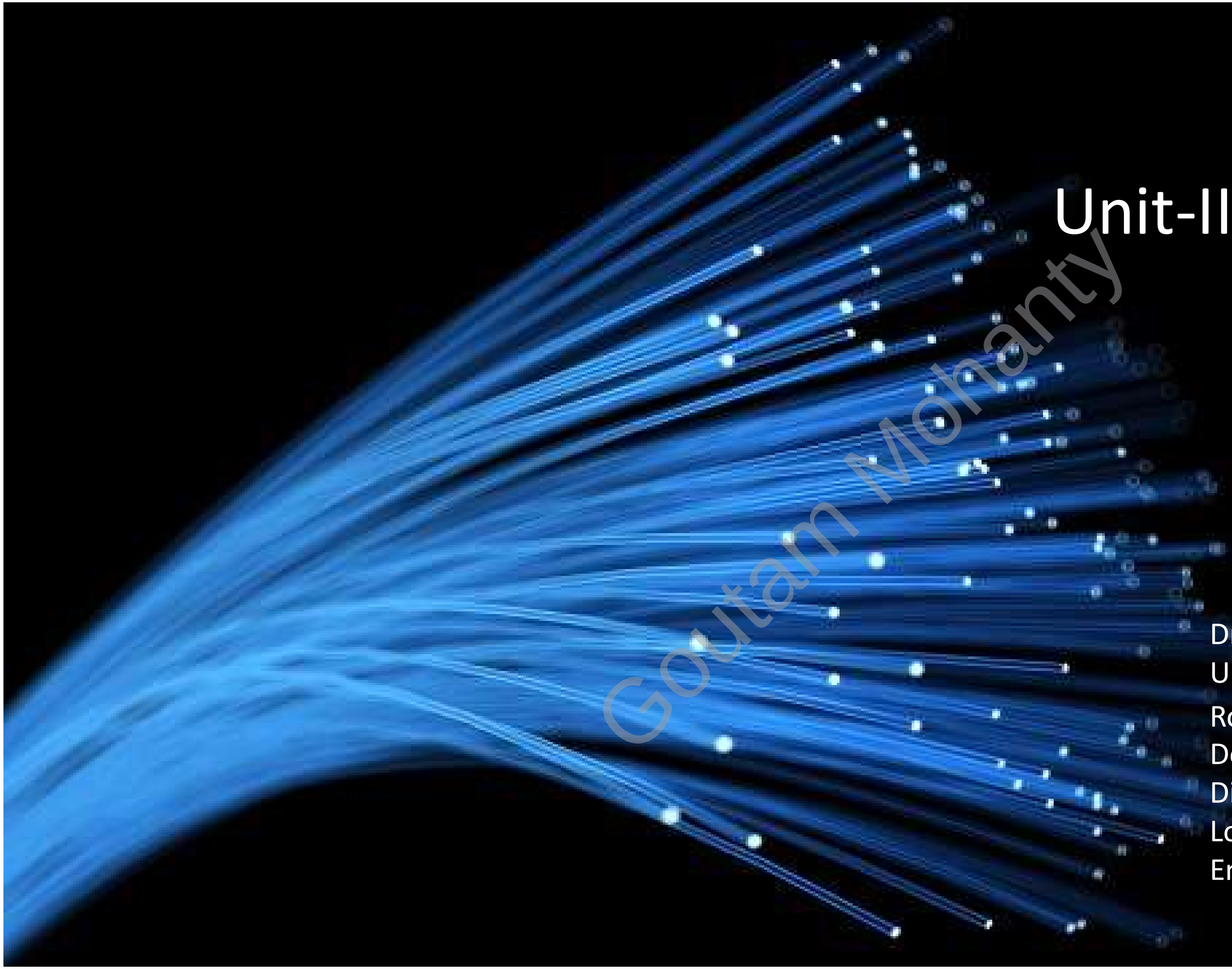

Unit-III: Optical Fiber

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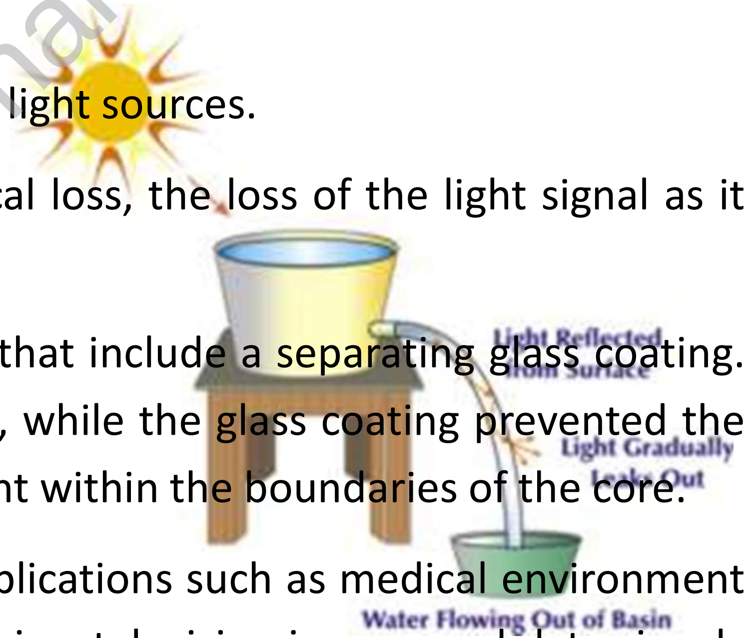
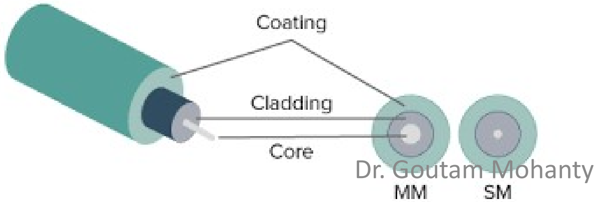
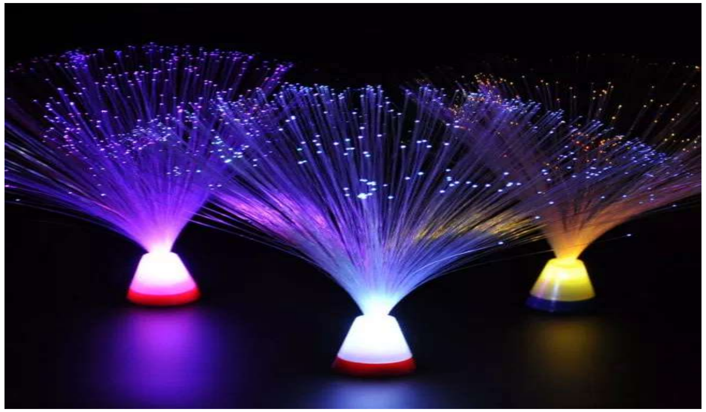
Introduction

- In 1870, John Tyndall demonstrated light can be guided along curved stream of water.
- During 1930, other ideas were developed with this fiber optic such as transmitting images through a fiber.
- During the 1960s, Lasers were introduced as efficient light sources.
- In 1970s, All glass fibers experienced excessive optical loss, the loss of the light signal as it traveled the fiber limiting transmission distance.
- This motivated the scientists to develop glass fibers that include a separating glass coating. The innermost region was used to transmit the light, while the glass coating prevented the light from leaking out of the core by reflecting the light within the boundaries of the core.
- Today, you can find fiber optics used in variety of applications such as medical environment to the broadcasting industry. It is used to transmit voice, television images and data signals through small flexible threads of glass or plastic.



- An optical fiber is a very thin, flexible and cylindrical shape of structure which allow to guide light waves through them. It is just like a human hair.
- The THREE principal section of optical fiber are:
  - ✓ Core – inner most section made of glass (or silica, SiO_2) or plastic
  - ✓ Cladding- surrounding of core section made of glass or plastic
  - ✓ Jacket- outermost section made of plastic or polymer or others which protects from abrasion, moisture, mechanical shocks, or any hazardous environment.
- Most optical fibers used in communication have dimension 0.25mm to 0.5mm (including outer coating)
- The working of fiber optics is based on Total Internal Reflection(TIR) principle.





Total Internal Reflection

- When light travels from a medium with a higher refractive index to lower refractive index and it strikes the boundary at more than the critical angle all light will be reflected back to the incident medium. This phenomenon is called as total internal reflection(TIR)
- The angle at which the refraction angle is 90^0 and the refracted ray emerges parallel to the interface is called critical angle.

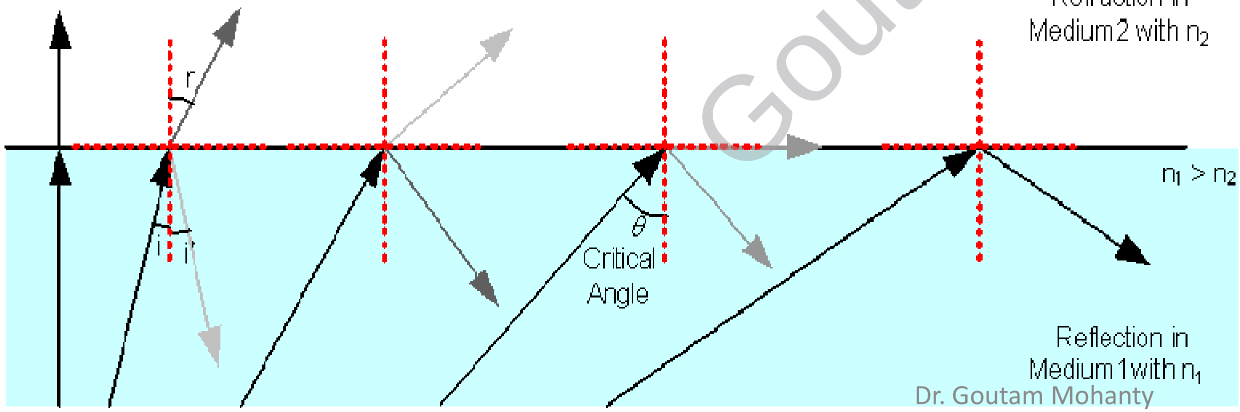
Condition for TIR:

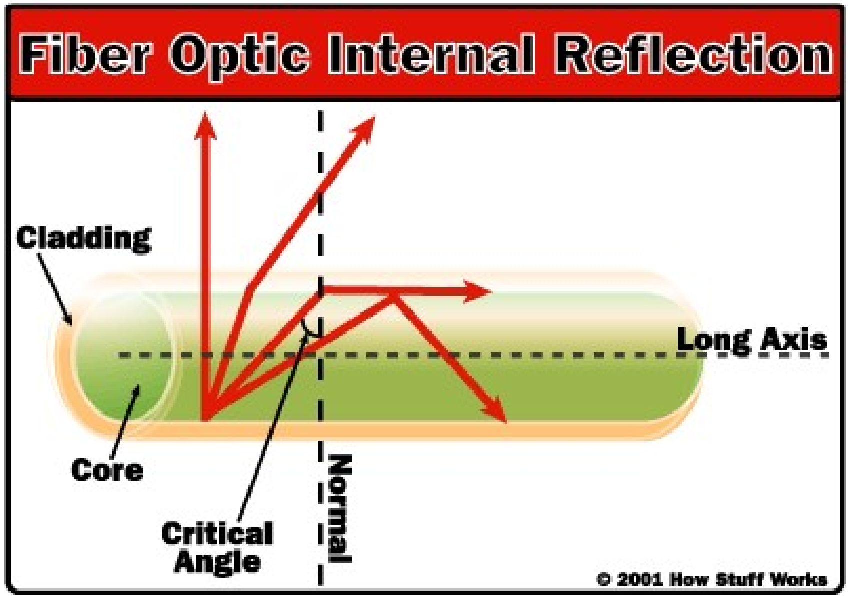
✓ RI of incident medium > RI of refracted medium

✓ Angle of incident > Critical angle

$$\boxed{\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}}$$

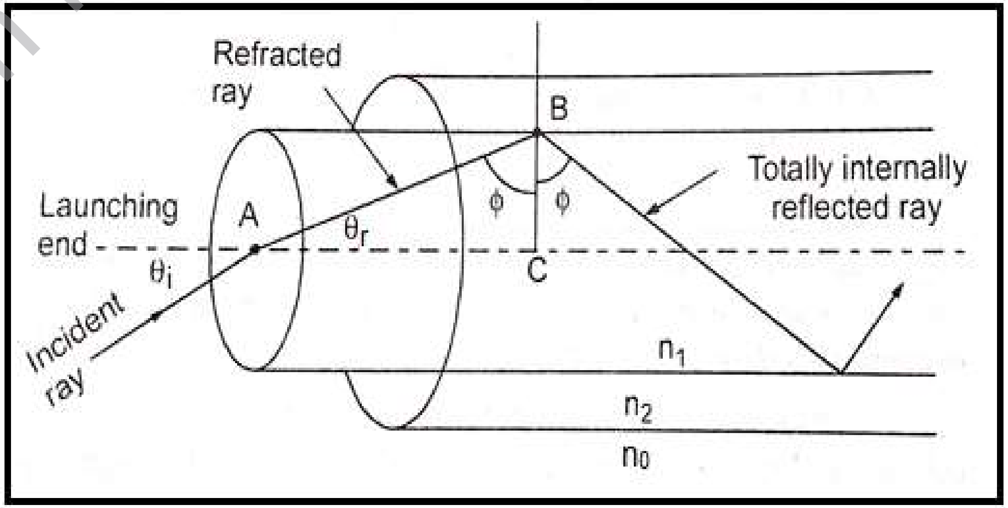
Snell's Law





Light propagation in Fiber

- Let us consider light propagation in an optical fibre. The end at which the light enters the fibre is called the launching end. Let the refracting index of the core be n_1 and the refractive index of the cladding be n_2 ($n_2 < n_1$). Let the outside medium from which the light is launched into the fibre have a refractive index n_0. Let a light ray enter the fibre at an angle θ_i to the axis of the fibre (shown in Figure). Let the refracted ray make an angle θ_r with the axis and strikes the core-cladding interface at an angle ϕ.
- If $\phi > \theta_c$ (critical angle), the ray undergoes total internal reflection at the interface. As long as the angle $\phi > \theta_c$ the light remains within the fibre.



- Applying Snell's Law to the launching face of the fibre, we get,

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0}$$

- From triangle ABC,
  we have $\sin\theta_r = \sin(90° - \phi) = \cos(\phi)$

$$\sin\theta_i = \sin\theta_r \frac{n_1}{n_0}$$

$$\sin\theta_i = \cos\phi . \frac{n_1}{n_0}$$

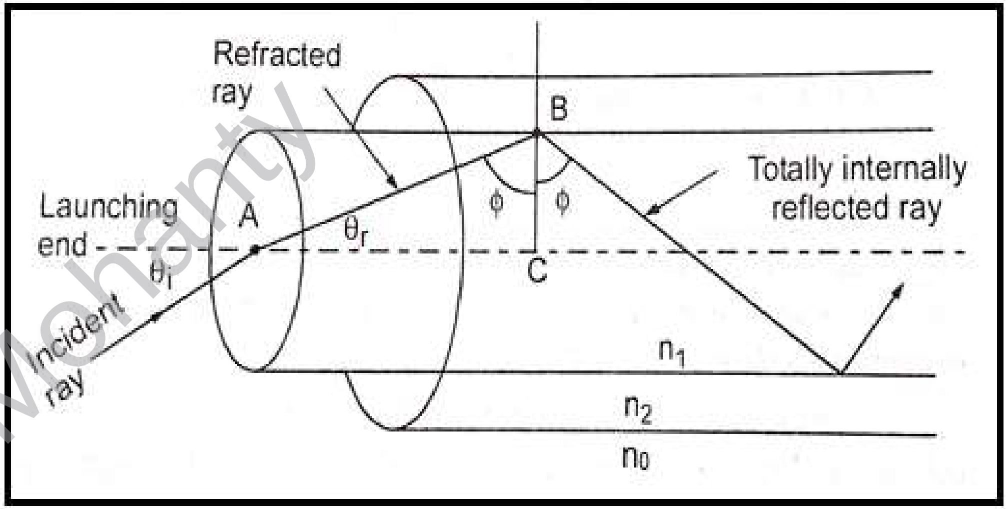
Light propagation in Fiber

- When $\phi = \theta_c$ (critical angle), $\theta_i = \theta_{max}$

- $sin\theta_{max} = \frac{n_1}{n_0} cos\theta_c$

- But $sin\theta_c = \frac{n_2}{n_1}$ and $cos\theta_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$

- Then $$\boxed{\sin\theta_{max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}}$$



- If $(n_1^2 - n_2^2)^{0.5} > n_0$, then for all values of θ_i TIR will occur.

- If $n_0 = 1$, the maximum value of $\sin\theta_i$ for a ray to be guided is given by,

$$\boxed{\sin\theta_m = \sqrt{{n_1}^2 - {n_2}^2}}$$

- Thus, $$\boxed{\theta_m = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2}}$$

- The angle θ_m, is called the **acceptance angle** of the fibre. Acceptance, angle may be defined as the maximum angle that a light ray can have relative to the axis of the fibre and propagates down the fibre.

- The light rays contained within the cone having a full angle $2\theta_m$, are accepted and transmitted along the fibre. This cone is therefore known as **acceptance cone**.

- **Fraction Refractive Index Change**: This parameter is defined as the ratio of the difference between the refractive indices of the core and the cladding to the refractive index of core. It is denoted by Δ and expressed as:

$$\boxed{\Delta = \frac{n_1 - n_2}{n_1}}$$

- Δ is always positive because refractive index of core is always greater than the refractive index of cladding for the total internal reflection condition.

Numerical Aperture:

- The Numerical aperture (NA) is defined as the sine of the acceptance angle. This angle is a measure of the light gathering power of the fibre. It is expressed as

$$\boxed{\mathrm{NA} = \sin\theta_m} \Rightarrow \boxed{\mathrm{NA} = \sqrt{{n_1}^2 - {n_2}^2} = n_1\sqrt{2\Delta}}$$

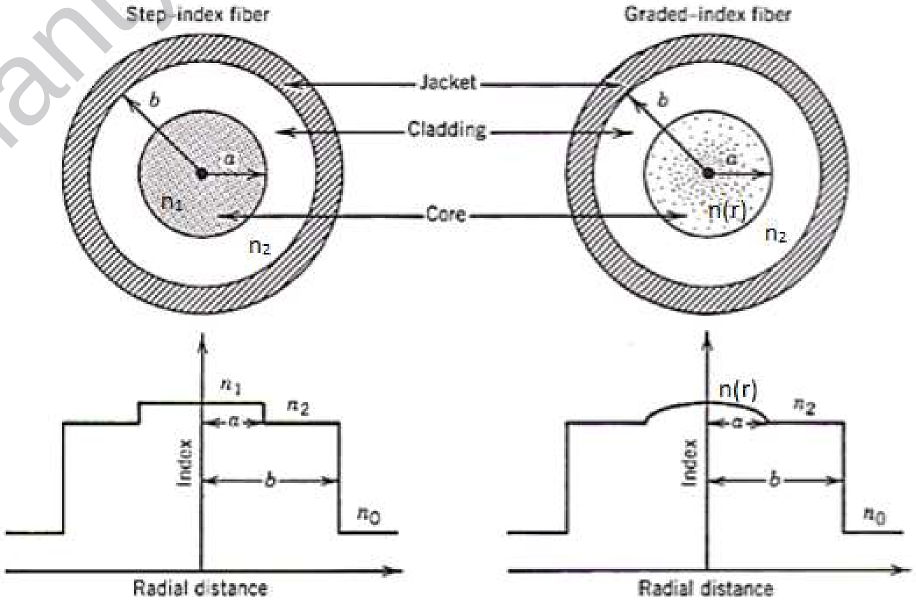
- Numerical aperture is a measure of the amount of light that can be accepted by a fibre, For a typical optical fibre n_2=1.458, Δ = 0.01 and the corresponding NA=0.2.

- Thus the fibre would accept light incident over a cone with a semi-angle $\sin^{-1}(0.2) = 11.5^0$ about the axis.

Classification based on RI:

Based on refractive index profile, optical fiber are TWO types:

- ✓ Step Index Optical Fiber: RI profile makes a step change at core-cladding interface and $n_1 > n_2$
- ✓ Graded Index Optical Fiber: RI of core is decreases with increasing radial distance from axis of core but RI of cladding is constant. $n_1 > n_2$



Cross section and refractive-index profile for step-index and graded-index

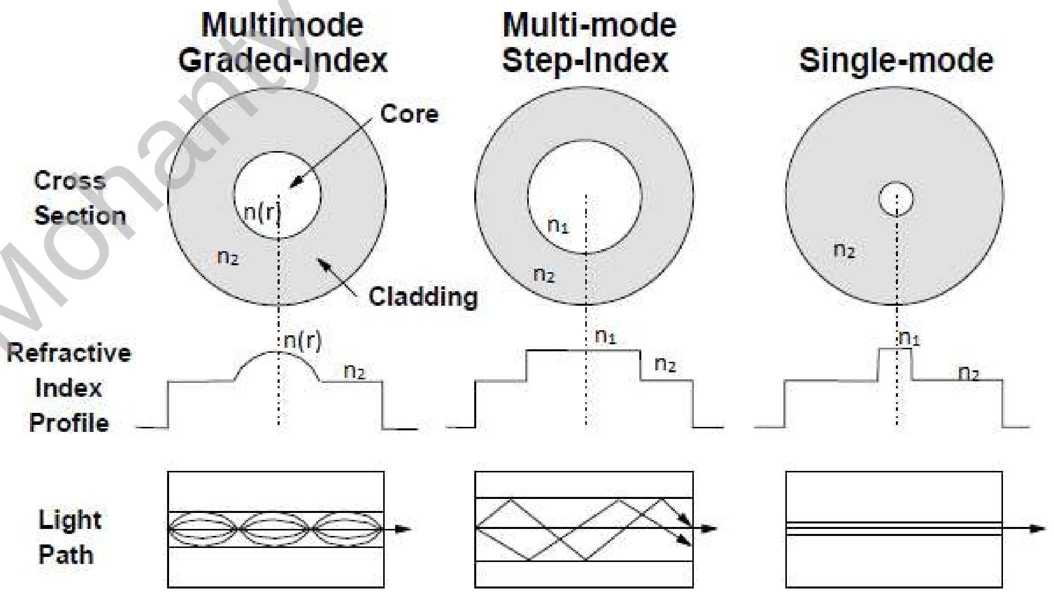
Classification based on Mode:

Based on modes, optical fibers are classified into TWO types:

- ✓ Single mode fiber(SMF)- supports only ONE propagation path because very small core diameter. Core diameter is about 8 μm-10 μm.
- ✓ Multimode fiber(MMF)- supports many propagation path because they have large core diameter. Core diameter is about 50 μm-100 μm.

❑ Multimode is again **TWO types**:

- Multimode step index fiber
- Multimode graded index fiber



Single mode fibre	Multimode fibre
1. Single-mode fibre sustains only one mode of propagation. 2. Small radii of single mode fibres make it difficult to launch optical power into the fibre. 3. Single mode fibres must generally be excited with laser diode (LD). 4. Single mode fibres are free from intra-modal dispersion. 5. Attenuation in single mode fibre is between 2 to 5 dB/km with a scattering limit of around 1 dB/km at a wavelength of 850 nm. 6. Single mode fibre is used for very long-haul communication. 7. Single mode fibre have higher bandwidth (> 500 MHz-km). 8. V-number for single mode fibre V< 2.405. 9. Single mode fibre is best designed for longer transmission distances making it suitable for long-distance telephony and multi-channel television broadcast system.	1. Multimode fibre can propagate hundreds of modes. 2. Large radii of-multimode fibres make it easier to launch optical power into the fibre 3. Light can be launched into a multimode fibre using a light emitting diode (LED). 4. Multimode fibres suffer intermodal dispersion 5. Attenuation in multimode step index fibre between 2.6 to 50 dB/km at a wavelength of 850 nm and in multimode graded index fibre is between 2 to 10 dB/km at a wavelength of 850nm 6. Multimode step index fibre is used for short-haul application and multimode graded index fibre is suited for medium haul application. 7. Bandwidth in multimode step index fibre is 6 to 50 MHz-km and in multimode graded index fibre is 800 MHz-km to 3 GHz-km 8. V-number for multimode fibre V>2.405. 9. MIultimode fibre is best designed for short transmission distances, and is stilted for use in LAN systems and video surveillance.

V-number:

- An optical fiber is characterized by one more important parameter, known as V-number which is more generally normalized frequency of the fiber. It is given by the relation:

$$\boxed{V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2}}$$

Where a is radius of the core and λ is free space wavelength.

- In terms of NA, it is given as,

$$\boxed{V = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi a}{\lambda} n_1\sqrt{2\Delta}}$$

- The max number of modes supported by step index fiber is $\boxed{N_{max} = \frac{V^2}{2}}$
- The max number of modes supported by graded index fiber is $\boxed{N_{max} = \frac{V^2}{4}}$
- For single mode fiber V < 2.405 and for multimode fiber V >2.405
- The wavelength correspond to the value V=2.405 is called as cut off wavelength of the fiber and is given by $\boxed{\lambda_c = \frac{\lambda V}{2.405}}$

Losses in Optical Fiber

Attenuation:

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

Def^{n}-. Attenuation is defined as the ratio of optical power output to the optical power input in the fiber , of length L.

$$\boxed{\alpha = \frac{10}{L}\, log_{10} \frac{P_i}{P_o} \text{ [in db/km]}}$$

(or)

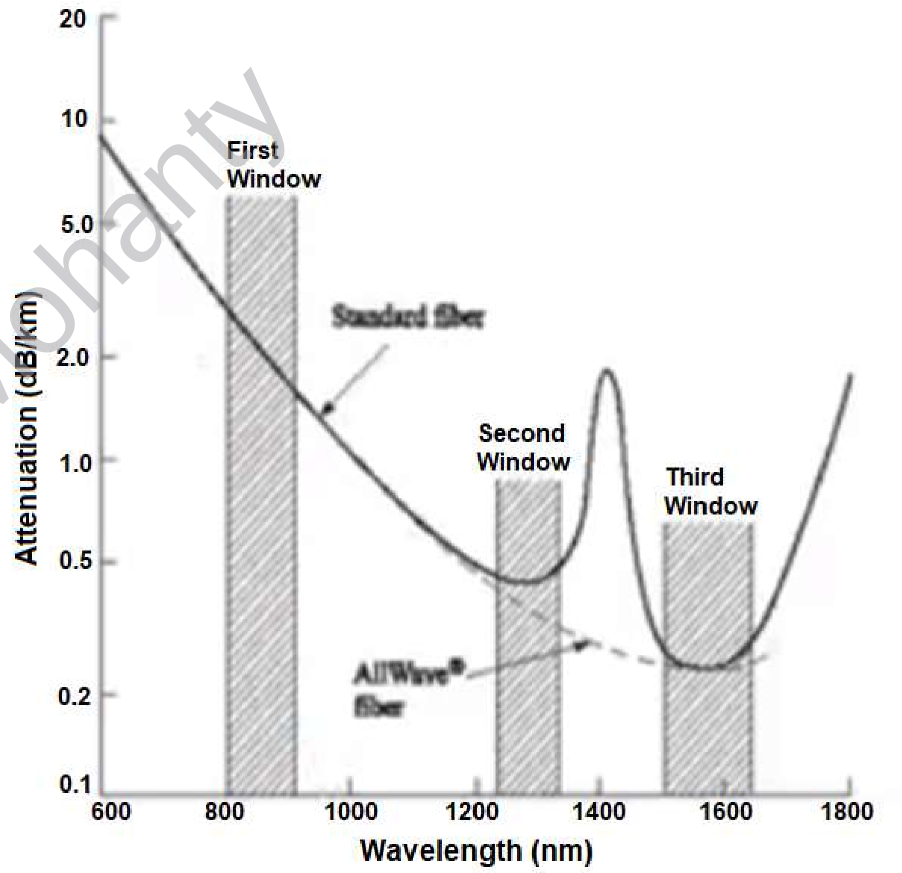
$$\boxed{\alpha = \frac{20}{L}\, log_{10} \frac{V_i}{V_o} \text{ [in db/km]}}$$

where, P_i= Input Power, P_o= Output Power and α = attenuation constant

Types of losses

The various losses in the cables are due to

- ➢ Absorption Loss
- ➢ Bending Loss
- ➢ Dispersion Loss
- ➢ Scattering Loss



ABSORPTION LOSS:

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

Two types:

- Intrinsic Absorption
- Extrinsic Absorption

1.Intrinsic Absorption:

- It is caused by the interaction with one or more components of the glass.
- It occurs when photon interacts with an electron in the valence band & excites it to a higher energy level near the UV region.

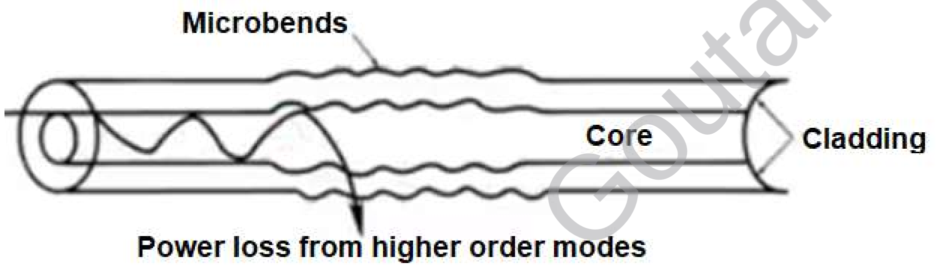
2.Extrinsic Absorption:

- It is also called impurity adsorption.
- Results from the presence of transition metal ions like iron, chromium, cobalt, copper and from OH ions i,.e in water.

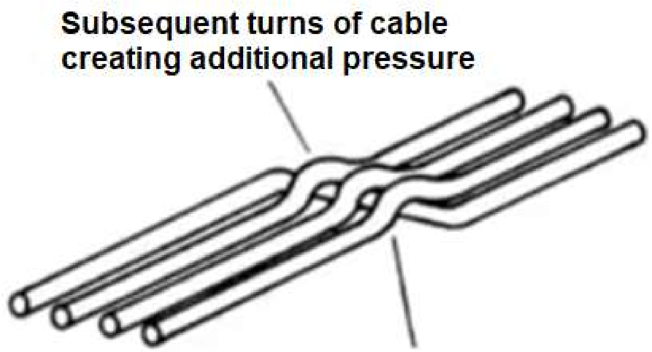
BENDING LOSS:

The loss which exists when an optical fiber undergoes bending is called bending losses. There are two types of bending:

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



(Microscopic bending)



(Macroscopic Bending)

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:

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. It is TWO types

✓ **Material Dispersion:**

- It is also known as spectral dispersion or chromatic dispersion. Results because of variation due to Refractive Index of core as a function 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 LOSS:

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

  1. Linear Scattering

  2. Non-linear Scattering

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 oxides like $Si0_2$, P_20_5,etc. compositions, fluctuations can occur because of these several oxides which rise to Rayleigh scattering losses.

B. Mie Scattering Losses:

- ✓ These losses results from the compositional fluctuations and structural in homogeneities & defects created during fiber fabrications, causes the light to 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.

NON LINEAR SCATTERING:

➢ SBS Scattering

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

$$P_B = 4.4\text{x } 10^{-3}\, d^2\, \lambda^2\, \alpha\, B \text{ watts}$$

where, λ = operating wavelength um,

d= fiber core diameter um

and B = source bandwidth in GHz

➢ SRS Scattering

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

$$P_R = 5.9\text{x}10^{-2}\, d^2\, \lambda\, \alpha \text{ dB watts}$$

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

Applications:

- Communication and broadcasting
- Healthcare industry
- Traffic control and security
- Military
- Sensor

Sample MCQ

If $F = x\hat{i} + y\hat{j} + zk$
then its divergence is __.

a. $\hat{i} + \hat{j} + \hat{k}$

b. 3

c. x + y + z

d. None

If V-number of the single mode step index fiber is 2.305, find the maximum number of supported guided mode ?

a. 4.5042

b. 2.6565

c. 1.6556

d. 1.2383

Dielectric are the substances which are

a. Conductor

b. Insulator

c. Semiconductor

d. None

The Stoke's theorem is

a. $\iint \vec{A}.\overrightarrow{dS} = \oint \vec{A}.\overrightarrow{dr}$

b. $\oint \vec{A}.\overrightarrow{dr} = \iint curl\, \vec{A}.\overrightarrow{dS}$

c. $\iint \vec{A}\,.\overrightarrow{dS} = \iiint div\, \vec{A}.dV$

d. $\iint \vec{A}\,.\overrightarrow{dS} = \iiint grad\, \vec{A}\, dV$

The ratio of Einstein Co-efficient A and B can be written as

a. (8πhc^3)/ν^3

b. (8πhc)/ν

c. (8πhc)/ν^3

d. (8πh ν^3)/c^3

A non-polar molecule is the one in which the center of gravity of +ve and –ve charges

a. coincides

b. gets separated by 1Å

c. gets separated by 10^{-8} m

d. None

Sample MCQ

Spontaneous emission of two atoms produces radiations

a. have random phase and random direction

b. have same phase and same direction

c. have random phase and same direction

d. have same phase and random direction

Temporal coherence is

a. Longitudinal

b. Transverse

c. both a & b

d. None

Holography is an ______ phenomenon.

a. Dispersion

b. Diffraction

c. Interference

d. None

Nd: YAG Laser is

a. 2-level

b. 3-level

c. 4-level

d. None

The V-number of the single mode fiber is ___.

a. $V < 2.405$

b. $V > 2.405$

c. $V = 2.405$

d. None

Each part of hologram contains the information about

a. Particular part of the object

b. Entire object

c. Important part of object

d. Front side of object

Thank You

ALL THE BEST