Unit-II

Fiber materials

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 distances 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 Fibers. The glass fibers are made from oxides. The most common oxide is silica whose refractive index is 1.458_at 850 nm. To get different index fibers, the dopants such as GeO_2, P_2O_5 are added to silica. GeO_2 and P_2O_3 increase the refractive index whereas fluorine or B203 decreases the refractive index.

Few fiber compositions are given below as follows,
(i) GeO_2 – SiO_2 Core: SiO_2 Cladding
(ii) P_2Q_5 – SiO_2, Core; SiO_2Cladding
The principle raw material for silica is sand. The glass composed of pure silica is referred to as silica glass, nitrous silica or fused silica. Some desirable properties of silica are,
(i) Resistance to 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 and infrared regions.
Basic Requirements and Considerations in Fiber Fabrication
(i) Optical fibers should have maximum reproducibility.
(ii) Fibers should be fabricated with good stable transmission characteristics i.e., the fiber should have invariable transmission characteristics in long lengths.
(iii) Different size, refractive index and refractive index profile, operating wavelengths material. Fiber must be available to meet different system applications.
(iv) The fibers must be flexible to convert into practical cables without any degradation of their characteristics.
(v) Fibers must be fabricated in such a way that a joining (splicing) of the fiber should not affect its transmission characteristics and the fibers may be terminated or connected together with less practical difficulties.

Fiber Fabrication in a Two Stage Process

(i) Initially glass is produced and then converted into perform or rod. Glass fiber is a mixture of selenides, sulfides and metal oxides. It can be classified into,

1. Halide Glass Fibers

2. Active Glass Fibers

3. Chalgenide Glass Fibers.

Glass is made of pure SiO_2 which refractive index 1.458 at 850 nm. The refractive index of SiO_2 can be increased (or) decreased by adding various oxides are known as dopant. The oxides GeO_2 or P_2O_3 increases the refractive index and B_2O_3 decreases the refractive index of SiO_2 .

The various combinations are,

(i) GeO_2 SiO_2 Core; SiO_2 cladding

(ii) P_2O_3 – SiO_2 Core; SiO_2 cladding

(iii) SiO_2 Core; B_2O_3, - SiO_2cladding

(iv) GeO_2- B_2O_3- SiO_2, Core; B_2O_3 - SiO_2cladding.

From above, the refractive index of core is maximum compared to the cladding.

(1) Halide Glass Fibers

A halide glass fiber contains fluorine, chlorine, bromine and iodine. The most common Halide glass fiber is heavy "metal fluoride glass". It uses ZrF_4 as a major component. This fluoride glass is known by the name ZBLAN Since it is constituents are ZrF_4, BaF_2, LaF_3 $A1F_3$, and NaF. The percentages of these elements to form ZBLAN fluoride glass is shown as follows, Materials These materials add up to make the core of a glass fiber. By replacing ZrF_4 by HaF_4, the lower refractive index glass is obtained. The intrinsic losses of these glasses is 0.01 to 0.001 dB/km

The percentages of these elements to form ZBLAN fluoride glass is shown as follows,

Materials	Molecular percentage
ZrF_4	54%
BaF_2	20%
LaF_3	4.5%
$A1F_3$	3.5%
NaF	18%

(2) Active Glass Fibers

Active glass fibers are formed by adding erbium and neodymium to the glass fibers. The above material performs amplification and attenuation

(3) Chalgenide Glass Fibers

Chalgenide glass fibers are discovered in order to make use of the nonlinear properties of glass fibers. It contains either "S", "Se" or "Te", because they are highly nonlinear and it also contains one element from “Cl”, "Br", “Cd”,”Ba” or”Si”.The mostly used chalgenide glass is AS_2-S_3, $AS_40S_58Se_2$ is used to make the core and AS2S3 is used to make the cladding material of the glass fiber. The insertion loss is around 1 dB/m. Plastic Optical Fibers Plastic optical fibers are the fibers which are made up of plastic material. The core of this fiber is made up of Polymethylmethacrylate (PMMA) or Perflourmated Polymer (PFP).Plastic optical fibers offer more attenuation than glass fiber and is used for short distance applications. These fibers are tough and durable due to the presence of plastic material. The modulus of this plastic material is two orders of magnitude lower than that of silica and even a 1 mm diameter graded index plastic optical fiber can be installed in conventional fiber cable routes. The diameter of the core of these fibers is 10-20 times larger than that of glass fiber which reduces the connector losses without sacrificing coupling efficiencies. So we can use inexpensive connectors, splices and transceivers made up of plastic injection-molding technology. Graded index plastic optical fiber is in great demand in customer premises to deliver high-speed services due to its high bandwidth.

SIGNAL DISTORTION IN OPTICAL FIBERS

Introduction

- One of the important property of optical fiber is signal attenuation. It is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair.
- Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes more broader. After sufficient length the broad pulses starts overlapping with adjacent pulses. This creates error in the receiver. Hence the distortion limits the information carrying capacity of fiber.

Attenuation

- Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.
- In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.
- The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additional chemicals to the basic silicon dioxide the optical properties of the glass can be changed.
- The Rayleigh scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases.
- The attenuation of fiber is governed by the materials from which it is fabricated, the manufacturing process and the refractive index profile chosen. Attenuation loss is measured in dB/km.

Attenuation Units

- As attenuation leads to a loss of power along the fiber, the output power is significantly less than the couples power. Let the couples optical power is p(0) i.e. at origin (z = 0).

Then the power at distance z is given by,

$$P(z) = P(0)e^{-\alpha_p z} \quad \dots (2.1.1)$$

where, α_p is fiber attenuation constant (per km).

$$\propto_p = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)}\right]$$

$$\boxed{\propto_{dB/km} = 10.\frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$\propto_{dB/km} = 4.343 \ \propto_p \ \text{per km}$$

This parameter is known as fiber loss or fiber attenuation.

- Attenuation is also a function of wavelength. Optical fiber wavelength as a function of wavelength is shown in Fig. 2.1.1.

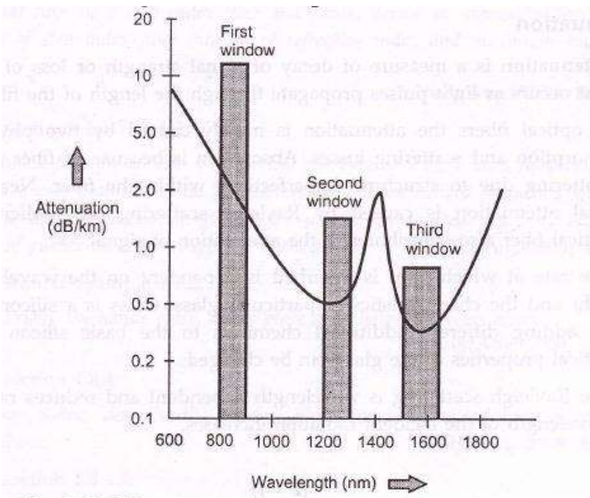

Fig. 2.1.1 Fiber attenuation as a function of wavelength

Example 2.1.1 : A low loss fiber has average loss of 3 dB/km at 900 nm. Compute the length over which –

a) Power decreases by 50 % b) Power decreases by 75 %.

Solution : $\alpha = 3$ dB/km

a) Power decreases by 50 %.

$\Rightarrow \qquad \frac{p(0)}{p(z)} = 50\ \% = 0.5$

α is given by,

$$\boxed{\alpha = 10 . \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$3 = 10 . \frac{1}{z} \log [0.5]$$

$\therefore$ $z = \mathbf{1\ km}$ **… Ans.**

b) $\frac{P(0)}{P(z)} = 25\ \% = 0.25$

Since power decrease by 75 %.

$$3 = 10 \times \frac{1}{z} \log[0.25]$$

$\therefore$ $z = \mathbf{2\ km}$ **… Ans.**

Example 2.1.2 : For a 30 km long fiber attenuation 0.8 dB/km at 1300nm. If a 200 µwatt power is launched into the fiber, find the output power.

Solution : $z = 30$ km

$\alpha = 0.8$ dB/km

$P(0) = 200\ \mu W$

Attenuation in optical fiber is given by,

$$\boxed{\alpha = 10 \times \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$0.8 = 10 \times \frac{1}{30} \log \left[\frac{200\ \mu W}{P(z)}\right]$$

$$2.4 = 10 \times \log \left[\frac{200\ \mu W}{P(z)}\right]$$

$$\left[\frac{200\ \mu W}{P(z)}\right] = 10^{2.4}$$

$\therefore$ $$P(z) = \left[\frac{200\ \mu W}{P(z)}\right] = 0.7962\ \mu W$$

Example 2.1.3 : When mean optical power launched into an 8 km length of fiber is 12 µW, the mean optical power at the fiber output is 3 µW.

Determine –

1) Overall signal attenuation in dB.
2) The overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB.

Solution : **Given** : z = 8 km

P(0) = 120 µW

P(z) = 3 µW

1) Overall attenuation is given by,

$$\alpha = 10\ .\log\left[\frac{P(0)}{P(z)}\right]$$

$$\alpha = 10\ .\log\left[\frac{120}{3}\right]$$

$$\alpha = 16.02\ \text{dB}$$

2) Overall attenuation for 10 km,

Attenuation per km $\propto_{dB} = \frac{16.02}{z} = \frac{16.02}{8} = 2.00\ \text{dB/km}$

Attenuation in 10 km link = 2.00 x 10 = 20 dB

In 10 km link there will be 9 splices at 1 km interval. Each splice introducing attenuation of 1 dB.

Total attenuation = 20 dB + 9 dB = **29 dB**

!

Example 2.1.4 : A continuous 12 km long optical fiber link has a loss of 1.5 dB/km.

i) What is the minimum optical power level that must be launched into the fiber to maintain as optical power level of 0.3 μW at the receiving end?

ii) What is the required input power if the fiber has a loss of 2.5 dB/km?

[July/Aug.-2007, 6 Marks]

Solution : Given data : z = 12 km

$\alpha = 1.5$ dB/km

$P(0) = 0.3\ \mu W$

i) Attenuation in optical fiber is given by,

$$\alpha = 10 \text{ x } \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)$$

$$1.5 = 10 \text{ x } \frac{1}{12} \log\left(\frac{0.3\ \mu W}{P(z)}\right)$$

$$\log\left(\frac{0.3\ \mu W}{P(z)}\right) = \frac{1.5}{0.833}$$

$$= 1.80$$

$$\left(\frac{0.3\ \mu W}{P(z)}\right) = 10^{1.8}$$

$$P(z) = \left(\frac{0.3\ \mu W}{10^{1.8}}\right) = \frac{0.3}{63.0}$$

$$P(z) = 4.76 \text{ x } 10^{-9} W$$

Optical power output = $\mathbf{4.76 \text{ x } 10^{-9}\ W}$ **… Ans.**

ii) Input power = ? P(0)

When $\alpha = 2.5$ dB/km

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z}\log\left(\frac{P(0)}{P(z)}\right)}$$

$$2.5 = 10 \text{ x } \frac{1}{z}\log\left(\frac{P(0)}{4.76 \text{ x } 10^{-9}}\right)$$

$$\log\left(\frac{P(0)}{4.76 \text{ x } 10^{-9}}\right) = \frac{2.5}{0.833} = 3$$

$$\frac{P(0)}{4.76 \text{ x } 10^{-9}} = 10^3 = 1000$$

$\therefore$ $P(0) = 4.76\ \mu W$

Input power= **4.76 μW** **… Ans.**

Example 2.1.5 : Optical power launched into fiber at transmitter end is 150 μW. The power at the end of 10 km length of the link working in first windows is – 38.2 dBm. Another system of same length working in second window is 47.5 μW. Same length system working in third window has 50 % launched power. Calculate fiber attenuation for each case and mention wavelength of operation. **[Jan./Feb.-2009, 4 Marks]**

Solution : Given data:

$P(0) = 150\ \mu W$

$z = 10$ km

$$P(z) = -38.2 \text{ dBm} \Rightarrow \begin{cases} -38.2 = 10 \log\frac{P(z)}{1 \text{ mW}} \\ P(z) = 0.151\ \mu W \end{cases}$$

$z = 10$ km

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z}\log\left[\frac{P(0)}{P(z)}\right]}$$

Attenuation in 1st window:

$$\alpha_1 = 10 \text{ x } \frac{1}{10}\log\left[\frac{150}{0.151}\right]$$

$$\propto_1 = \mathbf{2.99\ dB/km}$$ **… Ans.**

Attenuation in 2nd window:

$$\propto_2 = 10\ \text{x}\ \frac{1}{10}\log\left[\frac{150}{47.5}\right]$$

$$\propto_2 = \mathbf{0.49\ dB/km}$$ **… Ans.**

Attenuation in 3rd window:

$$\propto_3 = 10\ \text{x}\ \frac{1}{10}\log\left[\frac{150}{75}\right]$$

$$\propto_3 = \mathbf{0.30\ dB/km}$$ **… Ans.**

Wavelength in 1st window is 850 nm.

Wavelength in 2nd window is 1300 nm.

Wavelength in 3rd window is 1550 nm.

Example 2.1.6 : The input power to an optical fiber is 2 mW while the power measured at the output end is 2 μW. If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.

[July/Aug.-2006, 6 Marks]

Solution : Given : $P(0) = 2$ mwatt $= 2 \times 10^{-3}$ watt

$P(z) = 2$ μwatt $= 2 \times 10^{-6}$ watt

$\alpha = 0.5$ dB/km

$$\boxed{\alpha = 10\ \text{x}\ \frac{1}{z}\left[\frac{P(0)}{P(z)}\right]}$$

$$0.5 = 10\ \text{x}\ \frac{1}{z}\log\left[\frac{2 \times 10^{-3}}{2 \times 10^{-6}}\right]$$

$$0.5 = \frac{1}{z} \text{x}\, 3$$

$$z = \frac{3}{0.05}$$

$z = \mathbf{60\ km}$ **… Ans.**

Absorption

- Absorption loss is related to the material composition and fabrication process of fiber. Absorption loss results in dissipation of some optical power as hear in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.
- Absorption is caused by three different mechanisms.
  1) Absorption by atomtic defects in glass composition.
  2) Extrinsic absorption by impurity atoms in glass matts.
  3) Intrinsic absorption by basic constituent atom of fiber.

Absorption by Atomic Defects

- Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules, high density clusters of atom groups. These absorption losses are negligible compared with intrinsic and extrinsic losses.
- The absorption effect is most significant when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions etc. The radiation dames the internal structure of fiber. The damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy. The total dose a material receives is expressed in rad (Si), this is the unit for measuring radiation absorbed in bulk silicon.

$$1 \text{ rad (Si)} = 0.01 \text{ J.kg}$$

The higher the radiation intensity more the attenuation as shown in Fig 2.2.1.

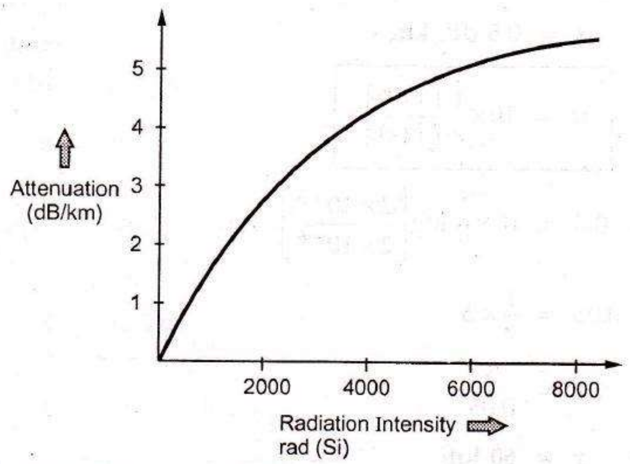

Fig. 2.2.1 Ionizing radiation intensity Vs fiber attenuation

Extrinsic Absorption

- Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques.
- Another major extrinsic loss is caused by absorption due to **OH (Hydroxil)** ions impurities dissolved in glass. Vibrations occur at wavelengths between 2.7 and 4.2 μm. The absorption peaks occurs at 1400, 950 and 750 nm. These are first, second and third overtones respectively.
- Fig. 2.2.2 shows absorption spectrum for OH group in silica. Between these absorption peaks there are regions of low attenuation.

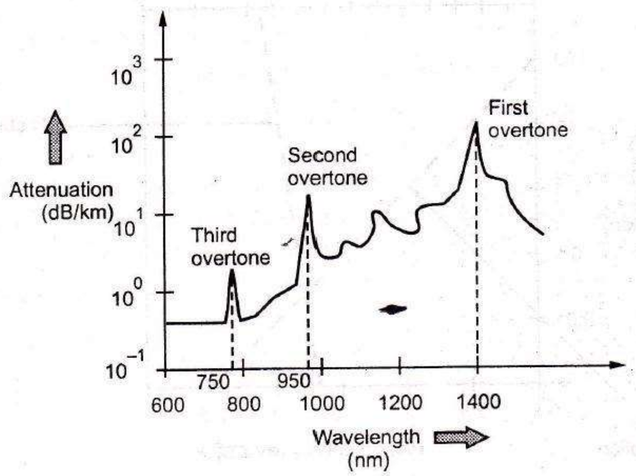

Fig. 2.2.2 Absorption spectra for OH group

Intrinsic Absorption

- Intrinsic absorption occurs when material is in absolutely pure state, no density variation and inhomogenities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material.
- Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region.
- The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valene band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ).
- In the IR (infrared) region above 1.2 μm the optical waveguide loss is determined by presence of the OH ions and inherent IR absorption of the constituent materials. The inherent IR absorption is due to interaction between the vibrating band and the electromagnetic field of optical signal this results in transfer of energy from field to the band, thereby giving rise to absorption, this absorption is strong because of many bonds present in the fiber.
- Attenuation spectra for the intrinsic loss mechanism in pure Ge is shown in Fig. 2.2.3.

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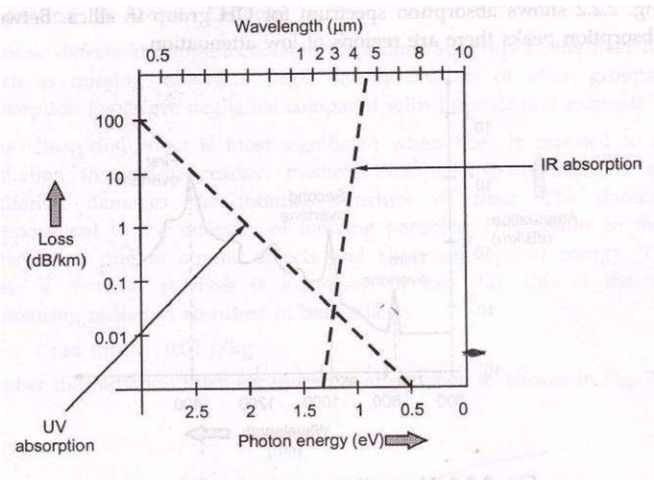

Fig. 2.2.3 Attenuation spectra for intrinsic loss

- The ultraviolet loss at any wavelength is expressed as,

$$\propto_{uv} = \frac{154.2}{46.6\,x + 60} \times 10^{-2} \times e^{\left(\frac{4.63}{\lambda}\right)} \qquad \ldots (2.2.1)$$

where, x is mole fraction of GeO_2.

λ is operating wavelength.

α_{uv} is in dB/km.

- The loss in infrared (IR) region (above 1.2 μm) is given by expression :

$$\propto_{IR} = 7.81 \times 10^{11} \times e^{\left(\frac{-48.48}{\lambda}\right)} \qquad \ldots (2.2.2)$$

The expression is derived for GeO_2-SiO_2 glass fiber.

Rayleigh Scattering Losses

- Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. SiO_2, GeO_2 and P_2O_5), these are the major cause of compositional structure fluctuation. These two effects results to variation in refractive index and Rayleigh type scattering of light.
- **Rayleigh scattering** of light is due to small localized changes in the refractive index of the core and cladding material. There are two causes during the manufacturing of fiber.

- The first is due to slight fluctuation in mixing of ingredients. The random changes because of this are impossible to eliminate completely.
- The other cause is slight change in density as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength (highest frequency) suffers most scattering. Fig. 2.3.1 shows graphically the relationship between wavelength and Rayleigh scattering loss.

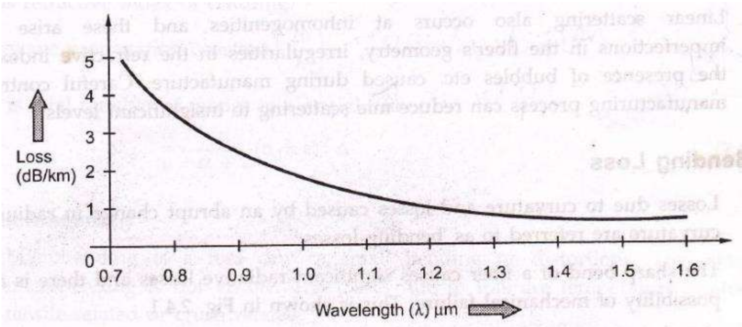

Fig. 2.3.1 Scattering loss

- Scattering loss for single component glass is given by,

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} (n^2 - 1)^2 k_B T_f \beta_T \text{ nepers} \qquad \ldots (2.3.1)$$

where, n = Refractive index

k_B = Boltzmann's constant

β_T = Isothermal compressibility of material

T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies (fictive temperature)

Another form of equation is

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \text{ nepers} \qquad \ldots (2.3.2)$$

where, P = Photoelastic coefficient

- Scattering loss for multicomponent glasses is given by,

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} (\delta_n^2)^2 \delta v$$

where, δ_n^2 = Mean square refractive index fluctuation

δv = Volume of fiber

- Multimode fibers have higher dopant concentrations and greater compositional fluctuations. The overall losses in this fibers are more as compared to single mode fibers.

Mie Scattering :

- Linear scattering also occurs at inhomogenities and these arise from imperfections in the fiber's geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce mie scattering to insignificant levels.

Bending Loss

- Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as 'bending losses.'
- The sharp bend of a fiber causes significant radiative losses and there is also possibility of mechanical failure. This is shown in Fig. 2.4.1.

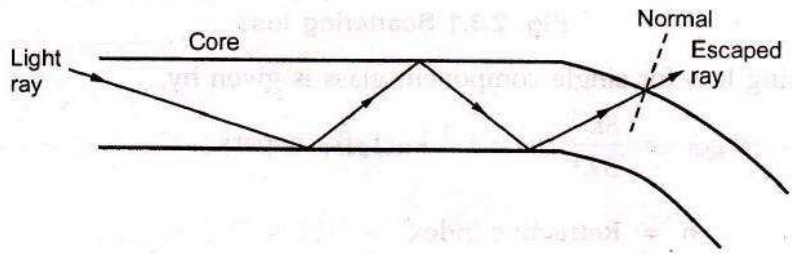

Fig. 2.4.1 Bending loss

- As the core bends the normal will follow it and the ray will now find itself on the wrong side of critical angle and will escape. The sharp bends are therefore avoided.
- The radiation loss from a bent fiber depends on –
  i) Field strength of certain critical distance x_c from fiber axis where power is lost through radiation.
  ii) The radius of curvature R.
- The higher order modes are less tightly bound to the fiber core, the higher order modes radiate out of fiber firstly.
- For multimode fiber, the effective number of modes that can be guided by curved fiber is given expression :

$$N_{eff} = N_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{2}{2\,n_2\,k\,R}\right)^{2/3}\right]\right\} \qquad \ldots (2.4.1)$$

where,

α is graded index profile.

Δ is core – cladding index difference.

n_2 is refractive index of cladding.

k is wave propagation constant $\left(\frac{2\pi}{\lambda}\right)$.

N_{∞} is total number of modes in a straight fiber.

$$N_{\infty} = \frac{\alpha}{\alpha+2}(n_1\,k\,a)^2\Delta \qquad \ldots (2.4.2)$$

Microbending

- Microbending is a loss due to small bending or distortions. This small microbending is not visible. The losses due to this are temperature related, tensile related or crush related.
- The effects of microbending on multimode fiber can result in increasing attenuation (depending on wavelength) to a series of periodic peaks and troughs on the spectral attenuation curve. These effects can be minimized during installation and testing. Fig. 2.4.2 illustrates microbening.

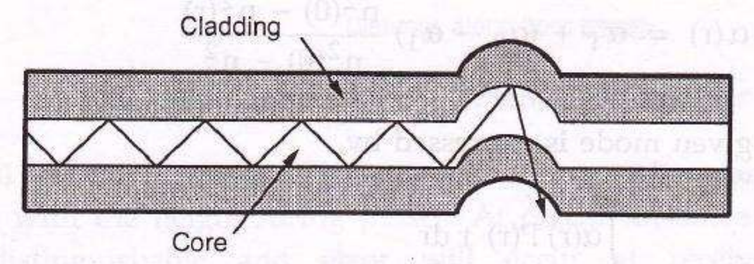

Fig. 2.4.2 Microbending

Macrobending

- The change in spectral attenuation caused by macrobending is different to microbending. Usually there are no peaks and troughs because in a macrobending no light is coupled back into the core from the cladding as can happen in the case of microbends.

- The macrobending losses are cause by large scale bending of fiber. The losses are eliminated when the bends are straightened. The losses can be minimized by not exceeding the long term bend radii. Fig. 2.4.3 illustrates macrobending.

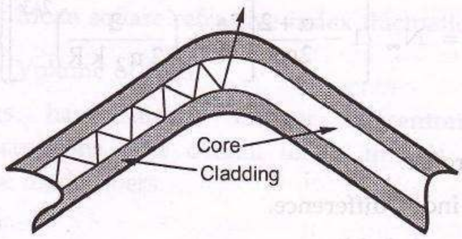

Fig. 2.4.3 Macrobending

Core and Cladding Loss

- Since the core and cladding have different indices of refraction hence they have different attenuation coefficients α_1 and α_2 respectively.
- For step index fiber, the loss for a mode order (v, m) is given by,

$$\propto_{v\,m} = \propto_1 \frac{P_{core}}{P} + \propto_2 \frac{P_{cladding}}{P} \qquad \ldots (2.5.1)$$

For low-order modes, the expression reduced to

$$\propto_{v\,m} = \propto_1 + (\propto_2 + \propto_1) \frac{P_{cladding}}{P} \qquad \ldots (2.5.2)$$

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

- For graded index fiber, loss at radial distance is expressed as,

$$\propto (r) = \propto_1 + (\propto_2 - \propto_1) \frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2} \qquad \ldots (2.5.3)$$

The loss for a given mode is expressed by,

$$\propto_{Graded\ Index} = \frac{\int_0^\infty \propto(r)\, P(r)\, r\, dr}{\int_0^\infty P(r)\, r\, dr} \qquad \ldots (2.5.4)$$

where, P(r) is power density of that model at radial distance r.

Signal Distortion in Optical Waveguide

- The pulse get distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

Information Capacity Determination

- Dispersion and attenuation of pulse travelling along the fiber is shown in Fig. 2.6.1.

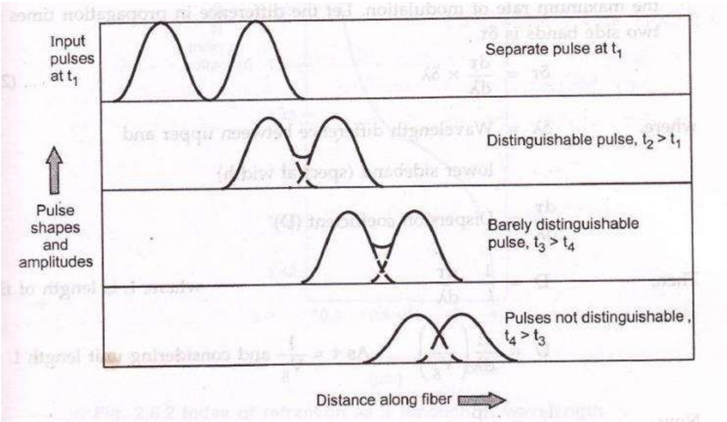

Fig. 2.6.1 Dispersion and attenuation in fiber

- Fig. 2.6.1 shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are not even distinguishable and error will occur at receiver. Therefore the information capacity is specified by bandwidth-distance product (MHz . km). For step index bandwidth distance product is 20 MHz . km and for graded index it is 2.5 MHz . km.

Group Delay

- Consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components in the wavelength band. All the spectral components travel independently and they observe different **time delay** and **group delay** in the direction of propagation. The velocity at which the energy in a pulse travels along the fiber is known as **group velocity**. Group velocity is given by,

$$V_g = \frac{\partial w}{\partial \beta} \qquad \ldots (2.6.1)$$

- Thus different frequency components in a signal will travel at different group velocities and so will arrive at their destination at different times, for digital modulation of carrier, this results in dispersion of pulse, which affects the maximum rate of modulation. Let the difference in propagation times for two side bands is δτ.

$$\delta\tau = \frac{d\tau}{d\lambda}\, x\, \delta\lambda \qquad \text{... (2.6.2)}$$

where, $\delta\tau$ = Wavelength difference between upper and lower sideband (spectral width)

$\frac{d\tau}{d\lambda}$ = Dispersion coefficient (D)

Then, $D = \frac{1}{L} \cdot \frac{d\tau}{d\lambda}$ where, L is length of fiber.

$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)$ As $\tau = \frac{1}{V_g}$ and considering unit length L = 1.

Now $\frac{1}{V_g} = \frac{d\beta}{d\omega}$

$$\frac{1}{V_g} = \frac{d\lambda}{d\omega} x \frac{d\beta}{d\lambda}$$

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

∴

$$D = \frac{d}{d\lambda}\left(\frac{-\lambda^2}{2\pi\, c} \cdot \frac{d\beta}{d\lambda}\right) \qquad \text{... (2.6.3)}$$

- Dispersion is measured in picoseconds per nanometer per kilometer.

Material Dispersion

- Material dispersion is also called as chromatic dispersion. Material dispersion exists due to change in index of refraction for different wavelengths. A light ray contains components of various wavelengths centered at wavelength λ_{10}. The time delay is different for different wavelength components. This results in time dispersion of pulse at the receiving end of fiber. Fig. 2.6.2 shows index of refraction as a function of optical wavelength.

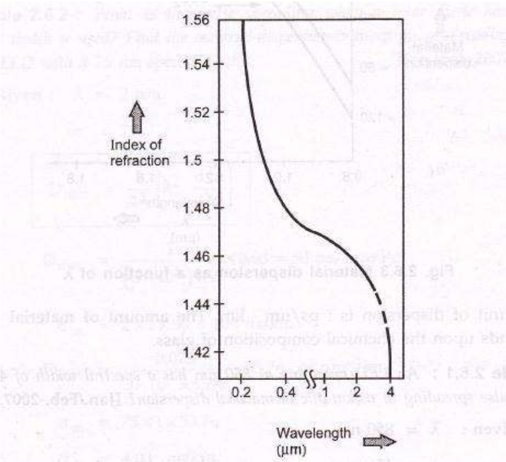

Fig. 2.6.2 Index of refraction as a function of wavelength

- The material dispersion for unit length (L = 1) is given by

$$\boxed{D_{mat} = \frac{-\lambda}{c} x \frac{d^2 n}{d\lambda^2}} \quad \ldots (2.6.4)$$

where, c = Light velocity

λ = Center wavelength

$\frac{d^2 n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength

Negative sign shows that the upper sideband signal (lowest wavelength) arrives before the lower sideband (highest wavelength).

- A plot of material dispersion and wavelength is shown in Fig. 2.6.3

i

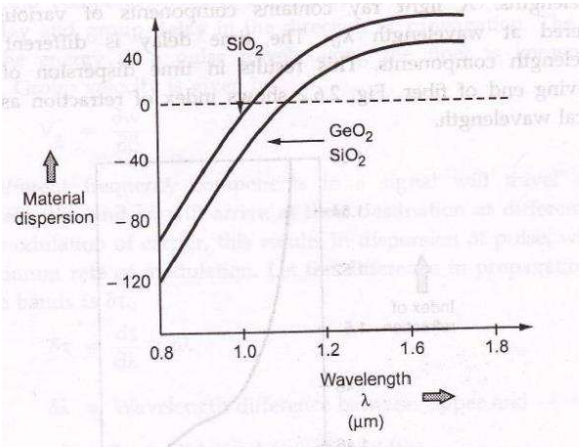

Fig. 2.6.3 Material dispersion as a function of λ

- The unit of dispersion is : ps/nm . km. The amount of material dispersion depends upon the chemical composition of glass.

Example 2.6.1 : An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion? **[Jan./Feb.-2007, 3 Marks]**

Solution : Given : $\lambda = 850$ nm

$\sigma = 45$ nm

R.M.S pulse broadening due to material dispersion is given by,

$$\sigma_m = \sigma LM$$

Considering length $L = 1$ metre

$$\boxed{\text{Material dispersion constant } D_{mat} = \frac{-\lambda}{c} \cdot \frac{d^2n}{d\lambda^2}}$$

For LED source operating at 850 nm, $\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = 0.025$

$$\therefore \quad M = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = \frac{1}{(3 \times 10^5)(850)} \times 0.025$$

$$M = 9.8 \text{ ps/nm/km}$$

$$\therefore \quad \sigma_m = 45 \times 1 \times 9.8 = 441 \text{ ps/km}$$

σ_m = **441 ns/km** **… Ans.**

Example 2.6.2 : What is the pulse spreading when a laser diode having a 2 nm spectral width is used? Find the the material-dispersion-induced pulse spreading at 1550 nm for an LED with a 75 nm spectral width **[Jan./Feb.-2007, 7 Marks]**

Solutions : Given : λ = 2 nm

σ = 75

$$\boxed{D_{mat} = \frac{1}{c\lambda}\left|\lambda^2 . \frac{d^2n}{d\lambda^2}\right|}$$

$$D_{mat} = \frac{1}{(3 \text{ x } 10^5) \text{ x } 2} \text{ x } 0.03 = 50 \text{ ps/nm/km}$$

σ_m = 2 x 1 x 50 = **100 ns/km** **… Ans.**

For LED $$D_{mat} = \frac{0.025}{(3 \text{ x } 10^5) \text{ x } 1550} = 53.76 \text{ ps nm}^{-1}\text{km}^{-1}$$

σ_m = 75 x 1 x 53.76

σ_m = **4.03 ns/km** **… Ans.**

Waveguide Dispersion

- Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a 'drag' effect between the core and cladding portions of the power.
- Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion.
- The group delay (τ_{wg}) arising due to waveguide dispersion.

$$(\tau_{wg}) = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(kb)}{dk}\right] \quad \text{… (2.6.5)}$$

Where, b = Normalized propagation constant

k = 2π / λ (group velocity)

Normalized frequency V,

$$V = ka(n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$V = k\,a\,n_2\sqrt{2\Delta}\ \text{(For small } \Delta\text{)}$$

∴

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\,\Delta\,\frac{d\,(V_b)}{dV}\right] \quad \ldots (2.6.6)$$

The second term $\frac{d(V_b)}{dV}$ is waveguide dispersion and is mode dependent term..

- As frequency is a function of wavelength, the group velocity of the energy varies with frequency. The produces additional losses (waveguide dispersion). The propagation constant (b) varies with wavelength, the causes of which are independent of material dispersion.

Chromatic Dispersion

- The combination of material dispersion and waveguide dispersion is called chromatic dispersion. These losses primarily concern the spectral width of transmitter and choice of correct wavelength.
- A graph of effective refractive index against wavelength illustrates the effects of material, chromatic and waveguide dispersion.

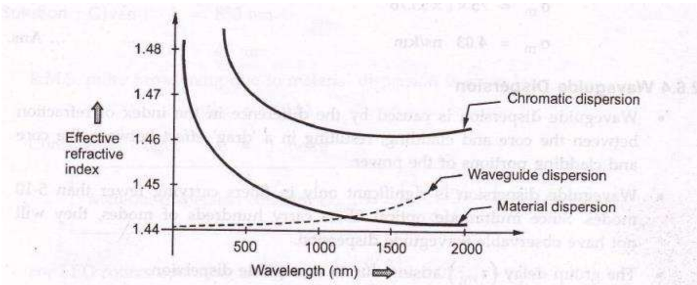

Fig. 2.6.4 Graph of effective refractive index against wavelength showing effects of chromatic, waveguide and material dispersion

- Material dispersion and waveguide dispersion effects vary in vary in opposite senses as the wavelength increased, but at an optimum wavelength around 1300 nm, two effects almost cancel each other and chromatic dispersion is at minimum. Attenuation is therefore also at minimum and makes 1300 nm a highly attractive operating wavelength.

Modal Dispersion

- As only a certain number of modes can propagate down the fiber, each of these modes carries the modulation signal and each one is incident on the boundary at a different angle, they will each have their own individual propagation times. The net effect is spreading of pulse, this form o dispersion is called modal dispersion.
- Modal dispersion takes place in multimode fibers. It is moderately present in graded index fibers and almost eliminated in single mode step index fibers.
- Modal dispersion is given by,

$$\boxed{\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right)}$$

where Δt_{modal} = Dispersion

n_1 = Core refractive index

Z = Total fiber length

c = Velocity of light in air

Δ = Fractional refractive index $\left(\frac{n_1 - n_2}{n_1}\right)$

Putting $\Delta = \frac{(NA^2)Z}{2n_1 c}$ in above equation

$$\boxed{\Delta t_{modal} = \frac{(NA^2)Z}{2n_1\ c}}$$

- The modal dispersion Δt_{modal} describes the optical pulse spreading due to modal effects optical pulse width can be converted to electrical rise time through the relationship.

$$t_{r\ mod} = 0.44\ (\Delta t_{modal})\pi r^2$$

Signal distortion in Single Mode Fibers

- The pulse spreading σ_{wg} over range of wavelengths can be obtained from derivative of group delay with respect to λ.

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

$$= L\left|D_{wg}(\lambda)\right|\sigma_\lambda$$

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

$$= \frac{n_2 L\Delta\sigma_\sigma}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right] \qquad \ldots (2.6.7)$$

where, $$\boxed{D_{wg}(\lambda) = \frac{-n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]} \qquad \ldots (2.6.8)$$

- This is the equation for waveguide dispersion for unit length.

Example 2.6.3 : For a single mode fiber $n_2 = 1.48$ and $\Delta = 0.2$ % operating at A = 1320 nm, compute the waveguide dispersion if $V.\frac{d^2(Vb)}{dv^2} = 0.26$.

Solution : $n_2 = 1.48$

$\Delta = 0.2$

$\lambda = 1320$ nm

Waveguide dispersion is given by,

$$\boxed{D_{wg}(\lambda) = \frac{-n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]}$$

$$= \frac{-1.48 \text{ x } 0.2}{3 \text{ x } 10^5 \text{ x } 1320}[0.20]$$

= -1.943 picosec/nm . km.

Higher Order Dispersion

- Higher order dispersive effective effects are governed by dispersion slope S.

$$S = \frac{dD}{d\lambda}$$

where, D is total dispersion.

Also, $$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{4\pi c}{\lambda^3}\right)\beta_2$$

where,

β_2 and β_3 are second and third order dispersion parameters.

- Dispersion slope S plays an important role in designing WDM system

Dispersion Induced Limitations

- The extent of pulse broadening depends on the width and the shape of input pulses. The pulse broadening is studied with the help of wave equation.

Basic Propagation Equation

- The basic propagation equation which governs pulse evolution in a single mode fiber is given by,

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \cdot \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = 0$$

where,

β_1, β_2 and β_3 are different dispersion parameters.

Chirped Gaussian Pulses

- A pulse is said to b e chirped if its carrier frequency changes with time.
- For a Gaussian spectrum having spectral width σ_ω, the pulse broadening factor is given by,

$$\frac{\sigma^2}{\sigma_0^2} = \left(1 + \frac{C\beta_2 L}{2\sigma_2^2}\right)^2 + (1 + V_\omega^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1 + C + V_\omega^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2\sigma_0^3}}\right)\pi r^2$$

where, $V_\omega = 2\sigma_\omega \sigma_0$

Limitations of Bit Rate

- The limiting bit rate is given by,

$$4B\,\sigma \leq 1$$

- The condition relating bit rate-distance product (BL) and dispersion (D) is given by,

$$BL\ |D|\sigma_\lambda \leq \frac{1}{4}$$

$$BL\ |S|\sigma_\lambda^2 \leq \frac{1}{\sqrt{8}}$$

where, S is dispersion slope.

- Limiting bit rate a single mode fibers as a function of fiber length for σ_λ = 0, a and 5nm is shown in fig. 2.6.5.

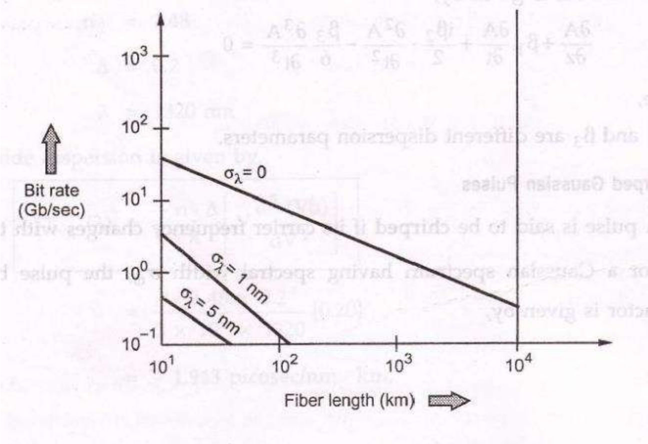

Fig. 2.6.5 Dependence of bit rate on fiber length

Polarization Mode Dispersion (PMD)

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

Pulse Broadening in GI Fibers

- The core refractive index varies radially in case of graded index fibers, hence it supports multimode propagation with a low intermodal delay distortion and high data rate over long distance is possible. The higher order modes travelling in outer regions of the core, will travel faster than the lower order modes travelling in high refractive index region. If the index profile is carefully controlled, then the transit times of the individual modes will be identical, so eliminating modal dispersion.
- The r.m.s pulse broadening is given as :

$$\sigma = \left(\sigma^2_{\text{intermodal}} + \sigma^2_{\text{intermodal}}\right)^{1/2} \quad \ldots (2.7.1)$$

where,

$\sigma_{\text{intermodal}}$ – R.M.S pulse width due to intermodal delay distortion.

$\sigma_{\text{intermodal}}$ – R.M.S pulse width resulting from pulse broadening within each mode.

- The intermodal delay and pulse broadening are related by expression given by Personick.

$$\sigma_{\text{intermodal}} = \left(\langle\tau_g^2\rangle - \langle\tau_g\rangle^2\right)^{1/2} \quad \ldots (2.7.2)$$

Where τ_g is group delay.

From this the expression for intermodal pulse broadening is given as:

$$\propto_{\text{intermodal}} = \frac{LN_1\Delta}{2c} \cdot \frac{\propto}{\propto + 1}\left(\frac{\propto + 2}{3 \propto + 2}\right)^{1/2} \text{x}$$

$$\left[c_1^2 + \frac{4c_1c_2(\propto+1)}{2\propto+1} + \frac{16\Delta^2 c_2^2(\propto+1)^2}{(5\propto+2)(3\propto+2)}\right]^{1/2} \quad \ldots (2.7.3)$$

$$c_1 = \frac{\propto - 2 - E}{\propto + 2} \; and \; c_2 = \frac{3 \propto - 2 - 2c}{2(\propto + 2)}$$

- The intramodal pulse broadening is given as :

$$\sigma^2_{intramodal} = \left(\frac{\sigma\lambda}{\lambda}\right)^2 \left\langle\left(\lambda \frac{d\tau g}{d\lambda}\right)^2\right\rangle \quad \ldots (2.7.4)$$

Where σ_λ is spectral width of optical source.

Solving the expression gives :

$$\sigma^2_{intramodal} = \frac{L}{c} \cdot \frac{\sigma\lambda}{\lambda}\left[\left(-\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right)^2 - N_1 c_1 \Delta\right.$$

$$\left.\left(2\lambda^2 \frac{d^2 n_1}{d\lambda^2} \cdot \frac{\propto}{\propto+1} - N_1 c_1 \Delta \frac{4\propto^2}{(\propto+2)(3\propto+2)}\right)\right]^{1/2} \quad \ldots (2.7.5)$$