18PYB101J MODULE-5 LECTURE 14

- **Types of optical fibre**
- **Optical fibre based on mode types**
- **Losses in Fiber optics**

Types of optical fibers

Optical fibers are classified based on

- Material
- Number of modes
- Refractive index profile

Optical fibers based on material

Optical fibers are made up of materials like silica and plastic. The basic optical fiber material must have the following properties:

(i) Efficient guide for the light waves

(ii) Low scattering losses

(iii) The absorption, attenuation and dispersion of optical energy must be low.

Based on the material used for fabrication, they are classified into two types:

- Glass fibers and
- Plastic fibers

Glass fibers

- The glass fibers are generally fabricated by fusing mixtures of metal oxides and silica glasses.
- Silica has a refractive index of 1.458 at 850 nm. To produce two similar materials having slightly different indices of refraction for the core and cladding, either fluorine or various oxides such as B_2O_3, GeO_2 or P_2O_3 are added to silica.
- **Examples:**
    - SiO_2 core; P_2O_3 – SiO_2 cladding
    - GeO_2 – SiO_2 core; SiO_2 cladding
    - P_2O_5 – SiO_2 core; SiO_2 cladding

Plastic fibers

- The plastic fibers are typically made of plastics and are of low cost.
- Although they exhibit considerably greater signal attenuation than glass fibers, the plastic fibers can be handled without special care due to its toughness and durability.
- Due to its high refractive index differences between the core and cladding materials, plastic fibers yield high numerical aperture and large angle of acceptance.

Examples:

- A polymethyl methacrylate core ($n1$ = 1.59) and a cladding made of its co-polymer ($n2$ = 1.40).
  - A polysterene core ($n1$ = 1.60) and a methylmetha crylate cladding ($n1$ = 1.49).

Optical fibers based on modes or mode types

- Mode is the one which describes the nature of propagation of electromagnetic waves in a wave guide.
- i.e. it is the allowed direction whose associated angles satisfy the conditions for total internal reflection and constructive interference.
- Based on the number of modes that propagates through the optical fiber, they are classified as:
  - Single mode fibers
  - Multi mode fibers

Single mode fibers

- In a fiber, if only one mode is transmitted through it, then it is said to be a single mode fiber.
- A typical single mode fiber may have a core radius of 3 μm and a numerical aperture of 0.1 at a wavelength of 0.8 μm.
- The condition for the single mode operation is given by the V number of the fiber which is defined as $$V = \frac{2\pi n_1 a\left(\sqrt{2\Delta}\right)}{\lambda}$$ such that $V \leq 2.405$.
- Here, n_1 = refractive index of the core; a = radius of the core; λ = wavelength of the light propagating through the fiber; Δ = relative refractive indices difference.

The single mode fiber has the following characteristics:

- Only one path is available.
- V-number is less than 2.405
- Core diameter is small
- No dispersion
- Higher band width (1000 MHz)
- Used for long haul communication
- Fabrication is difficult and costly

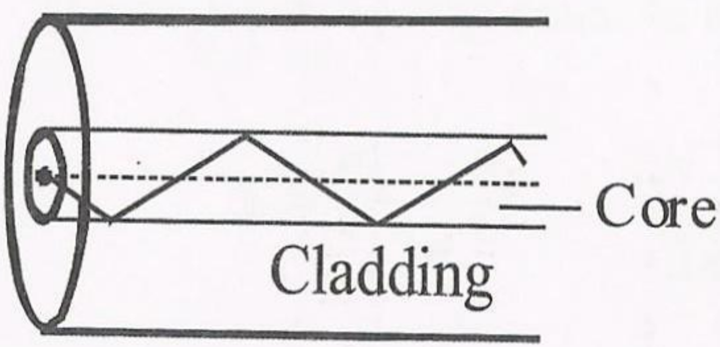


Fig. 3.26 Single mode fiber

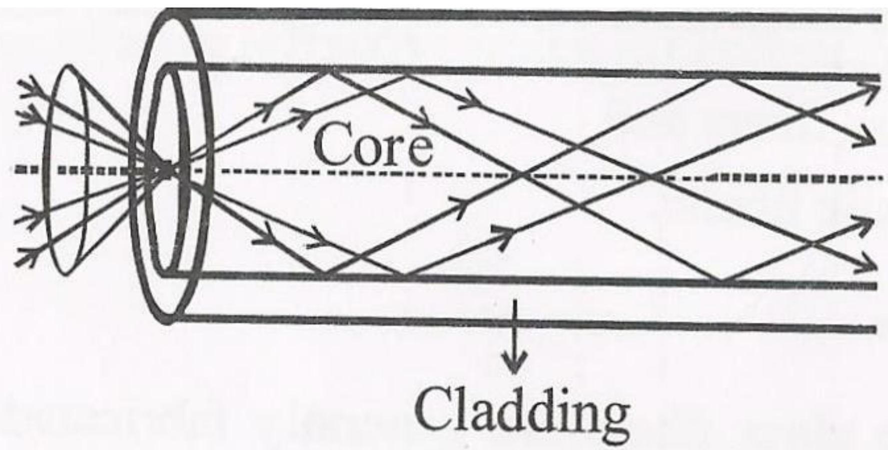


Fig. 3.27 Multi mode fiber.

Multi mode fibers

- If more than one mode is transmitted through optical fiber, then it is said to be a multimode fiber.
- The larger core radii of multimode fibers make it easier to launch optical power into the fiber and facilitate the end to end connection of similar powers.

Some of the basic properties of multimode optical fibers are listed below:

- More than one path is available
- V-number is greater than 2.405

- Core diameter is higher
- Higher dispersion
- Lower bandwidth (50MHz)
- Used for short distance communication
- Fabrication is less difficult and not costly

Optical fibers based on refractive index profile

Based on the refractive index profile of the core and cladding, the optical fibers are classified into two types:

- Step index fiber
- Graded index fiber.

Step index fiber

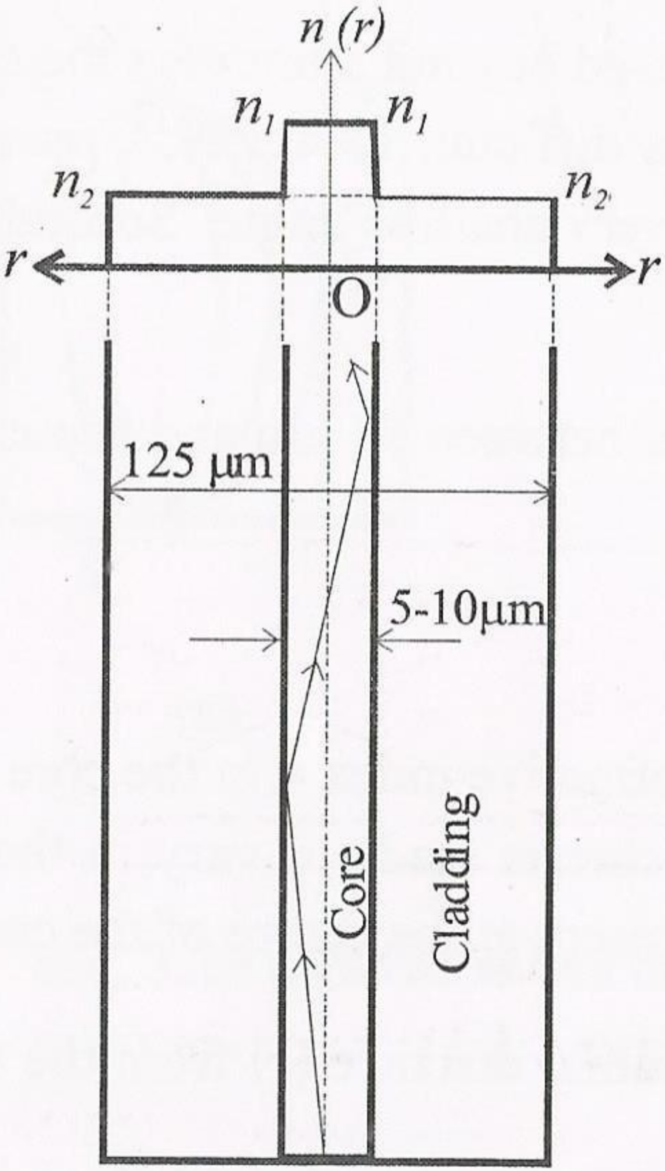
- In a step index fiber, the refractive index changes in a step fashion, from the centre of the fiber, the core, to the outer shell, the cladding.
- It is high in the core and lower in the cladding. The light in the fiber propagates by bouncing back and forth from core-cladding interface.
- The step index fibers propagate both single and multimode signals within the fiber core.
- The light rays propagating through it are in the form of meridinal rays which will cross the fiber core axis during every reflection at the core – cladding boundary and are propagating in a zig – zag manner.

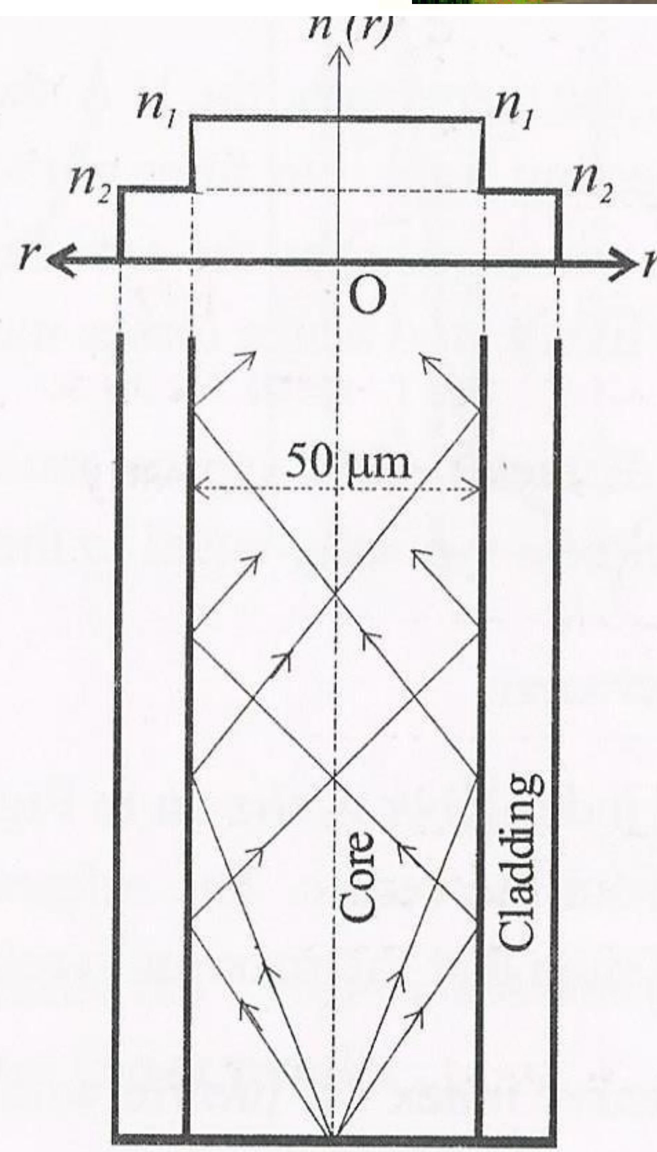
The refractive index (n) profile with reference to the radial distance (r) from the fiber axis is given as:

when $r = 0, \quad n(r) = n_1$

$$r < a, \quad n(r) = n_1$$

$$r \geq a, \quad n(r) = n_2$$


n (r)
n_1
n_1
n_2
n_2
r
r
O
125 μm
5-10μm
Core
Cladding


n (r)
n_1
n_1
n_2
n_2
r
r
O
50 μm
Core
Cladding

Step index single mode fibers

- The light energy in a single-mode fiber is concentrated in one mode only.
- This is accomplished by reducing Δ and or the core diameter to a point where the V is less than 2.4.
- In other words, the fiber is designed to have a V number between 0 and 2.4.
- This relatively small value means that the fiber radius and Δ, the relative refractive index difference, must be small.
- No intermodal dispersion exists in single mode fibers because only one mode exists.

- With careful choice of material, dimensions and λ, the total dispersion can be made extremely small, less than 0.1 ps /(km × nm), making this fiber suitable for use with high data rates.
- In a single-mode fiber, a part of the light propagates in the cladding.
- The cladding is thick and has low loss.
- Typically, for a core diameter of 10 μm, the cladding diameter is about 120 μm.
- Handling and manufacturing of single mode step index fiber is more difficult.

Step index multimode fibers

- A multimode step index fiber is shown.
- In such fibers light propagates in many modes.
- The total number of modes MN increases with increase in the numerical aperture.
- For a larger number of modes, MN can be approximated by

$$M_N = \frac{V^2}{2} = 4.9\left[\frac{dn_1\sqrt{2\Delta}}{\lambda}\right]^2$$

where d = diameter of the core of the fiber and V = V – number or normalized frequency.

The normalized frequency V is a relation among the fiber size, the refractive indices and the wavelength. V is the normalized frequency or simply the V number and is given by

$$V = \left(\frac{2\pi a}{\lambda}\right) \times \mathrm{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times n_1 \times (2\Delta)^{\frac{1}{2}}$$

where a is the fiber core radius, λ is the operating wavelength, $n1$ the core refractive index and Δ the relative refractive index difference.

To reduce the dispersion, the N.A should not be decreased beyond a limit for the following reasons:

- First, injecting light into fiber with low N.A becomes difficult. Lower N.A means lower acceptance angle, which requires the entering light to have a very shallow angle.
- Second, leakage of energy is more likely, and hence losses increase.

The core diameter of the typical multimode fiber varies between 50 µm and about 200 µm, with cladding thickness typically equal to the core radius.

Graded index fibers

- A graded index fiber is shown in Fig.3.30. Here, the refractive index *n* in the core varies as we move away from the centre.
- The refractive index of the core is made to vary in the form of parabolic manner such that the maximum refractive index is present at the centre of the core.
- The refractive index (*n*) profile with reference to the radial distance (*r*) from the fiber axis is given as:

when $r = 0, n(r) = n_1$

$$r < a, n(r) = n_1\left[1-\left(2\Delta\left[\frac{r}{a}\right]^2\right)\right]^{\frac{1}{2}}$$

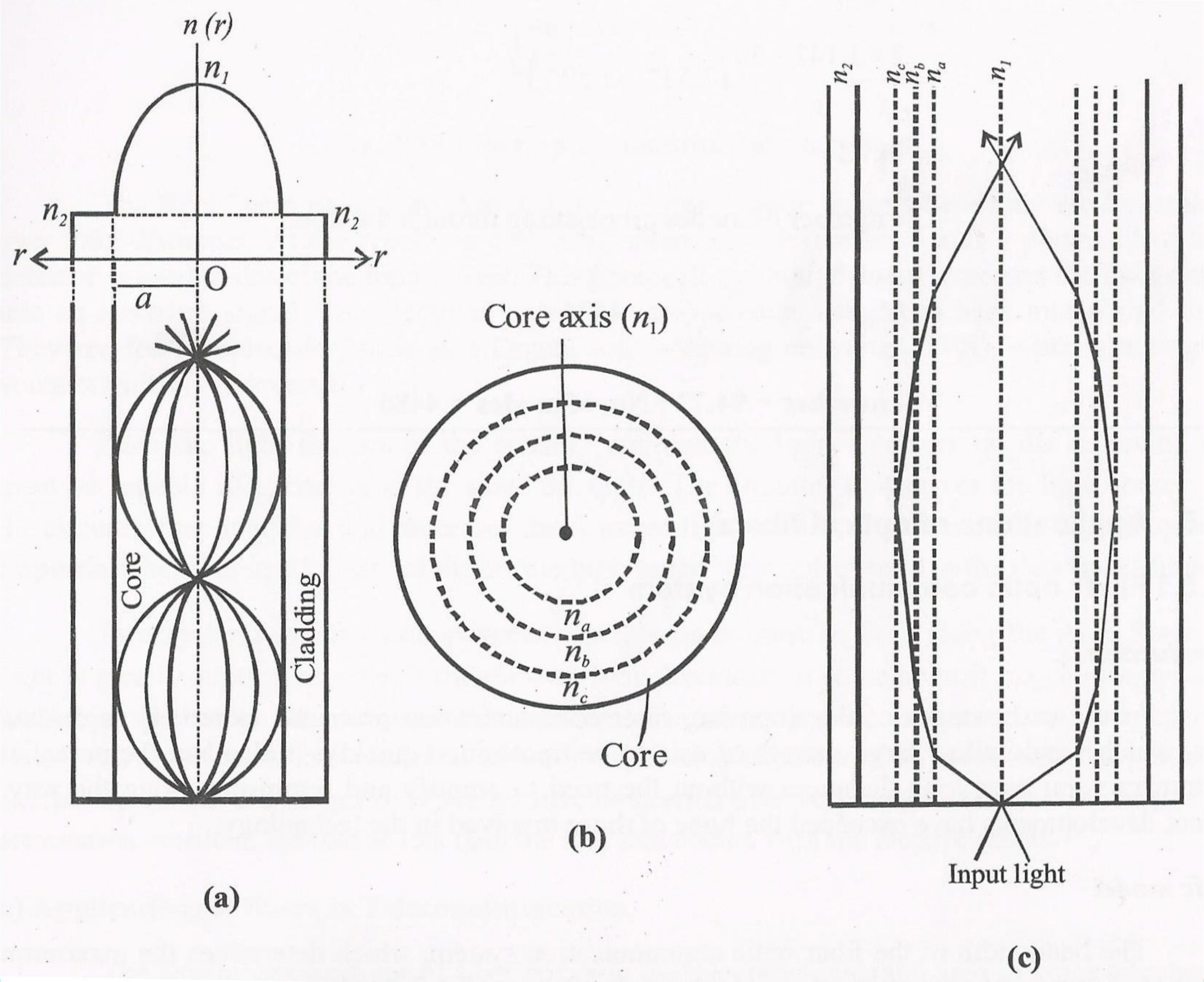
$$r \geq a, n(r) = n_2 = n_1(1-2\Delta)^{\frac{1}{2}}$$

At the fiber centre we have *n1*; at the cladding we have *n2*; and in between we have *n(r)*, where n is the function of the particular radius as shown in Fig. simulates the change in *n* in a stepwise manner.

- Each dashed circle represents a different refractive index, decreasing as we move away from the fiber center.
- A ray incident on these boundaries between $n_a - n_b$, $n_b - n_c$ etc., is refracted.
- Eventually at n_2 the ray is turned around and totally reflected.
- This continuous refraction yields the ray tracings as shown in Fig.

- The light rays will be propagated in the form skew rays (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical or spiral manner.

- The effective acceptance angle of the graded-index fiber is somewhat less than that of an equivalent step-index fiber. This makes coupling fiber to the light source more difficult.



(a) index profile (b) stepwise index profile (c) ray tracing in stepwise index profile

The number of modes in a graded-index fiber is about half that in a similar step-index fiber,

$$M_N = \frac{V^2}{4}$$

The lower the number of modes in the graded-index fiber results in lower dispersion than is found in the step-index fiber. For the graded-index fiber the dispersion is approximately (Here L = Length of the fiber; c = velocity of light).

$$\Delta t = \frac{L n_1 \Delta^2}{8c}$$

(Here L = Length of the fiber; c = velocity of light).

- The size of the graded-index fiber is about the same as the step-index fiber. The manufacture of graded-index fiber is more complex. It is more difficult to control the refractive index well enough to produce accurately the variations needed for the desired index profile.

Worked Example

Calculate the V – number and number of modes propagating through the fiber having a = 50 μm, n1 = 1. 53, n2 = 1.50 and λ = 1μm.

$n1 = 1.53 \quad ; \quad n2 = 1.50; \lambda = 1\mu m.$

$$\text{V - Number} = \left(\frac{2\pi a}{\lambda}\right) \times \text{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times (n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$= \frac{2 \times 3.142 \times 50}{1}\left(1.53^2 - 1.50^2\right)^{\frac{1}{2}}$$

$$= 94.72$$

The number of modes propagating through the fiber $M_N = \frac{V^2}{2} = \frac{94.72^2}{2} = 4486$

V – number = 94.72 ; No. of modes = 4486

Find the core radius necessary for single mode operation at 850 nmof step index fiber with n_1 = 1.480 and n_2 = 1.465.

Hint: V – number = 2.405 (for single mode fiber)

$$V = \left(\frac{2\pi a}{\lambda}\right) \times \mathrm{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times n_1 \times (2\Delta)^{\frac{1}{2}}$$

a= core radius = 1.554 μm

Losses in Fiber optics

Losses in Fiber Optics

- **Attenuation**
- **Bend loss-micro, macro**
- **Absorption**
- **Dispersion-Intermodal, Intramodal**
- **Scattering losses-Linear, Non linear**

Attenuation

- Attenuation means loss of light energy as the light pulse travels from one end of the cable to the other.
- It is also called as signal loss or fiber loss.
- It also decides the number of repeaters required between transmitter and receiver.
- Attenuation is directly proportional to the length of the cable.

Attenuation

- Attenuation is defined as the ratio of optical output power to the input power in the fiber of length L.

  $\alpha = 10 \log_{10} P_i/P_o$ [in db/km]

  where, P_i= Input Power

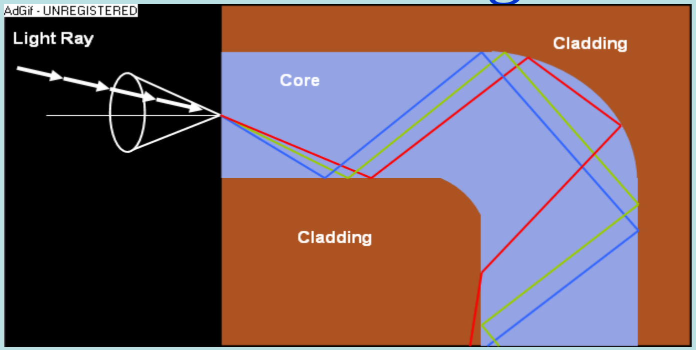
  P_o= Output Power, α is attenuation constant

The various losses in the cable are due to

- – Bending
- – Absorption
- – Dispersion
- – Scattering

Bending losses

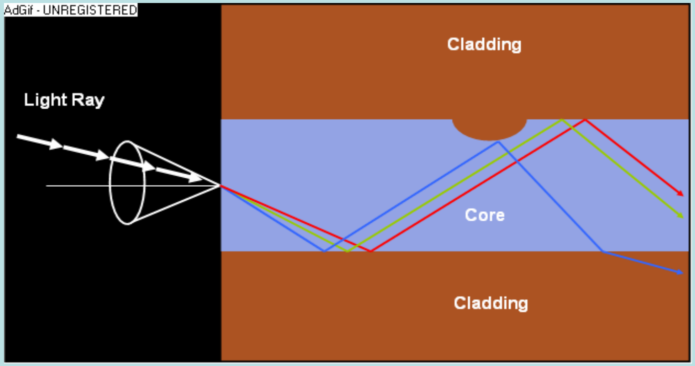
- The loss which exists when an optical fiber undergoes bending is called bending losses.



There are two types of bending

i) Macroscopic bending

Bending in which complete fiber undergoes bends which causes certain modes not to be reflected and therefore causes loss to the cladding.



ii) Microscopic Bending

Either the core or cladding undergoes slight bends at its surface. It causes light to be reflected at angles when there is no further reflection.

Absorption Loss

- Absorption of light energy due to heating of ion impurities results in dimming of light at the end of the fiber.

  There are two types of absorption:

  1. Intrinsic Absorption:

  – Caused by the interaction with one or more components of the glass

  – Occurs when photon interacts with an electron in the valence band & excites it to a higher energy level near the UV region.

  2. Extrinsic Absorption

  – Also called impurity absorption.

  – Results from the presence of transition metal ions like iron, chromium, cobalt, copper & from OH ions i.e. from water.

Dispersion Loss

- As an optical signal travels along the fiber, it becomes increasingly distorted. This distortion is a sequence of intermodal and intramodal dispersion.

Two types of dispersion are:

1. Intermodal Dispersion:
   - Pulse broadening due to intermodal dispersion results from the propagation delay differences between modes within a multimode fiber.
2. Intramodal Dispersion:

It is the pulse spreading that occurs within a single mode.

- Material Dispersion
- Waveguide Dispersion

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Dispersion Loss

- Material Dispersion:

  Also known as spectral dispersion or chromatic dispersion.

  Results because of variation due to Refractive Index of core as a function of wavelength, because of which pulse spreading occurs even when different wavelengths follow the same path.

- Waveguide Dispersion:

  Whenever any optical signal is passed through the optical fiber, practically 80% of optical power is confined to core & rest 20% optical power into cladding.

Scattering Losses

- It occurs due to microscopic variations in the material density, compositional fluctuations, structural in homogeneities and manufacturing defects.
- Linear Scattering

    Rayleigh Scattering losses

    Mie Scattering Losses

    Waveguide Scattering Losses

- Non-linear Scattering

    Stimulated Brillouin Scattering(SBS)

    Stimulated Raman Scattering(SRS)

Linear Scattering

a) Rayleigh Scattering Losses:

- These losses are due to microscopic variation in the material of the fiber.
- Unequal distribution of molecular densities or atomic densities leads to Rayleigh Scattering losses
- Glass is made up of several acids like SiO2, P2O5,etc. compositions, fluctuations can occur because of these several oxides which rise to Rayleigh scattering losses

Linear Scattering

b) Mie Scattering Losses:

These losses results from the compositional fluctuations & Structural inhomogenerics & defects created during fiber fabrications, causes the light to scatter outside the fiber.

c) Waveguide Scattering Losses:

It is a result of variation in the core diameter, imperfections of The core cladding interface, change in RI of either core or cladding.

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Non-Linear Scattering

a) SBS Scattering:

Stimulated Brillouin Scattering(SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber.

b) SRS Scattering:

Stimulated Raman Scattering is similar to SBS except that high frequency optical phonon rather than acoustic phonon is generated in scattering processes.

Phonon:

Collective excitation in a periodic arrangement of atoms or molecules in solid.