

Introduction to

# OPTICAL FIBERS

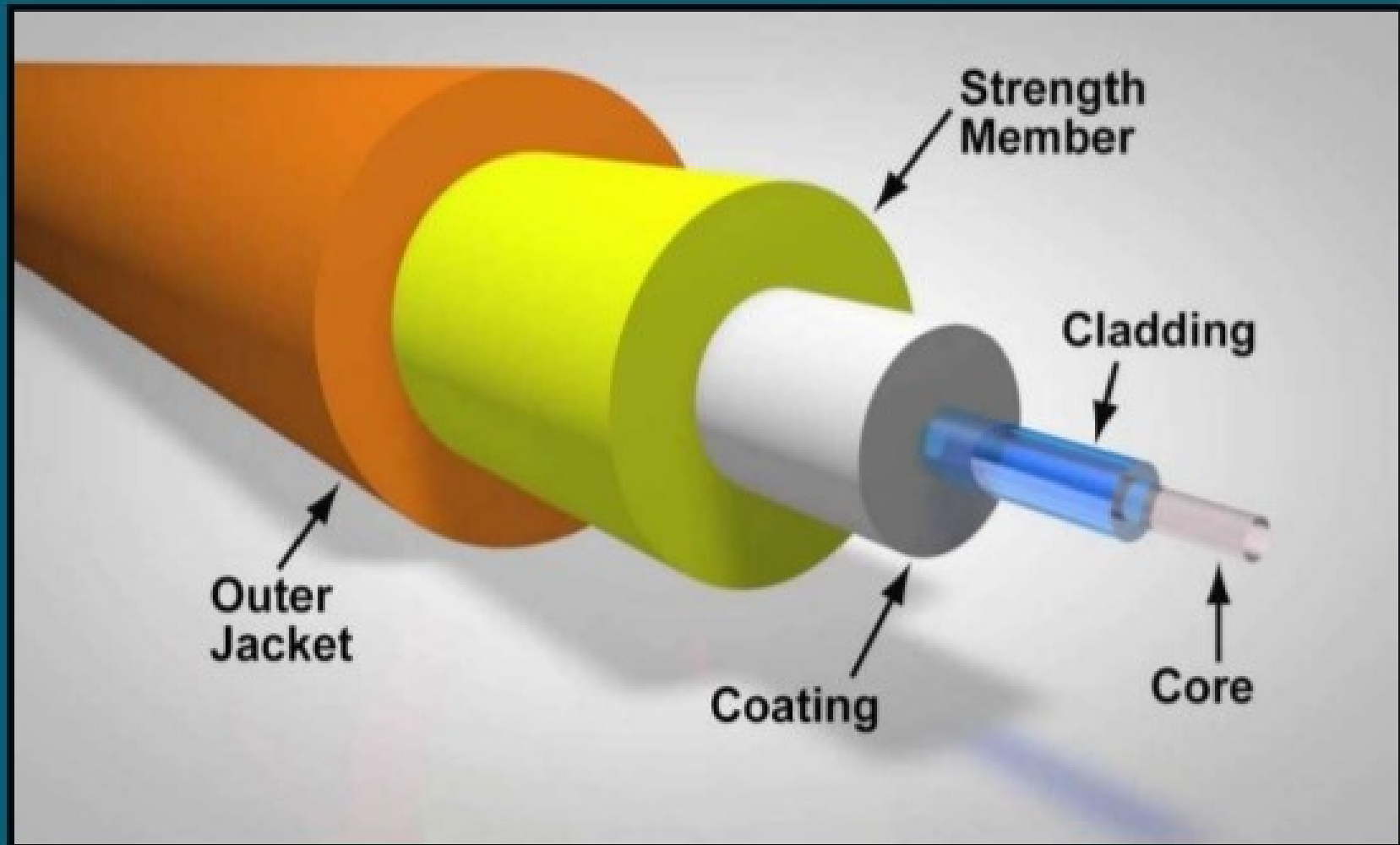


# What is Optical Fiber ?

- An optical fiber is a hair thin cylindrical fiber of glass or any transparent dielectric medium.
- The fiber which are used for optical communication are wave guides made of transparent dielectrics.
- Its function is to guide visible and infrared light over long distance.



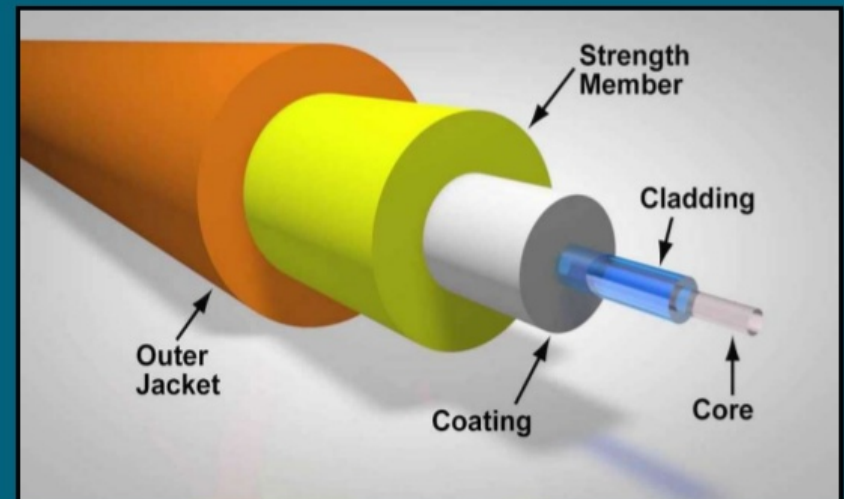
# Structure of optical fiber



## Conti...

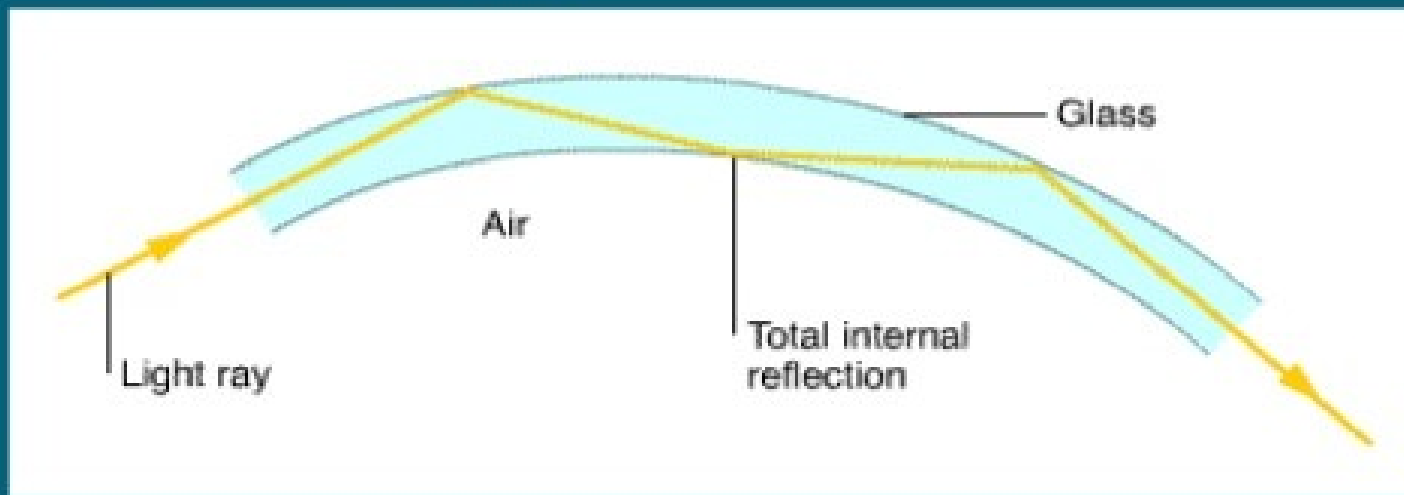
- **Core**- central tube of very thin size made up of optically transparent dielectric medium and carries the light from transmitter to receiver. The core diameter can vary from about 5 $\mu$ m-100  $\mu$ m.
- **Cladding**- outer optical material surrounding the core having reflecting index lower than core. It helps to keep the light within the core throughout the phenomena of total internal reflection.
- **Buffer Coating**- plastic coating that protects the fiber made of silicon rubber. The typical diameter of fiber after coating is 250-300 $\mu$ m.

## Structure of optical fiber



# Working principle

- Total Internal Reflection(TIR)

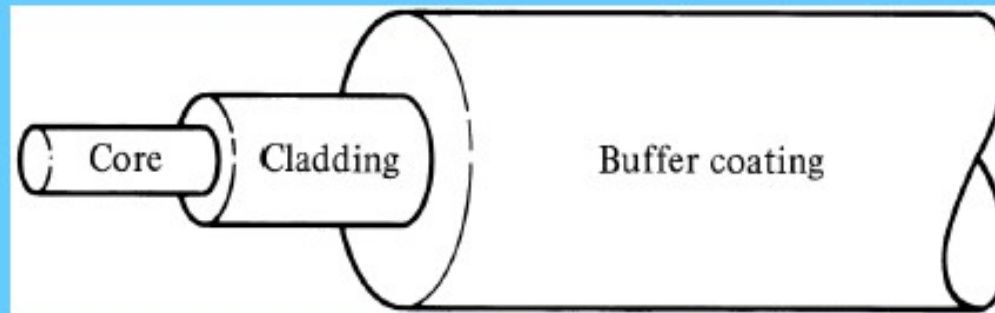


- When an ray of light travels from a denser to a rarer medium such that the angle of incidence is greater than the critical angle, the ray reflects back into the same medium this phenomena is called TIR.
- In the optical fiber the rays undergo repeated total number of reflections until it emerges out of the other end of the fiber, even if fiber is bend.

# OPTICAL FIBER

- An optical fiber is a long cylindrical dielectric waveguide, usually of circular cross-section, transparent to light over the operating wavelength.

## Fiber Structure



- A single solid dielectric of two concentric layers.
  - Inner layer - **Core** of radius ' $a$ ' and refractive index ' $n_1$ '
  - Outer layer – **Cladding** refractive index ' $n_2$ '.

$$n_2 < n_1 \rightarrow \text{condition necessary for TIR}$$

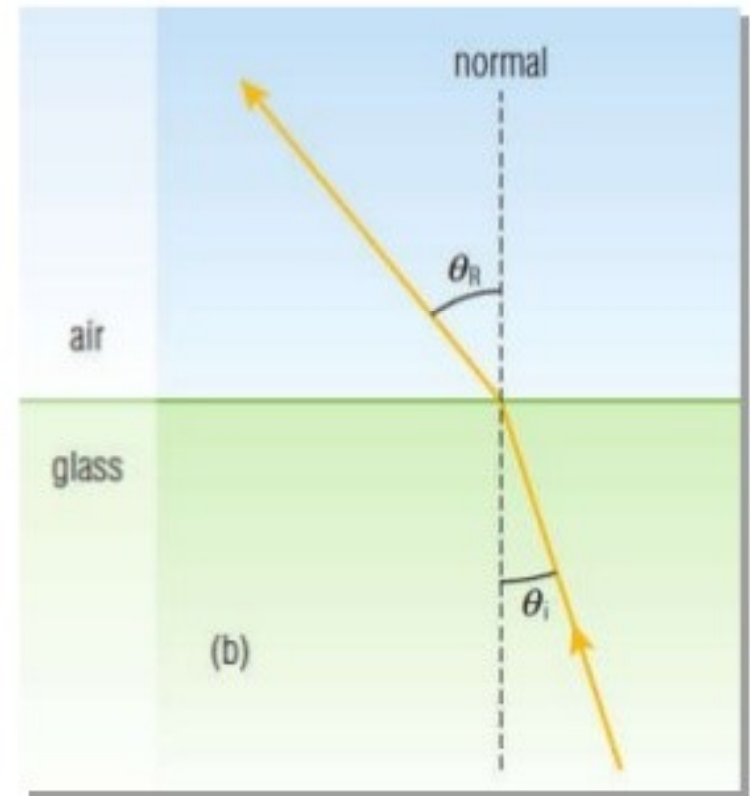
# Optical Fiber Wave guiding

- ❑ To understand transmission mechanisms of optical fibers with dimensions approximating to those of a human hair;
  - Necessary to consider the optical waveguiding of a cylindrical glass fiber.
- Fiber acts as an open optical waveguide – may be analyzed using simple ray theory – **Geometric Optics**
  - Not sufficient when considering all types of optical fibers
- **Electromagnetic Mode Theory** for Complete Picture

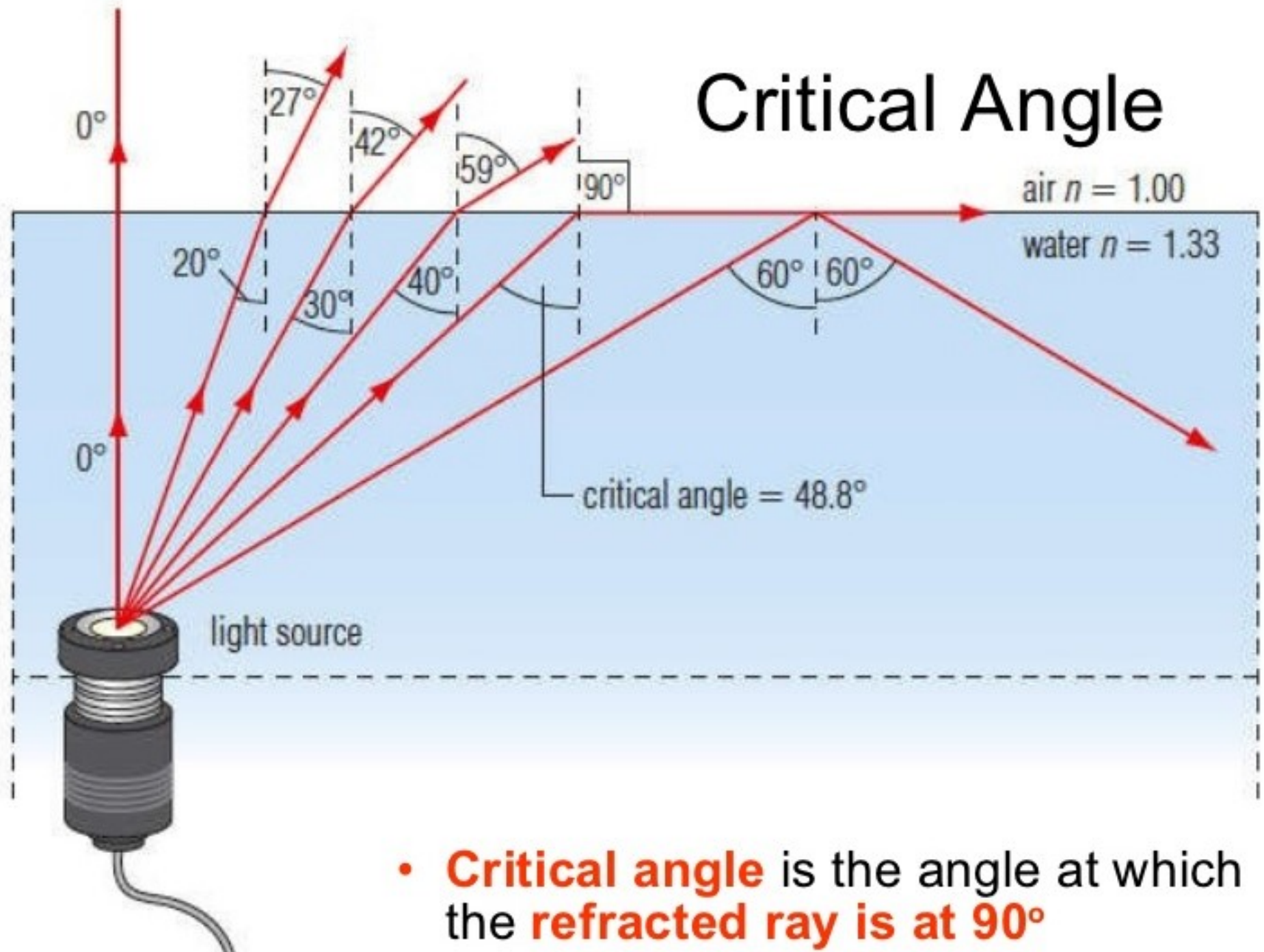
# Total Internal Reflection

Recall:

- When light passes from a dense material into a less dense medium, light reflects **away** from the **normal**



# Critical Angle



- **Critical angle** is the angle at which the **refracted ray is at  $90^\circ$**

## Total Internal Reflection; Fiber Optics

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

$$\sin(\theta_1) = \frac{n_2}{n_1} \sin(\theta_2)$$

**Suppose  $n_2 < n_1$**

- largest possible value of  $\sin(\theta_2)$  is 1 (when  $\theta_2 = 90^\circ$ )
- therefore, largest possible value of  $\sin(\theta_1)$  is

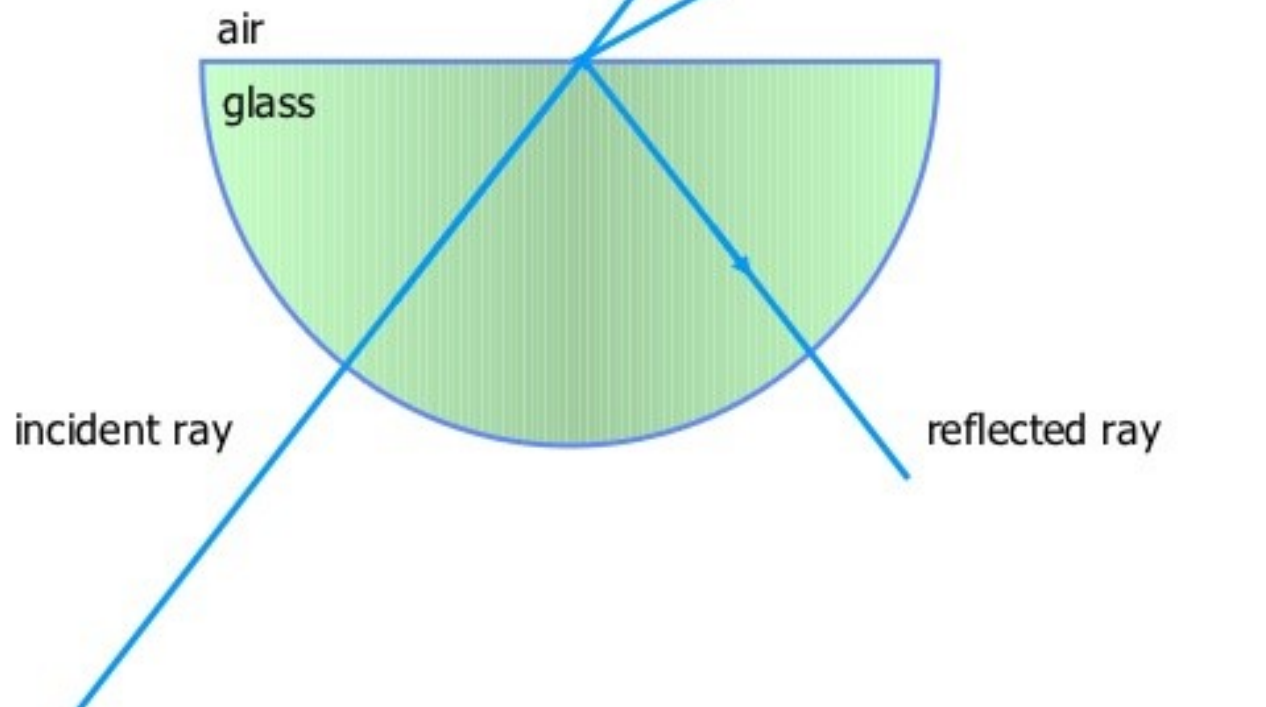
$$\sin(\theta_{1,\max}) = \sin(\theta_c) = \frac{n_2}{n_1}.$$

For  $\theta_1$  larger than  $\theta_c$ , Snell's Law cannot be satisfied!

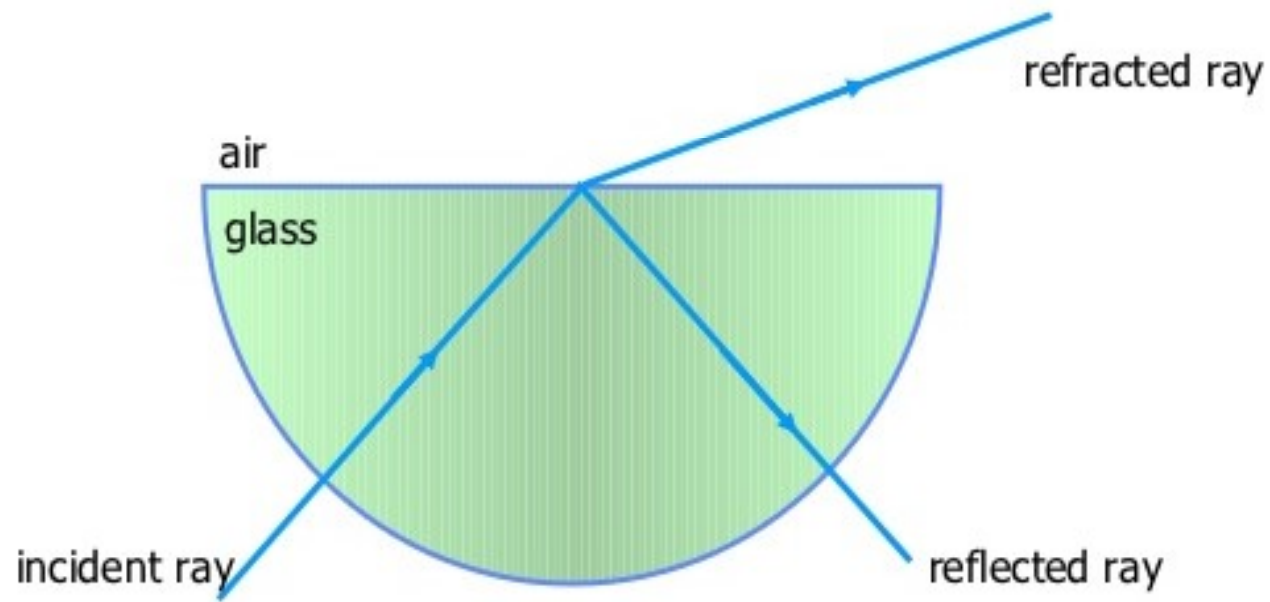
- for  $\theta_1 > \theta_c$ : no refracted ray, light is **totally reflected**
- $\theta_c$  is called the critical angle of total internal reflection

# Total Internal Reflection

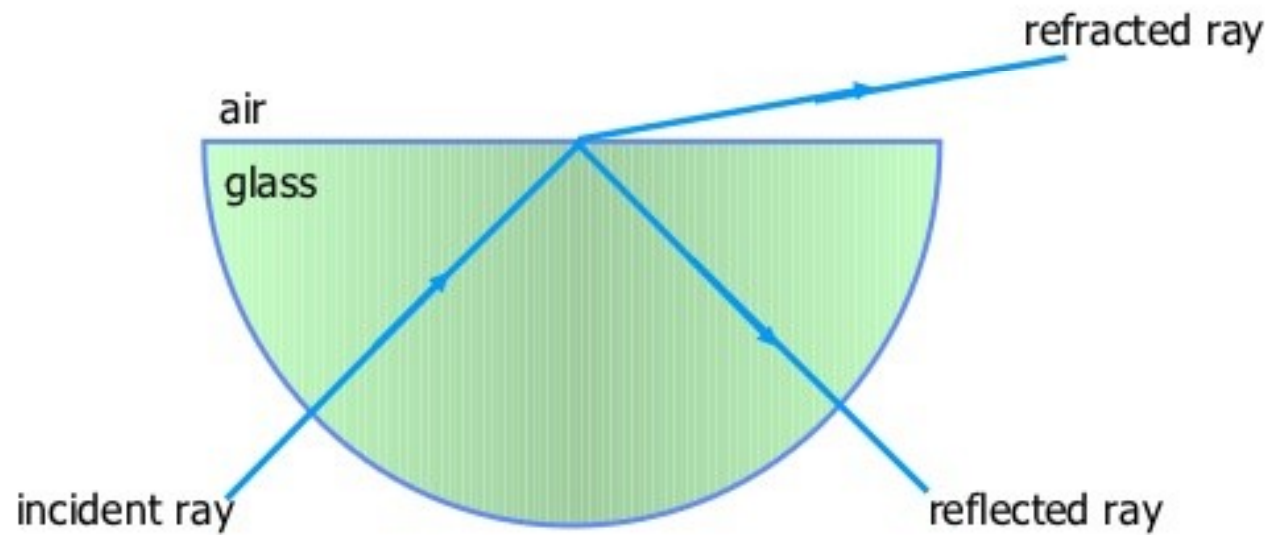
- A light ray hits the inside face of a semicircular block as follows.
- What will happen as the angle of incidence increases?



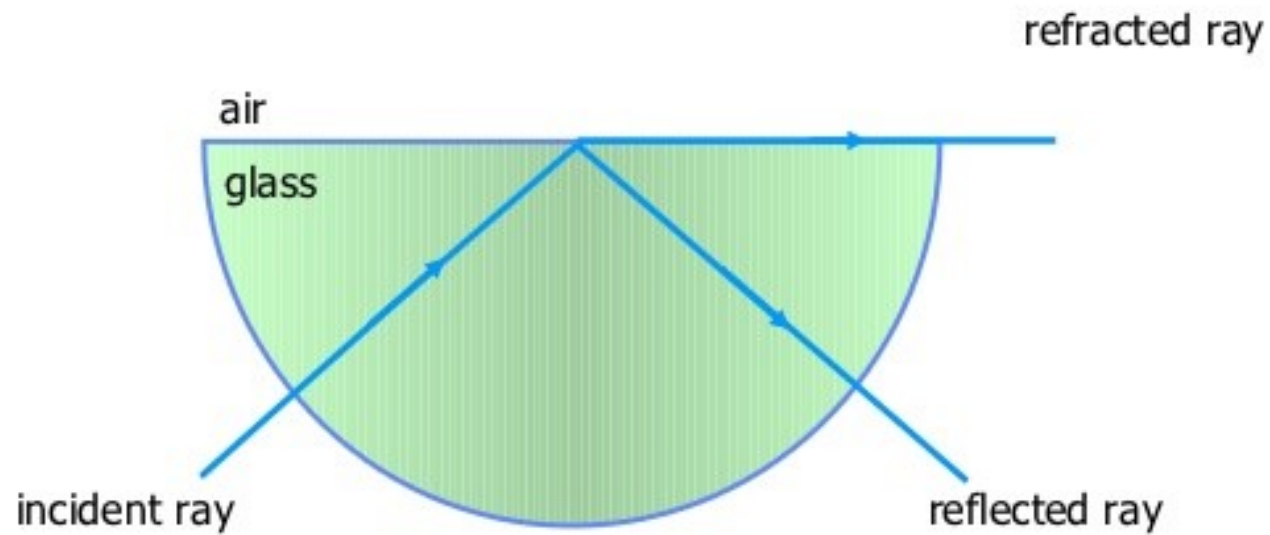
# Total Internal Reflection



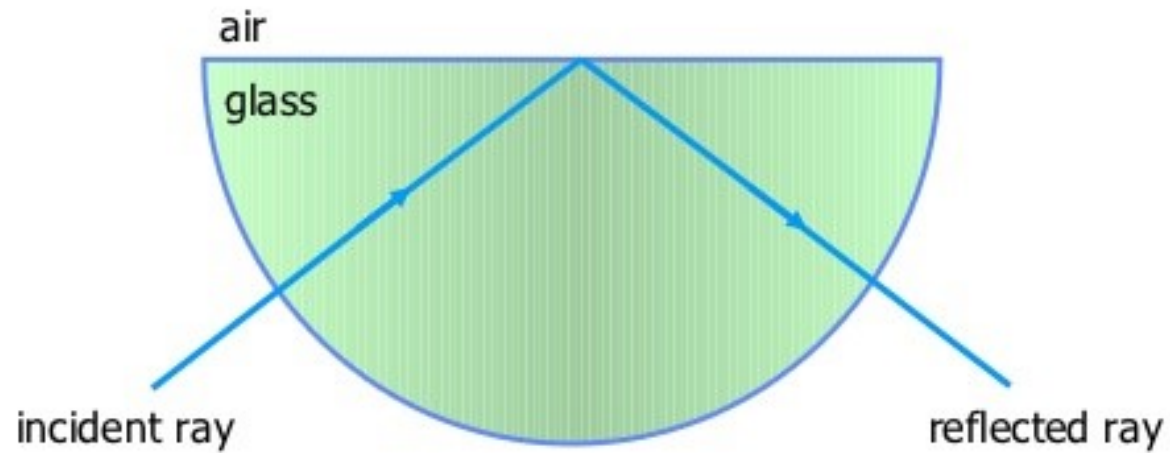
# Total Internal Reflection



# Total Internal Reflection

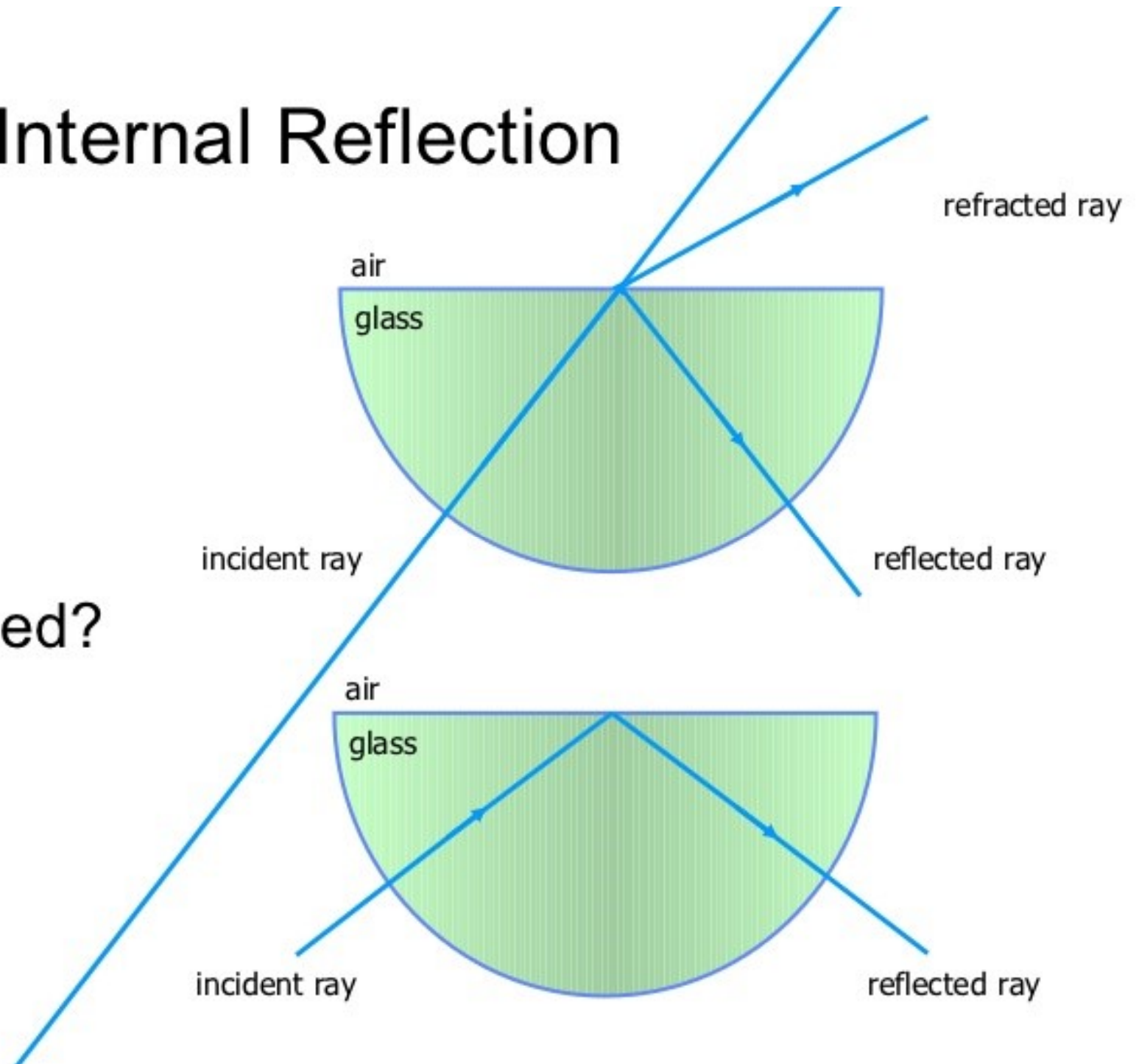


# Total Internal Reflection



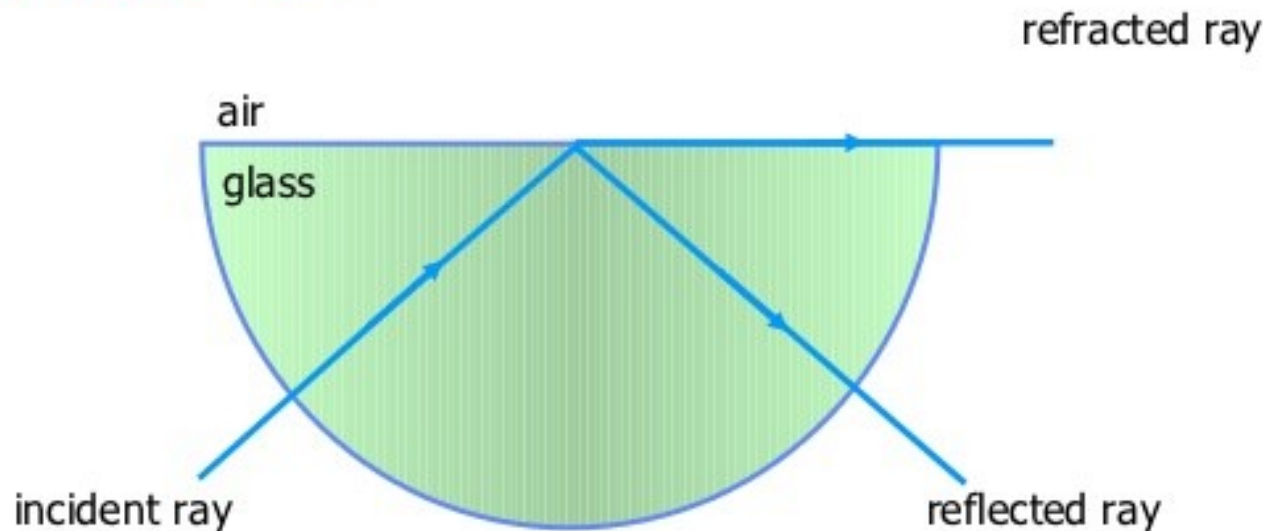
# Total Internal Reflection

What happened?



# Total Internal Reflection

- Angle of refraction is at  $90^\circ$ , parallel to the surface of the medium
- At this point the angle of incidence = critical angle (C)
- **Angle of incidence = C when angle of refraction =  $90^\circ$**



# Calculating Critical Angle

- Snell's Law:  $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- Critical angle  $C = \theta_1$  thus solve for  $\theta_1$

At the critical angle, the refracted ray is a  $90^\circ = \theta_2$

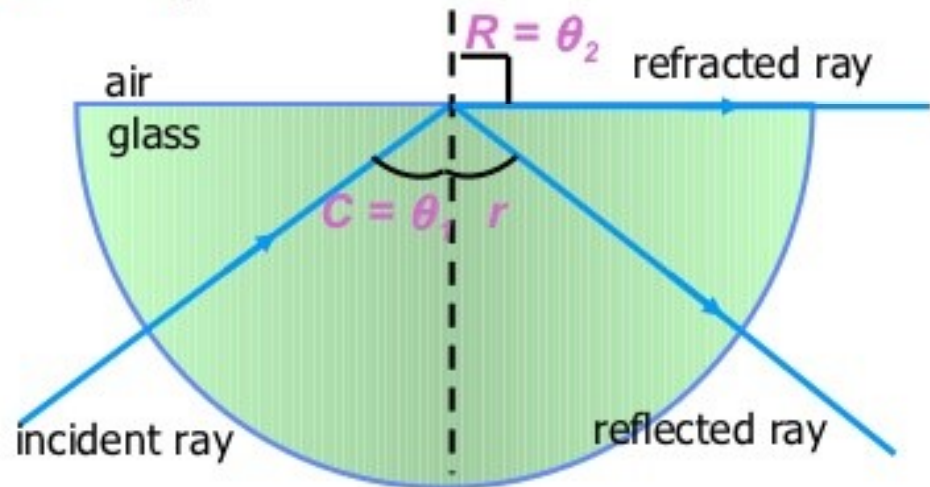
- $n_1 \sin\theta_1 = n_2 \sin 90^\circ$  ( $\sin 90^\circ = 1$ )
- $n_1 \sin\theta_1 = n_2 \cdot 1$
- $n_1 \sin\theta_1 = n_2$

Rearrange equation to get:

- $\sin\theta_1 = n_2 / n_1$
- $\theta_1 = \sin^{-1} (n_2 / n_1)$

If medium 2 = air, then  $n_2 = 1$

- $\theta_1 = \sin^{-1} (1 / n_1)$
- $C = \sin^{-1} (1 / n_1)$



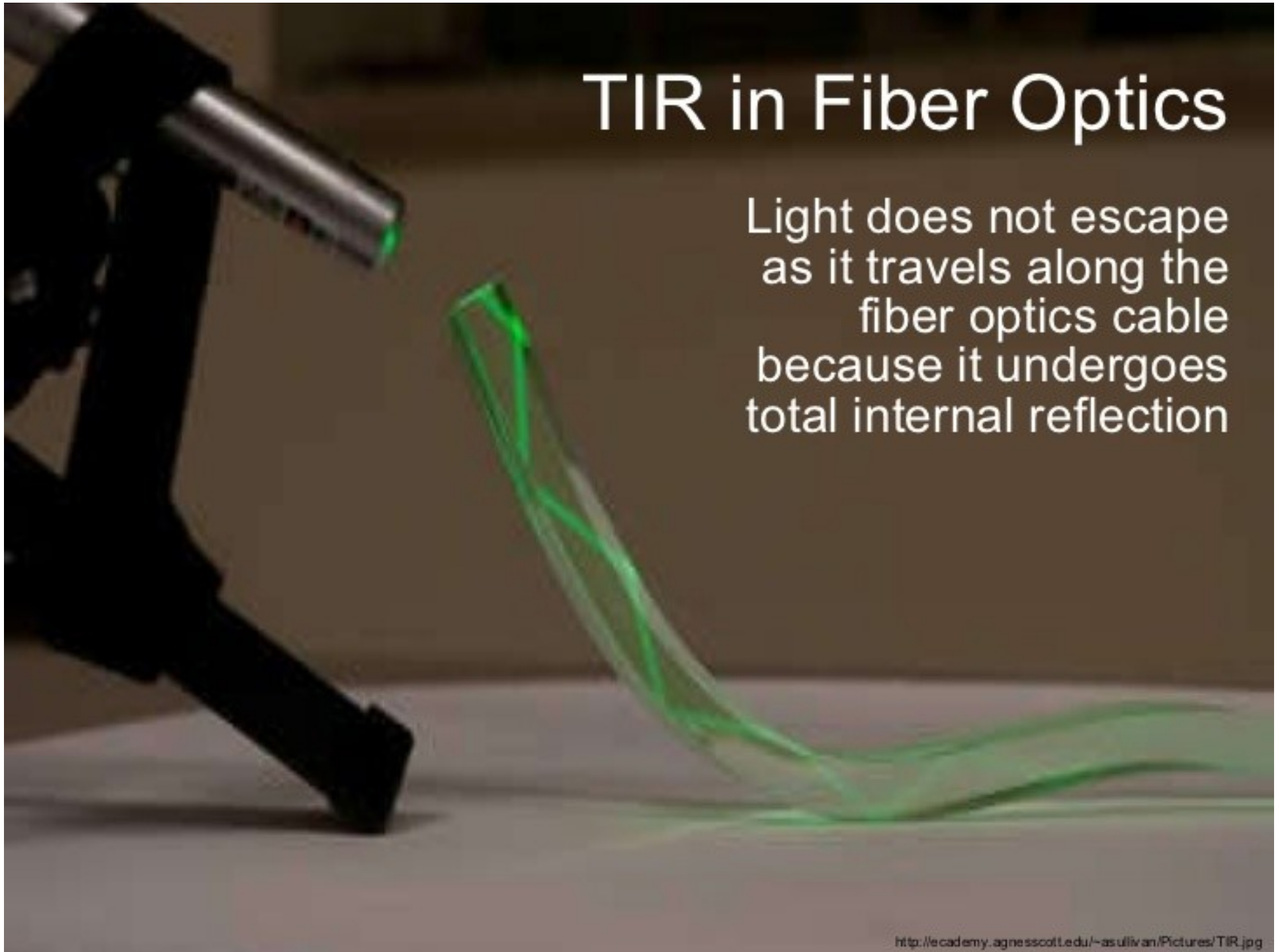
# TOTAL INTERNAL REFLECTION

- **critical angles of different materials**

| Medium  | Refractive index | Critical angle |
|---------|------------------|----------------|
| Glass   | 1.50–1.70        | 30°–42°        |
| Water   | 1.33             | 49°            |
| Perspex | 1.5              | 42°            |
| Diamond | 2.42             | 24°            |

# TIR in Fiber Optics

Light does not escape  
as it travels along the  
fiber optics cable  
because it undergoes  
total internal reflection





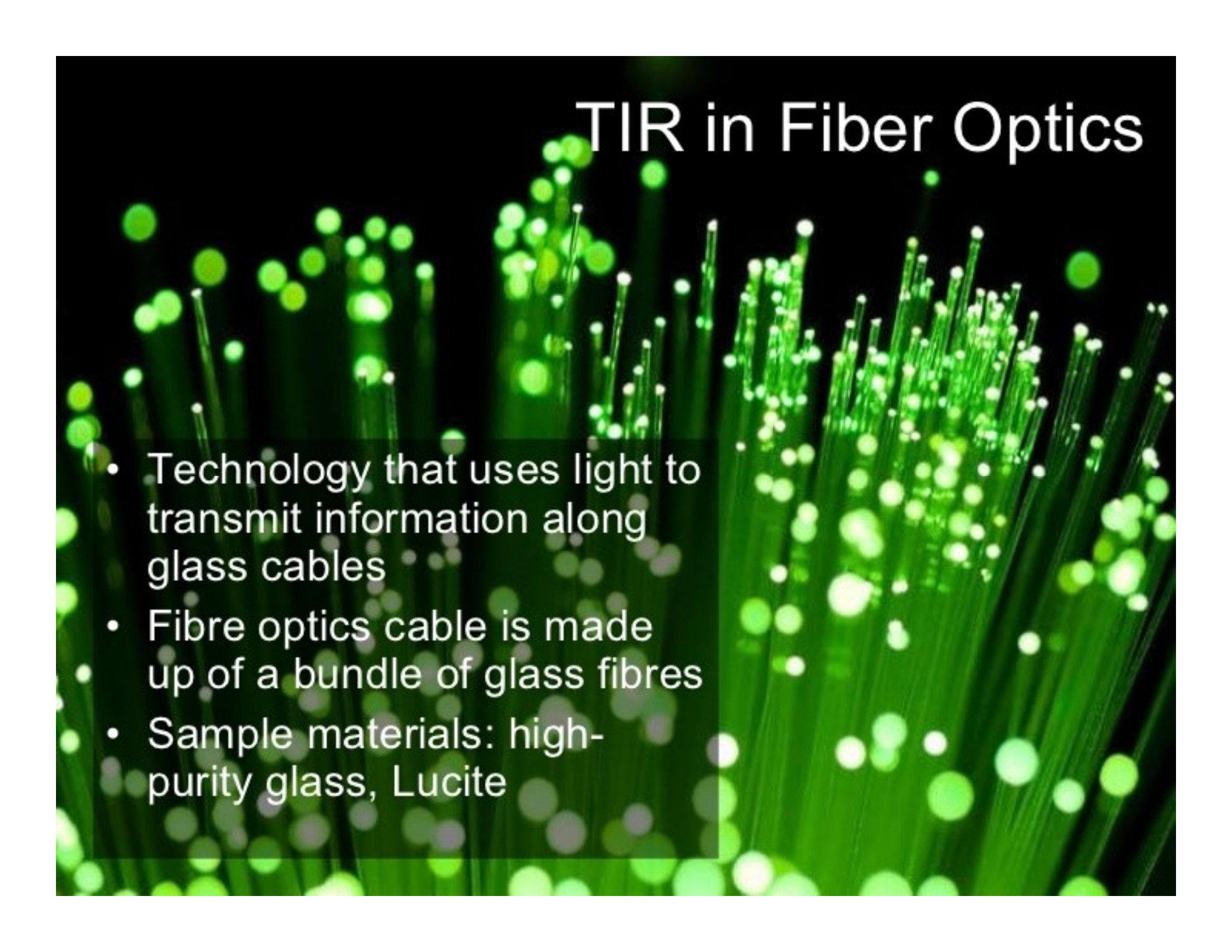
# TIR in Diamonds

Sparkling is due to:

2. Cut of diamond faces
3. High index of refraction which means a very small critical angle ( $n = 2.42$ ,  $C = 24.4^\circ$ )

Incident rays can undergo multiple TIR inside a diamond before exiting the top of the diamond.

# TIR in Fiber Optics



- Technology that uses light to transmit information along glass cables
- Fibre optics cable is made up of a bundle of glass fibres
- Sample materials: high-purity glass, Lucite

# Classification of optical fiber

- Optical fiber is classified into two categories based on:-

## 1) The number of modes-

- Single mode fiber(SMF) and
- Multi-mode fiber(MMF)

## 2) The reflective index-

- Step index optical fiber
- Graded- index optical fiber

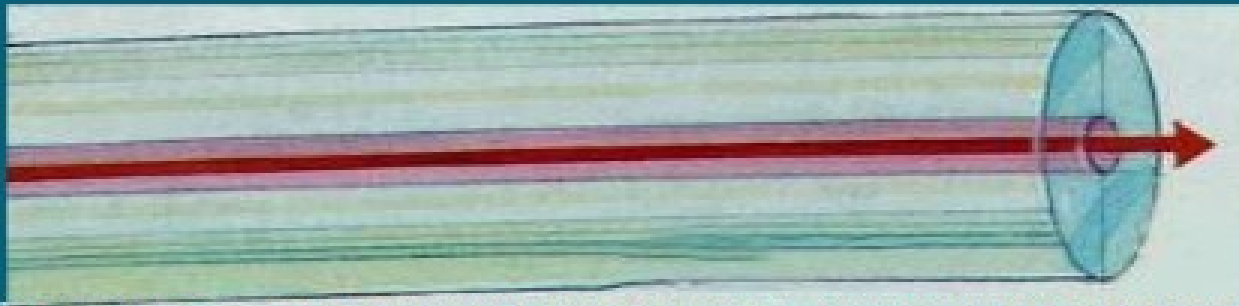
# MODE OF PROPAGATION

- Two main categories of optical fiber used in fiber optic communications are multi-mode optical fiber and single-mode optical fiber.



# On basis of number of modes:-

## Single mode fiber-



- ❖ In single mode fiber only one mode can propagate through the fiber.
- ❖ It has small core diameter (5 $\mu$ m) and high cladding diameter (70 $\mu$ m).
- ❖ Difference between the refractive index of core and cladding is very small.
- ❖ There is neither dispersion nor degradation therefore it is suitable for long distance communication.
- ❖ The light is passed through the single mode fiber through laser diode.

# SINGLE-MODE FIBERS

- **Single-mode fibers** – used to transmit one signal per fiber (used in telephone and cable TV). They have small cores(9 microns in diameter) and transmit infra-red light from laser.

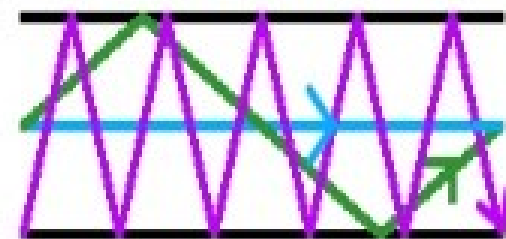
# SINGLE-MODE FIBERS

- Single-mode fiber's smaller core (<10 micrometres) necessitates more expensive components and interconnection methods, but allows much longer, higher-performance links.

# Multi- mode fiber

- ❖ It allows a large number of modes for light ray travelling through it.
- ❖ The core diameter is 40um and that of cladding is 70um.
- ❖ The relative refractive index difference is also large than single mode fiber.
- ❖ There is signal degradation due to multimode dispersion.
- ❖ It is not suitable for long distance communication due to large dispersion and attenuation of signal.

Single-mode fiber



Multi-mode fiber

# MULTI-MODE FIBERS

- **Multi-mode fibers** – used to transmit many signals per fiber (used in computer networks). They have larger cores(62.5 microns in diameter) and transmit infra-red light from LED.

# MULTI-MODE FIBERS

- Multimode fiber has a larger core ( $\geq 50$  [micrometres](#)), allowing less precise, cheaper transmitters and receivers to connect to it as well as cheaper connectors.

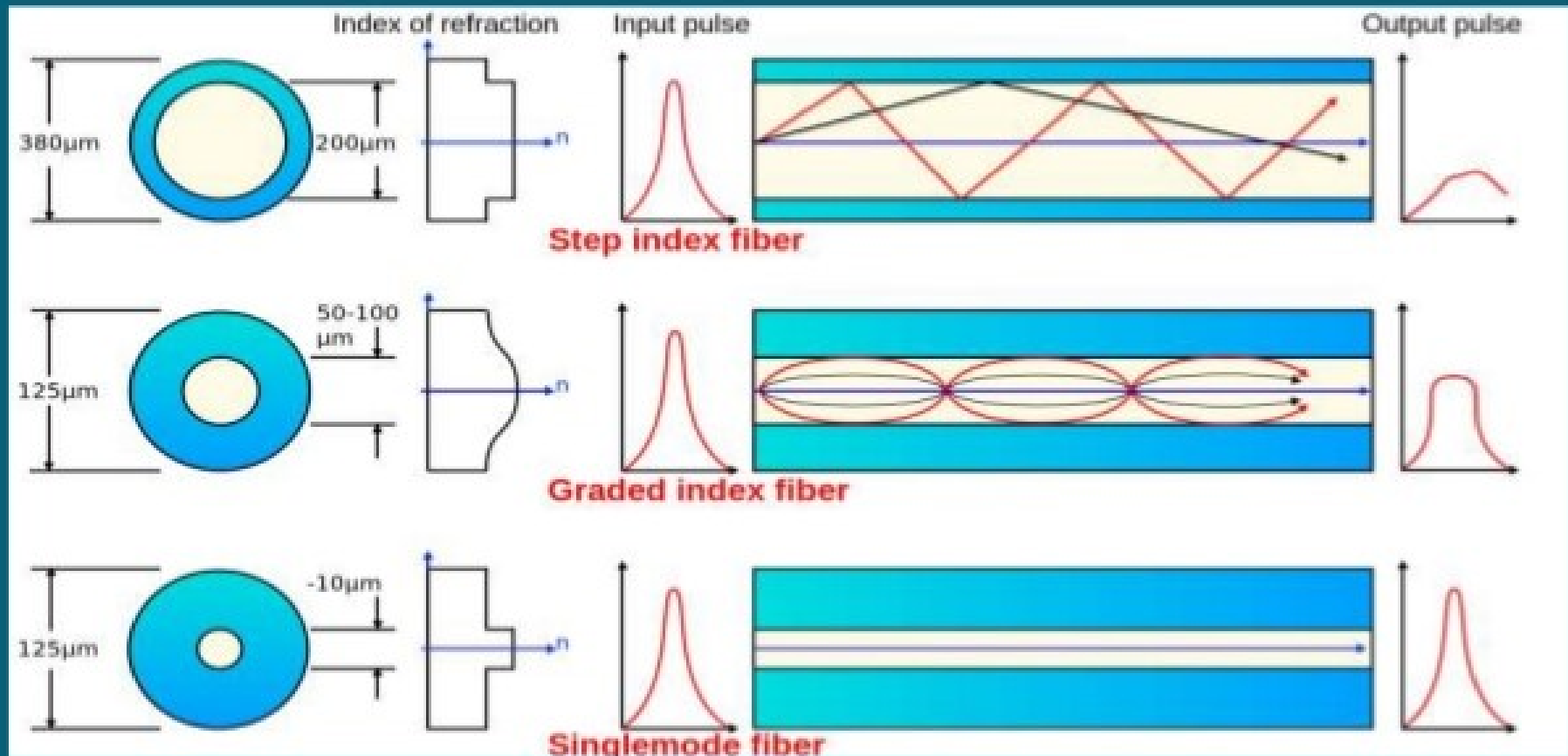


# MULTI-MODE FIBERS

- However, multi-mode fiber introduces multimode distortion which often **limits the bandwidth** and length of the link. Furthermore, because of its higher dopant content, multimode fiber is usually **more expensive and exhibits higher attenuation**.

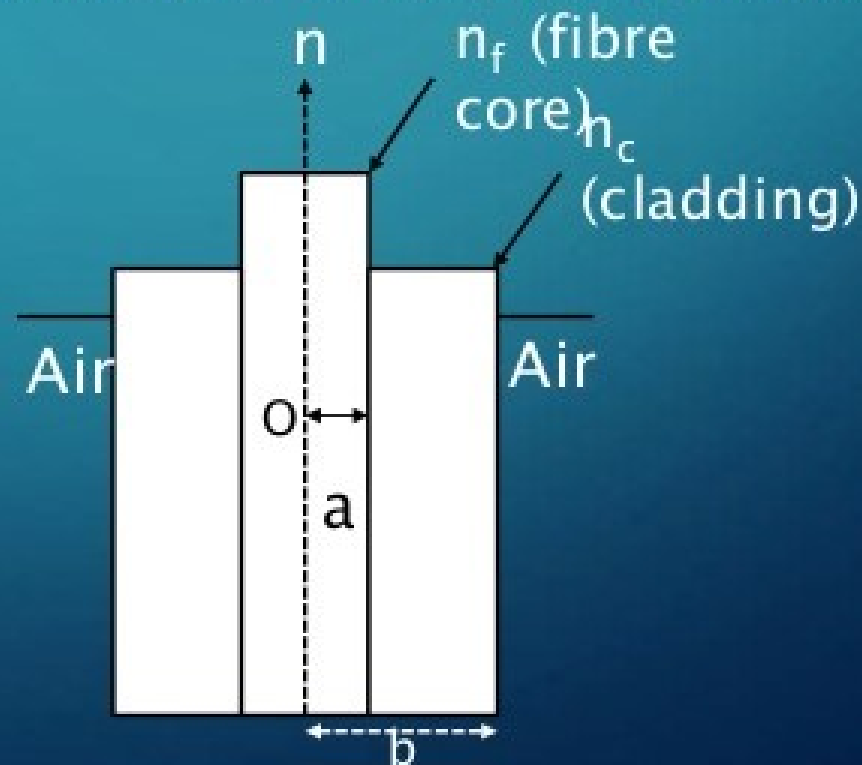
# On the basis of refractive index

- There are two type of optical fiber:-
  - 1) Step index optical fiber
  - 2) Graded- index optical fiber



## STEP-INDEX PROFILE

In this type of optical fibre the fibre core has a uniform refractive index  $n_f$  and cladding also has uniform refractive index  $n_c$  such that  $n_f > n_c$ . The figure below represents the step-index optical fibre where  $a$  and  $b$  are the radii of the core and cladding, respectively.



# Step Index Fibers

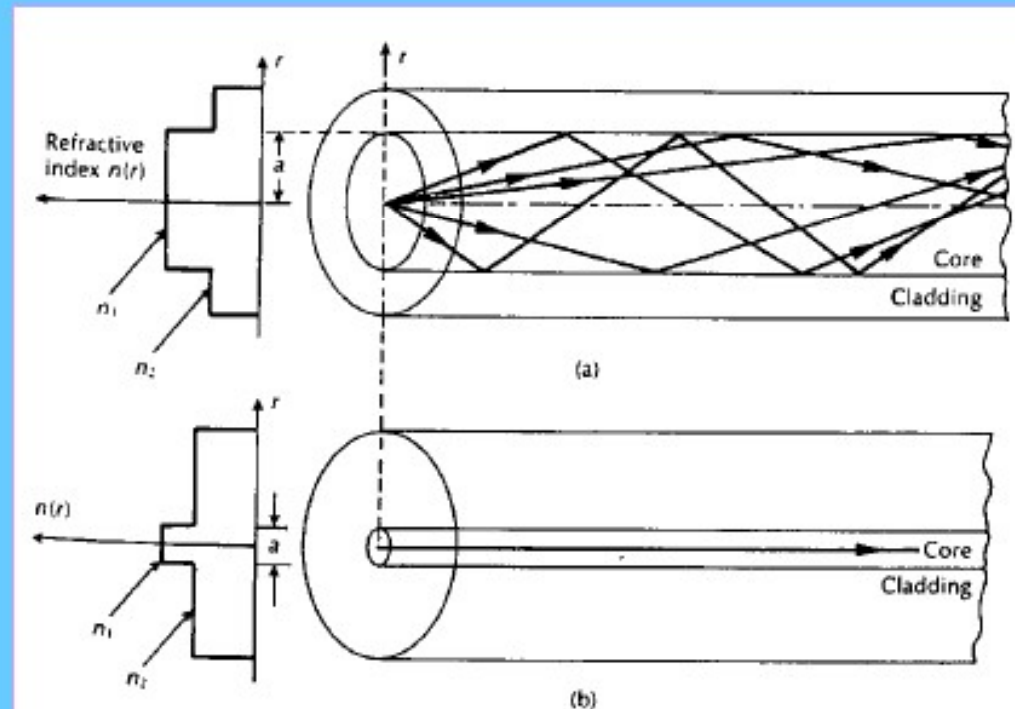
Fiber with a core of constant refractive index  $n_1$  and a cladding of slightly lower refractive index  $n_2$ .

- Refractive index profile makes a step change at the core-cladding interface

## Refractive index profile

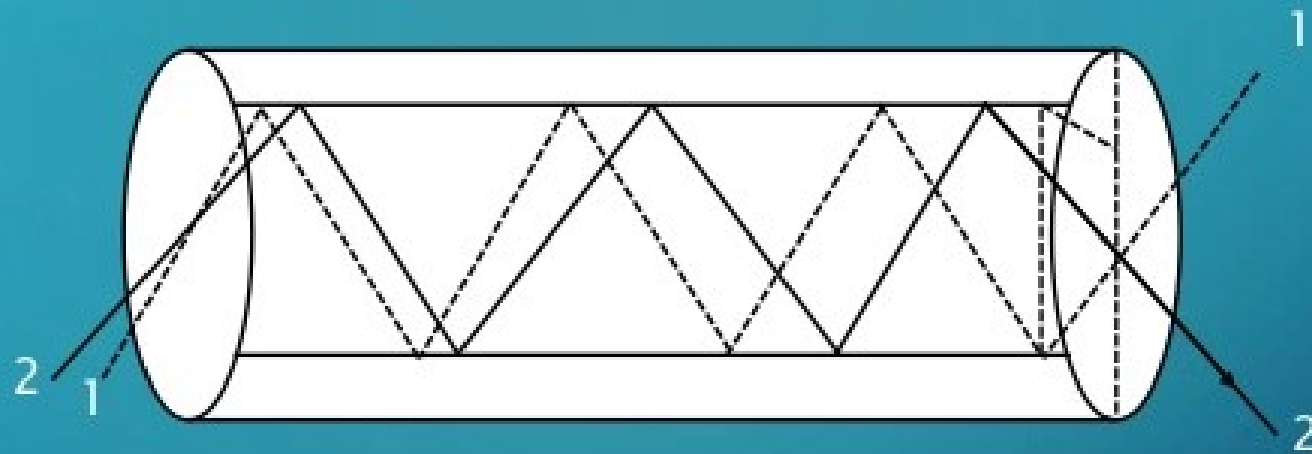
$$n(r) = \begin{cases} n_1 & ; r < a \text{ (core)} \\ n_2 & ; r \geq a \text{ (cladding)} \end{cases}$$

- Multimode Step Index
- Single mode Step Index



The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber. (b) single-mode step index fiber.

The following figure shows the path of rays:



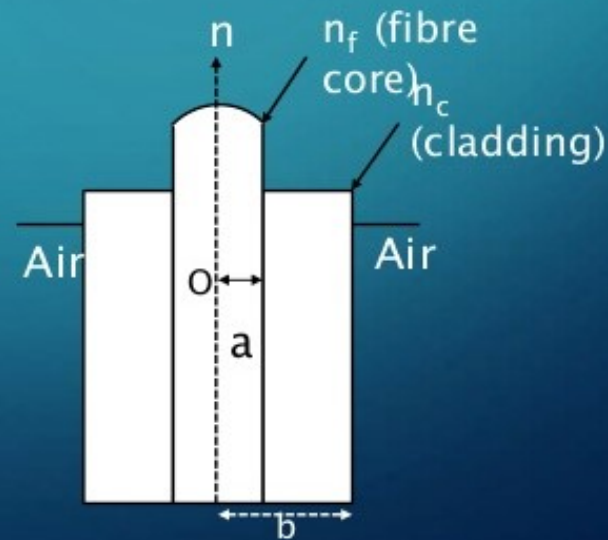
The rays entering at different angles, travel different paths and emerge out the fibre at different time along different directions. Two rays are shown in figure. Clearly, an input pulse widens as it travels along the fibre.

# STEP-INDEX

- A step-index fiber has a central core with a uniform refractive index. An outside cladding that also has a uniform refractive index surrounds the core;
- however, the refractive index of the cladding is less than that of the central core.

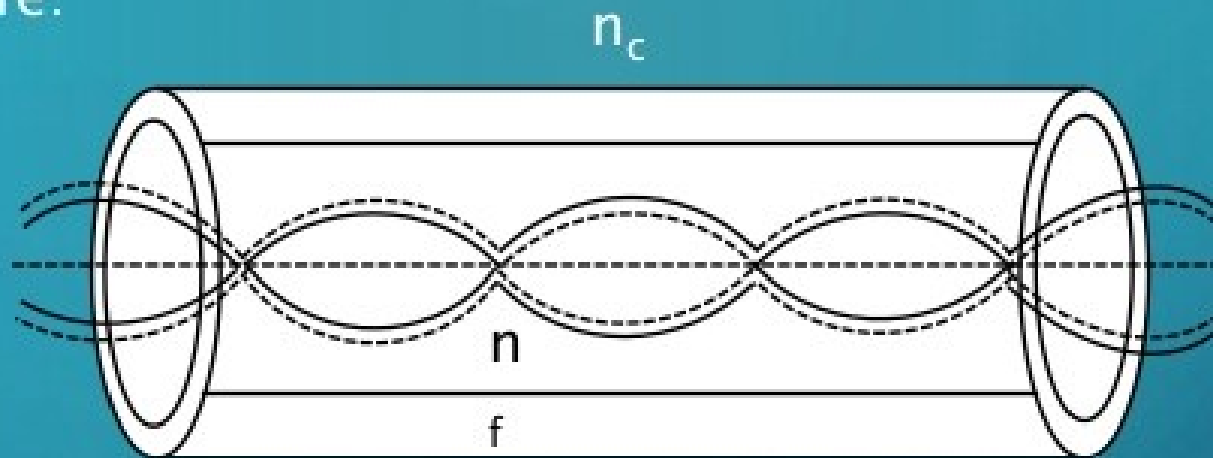
## Graded-index profile

In graded-index optical fibre the core has non-uniform refractive index which increases from axis towards the cladding. The cladding has a uniform refractive index.



Gradient index fibers have a nonlinear but rotationally symmetric refractive index profile, which falls off gradually from the center of the optical-fiber outwards.

The path of rays is shown in the following figure:



In this type, the entering ray is continuously bent and travels a periodic path along the axis. The rays entering at different angles follow different paths with same period in space and time. Thus there is a periodic self-focusing of the rays. In this type of fibre the pulse-dispersion is less than that in step-index fibre.

# GRADED-INDEX

- In **graded-index fiber**, the index of refraction in the core decreases continuously between the axis and the cladding. This causes light rays to bend smoothly as they approach the cladding, rather than reflecting abruptly from the core-cladding boundary.

## Single Index fiber:-

- ❖ Step-index optical fiber-the refractive index of core and cladding are constant.
- ❖ The light ray propagate through it in the form of meridiogal rays which cross the fiber axis during every reflection at the core cladding boundary.

## Graded Index Fiber:-

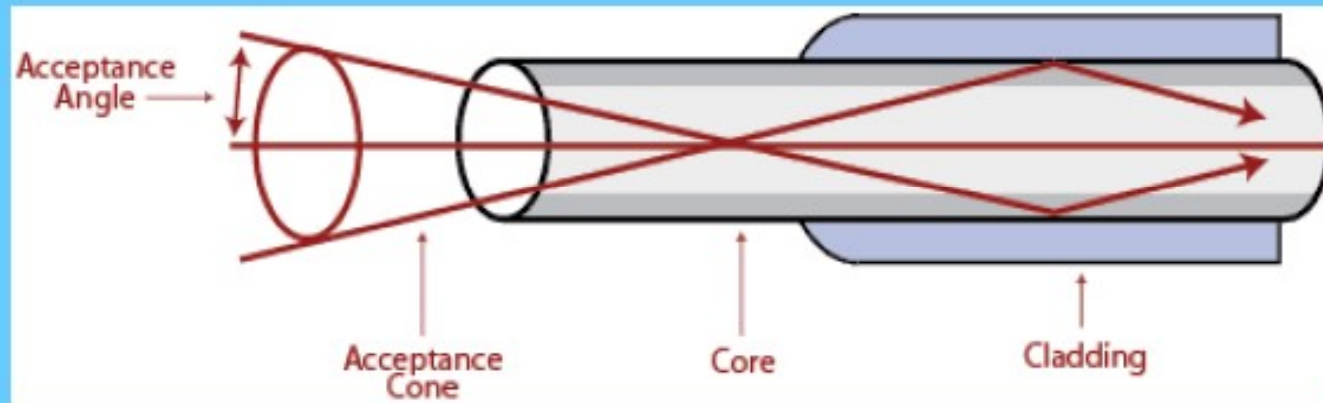
- ❖ In this type of fiber core has a non uniform refractive index that gradually decrease from the center towards the core cladding interface.
- ❖ The cladding has a uniform refractive index.
- ❖ The light rays propagate through it in the form of helical rays. They never cross the fiber axis.

## Characteristics of Optical fibers

1. **Wider bandwidth:** The optical carrier frequency is in the range  $10^{13}$  Hz to  $10^{15}$  Hz.
2. **Low transmission loss:** The fibers having a transmission loss of 0.002 dB/km.
3. **Dielectric waveguide:** Optical fibers are made from silica which is an electrical insulator. Therefore they do not pickup any electromagnetic wave or any high current lightning.
4. **Signal security:** The transmitted signal through the fibers does not radiate. Further the signal cannot be tapped from a Fiber in an easy manner.
5. **Small size and weight:** Fiber optic cables are developed with small radii, and they are flexible, compact and lightweight. The fiber cables can be bent or twisted without damage.

# Acceptance Cone

- ❖ For rays to be transmitted by TIR within the fiber core, they must be incident on the fiber core within an acceptance cone defined by the *conical half angle* “ $\theta_a$ ”.



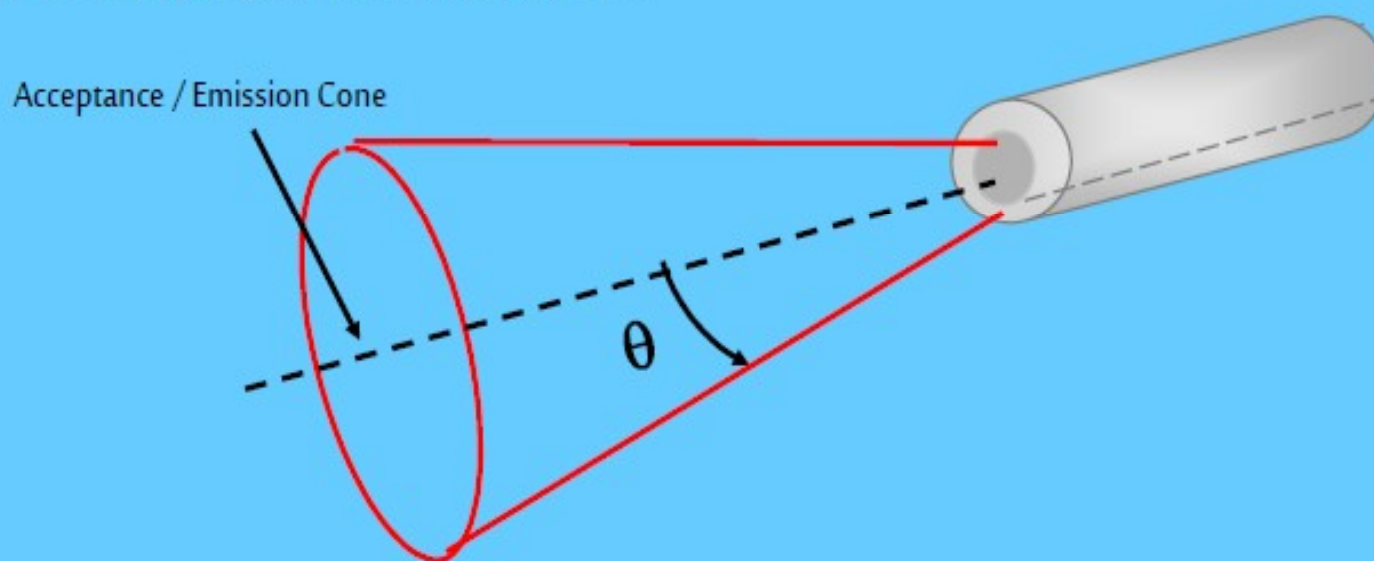
☞ ‘ $\theta_a$ ’ is the maximum angle to the axis at which light may enter the fiber in order to be propagated

⇒ **Acceptance angle** for the fiber

# Numerical Aperture (NA)

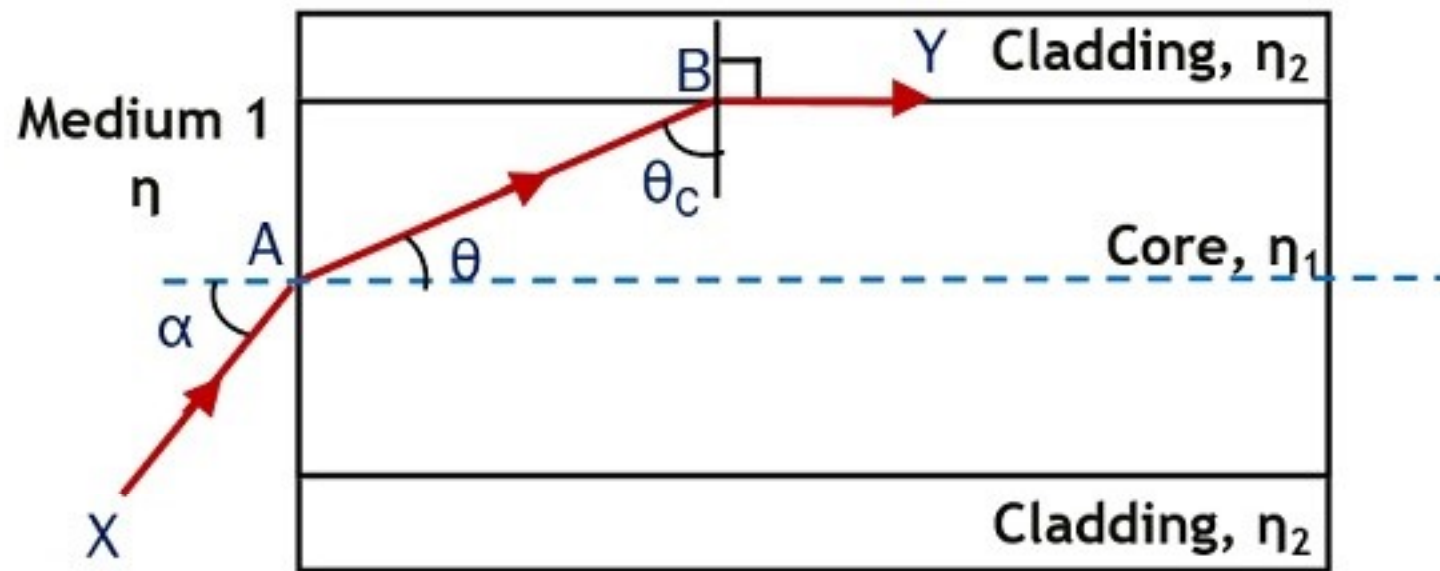
❑ A very useful parameter : measure of light collecting ability of fiber.

- Larger the magnitude of NA, greater the amount of light accepted by the fiber from the external source



$$NA = \sin \theta_a = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$$

- NA varies from **0.12- 0.20 for SMFs** and **0.20- 0.50 for MMFs**



Ray propagation through Optical Fiber

Circuit Globe

According to Snell's law, the incident and refracted ray propagate in the same plane. Hence, on applying Snell's law at medium 1 (usually air) and core interface. Then

$$\eta \sin \alpha = \eta_1 \sin \theta \quad \text{----- eq}^n 1$$

From the above figure, we can write

$$\theta = \frac{\pi}{2} - \theta_c \quad \text{----- eq}^n 2$$

On putting the value of  $\theta$  from the above equation in equation 1, we get,

$$\eta \sin \alpha = \eta_1 \sin \left( \frac{\pi}{2} - \theta_c \right)$$

$$\eta \sin \alpha = \eta_1 \cos \theta_c \quad (\text{by trigonometric identity})$$

$$\sin \alpha = \frac{\eta_1}{\eta} \cos \theta_c \quad \text{----- eq}^n 3$$

$$\cos \theta_c = \sqrt{1 - \sin^2 \theta_c} \quad \text{----- eq}^n 4$$

$$\eta_1 \sin \theta_c = \eta_2 \sin 90^\circ \quad \text{----- eq}^n 5$$

$$\eta_1 \sin \theta_c = \eta_2$$

$$\sin \theta_c = \frac{\eta_2}{\eta_1} \quad \text{----- eq}^n 6$$

$$\cos \theta_c = \sqrt{1 - \left[ \frac{\eta_2}{\eta_1} \right]^2}$$

Substituting the above value in equation 3, we get

$$\sin \alpha = \frac{\eta_1}{\eta} \sqrt{1 - \left[ \frac{\eta_2}{\eta_1} \right]^2}$$

$$\sin \alpha = \sqrt{\frac{\eta_1^2 - \eta_2^2}{\eta^2}} \quad \text{----- eq}^n 7$$

As we have already discussed that medium 1 is air, thus refractive index i.e.,  $\eta$  will be 1.

So more specifically we can say

$$\sin \alpha = \sqrt{\eta_1^2 - \eta_2^2}$$

$$NA = \sqrt{\eta_1^2 - \eta_2^2}$$

This is the expression for the numerical aperture of an optical fiber, having  $\eta_1$  as the refractive index of core and  $\eta_2$  as the refractive index of the cladding.

So we can conclude that as the numerical aperture shows the light collecting ability of the fiber thus its value must be high. As higher the value of NA, better will be the optical fiber.

However, the greater value of NA will be achieved only when the difference between the two refractive indices is high and for this either,  $\eta_1$  is to be high or  $\eta_2$  to be low.

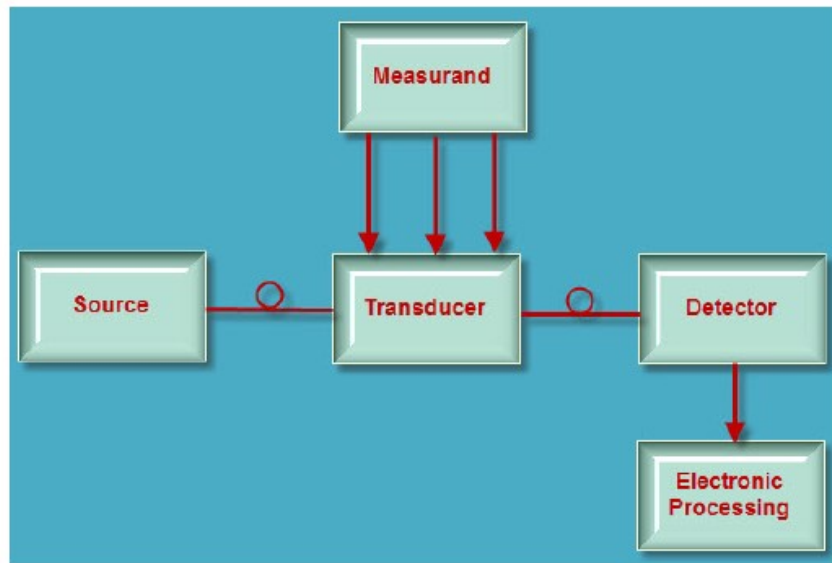
While, for optical signal propagation, the only motive is not to have high accepting range but also to propagate the accepted signal with minimal attenuation.

This is so because an optical fiber that has the greatest light gathering efficiency but does not allow light propagation through it properly, is not of any use.

## Fiber optic sensors

- ❑ The fiber optic sensors also called as optical fiber sensors.
- ❑ Optical fiber sensors are used to sense some quantities like temperature, pressure, vibrations, displacement or concentration of chemical species.
- ❑ Fiber optic sensors are supreme for insensitive conditions, including noise, high vibration wet and unstable environments .

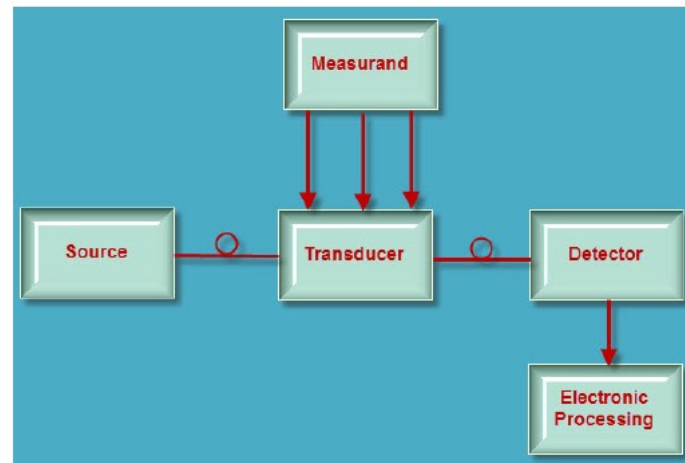
## Fiber optic sensors working principle



*Block Diagram Of Fiber Optic Sensor*

Basically, an FOS system is composed of a light source (Laser, LED, Laser diode etc), an optical-fiber; a sensing or modulating element or transducer (which transduces the measurand to an optical signal), an optical detector and the processing electronic unit (oscilloscope, optical spectrum analyzer etc.).

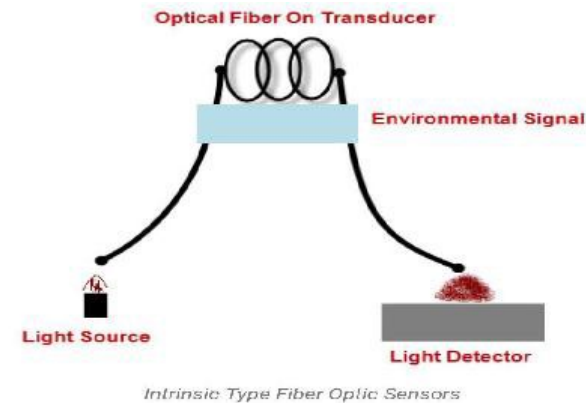
Light beam changes by the phenomena that is being measured. The principle of operation of an FOS is that a transducer modulates certain parameters of the optical system (wavelength, intensity, phase, polarization etc.) which causes a change in the characteristics of optical signal received by the detector.



*Block Diagram Of Fiber Optic Sensor*

# 1. Active fiber optic sensors

## (Intrinsic Type Fiber Optic Sensors)

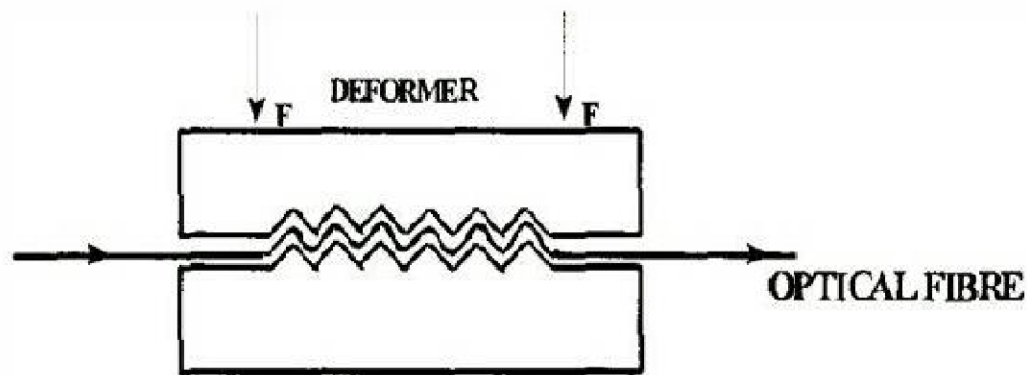


- ❑ In optical fiber communication, because the signal usually decays during long distance transformation, you need to add an amplifier to boost the signal.
- ❑ In such type of sensors, sensing takes place within the fiber itself.
- ❑ These type of sensors have their dependency on the optical fiber properties itself to convert an environmental action into a modulation of the light beam passing through it.
- ❑ Virtually, any environmental effect can be converted to an optical signal to be interpreted. Each environmental effect may be measured by dozens of different fiber optic sensors approaches.
- ❑ It has been designed in such a way that it sensed only the environmental effects. The most important characteristics of intrinsic fiber optic sensors is that it provides distributed sensing over long distances.

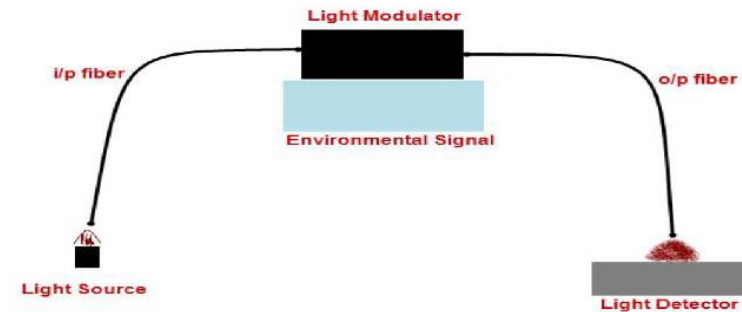
# PRESSURE SENSOR

In such type of sensors a fiber is sandwiched between a pair of toothed plates to induce micro bending .When pressure is applied to these toothed pairs, there is a redistribution of guided power between modes of fiber occurs, which changes the power at output end .Once we calibrate such change in optical power with applied pressure we can easily use such system as a pressure sensor.

A schematic diagram of such type of sensor is shown below.



## 2. Passive fiber optic Sensor (Extrinsic Type Fiber Optic Sensors)



*Extrinsic Type Fiber optic Sensors*

-Simply receive light data from the environment, it is commonly used for illumination (Fiber optical lighting).

- In such type of sensors, sensing takes place in a region outside of the fiber and essentially fiber serves as a conduit for the to and fro transmission of light to the sensing region efficiently and in a desired form.

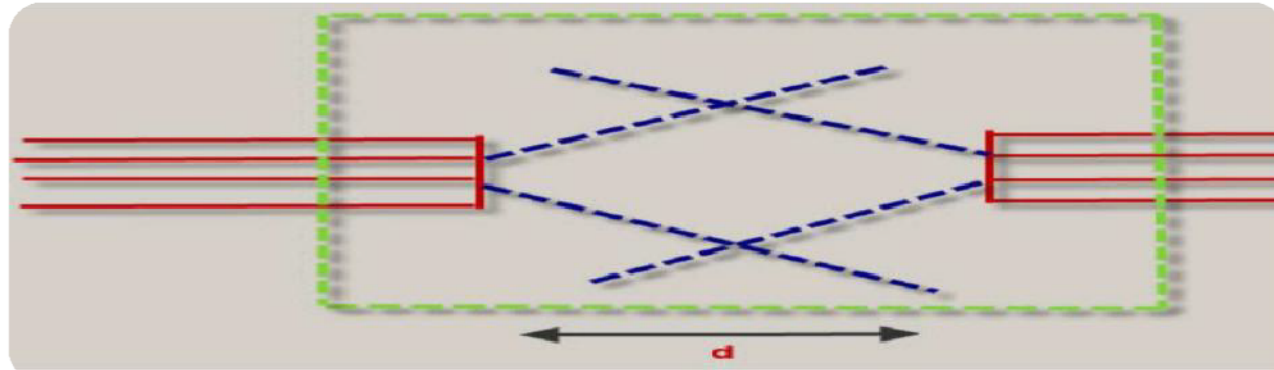
-These sensors may be used strictly as information carriers that lead up to a black box to impress information on a light beam that propagates to a remote receiver.

-The black box may contain mirrors, a gas or liquid cell ,a cantilevered arm or dozens of other mechanisms that may generate ,modulate or transform a light beam.

-The most important advantage of using these sensors is that their ability to reach places which seems to be unreachable.

# INTENSITY BASED FIBER OPTIC SENSORS:

These type of sensors use multimode fibers having large core size. They require more light to gather into it.



**Above fig. shows the vibration sensor that consists of two optical fibers held in close proximity to each other.**

When light is injected into one of the optical fiber, the light expand into a cone of light whose angle depends on their difference 'd'.

**These types of sensors faces many limitations regarding various losses such as losses due to connectors and splices, micro bending losses, macro bending losses and misalignment of light sources and detectors.**

To overcome these losses intensity based fiber optic sensors employ dual wavelength. One of the wavelengths is used for calibration of all the errors due to the undesired intensity variations by bypassing the sensing regions.