Engineering Physics

(PHY1701)

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- Light propagation through fibers,
- Acceptance angle,
- Numerical Aperture,
- Types of fibers - step index, graded index, single mode & multimode*,
- Attenuation, &
- Dispersion-intermodal and intramodal (AG 29-40, 65, 78)

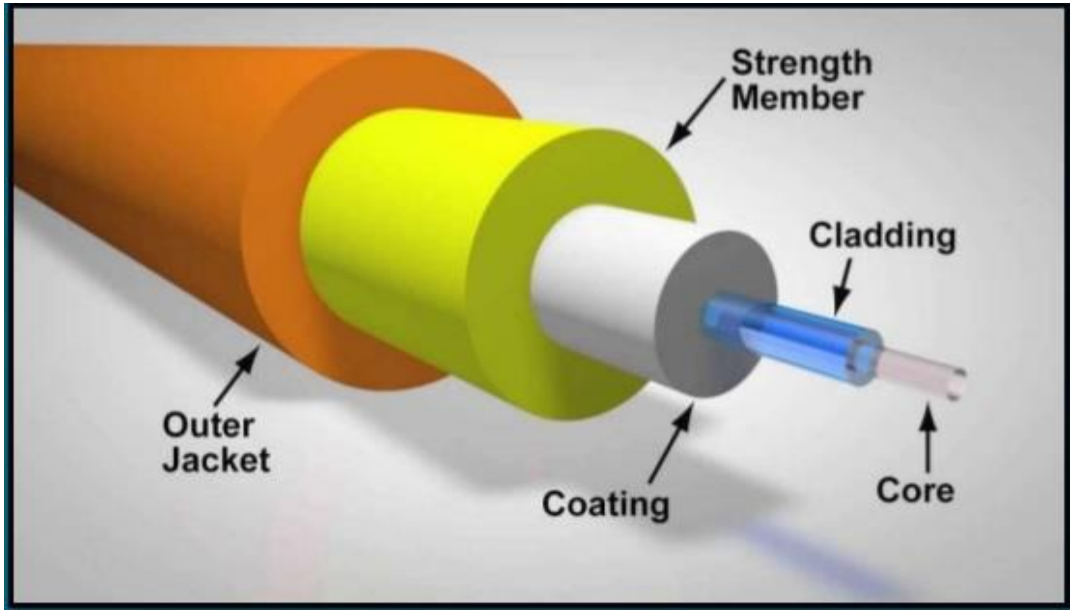
❖ Introduction to Fiber Optics, Ajoy Ghatak and K. Thyagarajan, Cambridge University Press, 2010 (AG)

What is an optical fiber

- An Optical fiber is a flexible, transparent fiber made of high quality glass (silica) or plastic, slightly thicker than a human hair.
- It either functions as a waveguide or light pipe that transmits light between two ends of the fiber or fiber cable.
- Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication.
- Fibers are used instead of metal wires because signals travel along them with less loss and are also safe to electromagnetic interference.
- The field of applied science and engineering concerned with the design and application of optical fibers is known as fiber optics.

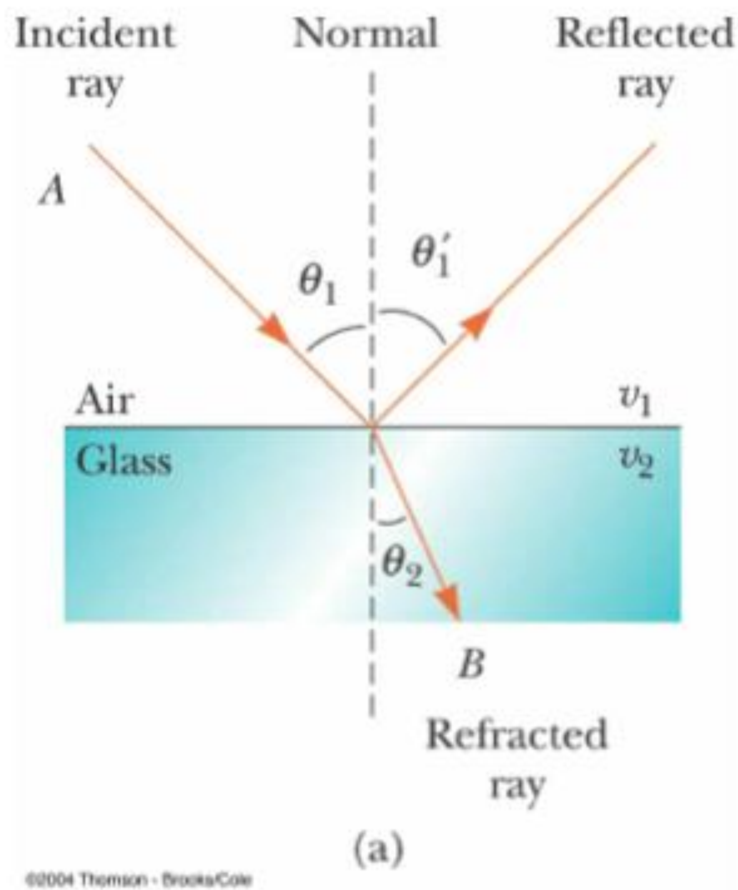
Principles of Light Transmission in a Fiber

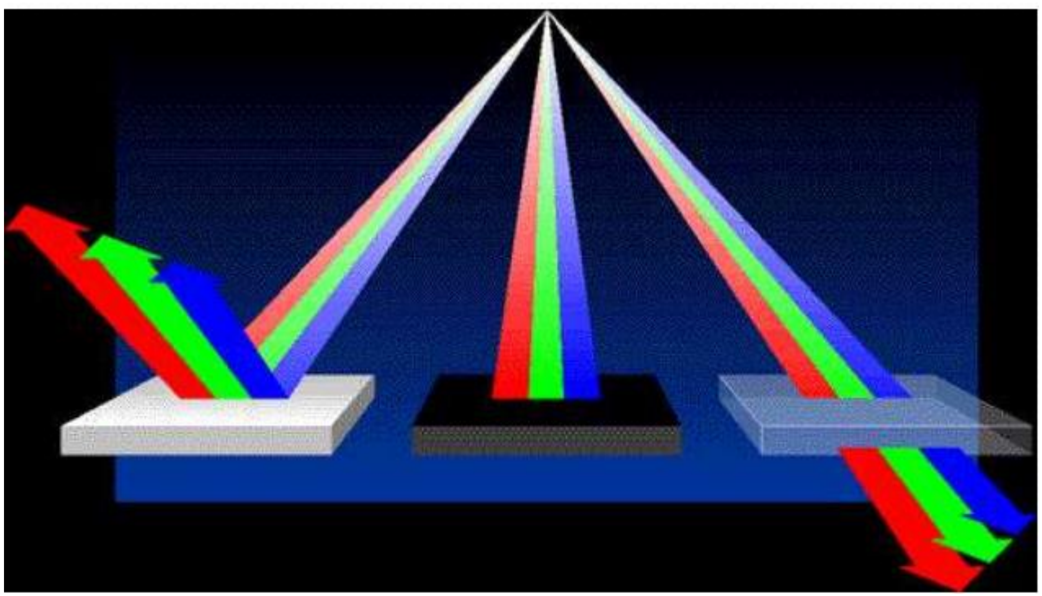
- Fiber optics deals with the transmission of light energy through transparent fibers.
- How an optical fiber guides light depends on the nature of light and structure of the optical fiber.
- A light wave is a form of energy that is moved by wave motion.
- In fiber optics, wave motion is the movement of light energy through an optical fiber



Properties of light

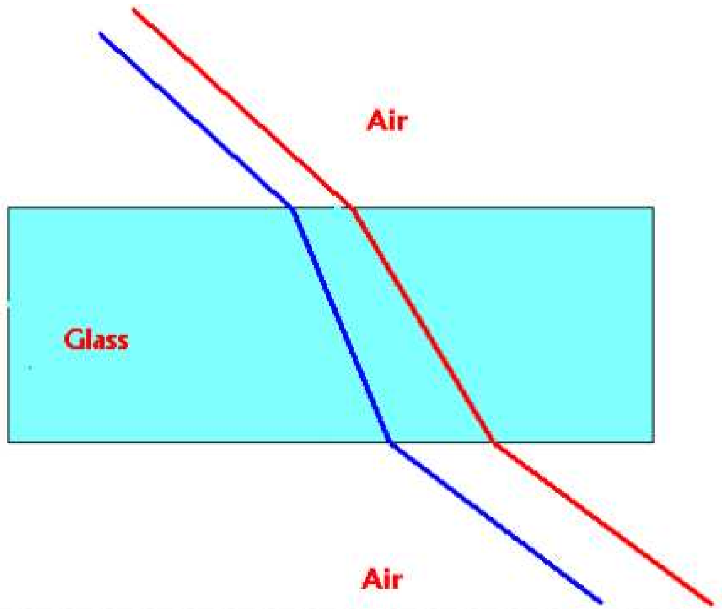
- When light waves strike an object, some of the waves are absorbed by the object, some are reflected by it, and some might pass through it.
- When light strikes an object it is:
    1) Reflected
    2) Transmitted
    3) Absorbed





Refraction:

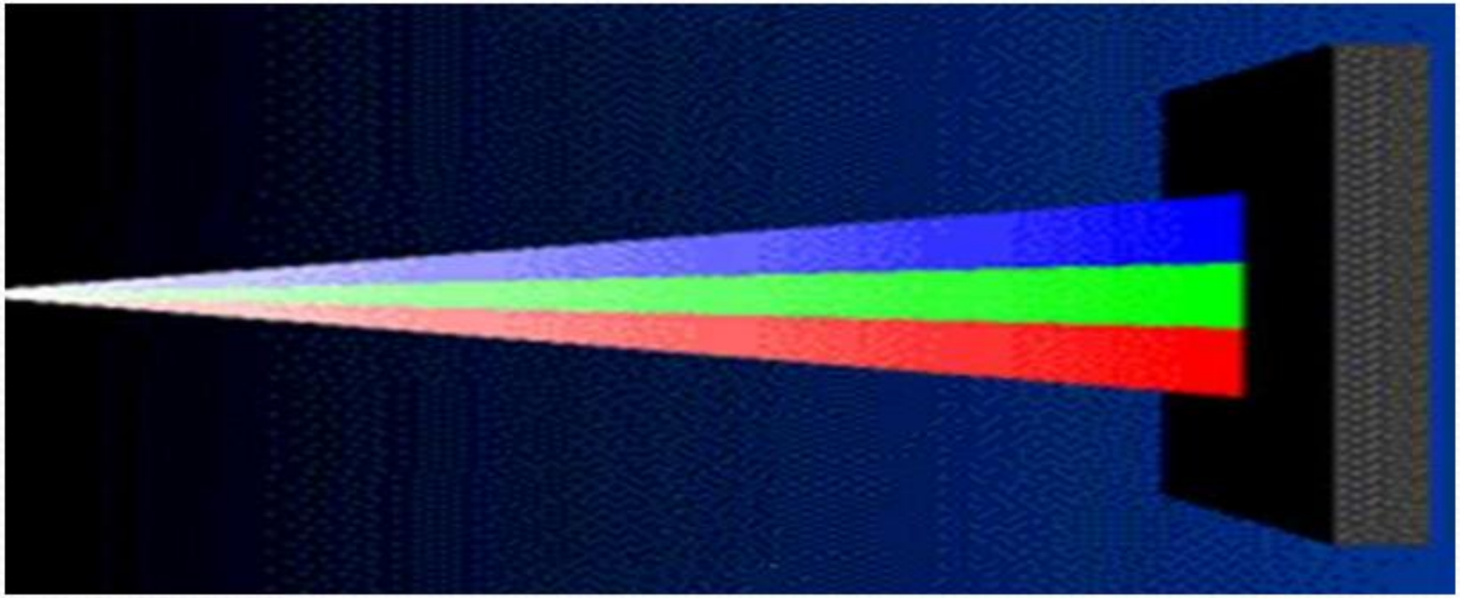
- When a light wave passes from one medium to another medium having different velocity of propagation, a change in the direction of the wave will occur.
- This change of direction as the wave enters the second medium is called refraction.



- Refraction- bending of light waves due to a change in speed
- Lens, curved glass or transparent material that Refracts light

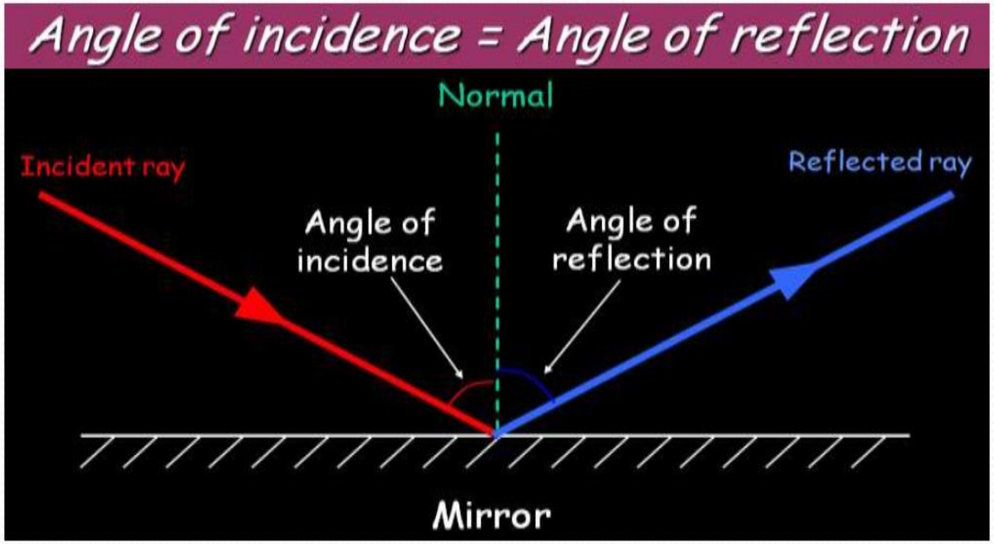
Absorption:

- A light wave is reflected and diffused from a piece of white paper.
- But if the light beam falls upon a piece of black paper, the black paper absorbs most of the light and very small amount of light is reflected from the paper.
- If the surface upon which the light beam falls is perfectly black, then there is no reflection; the light is totally absorbed.



Reflection:

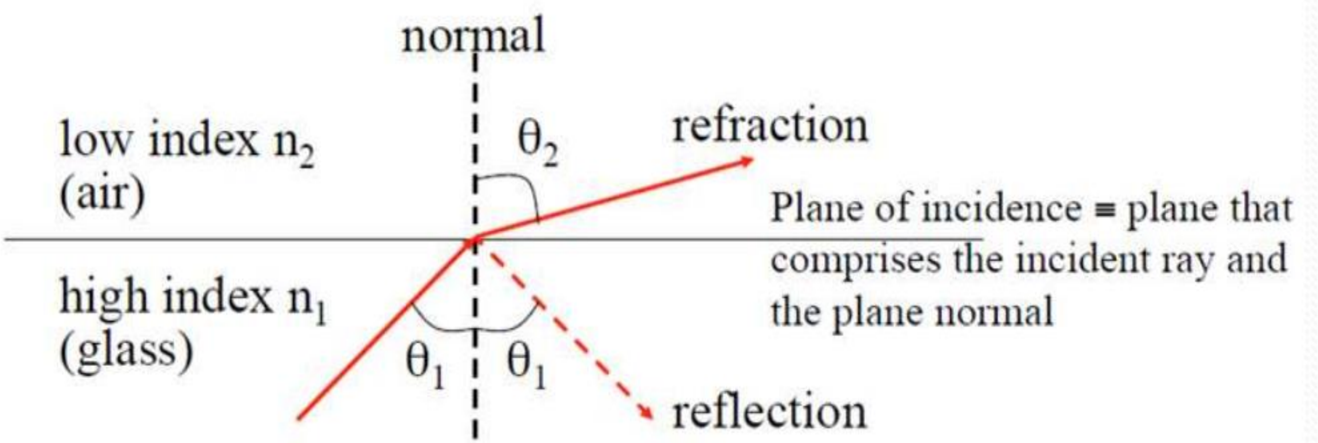
- Reflected waves are those waves that are neither transmitted nor absorbed but are reflected from the surface of the medium.
- When a wave approaches a reflecting surface such as a mirror, the wave that strikes the surface is called incident wave and the wave that bounces back is called the reflected wave.
- Light rays in homogeneous media are straight lines
- **Law of Reflection** – Reflection from a mirror or at the boundary between two media of different refractive index: the angle of reflection equals to the angle of incidence i.e. $\theta_r = \theta_i$
- The amount of incident energy that is reflected from a surface depend on:
  - The nature of the surface
  - The angle at which the wave strikes the surface



Snell's law of Refraction

- At the boundary between two media of different refractive index n the angle of refraction θ_t is related to the angle of incidence θ_i by

$$\mathbf{n_i \sin \theta_i = n_t \sin \theta_t}$$



- At the boundary between two media of different refractive index n the angle of refraction θ_t is related to the angle of incidence θ_i by

$$\mathbf{n_1 \sin \theta_1 = n_2 \sin \theta_2}$$

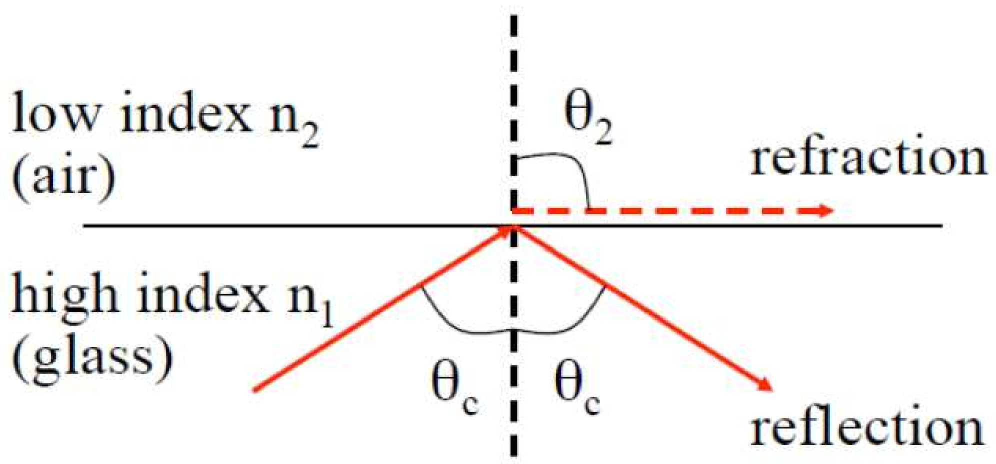
Critical Angle (θ_c) :

- The angle at which total internal reflection occurs is called the critical angle of incidence.
- At any angle of incidence (θ_1) greater than the critical angle, light is totally reflected back to the glass medium.
- For $n_1 > n_2$, the angle of refraction θ_2 is always greater than the angle of incidence θ_1.
- When the angle of refraction θ_2 is 90^o the refracted ray emerges parallel to the interface between the media

The critical angle is determined by using Snell's Law. The critical angle is given by :

$$\boxed{\sin \theta_c = n_2 / n_1}$$

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



Refractive index for some materials:

- Air --1.0
- Water ---1.33
- Magnesium fluoride ------------------------------1.38
- Fused silica (SiO_2)--------------------------------1.46
- Sapphire (Al_2O_3)---------------------------------1.8
- Lithium niobate ($LiNbO_3$)--------------------------2.25
- Indium phosphide (InP)-----------------------------3.21
- Gallium arsenide (GaAs) ---------------------------3.35
- Silicon (Si)---3.48
- Indium gallium arsenide phosphide (InGaAsP)-----------------3.51
- Aluminum gallium arsenide (AlGaAs)------------------------3.6
- Germanium (Ge) ------------------------------------4.0

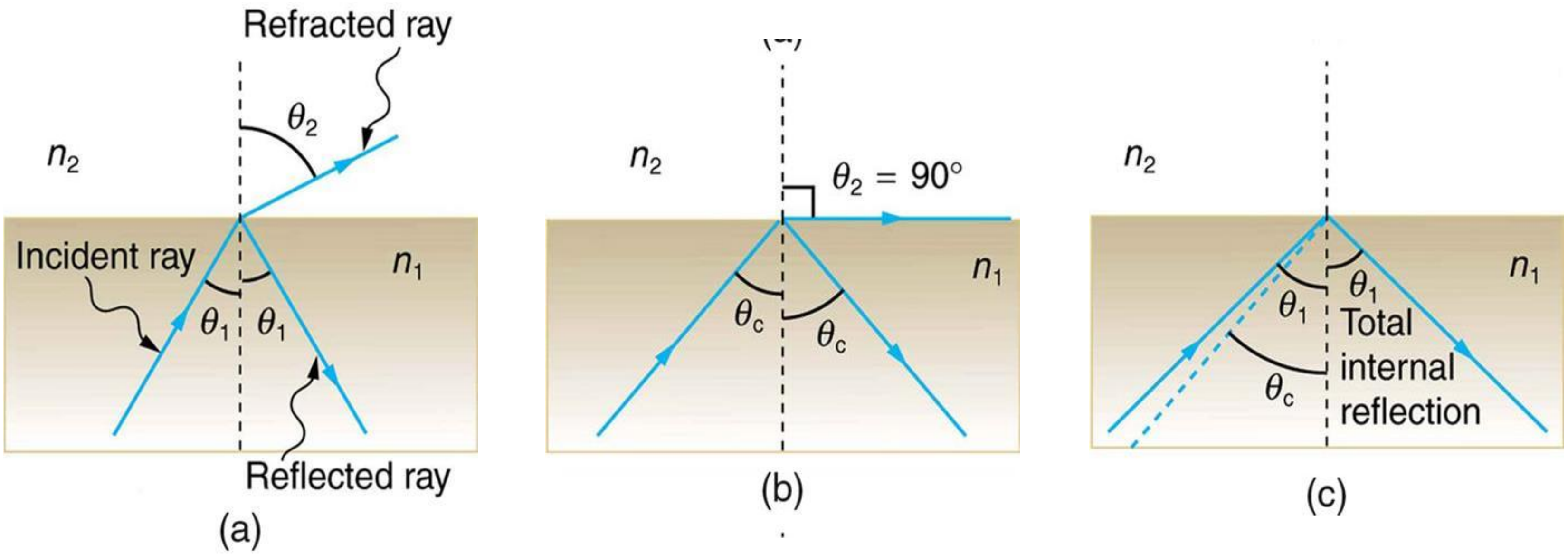
- **The index varies with a number of parameters, such as wavelength and temperature.**

Principle of optical fiber:

- Fiber-optic transmission of light depends on preventing light from escaping from the fiber.
- When a beam of light encounters a boundary between two transparent substances, some of the light is normally reflected, while the rest passes into the new substance.
- A principle called total internal reflection allows optical fibers to retain the light they carry.
- When light passes from a dense substance into a less dense substance, there is an angle, called the critical angle, beyond which 100 percent of the light is reflected from the surface between substances.
- Total internal reflection occurs when light strikes the boundary between substances at an angle greater than the critical angle.
- An optical-fiber core is clad (coated) by a lower density glass layer.

Total internal Reflection

➢ At angles of incidence $\theta_1 > \theta_c$ the light is totally reflected back into the incidence higher refractive index medium. This is known as total internal reflection.

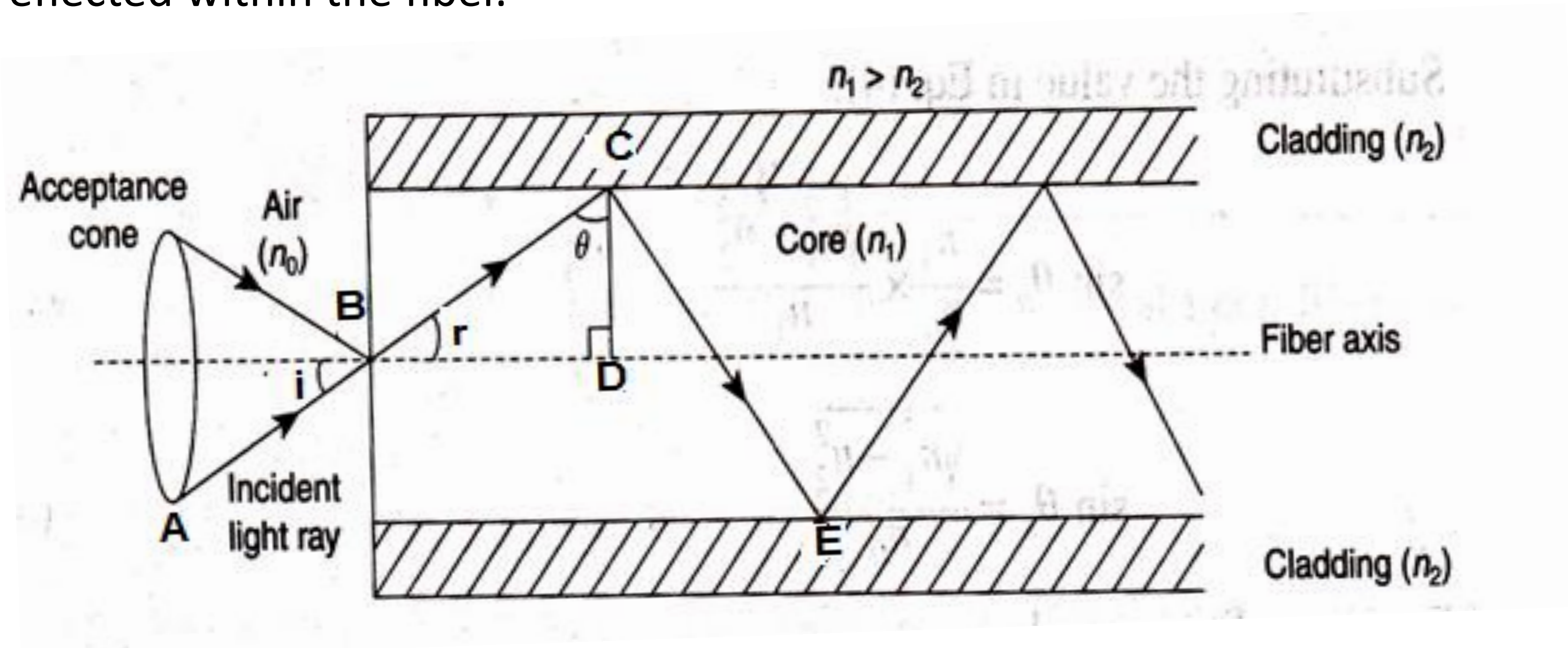


e.g. $n_1 = 1.44$, $n_2 = 1$, then $\theta_c = \sin^{-1}(1/1.44) = 44°$

Total internal reflection: $\theta_1 > \theta_c$

Acceptance angle:

- Consider a cylindrical fiber wire which consists of an inner core of refractive index n_1 and an outer cladding of refractive index n_2 where $n_1 > n_2$. Let n_0 be the refractive index of the medium from which the light ray enters the fiber. This end of the fiber is called launching end.
- Let the angle of incidence 'i' with axis of fiber as shown in figure. The ray refracts with an angle 'r' and strikes the core-cladding interface at an angle θ. Let θ be greater than critical angle θ_c, then the light will stay within the fiber. Now calculate the angle of incidence 'i' for which the angle of $\theta \geq \theta_C$, so that the light reflected within the fiber.



Acceptance angle:

- Applying Snell's law at the point of entry of the ray AB into the core, then we have

$$n_0 \sin i = n_1 \sin r \quad \text{----} (1)$$

From $\Delta BCD \Rightarrow r = (90 - \theta)$ or $\sin r = \sin(90 - \theta) \quad \text{----} (2)$

$$\sin r = \cos\theta$$

$$n_0 \sin i = n_1 \cos\theta$$

$$\Rightarrow \sin i = \frac{n_1}{n_0} \cos\theta \text{----} (3)$$

The largest value of I (I_{max}) occurs when $\theta = \theta_C$. Applying this condition in Eq. (3), we get

$$\sin(i_{max}) = \left(\frac{n_1}{n_0}\right) \cos\theta_C \quad \text{----} (4)$$

$$\because \sin\theta_C = \frac{n_2}{n_1}$$

Acceptance angle:

$$\Rightarrow \cos\theta_C = \sqrt{1-\sin^2\theta_C} = \sqrt{\frac{n_1^2-n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_1} \quad ----(5)$$

From Eq. (4) and (5), we have

$$\sin(i_{max}) = \left(\frac{n_1}{n_0}\right) \times \frac{\sqrt{n_1^2-n_2^2}}{n_1} = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad ----(6)$$

Generally the incident ray is launched from air medium , i.e., n_0=1. Therefore,

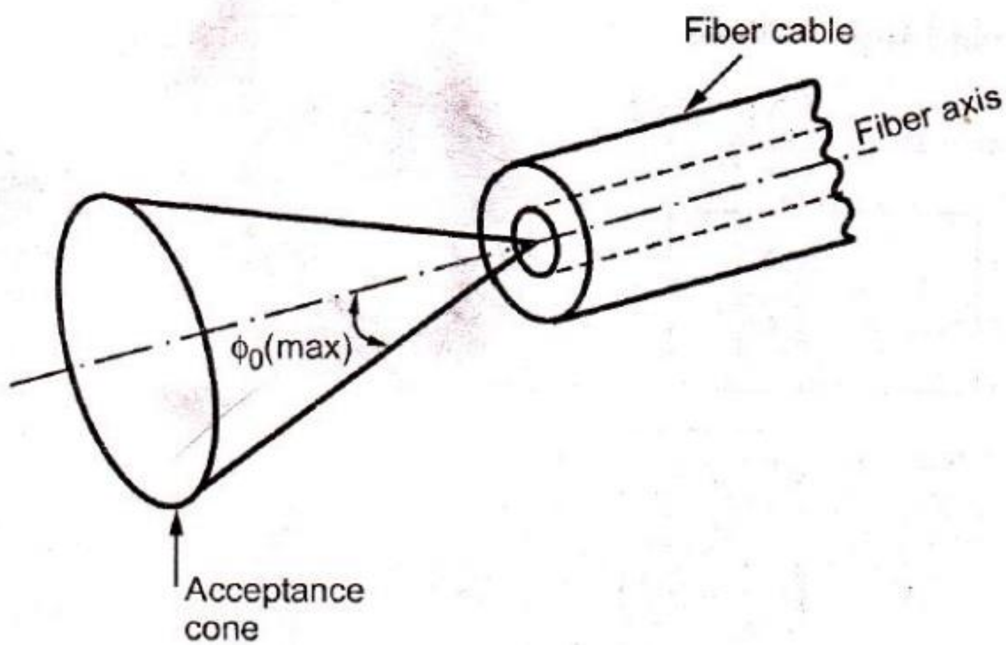
$$\sin(i_{max}) = \sqrt{(n_1^2-n_2^2)}$$

$$i_{max} = \sin^{-1}\sqrt{(n_1^2-n_2^2)}$$

Here i_{max} is called the acceptance angle of the fiber.

∴ ***<u>Acceptance angle</u> of fiber can be defined as "The maximum angle of incidence for which light confines to the denser medium"***

Acceptance cone:



The light rays contained within the cone having a full angle $2I_{max}$ are only be internally reflected and thus confined within the fiber for propagation and thes rays in the cone are accepted and transmitted along the fiber. Therefore, the cone is called **acceptance cone.**

Numerical aperture:

The light collecting capacity of an optical fiber is called Numerical aperture. Sine of the maximum acceptance angle is called numerical aperture (NA) of the fiber. Therefore

$$NA = sin(i_{max}) = \sqrt{\left(n_1^2 - n_2^2\right)}$$