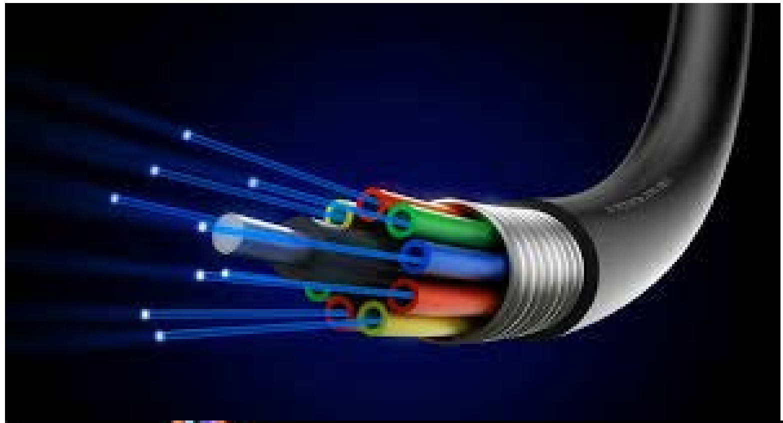
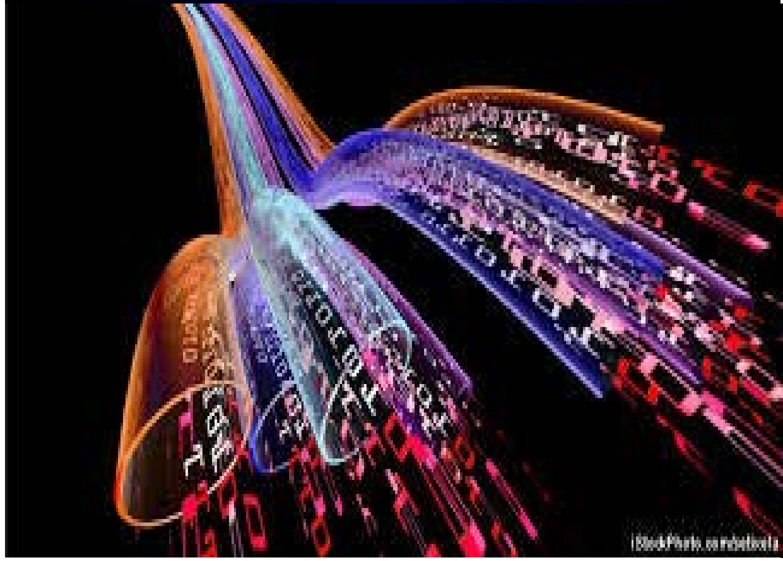
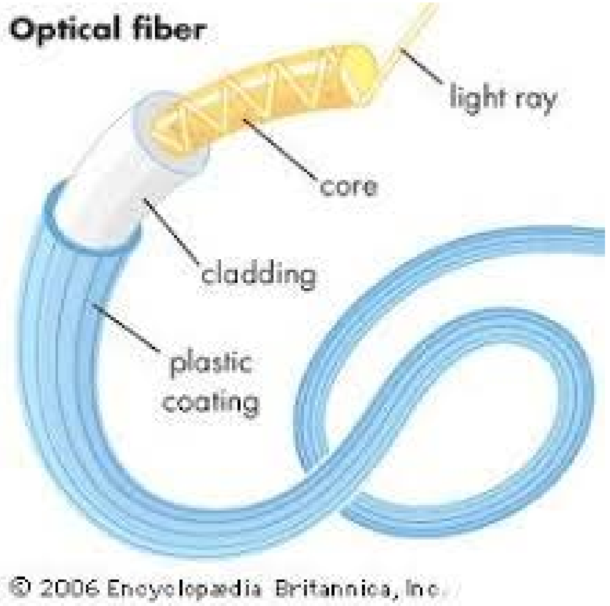
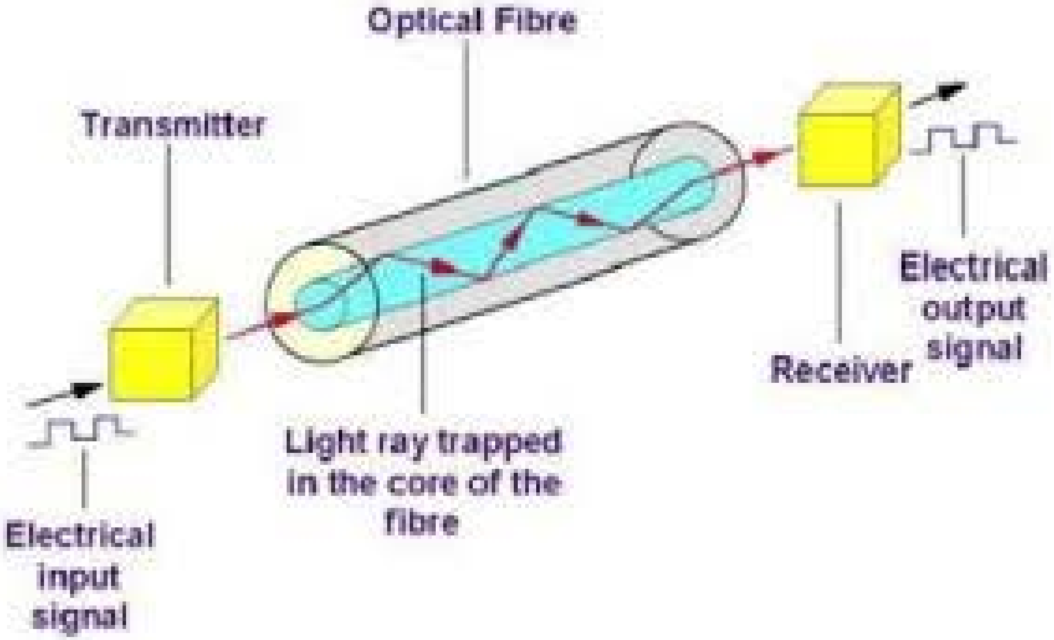
UNT-3: FIBER OPTICS

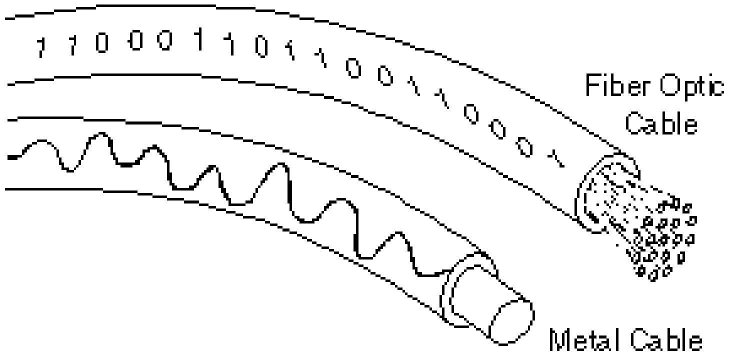
1. Introduction to Fiber Optics- WIT&WIL
2. Principle of optical- TIR
3. Construction of an Optical fiber and Properties,
4. Acceptance angle and acceptance cone,
5. Numerical aperture,
6. Types of fibers based on refractive index profiles,
7. Qualitative analysis of attenuation in optical fibers,
8. Application of Lasers and Optical fibers.











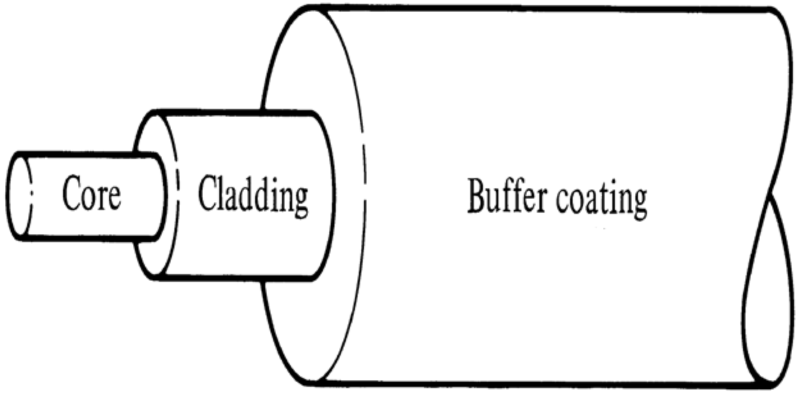
INTRODUCTION

- **Definition: An optical fiber is a very long, thin, flexible and transparent dielectric material made up of glass or plastic.**
- Optical fibers plays an important role in the field of communication to transmit data signals (like voice, television and digital data signals) from one place to other place.
- An optical fiber carries electromagnetic (light) waves of visible and infrared frequencies from one end to the other end of the fiber **by means of total internal reflection**.
- The transmission of light by total internal reflection was first demonstrated by **“John Tyndall” in 1870**, but the application of this phenomenon in the field of communication was first tried only from 1920.
- We know that light waves cannot travel far in open atmosphere. If they travel in open atmosphere energy dissipated very rapidly. Hence some kind of guiding channel is needed. **Optical fiber provides the necessary wave guide for light.**
- Hence optical fibers are used as dielectric wave guides for guiding the electromagnetic waves at an optical frequencies.
- Light waves can carry more information than that of radio waves and microwaves because of their higher frequencies ($\cong 10^{16} Hz$)
- **The main potential of an optical fiber**: it is possible to transmit simultaneously very large number of signals ($\cong$ 10,000). By using a metallic cable it is not possible to transmit simultaneously large number of signals.
- Example: **A metal wire is needed for guiding electric current. An Optical fiber is needed for guiding electromagnetic waves (light).**
- **Fiber optics is a technology, it is related to transportation of optical energy (light energy) in guiding media specifically glass fibers. Optical fibers can carry light over distances ranging from few meters to hundreds of kilometers.**

Structure (Construction) and dimensions of an Optical Fiber:-

An optical fiber is a very long, thin, flexible and transparent dielectric material made up of glass or plastic. Optical fiber mainly consists of three sections,

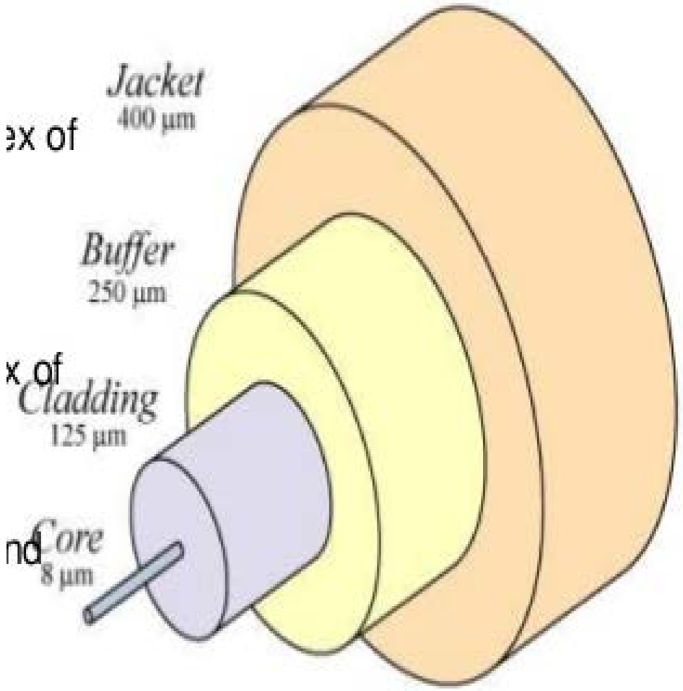
1. Core 2. Cladding 3. Protective (Buffer) Jacket



1. Core: It is an inner cylindrical material made up of glass or plastic. The refractive index of core is always greater than that of cladding. Core always carries the signal (as light). **The outer diameter of the core is ≅ 10-50μm.**

2. Cladding: It is a cylindrical shell of glass or plastic material in which core is inserted. Cladding always keeps the light waves with in the core because of its lower refractive index. Cladding protects the core from scratches and moisture. **The outer diameter of the cladding is ≅ 120-500μm.**

3. Protective Jacket: The cladding is enclosed in polyurethane jacket and it protects the fiber from surroundings (like moisture, abrasion and scratches). It can hold one or more cables in a fiber. **The outer diameter of the protective jacket is ≅ 250-600μm.**



Note: The refractive index of core is slightly greater than the refractive index of cladding. The normal standard values are 1.48 and 1.46 respectively for core and cladding.

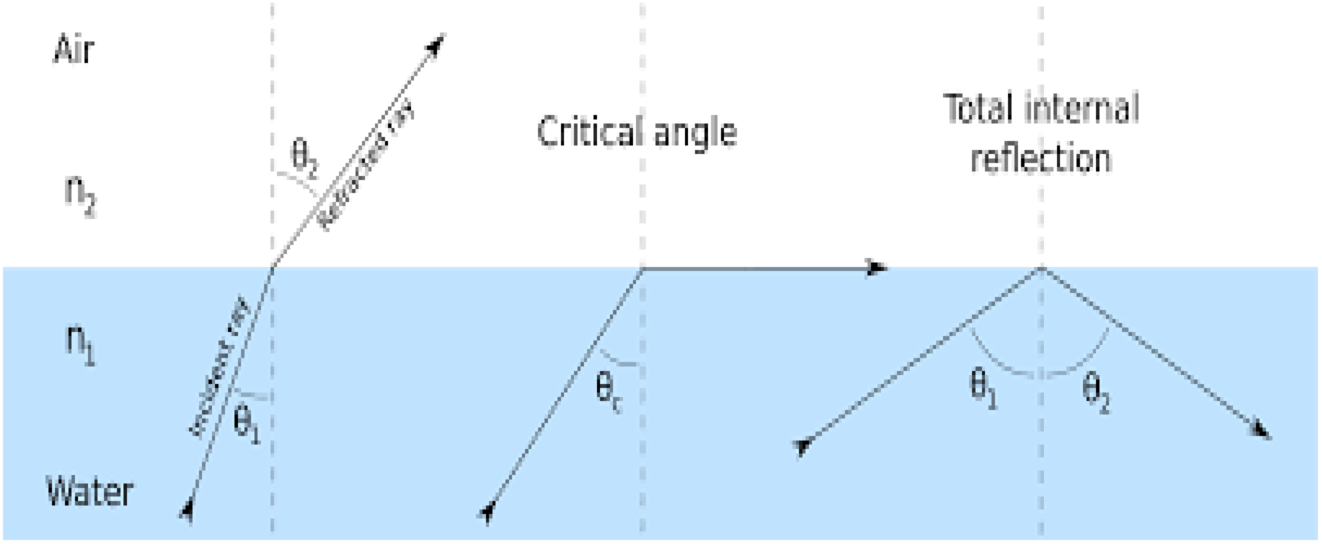
Principle of Optical Fiber: (Total Internal Reflection and its conditions)

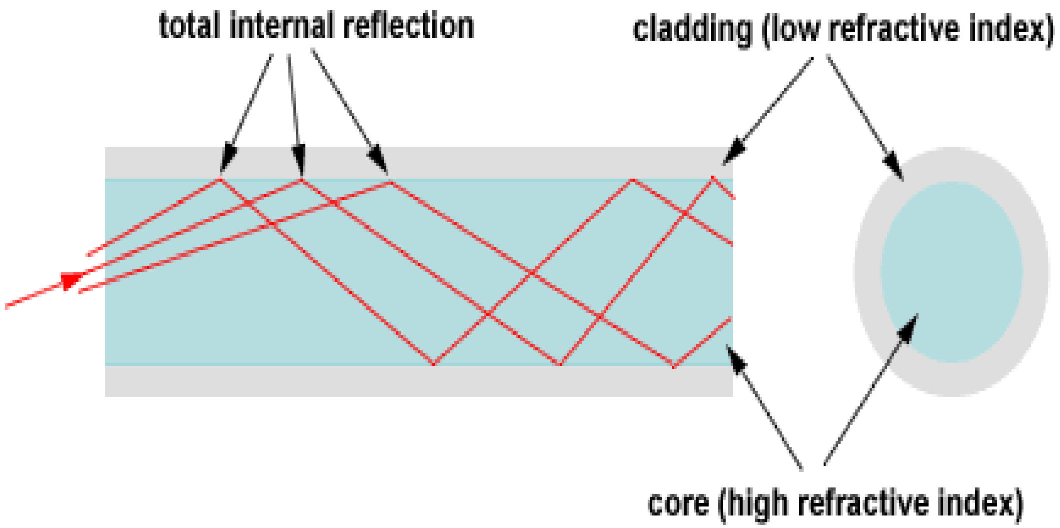
- The optical fiber works on the principle of total internal reflection. Once light ray enters into core, it propagates by means of multiple total internal reflections at core-cladding interface.
- The light in a fiber-optic cable travels through the core by constantly bouncing from the cladding this principle called total internal reflection.
- **For the total internal reflection (TIR), light ray should satisfy the following conditions,**

1. Light should travel from denser medium to rarer medium
2. Angle of incidence $(\theta_i) \geq$ Critical angle (θ_c)
3. Let n_1 and n_2 be the refractive indices of two media (core and cladding respectively) such that $n_1 > n_2$

- **What is critical angle?**

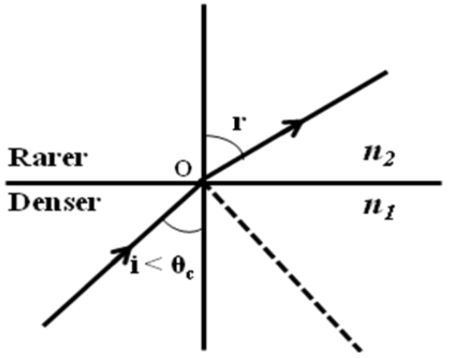
Critical angle is defined as the angle of incidence at which angle of refraction is 90◦





Expression for condition for TIR:

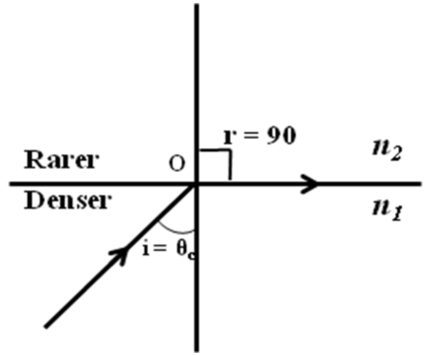
When a ray of light travelling in a medium of higher refractive index n_1 strikes a second medium of lower refractive index n_2 making an angle of incidence **'*i*'** with the normal, this ray is refracted into the second medium with angle of refraction **'r'** and moves away from the normal (as shown in figure 1).



- According to Snell's law, $n_1 Sin\, i = n_2 \sin r$
- When the angle of incidence *i* increase the angle of refraction *r* also increases.

For a particular angle of incidence, say for critical angle $i = \theta_c$, the angle of refraction *r* becomes 90º, that is the refracted ray propagates along the interface of two media (as shown in figure 2, middle).

If $i = \theta_c$, then $r = 90^o$,

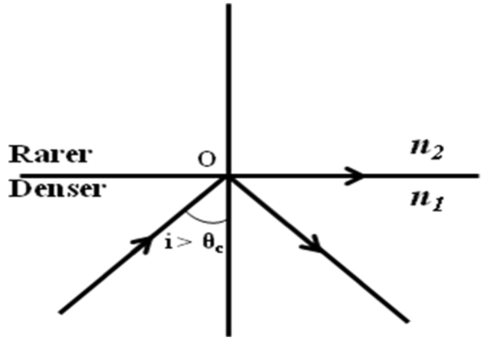


$$n_1 \sin \theta_c = n_2 \sin 90^0$$

$$\sin \theta_c = \frac{n_2}{n_1} \qquad \because \sin 90^0 = 1$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

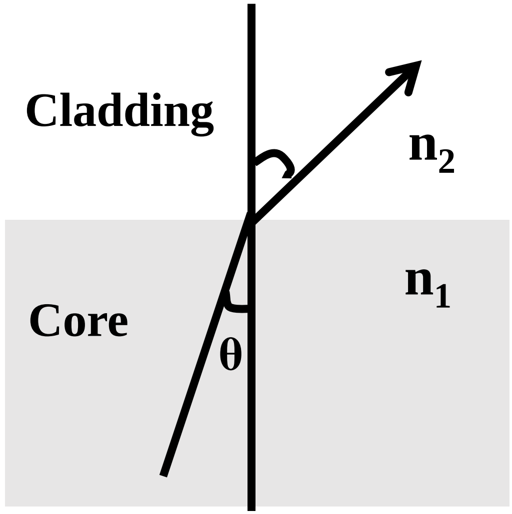
This is the expression for condition for internal reflection.



- If the angle of incidence further increases, the ray is totally reflected into the same medium (figure 3) this phenomenon is called total internal reflection. If $i > \theta_c$ then the total internal reflection will occur.

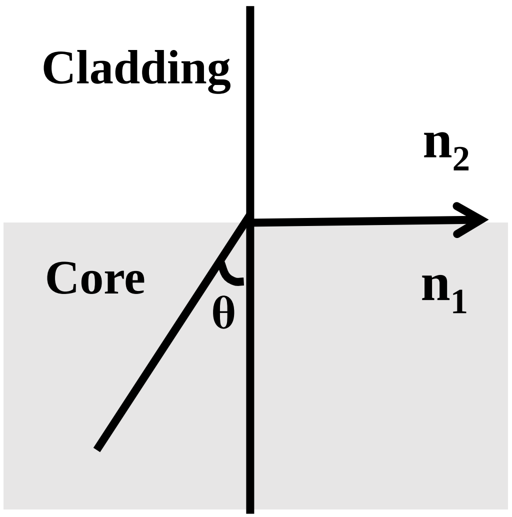
Importance of critical angle:

- When light travels from core to cladding, refraction takes place



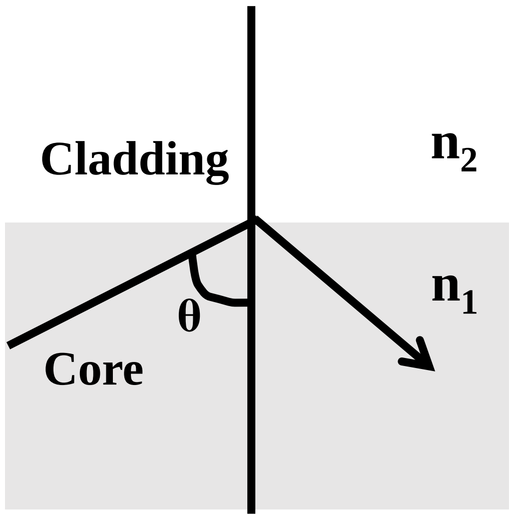
$\theta < \theta_c$

As the light travels from denser medium to rarer medium, the angle of refraction is greater than angle of incidence



$\theta = \theta_c$

With the increase in the angle of incidence, the angle of reflection also increases, at a particular angle called as **critical angle** ($\theta = \theta_c$) the refracted ray just grazes the interface between core and cladding



$\theta > \theta_c$

When the angle of incidence increased further the ray is reflected back in to the core at the interface obeying laws of reflection. This phenomenon is called as **total internal reflection**

Expression for Acceptance angle:

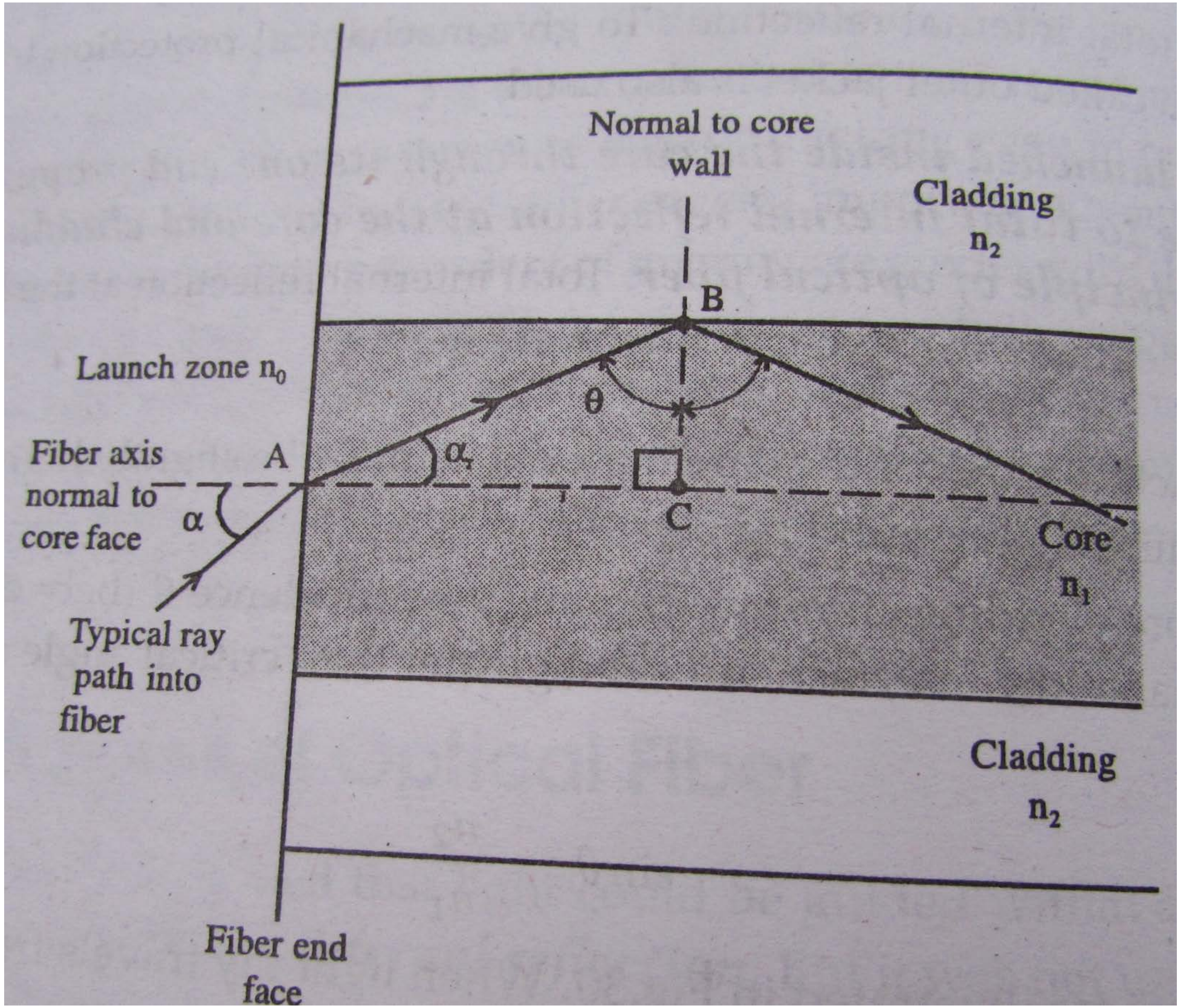
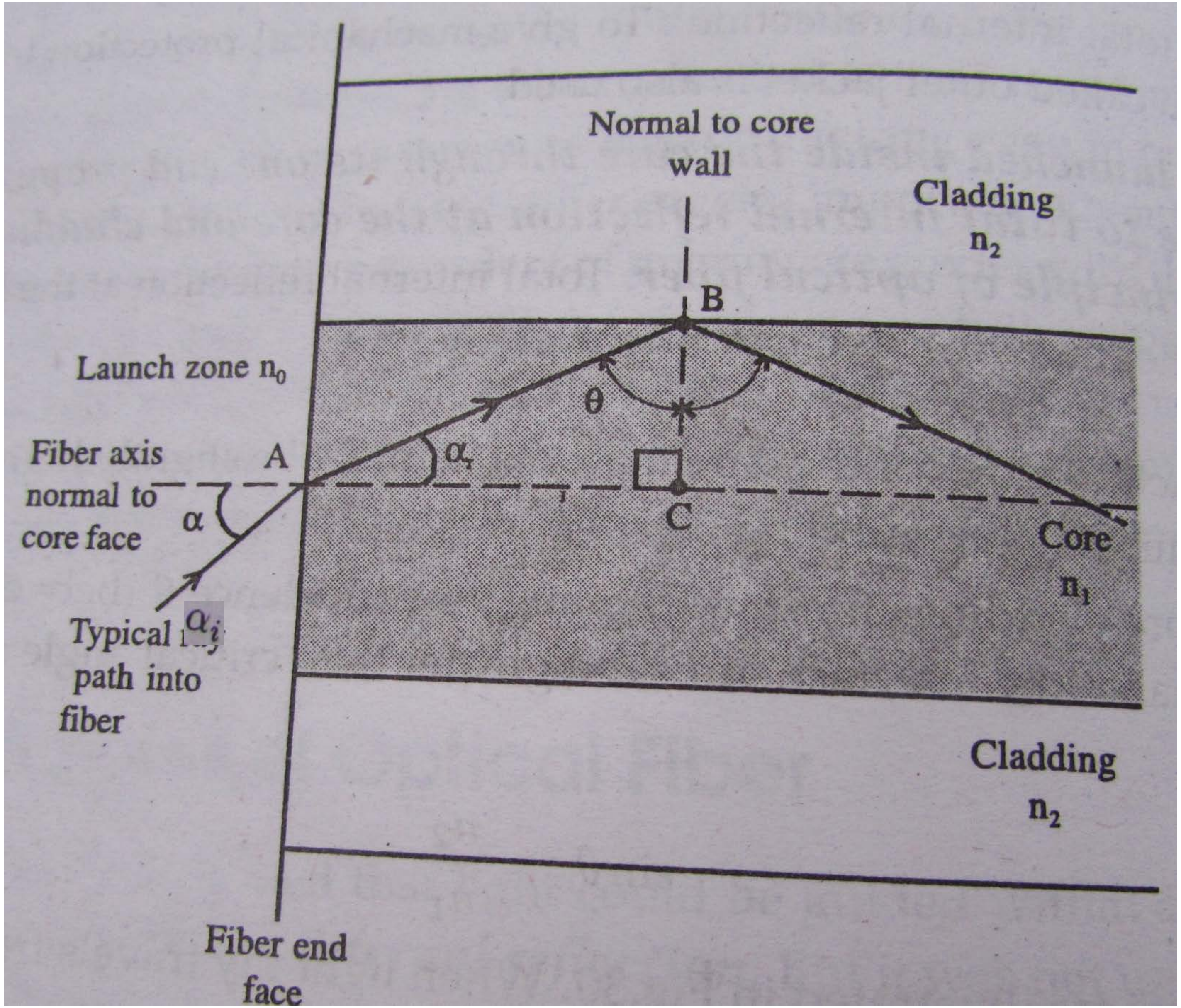


Fig. Path of a typical light ray launched into a fiber

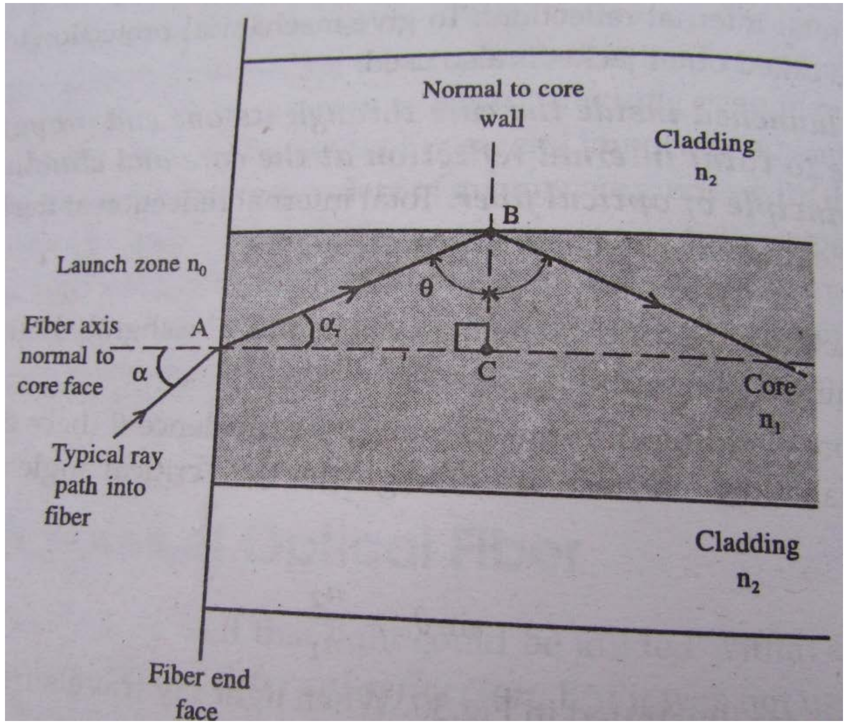
- When we launch the light beam in to the fiber at its one end the entire light may not pass through the core and propagate.
- Only the rays which make the angle of incidence greater than critical angle undergo total internal reflection and propagate through the core and all other rays are lost
- The maximum angle of incidence at the end face of an optical fiber for which the light ray can be propagated along core-cladding interface is known as maximum Acceptance angle. It is also called acceptance cone half angle.
- The light is launched from the air medium of refractive index n_0 ($n_0 = 1$) in to core of refractive index n_1, with an angle of incidence α_i to the fiber end face.
- This ray refracts with angle of refraction α_r from the fiber axis.



- From fig., Δ ABC,
- $\alpha_r = 90 - \theta$
- From Snell's law, $\frac{\sin\alpha_i}{\sin\alpha_r} = \frac{n_1}{n_0}$
- $\sin\alpha_i = \frac{n_1}{n_o}\sin\alpha_r$
- $\sin\alpha_i = \frac{n_1}{n_o}\sin(90 - \theta)$
- $\sin\alpha_i = \frac{n_1}{n_o}\cos\theta$
- $\sin\alpha_{max} = \frac{n_1}{n_o}\cos\theta_c$ (when $\alpha_i = \alpha_{max}$, $\theta = \theta_c$)
- At critical angle, refraction angle = 90^0
- $\text{Sin}^2\theta_c + \text{Cos}^2\theta_c = 1$
- $\text{Cos}\theta_c = \sqrt{1 - \text{Sin}^2\theta_c} = \sqrt{1 - \frac{n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$
- $\sin\alpha_{max} = \frac{n_1}{n_o} X \frac{\sqrt{n_1^2 - n_2^2}}{n_1} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$
- $\therefore\ \alpha_{i\,(max)} = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$

This maximum angle is called acceptance angle or acceptance cone half angle

Expression for Numerical aperture:



- The light gathering capacity of an optical fiber is called numerical aperture.
- Numerical Aperture (NA) is directly proportional to the acceptance angle, $\alpha_{i\,(max)}$ so numerical aperture can be represented by the Sine of acceptance angle of the fiber i.e., Sin (α_i).
- Expression for the NA can be obtained by applying Snell's law at points 'A' and 'B' in the adjacent diagram.
- Let n_1, n_2 and n_0 be the refractive indices of core, cladding and the surrounding medium (air) respectively.
- Apply Snell's law at the point 'A',

  $\frac{\sin\alpha_i}{\sin\alpha_r} = \frac{n_1}{n_0}$ -------(1)
- At point 'B' on core-cladding interface, the angle of incidence = (90-θ). Hence by applying Snell's law at B,
- n_1 Sin (90- θ) = n_2 Sin (90)
- n_1 Cos θ = n_2 $\Longrightarrow$ Cos θ = $\frac{n2}{n1}$
- $\therefore$ Sin θ = $\sqrt{1 - Cos^2\theta}$ $\Longrightarrow$ $\therefore$ Sin θ = $\sqrt{1 - \frac{n_2^2}{n_1^2}}$ --------(2)
- By substituting (2) in (1) we get,
- $n_0 Sin(\alpha_i) = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}} \Longrightarrow Sin(\alpha_i) = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$ ----(3)
- If surrounding medium of fiber is air, $n_0 = 1$

$\Longrightarrow$ $\therefore Sin(\alpha_i) = \sqrt{n_1^2 - n_2^2}$

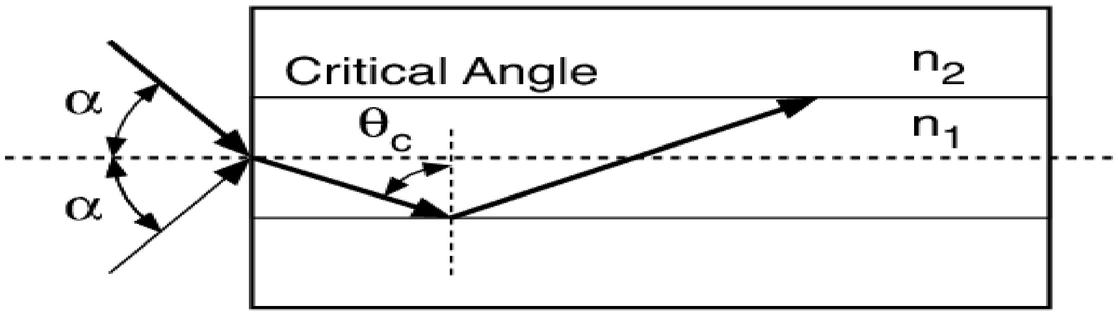
- According to definition of Numerical aperture, N.A = Sin (α_i) = $\sqrt{n_1^2 - n_2^2}$ -----(4)

- Let the fractional change in the refractive index (Δ) is the ratio between the difference in refractive indices of core and cladding to the refractive index of core,
- i.e., $\Delta = \frac{n_1 - n_2}{n_1}$ ----(5)
- $\therefore n_1 - n_2 = \Delta n_1$ ------(6)
- Equation (4) can be written as, N.A = $\sqrt{n_1^2 - n_2^2}$

N.A $= \sqrt{(n_1 - n_2)(n_1 + n_2)}$ --------(7)

- Substituting Eq (6) in (7) , we have, N.A = $\sqrt{\Delta n_1 (n_1 + n_2)}$
- If $n_1 \cong n_2$ So $(n_1 + n_2) = 2n_1$
- $\therefore$ Numerical Aperture, N.A = $\sqrt{2\Delta n_1^2} = n_1\sqrt{2\Delta}$ ----(8)

Numerical Aperture



NA = sin $\alpha = \sqrt{n_1^2 - n_2^2}$

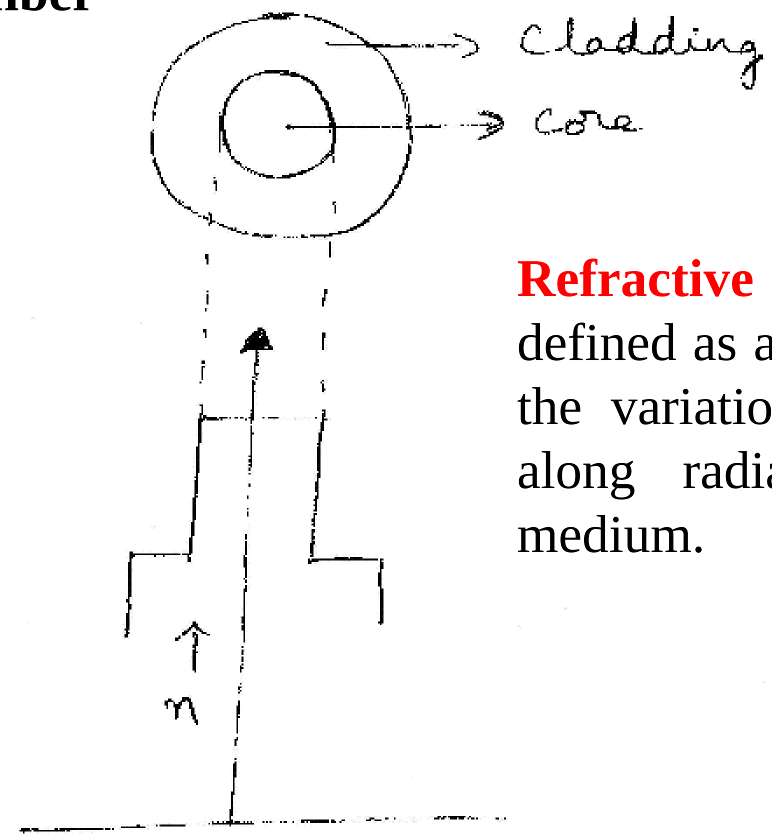
Full Acceptance Angle = 2α

<u>Conclusion :</u>

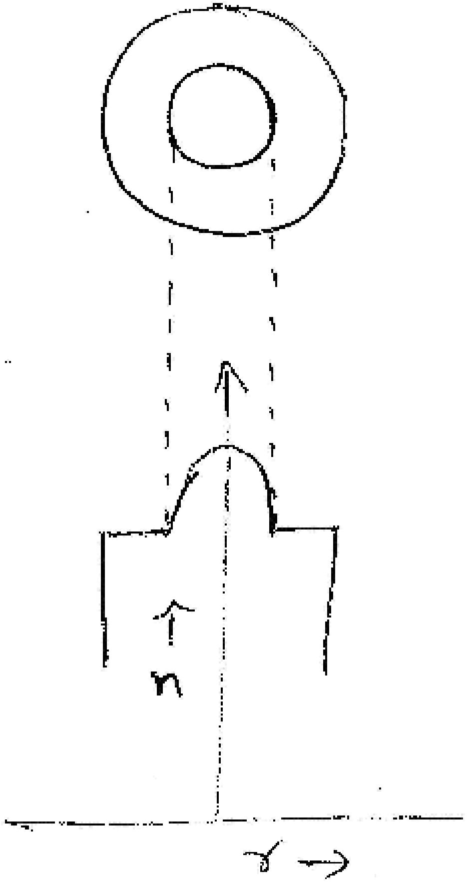
- Numerical Aperture can be increased by increasing 'Δ' and thus enhances the light gathering capacity of fiber.
- We can not increase 'Δ' to very large value because it leads to intermodal dispersion, which causes signal distortion.
- **condition for the light propagation in the fiber is,**

  Sin (θ_i)< N.A (θ_i = angle of incidence of light ray at one end of an optical fiber).

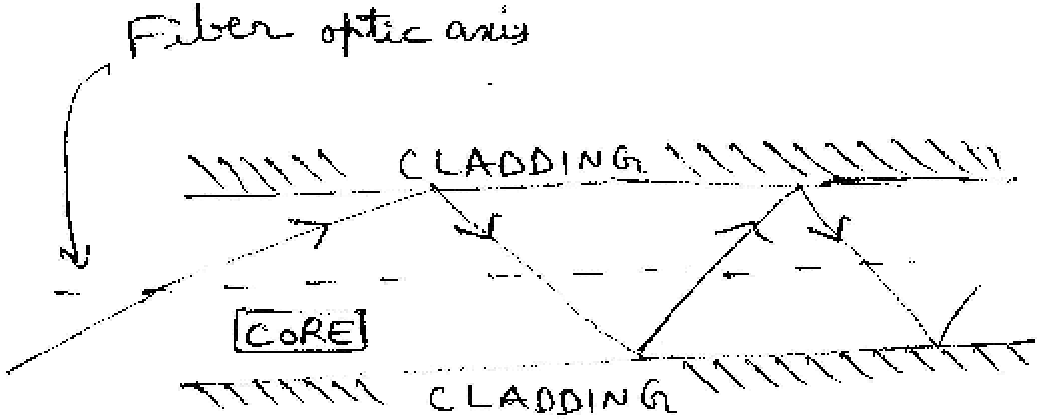
Step index fiber

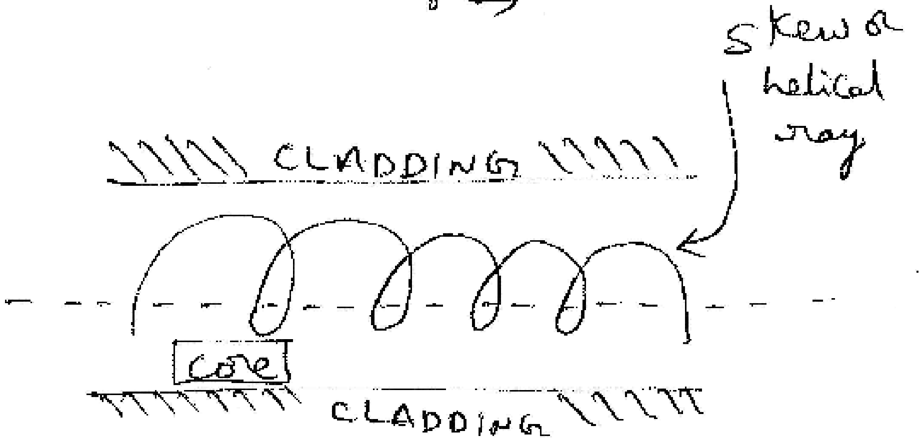


Graded index fiber



Refractive index profile is defined as a curve which explains the variation of refractive index along radial distance in core medium.





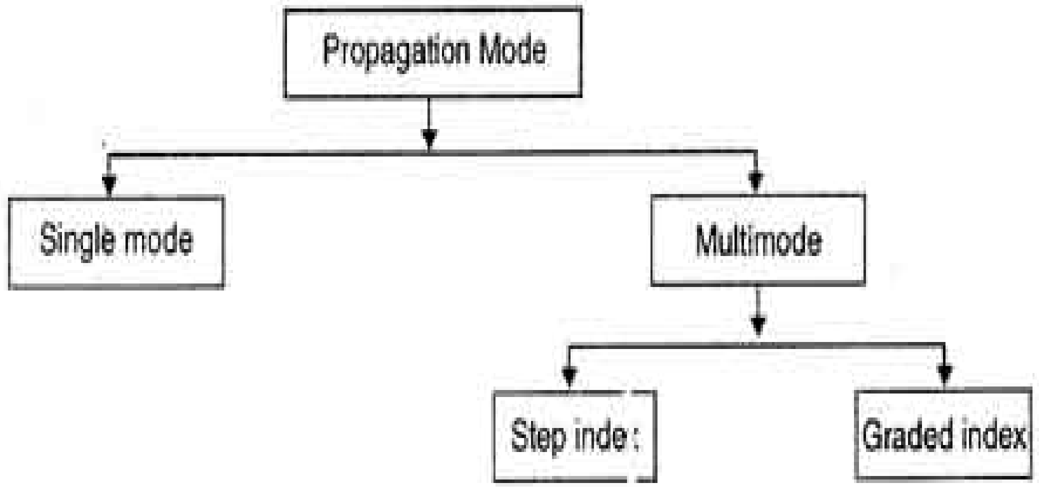
Classification of Optical fibers

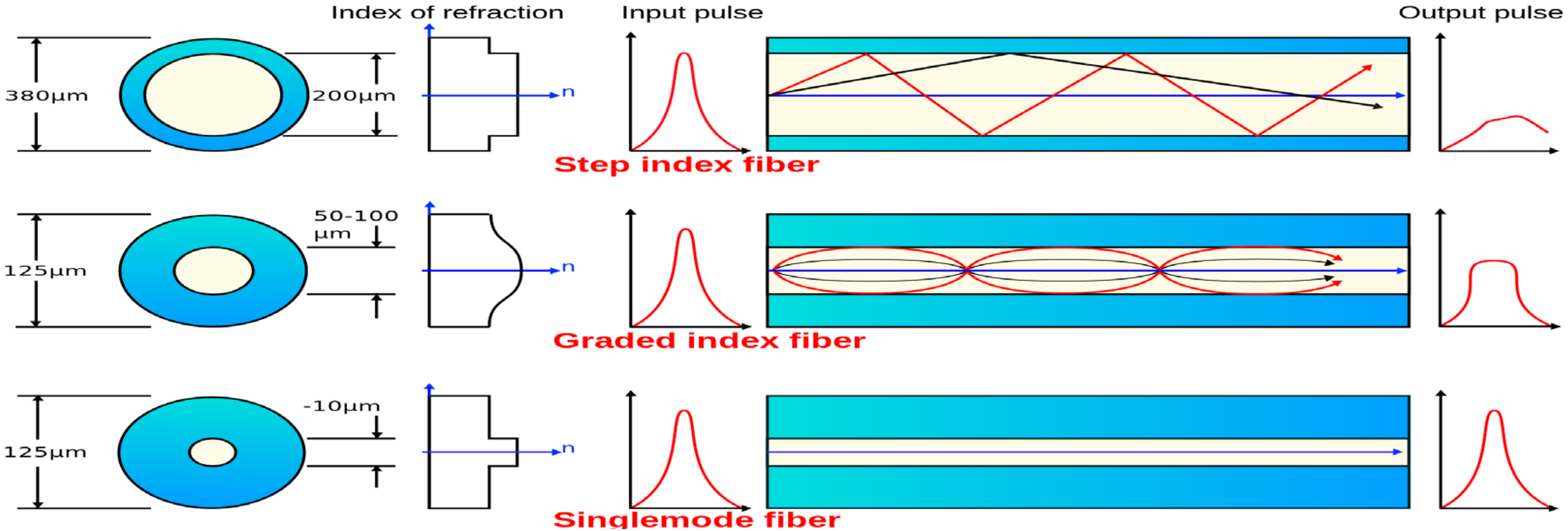
Based on the refractive index profiles of the core, optical fibers are classified into two categories.

(i) Step Index and

(ii) Graded Index fibers

Again based on mode of propagation all fibers are divided into single mode and multimode fibers.





1. Step Index Fibers:

In step index fibers, the refractive index is uniform throughout the core medium and undergoes an abrupt change at the interface of the core and cladding as shown in the Fig.1.

➢ Based on mode of propagation of light rays, step index fibers are of two types

(i) Single mode step index fibers and

(ii) Multi mode step index fibers. Mode means number of paths available for the light propagation.

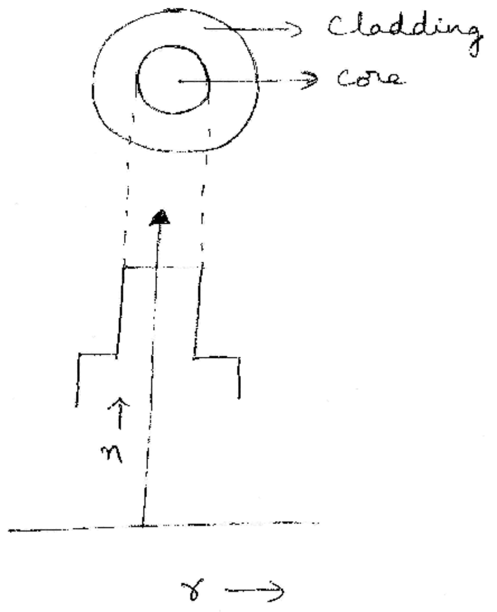


Fig.1: Refractive Index Profile Curve for Step Index Fiber

(i) Single mode step index fiber:

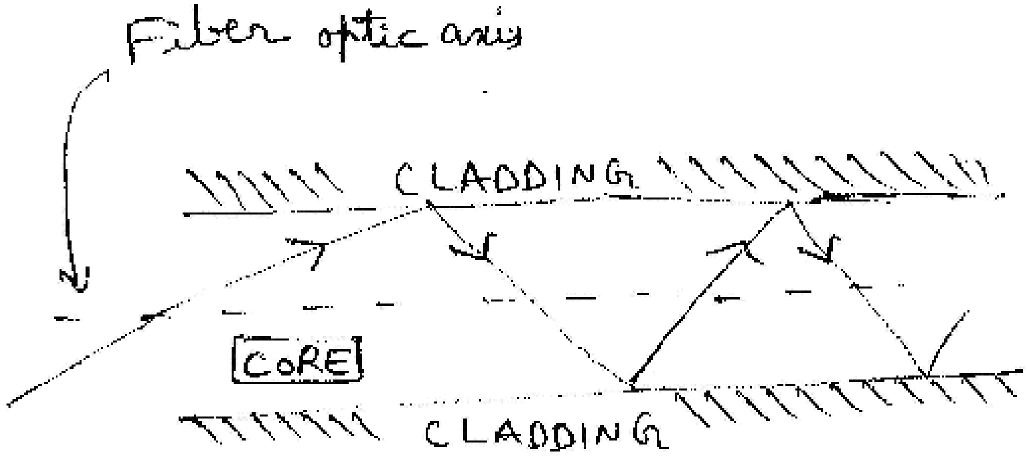
- The core diameter of this fiber is about 10 μm and outer diameter of cladding is 70 μm.
- There is only one path for the ray propagation so it is called single mode fiber.
- The light ray gets transmitted through this fiber in the form of meridional ray,

i.e., the light ray crosses the fiber axis after each total internal reflection, as shown in the adjacent diagram.

- Lasers are used as light source in these fibers. Mainly used in submarine cable system.

(ii) Multi mode step index fiber:

- Construction of a multimode fiber is similar to single mode fiber except that its core and cladding diameters.
- The core diameter of multimode step index fiber varies from 50 - 250 μm, cladding diameter is 100-250 μm.
- Light is propagated in this fiber as multiple total internal reflections.
- It is used in data links which has lower band width requirements.



2. Graded Index Fibers:

In graded index fibers, the refractive index of the core medium is maximum at the center and decreases in a parabolic manner as we move towards the cladding, as shown in the Fig.1.

- This fiber can be single mode or multimode fiber.
- The diameter of core varies from 50-200 μm and outer diameter of cladding varies from 100-250 μm.
- As refractive index changes continuously in core, the light rays suffers continuous refraction in core.
- The light ray propagates through this fiber in the form of skew or helical ray as shown in Fig.2. not due to TIR. From figure it is clear that this light ray never touches the fiber optic axis.
- Either LASER or LED is used as light source.
- Its typical applications are in the telephone trunk between central offices.

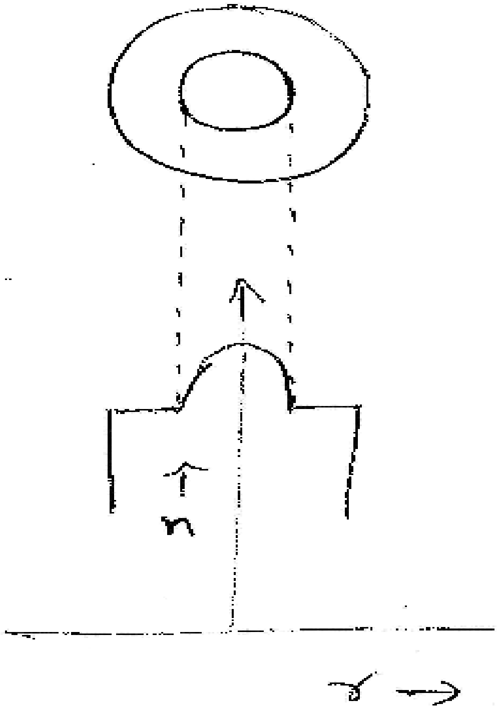
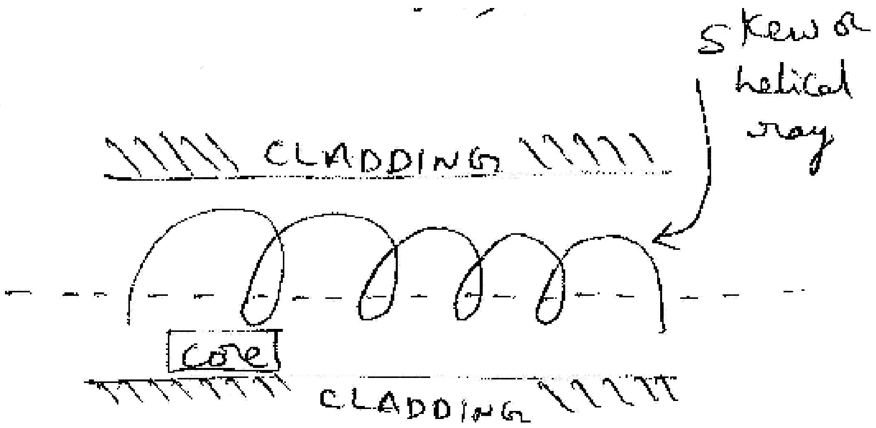
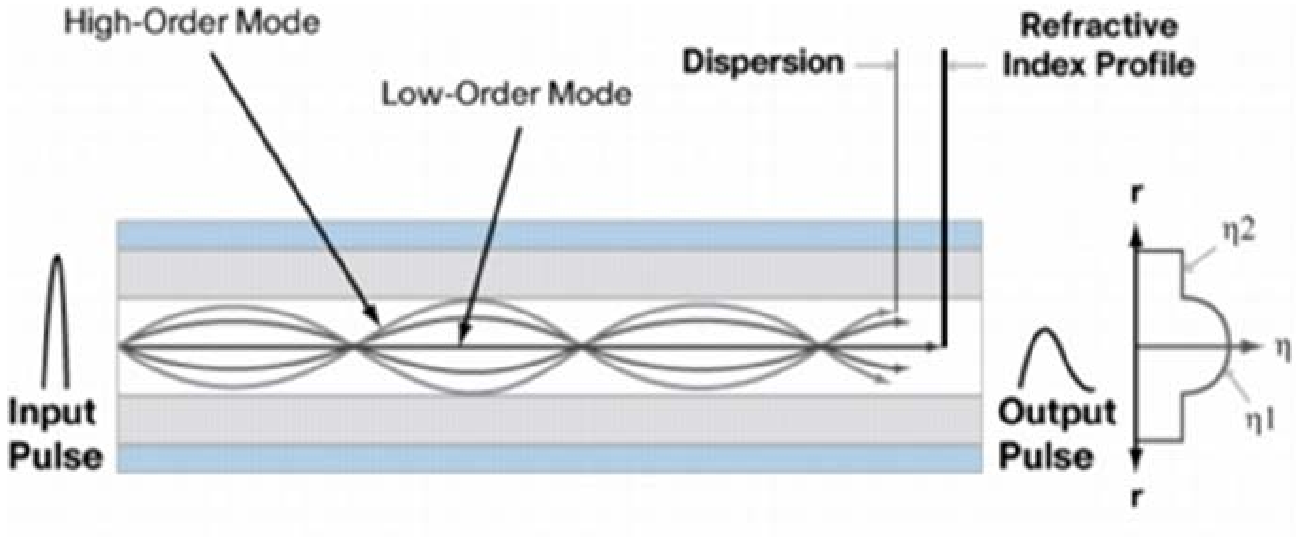


Fig.1: Refractive Index Profile Curve for Graded Index Fiber





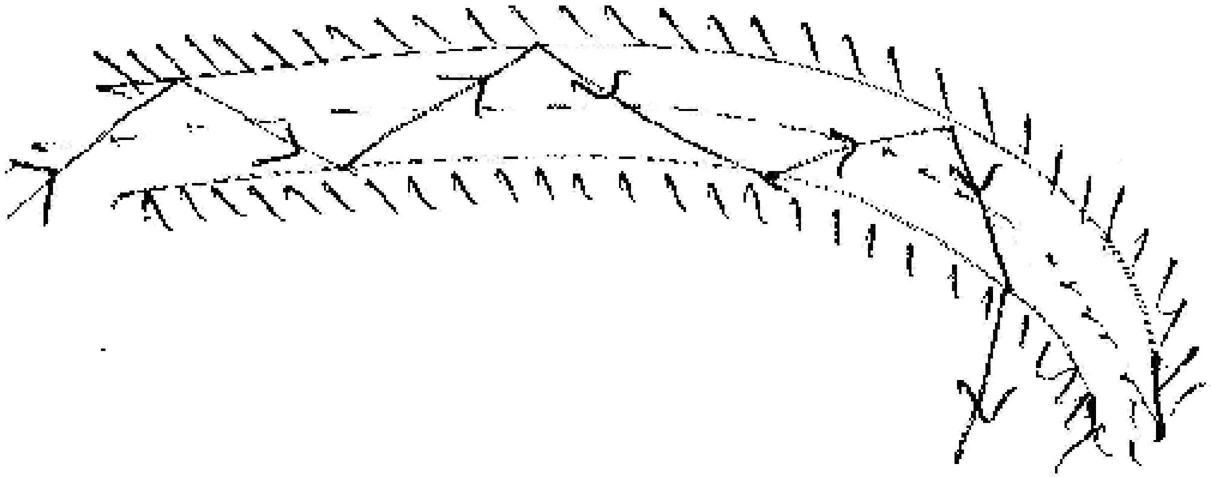
Multimode Graded Index

Attenuation:

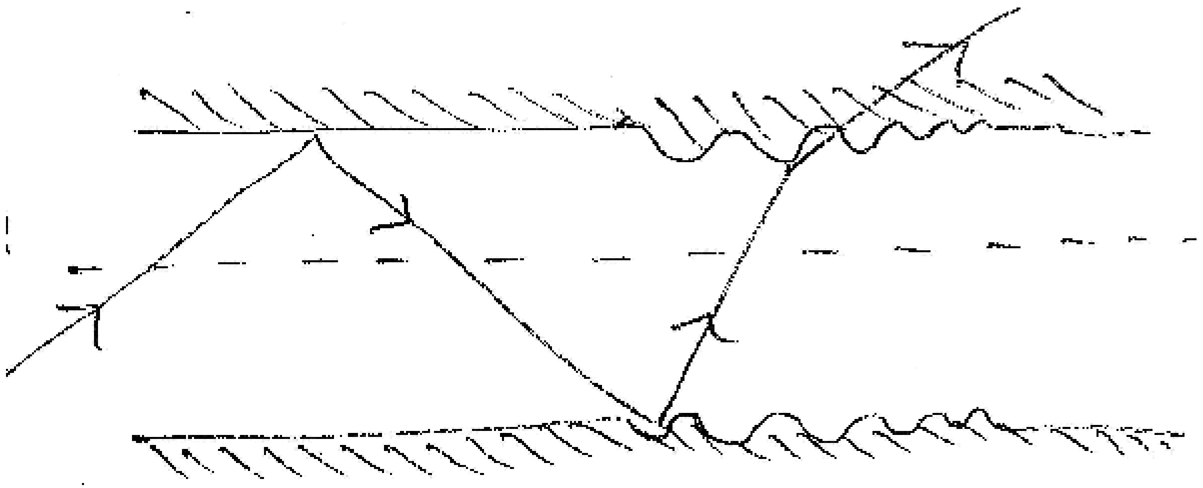
- Means Reduction of strength

Types of attenuation Losses:

- **Absorption losses**
- **Scattering losses**
- **Bending losses**
  - Macroscopic



  - Microscopic

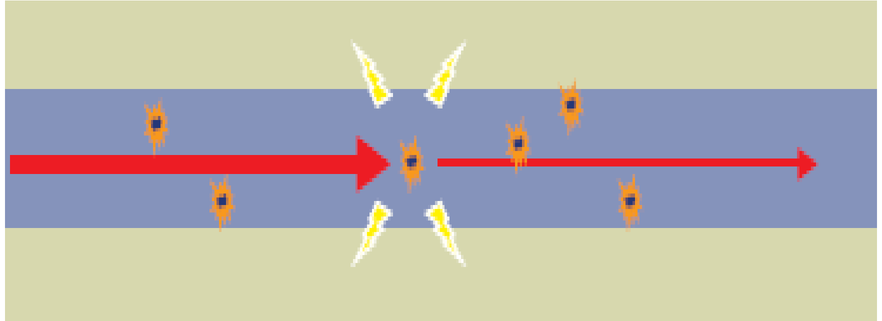


Attenuation in Optical fibers:

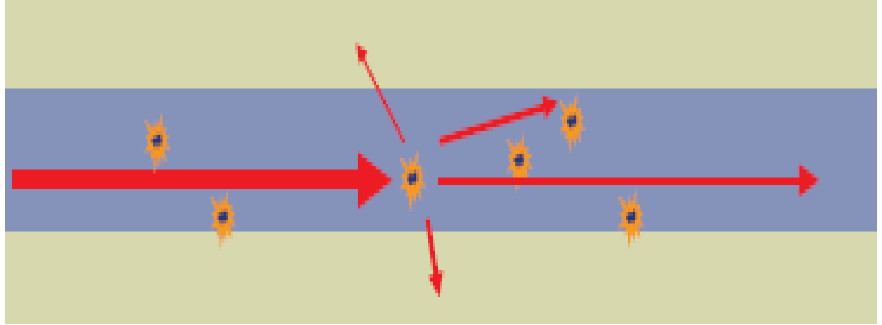
- Attenuation means reduction of strength. Though the phenomenon of total internal reflection assures the loss less transmission of light signal through the optical fiber, there are few factors that result in the attenuation of the light signal.
- A proper study of those attenuation factors helps us to minimize the losses and increase the efficiency of the optical fibers.
- The following are different attenuation factors.

1. Absorption losses
2. Scattering losses
3. Bending losses (macroscopic and microscopic bending losses)

Absorption



Scattering

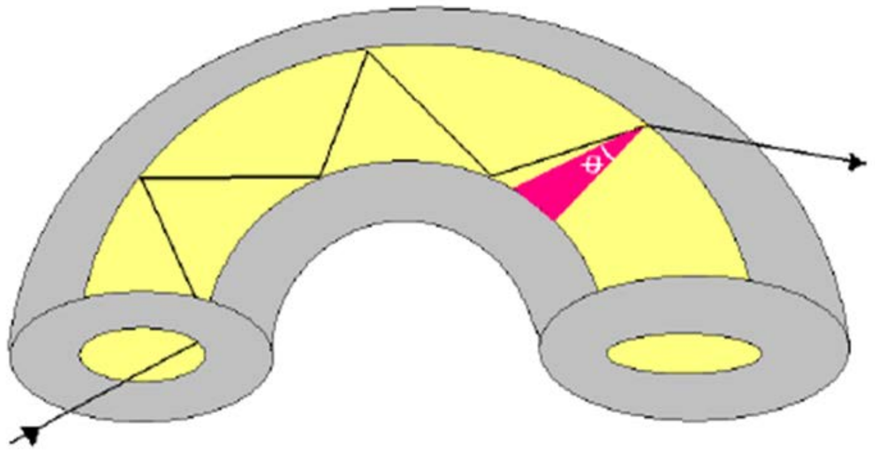


1. Absorption losses:

Every material has a characteristic of absorbing a fraction of incident light, this property is called intrinsic absorption. Besides the intrinsic absorption, the impurities present in the optical fiber also absorb light which is called impurity absorption. Such absorptions result in the reduction the signal strength which is propagating in an optical fiber cables.

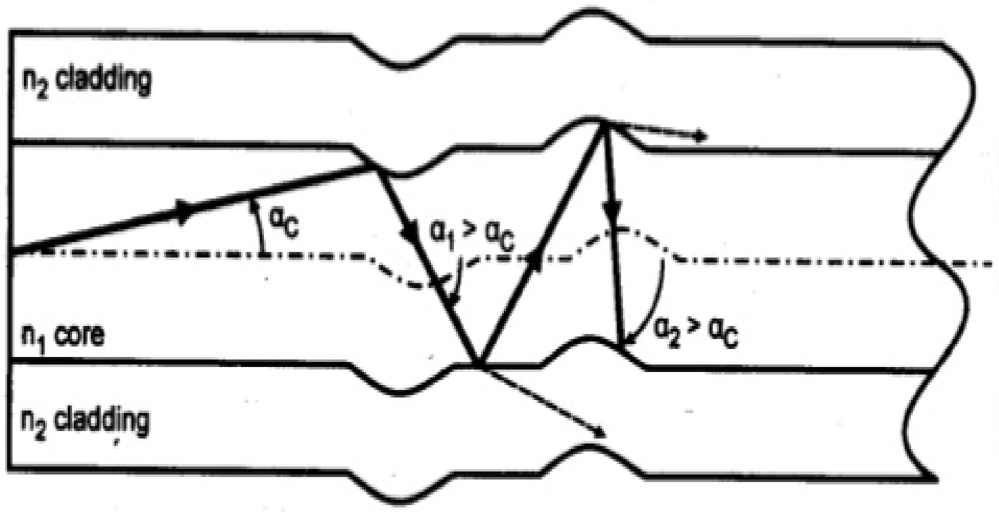
2. Scattering losses:

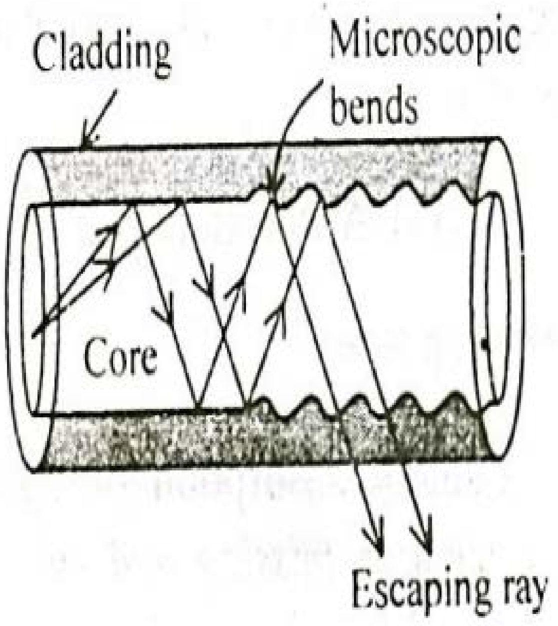
The light signal propagates through the core medium by means of total internal reflection. Presence of any kind of impurities in the core medium would certainly scatter the light signal in an unexpected direction and hence possibility to get refraction into the cladding medium. This is called scattering loss.



Macrobend loss.

Losses due to micro bending



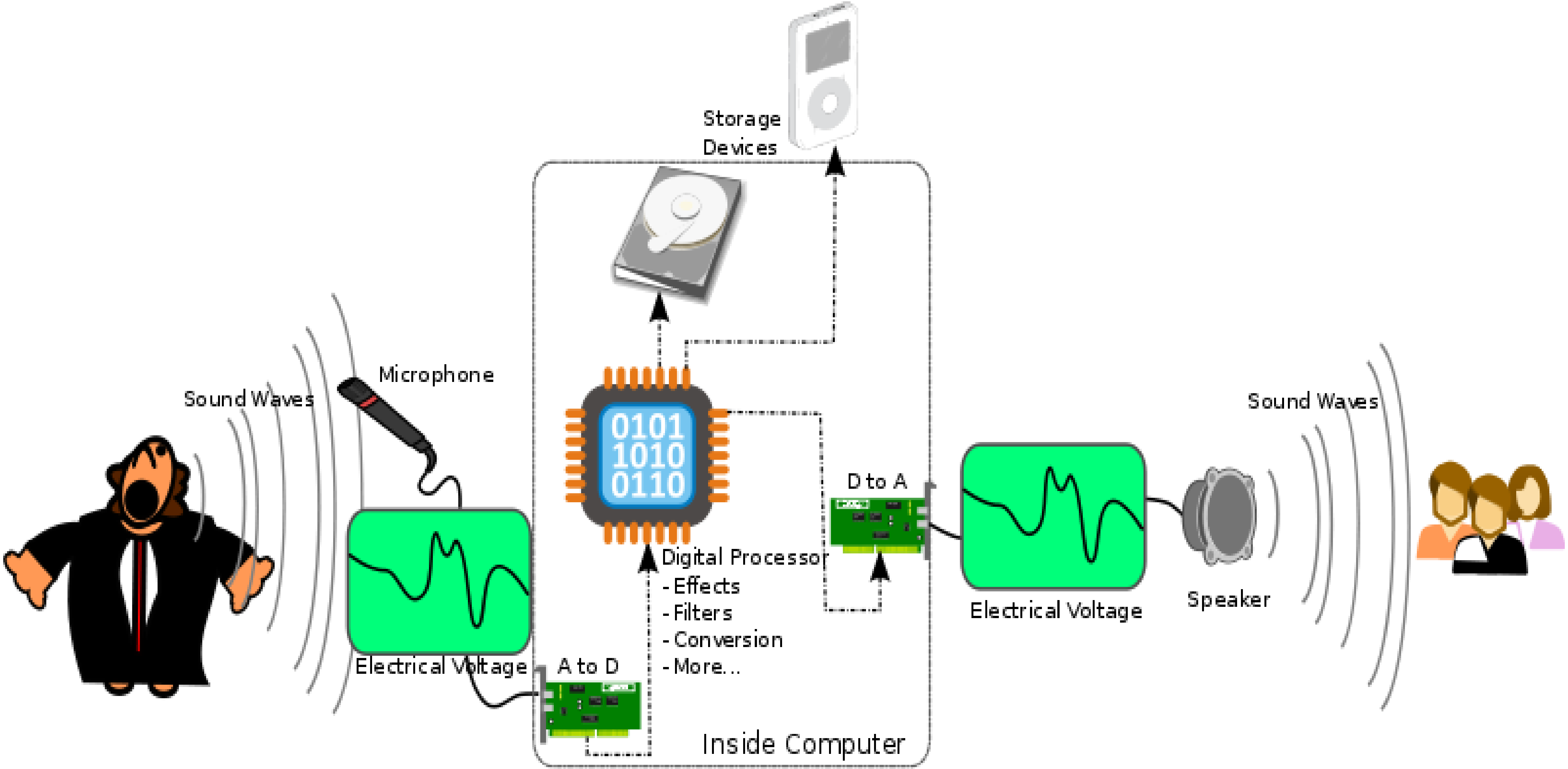


3. Bending Losses:

There are two kinds of bending losses, (i) Macroscopic bending losses and (ii) Microscopic bending losses.

If the radius of curvature of the bending of an optical fiber is greater than the radius of the optical fiber, then it is called macroscopic bending.

- As shown in the diagram, the light signal when it propagates through the bent fiber, gets leaked into cladding region as the condition for total internal reflection ($\theta_i > \theta_c$) is not satisfied in the bent region.
- If the radius of curvature of the bending of the fiber is lesser than the radius of the optical fiber, leakage of the signal into cladding region takes place such a loss is called microscopic bending loss. As shown in the diagram.


Storage Devices
Microphone
Sound Waves
0101
1010
0110
D to A
Sound Waves
Digital Processor
- Effects
- Filters
- Conversion
- More...
Electrical Voltage
Speaker
Electrical Voltage
A to D
Inside Computer

Block diagram for optical fibers in Communication system:

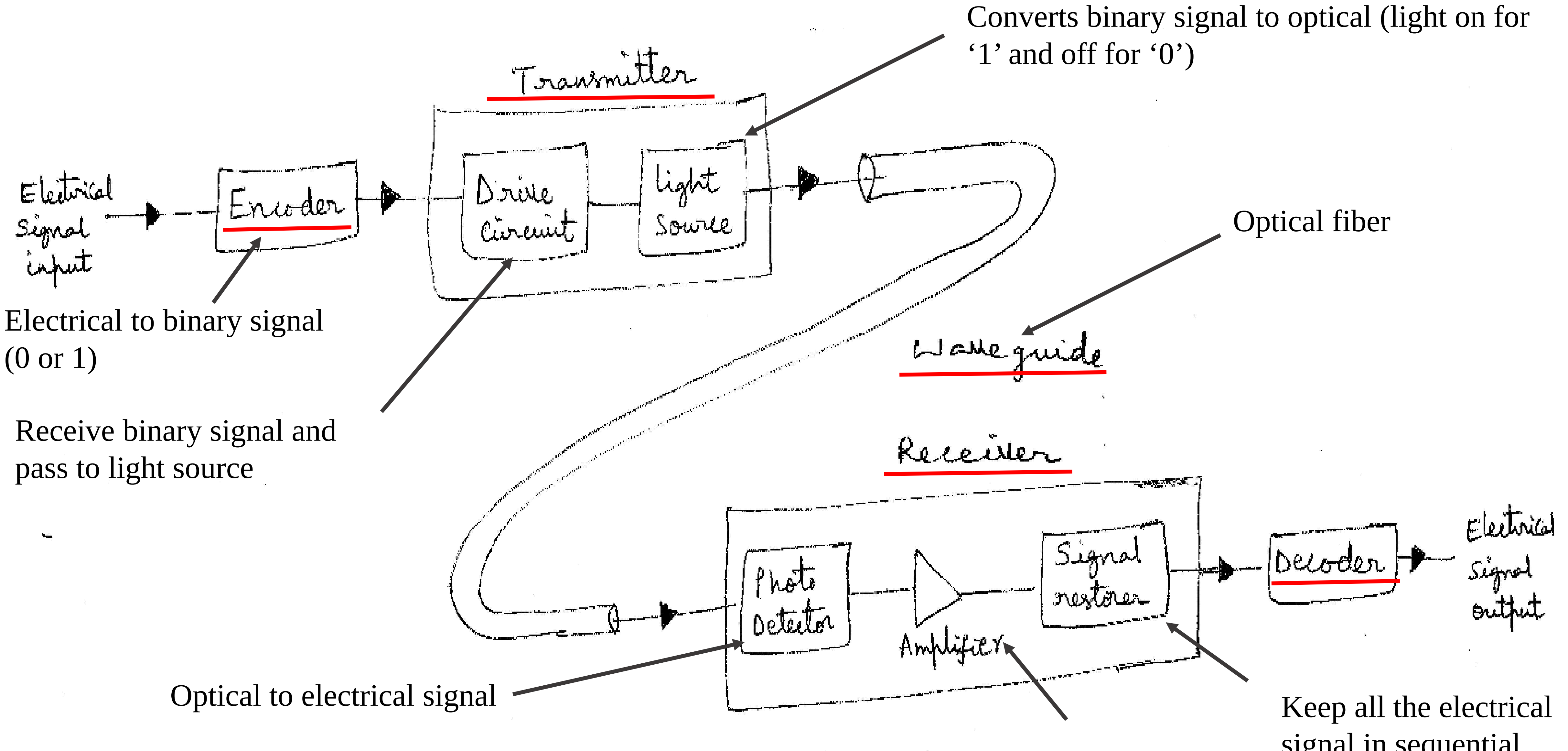


Fig: Optical Fiber Communication System

Application of Optical Fibers in Communication system:

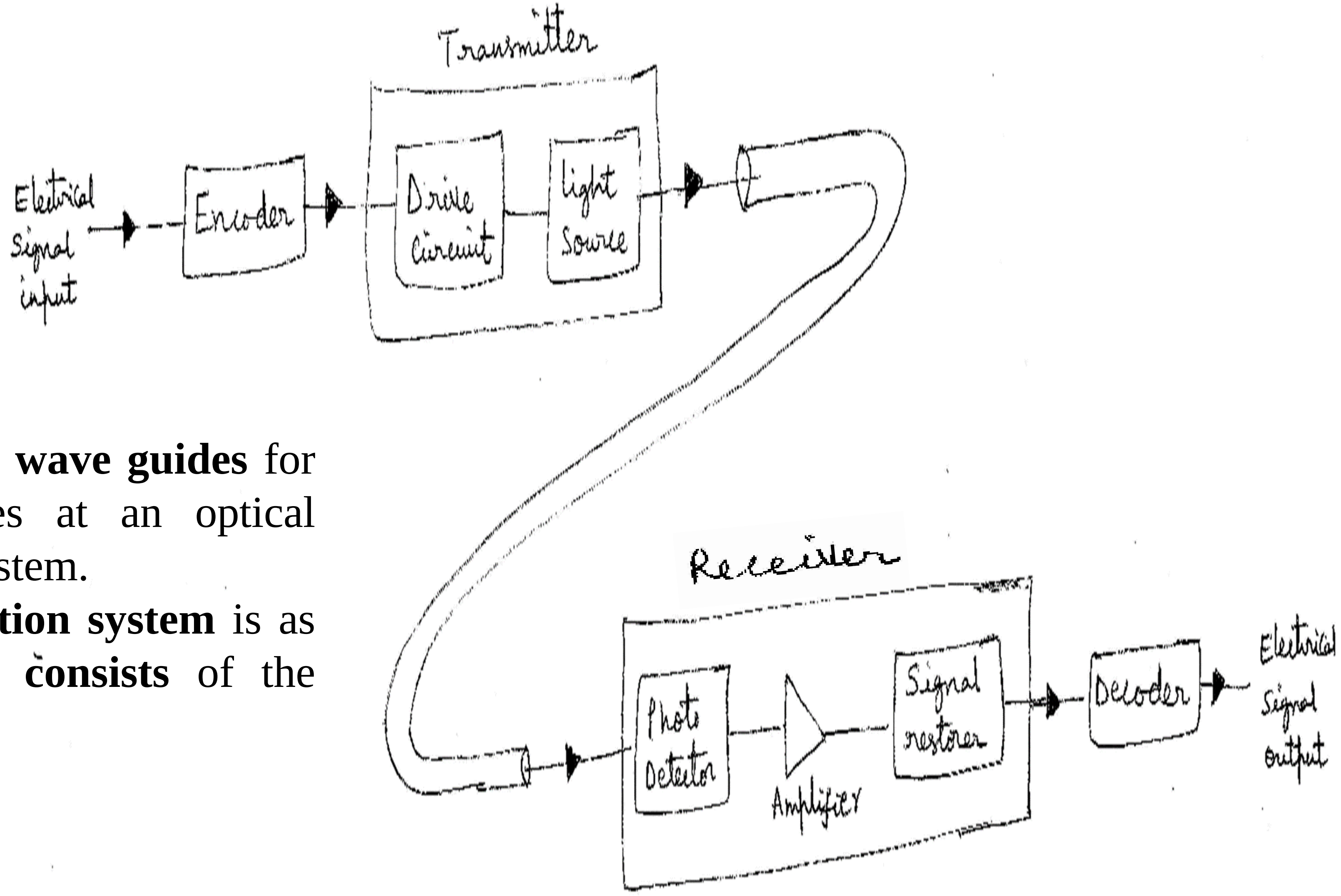


Fig: Optical Fiber Communication System

- Optical fibers are used as **dielectric wave guides** for guiding the electromagnetic waves at an optical frequencies in the communication system.
- A typical **optical fiber communication system** is as shown in the diagram. It **mainly consists** of the following parts.

i. **Encoder**
ii. **Transmitter**
iii. **Wave guide (fiber cable)**
iv. **Receiver**
v. **Decoder**

(i) <u>Encoder:</u>

Initially the audio signal (words spoken by us) is converted into electrical signal which is an analog form. Encoder is an electronic component that converts this analog signal into binary or digital signal.

<u>(ii) Transmitter:</u>

The digital signal from the encoder is fed to the transmitter which consists of two parts, one is drive circuit and the other is light source. Drive circuit receives the digital signal and feeds it to the light source.

Light source is usually LED or a diode LASER.

If digital ‘0’ is received, light source will be turned OFF. If digital ‘1’ is received the light source will be turned ON.

Thus light source converts electrical signals into optical signal.

(iii)<u> Wave Guide:</u>

Now the optical signals generated by the transmitter are connected to an optical fiber which acts as wave guide. The Signal traverses over longer distances through these wave guides.

(iv) <u>Receiver:</u>

The optical fiber signals are received by the receiver which consists of photo detector, amplifier and a signal restorer.

The photo detector receives the optical signals and generates the equivalent electrical signals.

These signals are amplified by the amplifier.

The signal restorer keeps all the electrical signals in a sequential form and supplies to decoder.

<u>(v) Decoder:</u>

It is an electronic component that converts the digital signals to analog signal.

Applications of Fiber Optics

- Fiber Optic Technology has grown tremendously over the years and today can be found in many surprising places.
- Main Applications of Fiber Optics are:
  - Communication Systems
  - Medicine
  - Sensors
  - Military
  - Electronics

Applications Of FIBRE OPTIC Cables-

- Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:
- **Medical**
  Used as light guides, imaging tools and also as lasers for surgeries
- **Defense/Government**
  Used as hydrophones for seismic and SONAR uses, as wiring in aircraft, submarines and other vehicles and also for field networking
- **Data Storage**
  Used for data transmission
- **Telecommunications**
  Fiber is laid and used for transmitting and receiving purposes
- **Networking**
  Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission
- **Industrial/Commercial**
  Used for imaging in hard to reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings

Applications of OFC :-

- Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:

Medical :- Used as light guides, imaging tools and also as lasers for surgeries

Defence/Government :- Used as hydrophones for seismic and SONAR uses, as wiring in aircraft, submarines and other vehicles and also for field networking

Data Storage :- Used for data transmission

Telecommunications :- Fiber is laid and used for transmitting and receiving purposes

Networking :- Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission.

Industrial/Commercial :- Used for imaging in hard to reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings.

Broadcast/CATV :- Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications
Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables. Fiber optic cables are also used in research and development and testing across all the above mentioned industries.

Applications of optical fiber communication

- As fibers are very flexible, they are used in flexible digital cameras.
- Fibers are used in mechanical imaging i.e. for inspection of mechanical welds in pipes and engines of rockets, space shuttles, airplanes.
- Fibers are used in medical imaging such as endoscopes and laparoscopes.
- Fibers can be used under sea communication.
- Fibers are used in military applications such as aircrafts, ships, tanks etc.
- Nuclear testing applications use optical fiber phase sensors and transducers
- Fibers are used in public utility organizations like railways, TV transmission etc.
- Fibers are used in LAN systems of offices, industrial plants and colleges etc.
- Fibers are used in telecommunication such as voice telephones, video phones, telegraph services, message services and data networks.