Lecture-V Programme: M. Sc./B.Sc. Physics

Basics of Optical Fiber and its Applications -I

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OBJECTIVES

The main objective of the lecture is to present the basic concepts of optical fibers that are very significant from the their applications point of view in telecommunication and sensing. Some parameters such as acceptance angle acceptance cone, numerical aperture (NA), attenuation, pulse dispersion, single-mode and multimode fibers, graded index, fibers and zero-dispersion wavelength are covered.

When you complete this lecture, you will be able to

- ❑ Express how light is guided through optical fibers.
- ❑ Distinguish between multimode and single-mode fibers.
- ❑ Find out the numerical aperture (NA), intermodal dispersion, and material dispersion.
- ❑ Understand zero-dispersion wavelength and dispersion-shifted fibers.
- ❑ Know the importance of plastic optical fibers with regard to their application in communication.

In the 1970s, that was known that the present copper technology would be in appropriate for future prospect in communication networks. In this view, the telecommunication industry devoted seriously in research into the direction of optical fibers. Optical fiber gives an attractive choice to wire transmission lines for instance twisted pair and coaxial cable (or coax).

Practically it has been observed that the optical fiber has the following advantages over copper wire transmission technology:

- ***Bandwidth:*** **It offers a extremely high capacity for carrying information. It has enough bandwidth that bit-serial transmission can be utilized, thus significantly overcome the size, cost, and complexity of the hardware.**

- ***Attenuation*:** **It offers small attenuation and is as a result able to transmitting over a long distance without the require of repeaters.**
- ***Noise susceptibility*:** **It neither radiates nor is influenced by electromagnetic interference (EMI). The resistance from EMI is owing to the absence of metal parts, which means that there is zero conduction current**
- ***Security*:** **It is much protected from malicious interception because it is not trouble-free to tap a fiber-optic cable without stopping communication.**
- ***Cost*:** **The cost of optical fibers has decreased noticeably since the turn of the century and will continue to fall. The cost of linked parts such as optical transmitters and receivers also is reducing.**

These notable benefits over electrical media have made fiber optics a potential applications in transmission medium in recent times. Though optical fiber is little expensive and is employed mostly for point-to-point links, there has been a quick switch from coax and twisted pair to optical fibers for telecommunication systems, instrumentation, cable TV networks, industrial automation, and data transmission systems.

An optical fiber is a dielectric waveguide operating at optical frequency.

Optical frequencies are 100 THz of order. From Figure 1, which is representing to an communication vai fiber so this system consists of three concentric cylindrical sections: the core, the cladding, and the jacket.

- **The core consists of one or more thin filaments prepared from glass or plastic.**
- **The cladding is the glass or plastic coating surrounding the core, which may be step index or graded index.**
- **The jacket surrounded one or a bundle of cladded fibers. The jacket is made of plastic or other materials to guard against moisture, crushing, and other forms of damage.**
- **A fiber-optic system is analogous to a classical transmission system. As shown in Figure 2, a fiber-optic system consists of a transmitter, a transmission medium, and a receiver.**

The transmitter accepts and transforms into optical signals electrical signals input in analog or digital form. The transmitter sends the optical signal by modulating the output of a light source (generally an LED or a laser) by changeable its intensity. The optical signal is transmitted over the optical fiber to a receiver.

At the receiver, the optical signal is converted back into an electrical signal by a photodiode. The performance of a fiber-optic connection depends on the numerical aperture (NA) (We have discussed it in next coming slides), attenuation, and dispersion characteristics of the fiber.

As signals propagate through the fiber, they become distorted owing to attenuation and dispersion.

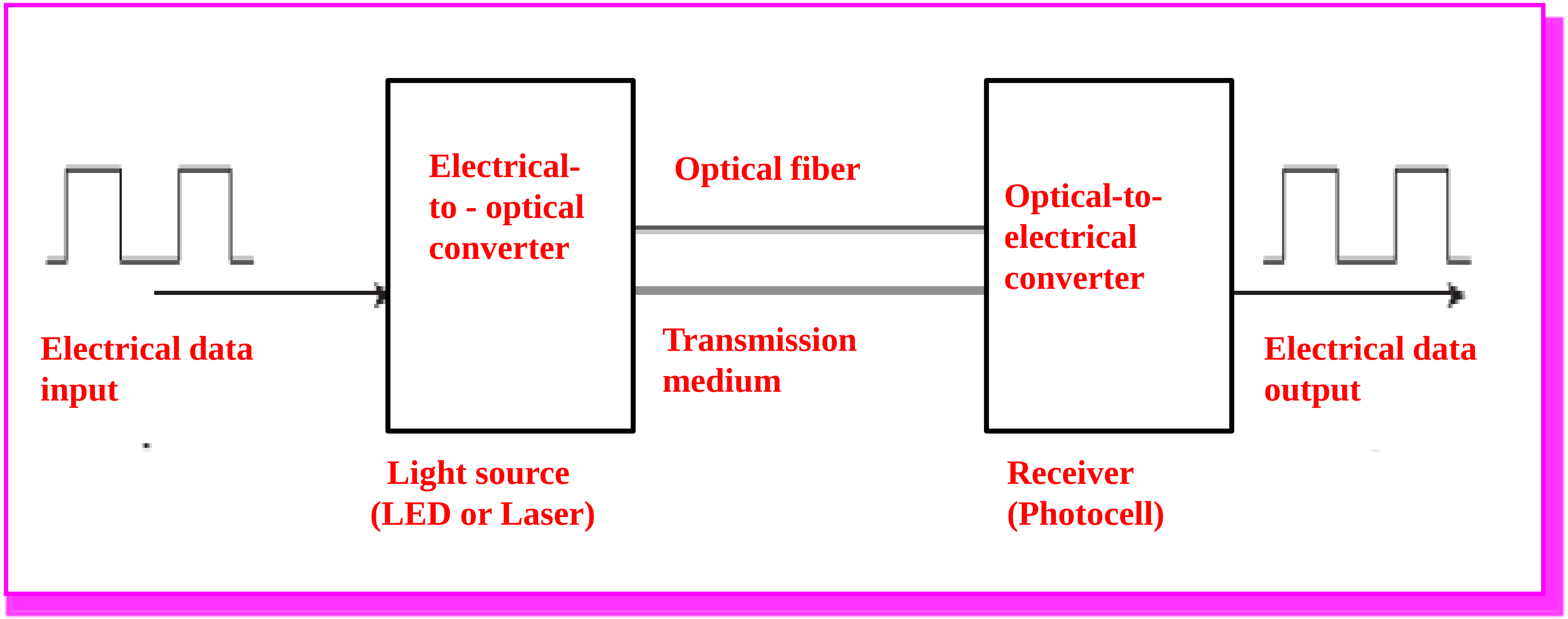

Figure 1: A schematic diagram of an optical fiber system. [Ref -1]

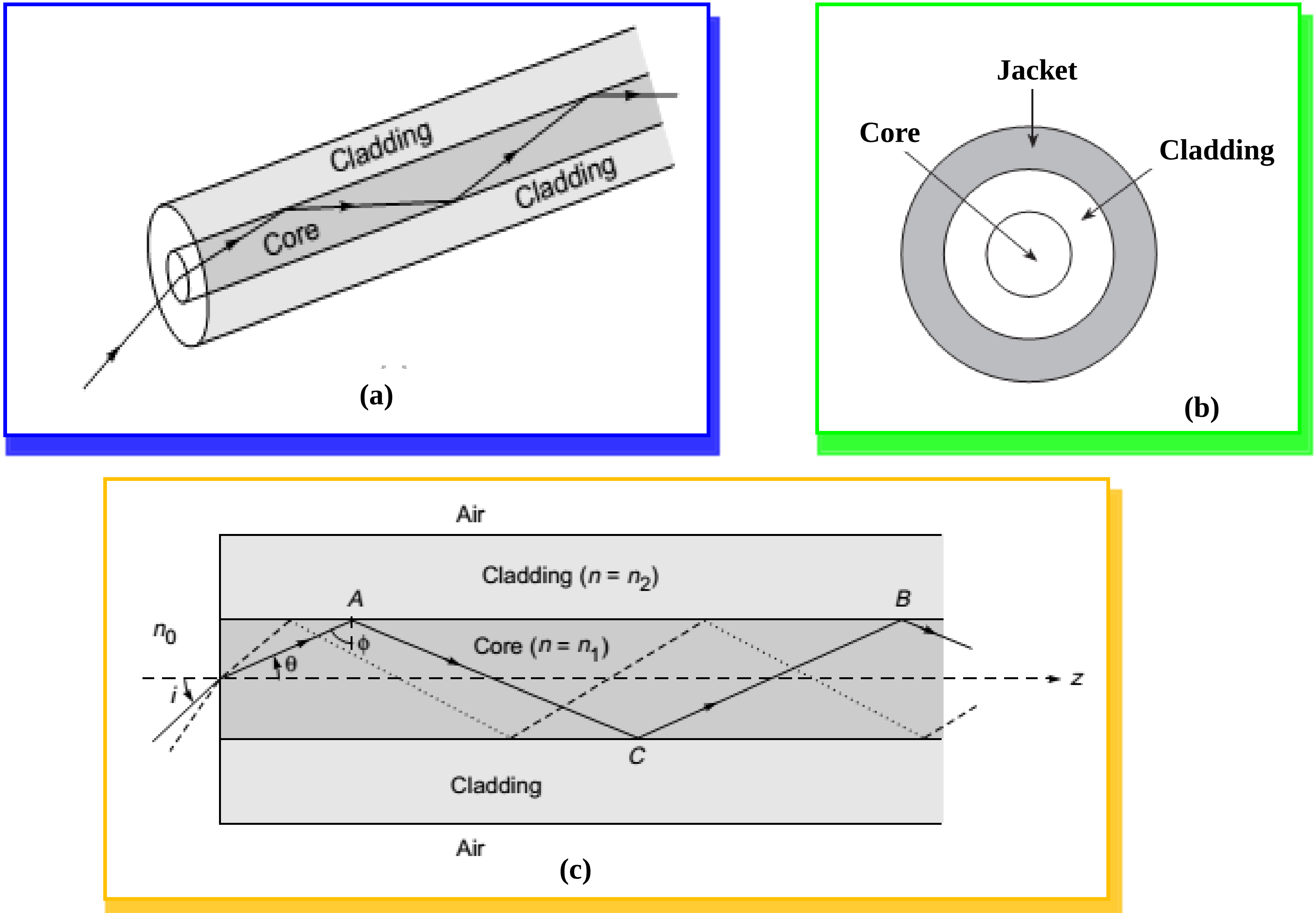

Figure 2. (a) A glass fiber consists of a cylindrical central core cladded by a material of slightly lower refractive index. (c) cross sectional view of a fiber (b) Light rays incident on the core-cladding interface at an angle greater than the critical angle are trapped inside the core of the fiber. Ref- 1, 3

Basic Principle of Fiber

As we know that light deviates from its original path while travelling from one medium to another. When light travels from denser medium to rarer medium, the refracted ray will go away from the normal as shown in Fig. 3(a).

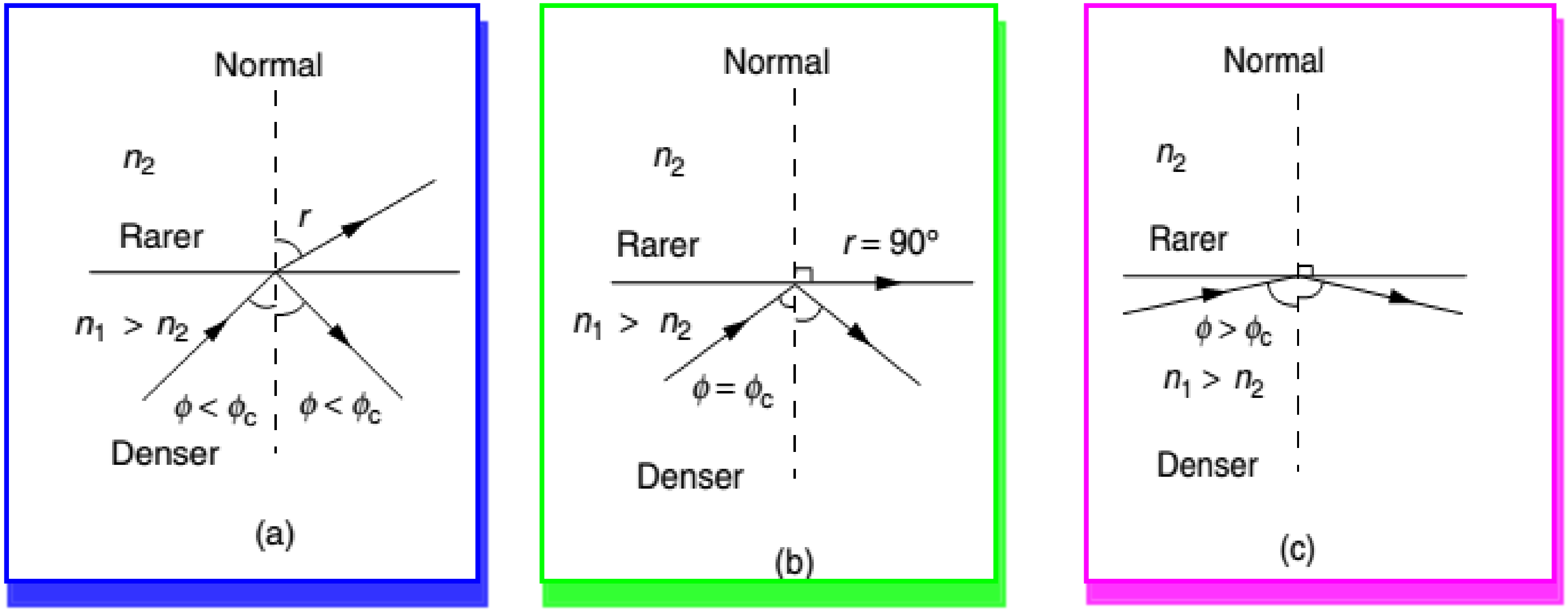

Figure 3: Total internal reflection. [Ref -5]

Let us consider the light propagation in an optical fiber. If the light enters the fiber, it follows two essential conditions for total internal reflection:

1. **Light wave should be propagated from denser medium to rarer.**
2. **The angle of incident should be more than the angle of incidence. In the fiber, the refractive index of the core n_1 is more than that of the refractive index of the cladding n_2 ($n_1 > n_2$). Hence, fist condition is satisfied. So, from Snell's law**

$$n_1 \sin \phi = n_2 \sin r \qquad \text{-------------- [1]}$$

It means that angle of incident raise the angle of refraction (Fig. 3b). If the angle of incident is equal to the critical angle of the core–cladding surface then the light ray makes 90 ° to the normal as shown in Fig. 3(b).

Here $\phi = \phi_c$ and $r = 90°$.

$$\phi_c = \sin^{-1}(n_1 / n_2) \qquad \text{-------------- [2]}$$

If incident angle is larger than critical angle of core–cladding interface then light ray is reflected back in same medium [Fig. 3(c)]. In this case, the reflected light ray is said to be totally internally reflected and this principle is utilized to propagate the light in optical fiber (Fig. 4).

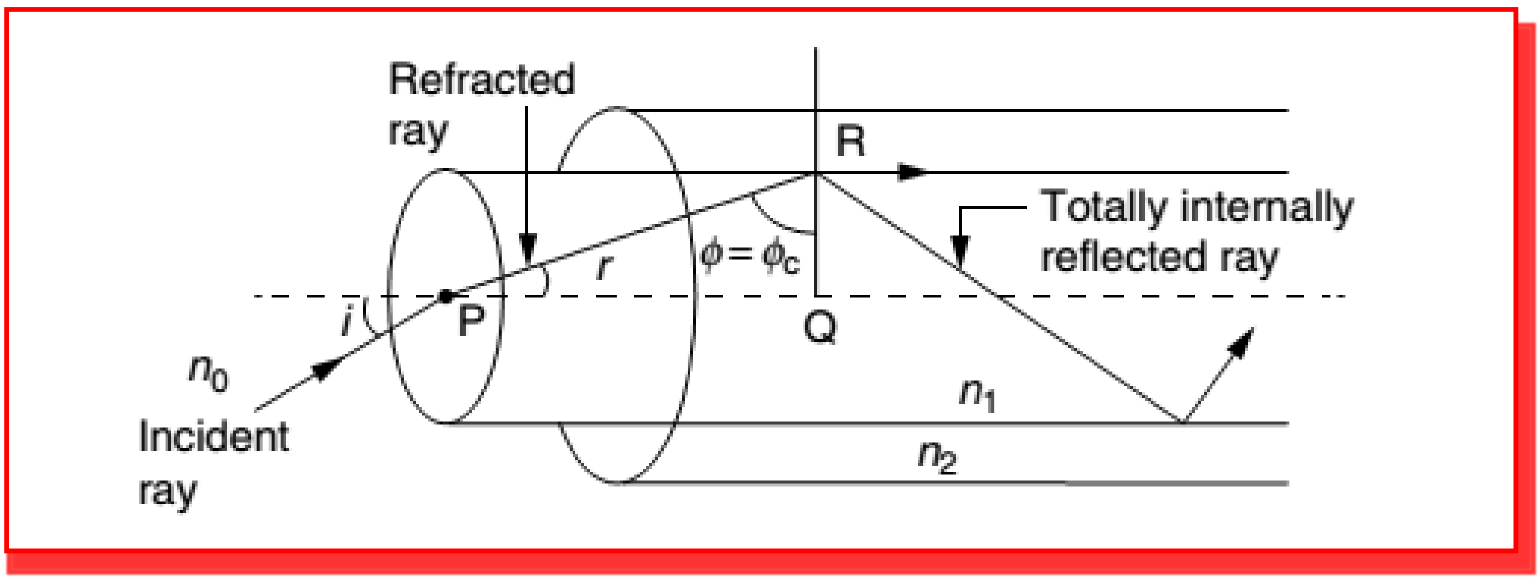

Figure 4 :Propagation of light in optical fiber using multiple internally reflection. [Ref -5]

Acceptance Angle, Acceptance Cone and Numerical Aperture

Acceptance Angle

As we have already discussed, light signal can be propagated in the fiber using the phenomena of TIR in which incident angle is greater than critical angle of core–cladding surface. In this way, light signal travels in the fiber. Thus, ***the external maximum angle at which light entering the core is transmitted through the fiber and propagated without being refracted is known as acceptance angle*****.**

To determine an expression for acceptance angle and numerical aperture, let us consider that the ray of light enters at angle *i* having refractive index n_0 of the surrounding medium. If light ray is refracted at point P making an angle *r* with the axis inside the core of refractive index n_1 as shown in Fig. 5, then using Snell's law

$$n_0 \sin i = n_1 \sin r \Rightarrow \frac{\sin i}{\sin r} = \frac{n_1}{n_0} \quad \text{------------ [3]}$$

In Δ PQR

$$r = 90 - \phi \text{ or } \sin r = \sin(90 - \phi) = \cos \phi \quad \text{------------ [4]}$$

From Eqs. (3) and (4), we have

$$\sin i = \frac{n_1}{n_0} \cos \phi \quad \text{------------ [5]}$$

For limiting case of total internal reflection $\phi = \phi_c$. Then, $i = i_{max}$. So

$$\sin i_{max} = \frac{n_1}{n_0}\cos\phi_c = \frac{n_1}{n_0}\sqrt{1-\sin^2\phi_c} \qquad \text{------------ [6]}$$

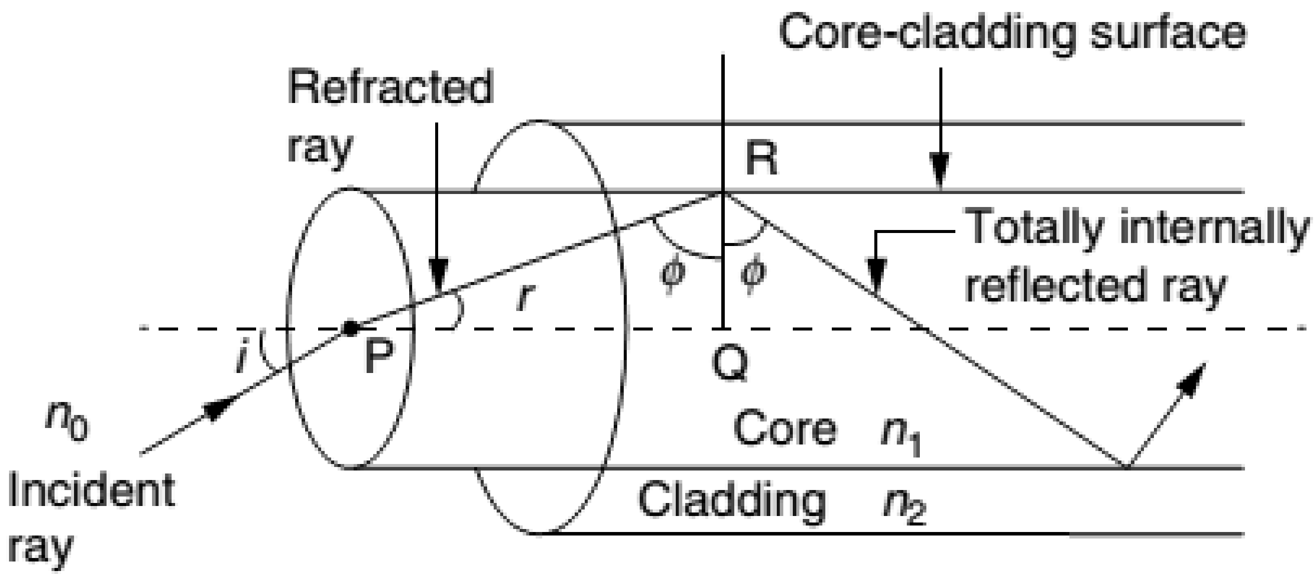

Figure 5: Light propagation in optical fiber. [Ref -5]

But $\sin\phi_c = n_2/n_1$/ So

$$\sin i_{max} = \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \frac{\sqrt{(n_1)^2-(n_2)^2}}{n_0} \quad \text{------------ [7]}$$

For air, $n_0 = 1$. So

$$i_{max} = \sin^{-1}\left[\frac{\sqrt{(n_1)^2-(n_2)^2}}{n_0}\right] \quad \text{------------ [8]}$$

This is the required expression for acceptance angle of a fiber with core and cladding refractive indices n_1 and n_2 respectively.

Thus, the critical angle determines the acceptance angle of the fiber. Hence the *maximum incident angle subtended by a ray on the fiber axis at the entry point of the fiber for which the ray suffers total internal reflection on striking the core cladding interface, is termed as a acceptance angle*.

- **Acceptance angle is different for different fibers and it depends on core material and the core diameter.**

Acceptance Cone

Only light that enters the fiber a certain range of angles can travel down the fiber without leaking out. The range of angles at entry point which make angles at the interface grater than the critical angle is called acceptance cone of the fiber (see figure 6). Acceptance cone is formed by rotating acceptance angle about the fiber axis and is also defined as the cone of light described at the entry end of the fiber with semi-angle less than

or equal to the acceptance angle of the fiber (or the cone formed with acceptance angle as vertex angle).

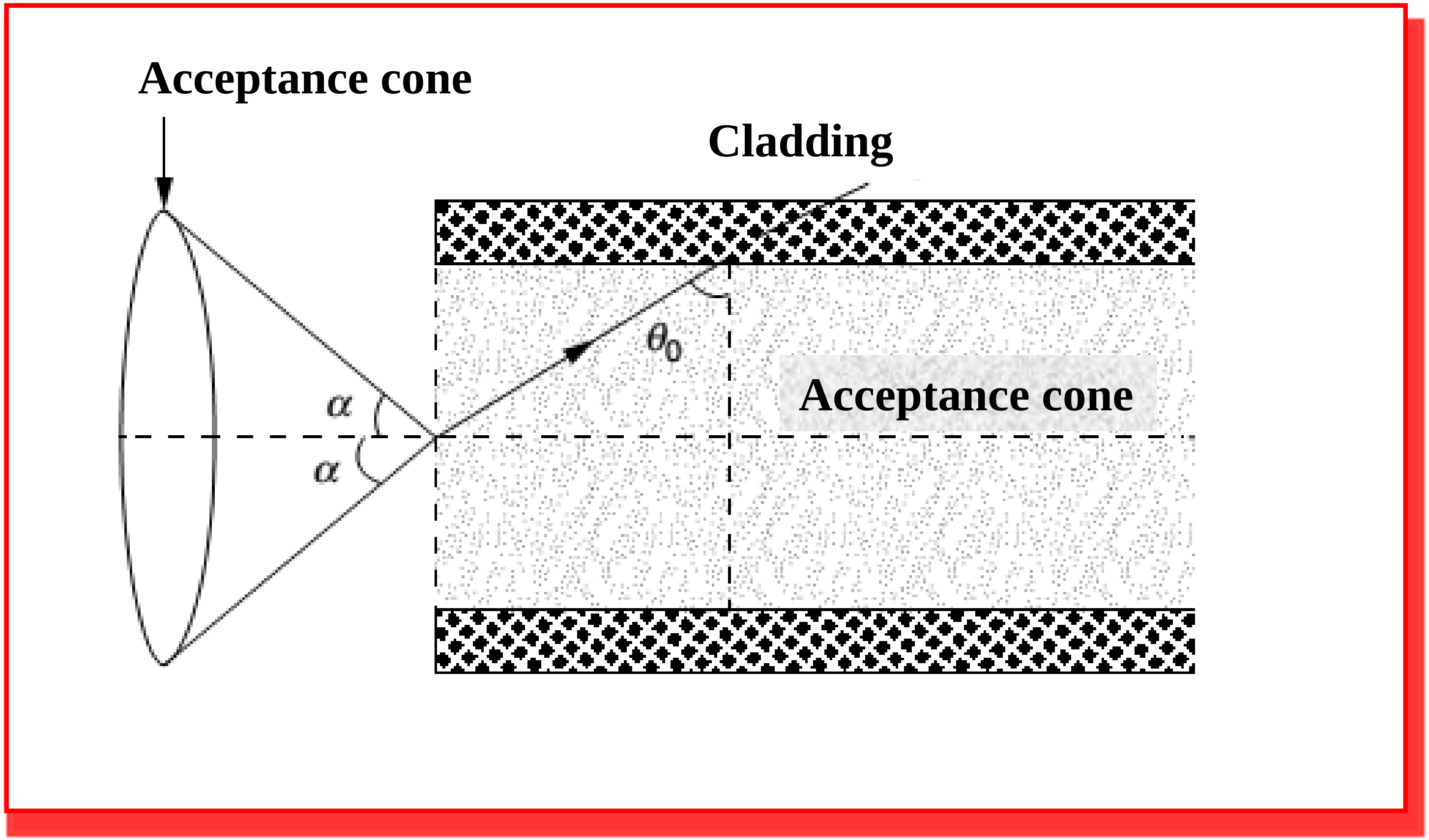

Figure- 6: Representation of acceptance cone. [Ref -5]

The light rays which are emerging from a cone defined by the acceptance angle would be totally reflected from the core-cladding interface and continue to propagate down to the core. On the other hand the rays which are emerging outside the acceptance cone on striking the interface totally absorbed by the cladding material and never propagate.

Numerical Aperture

We return to Fig. 2(a) and consider a ray which is incident on the entrance aperture of the fiber, making an angle *i* with the axis. Let the refracted ray make an angle θ with the axis. considering the outside medium to have a refractive index n_0 (which for most practical cases is unity - air), from Snell's law

$$\frac{\sin i}{\sin \theta} = \frac{n_1}{n_0} \qquad \text{------------- [9]}$$

Obviously if this ray has to suffer total internal reflection at the core-cladding interface, then

$$\sin\phi\ (=\cos\theta) > \frac{n_2}{n_1} \qquad \text{-------------- [10]}$$

$$\sin\theta < \sqrt{1-\left(\frac{n_2}{n_1}\right)^2} \qquad \text{-------------- [11]}$$

$$\sin i < \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{\frac{\left(n_1^2 - n_2^2\right)}{n_0^2}} \qquad \text{-------------- [12]}$$

In most cases, the outside medium is air, i.e., n_0 = 1; and therefore the maximum value of sin*i* for a ray to be guided is given by-

$$\sin i_m = \begin{cases} \sqrt{n_1^2 - n_2^2} & \text{if} \quad n_1^2 < n_2^2 + 1 \\ 1 & \text{if} \quad n_1^2 > n_2^2 + 1 \end{cases}$$

-------------- [13]

Thus, if a cone of light is incident on one end of the fiber, it will be guided through it provided the semi angle of the cone is less than im. The quantity sin im is known as the numerical aperture (NA) of the fiber and is a measure of the light-gathering power of the fiber. In almost all practical situations, $n_1^2 < n_2^2 + 1$ and therefore one defines the numerical aperture of the fiber by the following equation:

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

-------------- [14]

Thus, *numerical aperture is a number which defines the light acceptance or gathering capacity of a fiber*. Thus those fibers having high NA allow light to propagate down the fiber in rays both close to the axis and at various angles with the axis, allowing the efficient coupling of light into the fiber. However, this high NA increases the amount of dispersion. A low numerical aperture may therefore be desirable.

The numerical apertures for the fibers used in short distance communication are in the range of 0.4-0.5, whereas for long distance communications NA values are in the range of 0.1-0.3.

Numerical

Problem 1. **A fiber has a core index of 1.499 and a cladding index of 1.479. When surrounded by air what will be its (a) acceptance angle, (b) numerical aperture, and (c) the critical angle at the core– cladding interface?** **#[Ref- 4]**

SOLUTION

(**b**) From

$$NA = (n_f^2 - n_c^2)^{1/2} = (1.499^2 - 1.479^2)^{1/2}$$

$$NA = 0.244$$

which is a typical value.

(**c**) Since $$\sin\theta_{max} = \frac{1}{n_i} NA = NA$$

$$\theta_{max} = \sin^{-1}(0.244) = 14.1°$$

Hence $$2\theta_{max} = 28.2°$$

(**a**) The critical angle follows from

$$\sin\theta_c = \frac{n_t}{n_i} = \frac{n_c}{n_f} = \frac{1.479}{1.499}$$

Notice that $\sin\theta_c$ must be equal to or less than 1.

$$\theta_c = \sin^{-1} 0.9866$$

$$\theta_c = 80.6°$$

Problem 2. The fraction change of refractive index between the core material and the cladding material of a fiber is 1%. If the refractive index of the core material is 1.46, calculate the numerical aperture and acceptance angle.

Solution: The refractive index of the core material is 1.46 and the fractional difference of the refractive index between the core and cladding material, Δ = 1% of 1.46 = 0.0146. We have n_1 = 1.46. The numerical aperture is

$$NA = n_1\sqrt{2\Delta} = 1.46\sqrt{2\times 0.00146} = 1.46\times 0.171 = 0.25$$

The acceptance angle is

$$i_{max} = \sin^{-1}(0.25) = 14.5°$$

Answer- 14.5°

Problem 3-Calculate the numerical aperture, acceptance angle and the critical angle of the fiber from the following data: n_1 = 1 5. 0 and n_2 = 1 4. 5.

We know that the numerical aperture is

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

Here n_1 = 1.50 and n_2 = 1.45. So the numerical aperture is

$$\mathrm{NA} = \sin i_{\max} = \sqrt{(1.5)^2 - (1.450)^2} = 0.384$$

The acceptance angle is

$$i_{\max} = \sin^{-1}(0.384) = 22.58°$$

The critical angle is

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\left(\frac{1.45}{1.50}\right) = 75.16°$$

Problem 4- **If the fractional difference between the core and cladding refractive indices of the optical fiber is 0.0135 and numerical aperture NA is 0.2425, calculate the refractive indices of core and cladding materials.**

Solution: We have NA = $n\,(\Delta)^{1/2}$

Also we have

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

Given NA = 0.2425 and Δ = 0. .0135 So

$$n_1 = \frac{\text{NA}}{\sqrt{2\Delta}} = \frac{0.2425}{0.1643} = 1.48$$

$$\Delta = 0.0135 = \frac{n_1 - n_2}{n_1} = \frac{1.48 - n_2}{1.48}$$

$$\Rightarrow\ 1.48 - n_2 = 0.0135 \times 1.48$$

$$\Rightarrow\ n_2 = 1.476 - 0.02 = 1.46$$

References:

1. Elements of Electromagnetics, 2nd edition by M N O Sadiku.
2. Engineering Electromagnetics by W H Hayt and J A Buck.
3. Optics by Ajoy Ghatak
4. Optics by Eugene Hecht
5. Engineering Physics by A K Katiyar and C K Pandey

- **For any query/problem/suggestion contact me on whatsapp group or mail on me E-mail: arvindkumar@mgcub.ac.in**
- **Next ***** Basics of Optical Fiber and its Applications –**II** [Types of optical fiber, dispersion attenuation in fiber and different applications numerical.

Thank you