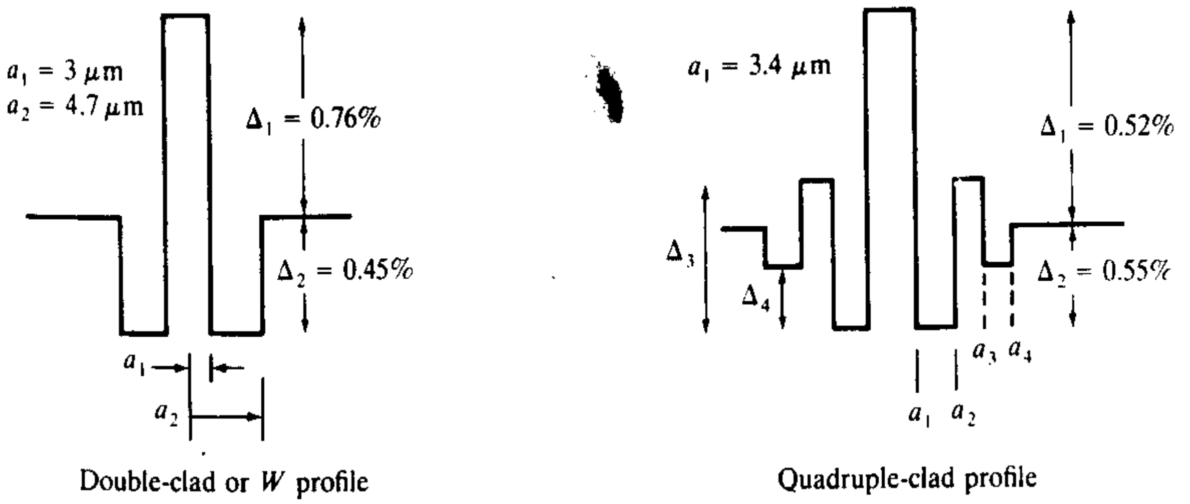


Typical Dispersion Characteristics



DISPERSION FLATTENED FIBERS:

An alternative is to reduce fiber dispersion by spreading the dispersion minimum out over a broader range. This approach is known as dispersion flattening. Dispersion flattened fibers are more complex to design than dispersion shifted fibers, because dispersion must be considered over a range of wavelengths.



(c)

NON ZERO DISPERSION SHIFTED FIBER [NZDSF]:

Positive & negative dispersion seriously effects the WGD. It causes non linearity. Developers designed NON ZERO DISPERSION SHIFTED FIBER [NZDSF] with variation in their RI's as shown in below figures.