4.1 Refraction, Refractive Index and Snell's law :

As long as a ray of light travels in a single medium, its direction does not change. That is, it moves in a straight line. But when a ray of light passes from one transparent medium to another transparent medium, its velocity changes. When the light ray enters obliquely from one transparent medium to another transparent medium, it deviates from the original direction at the surface separating the two media. This phenomenon is called refraction.

4.1.1 Refraction :

As we know, the speed of light varies in different mediums. Optically rarer media, such as vacuum or air, have higher velocity, while other denser transparent media have lower velocity. Hence the phenomenon of refraction occurs when a ray of light travels from one medium to another. The ray of refracted light is called a refracted ray.

In the previous standards, you have studied the refraction of light by the experiment with a transparent glass-slab (cuboid). Without repeating that experiment, let us once again understand the same phenomenon of refraction.

As shown in the **figure 4.1**, PQ is an incident ray. It forms the angle of incident i_1 with the normal. This incident ray PQ travels from the surface AB of the glass slab, from an optically rarer medium like air to an optically denser medium like glass. So its velocity decreases and it bends towards the normal and makes the angle of refraction r_1 where QR is a refracted ray. The refracted ray QR acts as an incident ray for the surface CD of the glass slab and forms an i_2 angle with the normal. Now when a light ray enters from an optically denser medium like glass to an optically rarer medium like air, its velocity increases, and it bends away from the normal. This is how the RS ray exits from the glass slab. That is why it is called an Emergent Ray. In the figure, e is the angle of emergence.

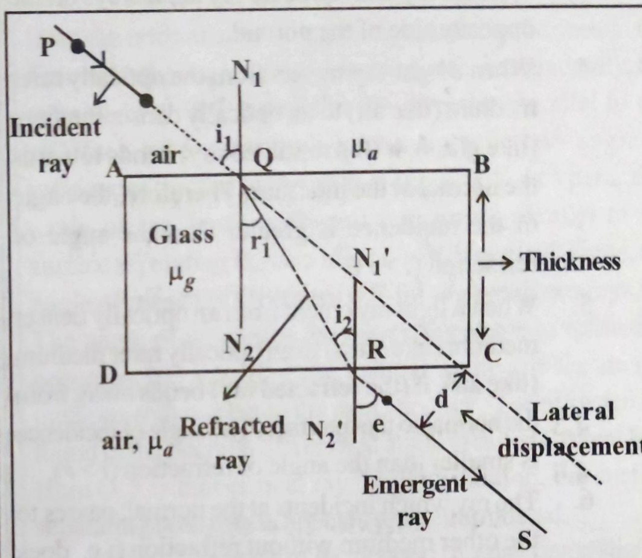


Fig. 4.1 : Light ray in the glass-slab

When a light-ray is refracted over two parallel refracting surfaces, the Emergent Ray is shifted from the direction of the incident ray as shown in the figure. Such a transfer of light rays is called the lateral shift.

Due to this lateral shift as a result of refraction, the pencil placed in a glass filled with water appears to be slanted from its surface. Anything placed at the bottom of a vessel filled with water or at the bottom of a swimming pool appears to be slightly upper than its original location. These phenomena are caused by the refraction of light. It is difficult to pierce a fish in a river as its location looks different from where it is due to the refraction of light.

The refractive index of the second medium with respect to that of the first medium (η_{21}) is defined as the ratio of the sine of the angle of incidence in the first medium to the sine of the angle of refraction in the second medium. The Refractive index has no unit as it is the ratio of two similar quantities.

4.1.2 Laws of Refraction :

1. The incident ray PQ, the refracted ray QR and the normal N_1Q $N_2$to the interface of two transparent media at the point of incidence, all lie in the same plane.
2. Incident ray and refracted ray both are in different optical media.
3. Incident ray and refracted ray are always on the opposite side of the normal.
4. When a light-ray travels from the optically rarer medium (like air) to an optically denser medium (like glass), it (the refracted ray) bends towards the normal at the interface. Therefore, the angle of the incidence is greater than the angle of refraction ($i > r$).
5. When a light ray enters from an optically denser medium (like glass) to an optically rarer medium (like air), it (the refracted ray) bends away from the normal to the interface. The angle of incidence is smaller than the angle of refraction ($i > r$).
6. The ray which incidents at the normal, passes to the other medium without refraction (i.e. does not change direction).

4.1.3 Refractive Index and Snell's law :

The ratio of the sine of an angle of incidence to the sine of an angle of refraction is always constant for the given two media. It is termed as a refractive index. Its symbol is μ (Mu). Sometimes η (Ita) is also written. It is known as Snell's law. It can be written in the form of a formula as follows :

$$\mu = \eta = \frac{\sin i}{\sin r} = \text{constant} \quad \text{... (1)}$$

Suppose the refractive index of the first medium is η_1 and that of the second medium is η_2. The refractive index of medium-2 relative to medium-1 is denoted by μ_{21} or η_{21}.

$$\mu_{21} = \eta_{21} = \frac{\sin i}{\sin r} = \text{constant} \quad \text{... (2)}$$

The refractive index of light can be represented as the ratio of the velocities of light in its two media. If the velocities of light in medium-1 and medium-2 are v_1 and v_2 respectively, then their ratio is called the refractive index of medium 1 relative to medium 2.

$$\therefore \ \mu_{21} = \eta_{21} = \frac{v_1}{v_2} \quad \text{... (3)}$$

4.1.4 Absolute Refractive Index :

The refractive index of a medium relative to a vacuum (or air) is called the absolute refractive index of the medium. However, the absolute refractive index is generally referred to only as the refractive index. It is represented by the ratio of the velocity (Speed) of light in vacuum (c) to the velocity (speed) of light in (v) in the given medium.

$$\mu = \eta = c/v \quad \text{... (4)}$$

μ = η = Refractive index

c = velocity of light rays in a vacuum.

v = velocity of light rays in medium.

v_1 = Velocity of light rays in medium – 1

η_1 = Refractive index of medium-1

v_2 = Velocity of light rays in medium – 2

η_2 = Refractive index of medium-2

Where, $\eta_1 = c/v_1$ and $\eta_2 = c/v_2$

$$\text{Therefore, } \eta_{21} = \frac{\eta_2}{\eta_1} = \frac{c/v_2}{c/v_1} = \frac{v_1}{v_2}$$

$$\therefore \ \eta_{21} = \frac{v_1}{v_2} \quad \text{... (5)}$$

From equations (02) and (05) ...

$$\mu_{21} = \eta_{21} = \frac{\sin i}{\sin r} = \frac{\eta_2}{\eta_1} = \frac{v_1}{v_2} = \text{constant}$$

Therefore, $\eta_1 \sin i = \eta_2 \sin r$ ... (6)

Equation (6) is also called the Snell's law. If a ray of light is refracted from air into glass, it is called the refractive index of glass relative to air.

$\therefore \ \eta_{ga} = \eta_g / \eta_a$

So $\eta_{ga} = 1/\eta_{ag}$

The optically denser a medium is, the more its refractive index is. The optically rarer a medium is, the lesser its refractive index is.

From the above equation (4) it can be said that the refractive index of the medium and the velocity of light in the medium are both inversely proportional to each other. Therefore, as the medium becomes optical denser, its refractive index goes increasing and the velocity of light in the medium decreases.

The absolute refractive index of some media is shown in **Table 4.1** below for information only.

Table 4.1 : Some established data regarding medium and its refractive index [20°C]

Medium	Refractive Index	Medium	Refractive Index
Air/ Vacuum	1.00	Glass / Benzene	1.501
Ice [0°C]	1.310	Quartz	1.554
Water	1.333	Diamond	2.471
Ethyl Alcohol	1.362	Polystyrene	1.595
Glycerine	1.473		

4.2 Total internal reflection and Critical angle :

4.2.1 Total Internal Reflection :

This phenomenon is based on the principle of refraction of light. **The figure** below will be helpful to understand the total internal reflection.

As shown in **figure 4.2**, a water container is filled with clear transparent water. A light source, fixed at the bottom of the container emits light rays in all directions. These rays are partially reflected and partially transmitted.

When a ray of light enters from an optically denser medium (here, water) to an optically rarer medium (air), it moves away from the normal at the interface. The AM ray is a normal ray that comes out without being refracted. The ray AO_1 forms the angle of incidence along the normal, which is slightly refracted and emitted in the form of ray O_1B (away from the normal) and partially reflected back to the water in the form of O_1C ray. The ray AO_2 forms angle of incidence (i) with the normal, which is slightly refracted and the ray exits in the form of O_2D (away from the normal) and returns to the water in the form of O_2E ray after being partially reflected. As the angle of incidence increases, so does the angle of refraction. And the ray of light moves away from the normal after being refracted, as can be seen in the figure. As the angle of incidence is increased gradually, the refracted ray O_3F travels in the direction parallel to the interface separating both media for a certain angle of incidence (i) equal to the critical angle (θ_c). At a particular angle of incidence, refracted ray moves parallel to the surface separating the two media. In this particular case, the angle of refraction becomes 90° for the incidence ray O_3f. The angle of incidence for which the angle of refraction becomes 90° is called the critical angle of the denser medium with respect to the rarer medium. The refracted ray found in the position of a critical angle is called Critical Ray. Here O_3F is that critical ray. In this situation, the surface separating both media appears to be illuminated.

Now, if the angle of incidence (i) is raised even slightly more than the critical angle (θ_c), the incident ray gets completely reflected back into the denser medium (water, in this case). That is, here, as shown in the figure, incident ray, AO_4 is fully reflected and returned back to the water in the form of O_4G. This phenomenon is called total internal reflection. This phenomenon is true for any angle of incidence larger than the critical angle. In this situation, the surface separating both media acts as a perfect mirror. Total Internal reflection also obeys the laws of reflection.

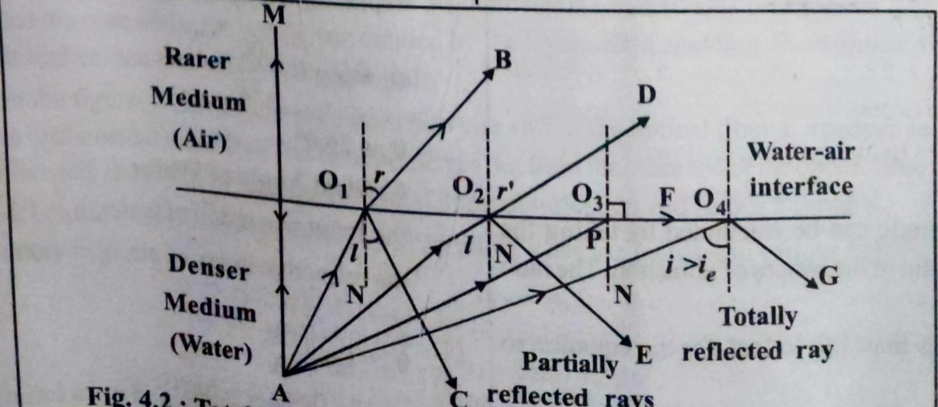


Fig. 4.2 : Total internal reflection in a glass vessel filled with water

4.2.2 Critical Angle :

In the previous paragraph, the phenomenon of total internal reflection was introduced. Total internal reflection (TIR) is the phenomenon that involves the reflection of all the incident light off the boundary.

In our introduction to TIR, we used the example of light traveling through water towards the boundary with a less dense material such as air. When the angle of incidence in water reaches a certain critical value, the refracted ray lies along the boundary, having an angle of refraction of 90-degrees. This angle of incidence is known as the critical angle; it is the largest angle of incidence for which refraction can still occur. For any angle of incidence greater than the critical angle, light will undergo total internal reflection.

So the critical angle is defined as the angle of incidence that provides an angle of refraction of 90-degrees. Make particular note that the critical angle is an angle of incidence value. For the water-air boundary, the critical angle is 48.6-degrees. For the crown glass-water boundary, the critical angle is 61.0-degrees. The actual value of the critical angle is dependent upon the combination of materials present on each side of the boundary.

Let's consider two different media - creatively named medium i (incident medium) and medium r (refractive medium). The critical angle is the θ_i that gives a θ_r value of 90-degrees. If this information is substituted into Snell's Law equation, a generic equation for predicting the critical angle can be derived. The derivation is shown below.

$$\eta_i \sin\theta_i = \eta_r \sin\theta_r$$

$$\eta_i \sin\theta_c = \eta_r \sin 90^o$$

$$\eta_i \sin\theta_c = \eta_r \qquad (\sin 90^o = 1)$$

$$\sin\theta_c = \frac{\eta_r}{\eta_i}$$

$$\theta_c = \sin^{-1}\frac{\eta_r}{\eta_i}$$

The critical angle can be calculated by taking the inverse-sine of the ratio of the indices of refraction. The ratio of $\frac{\eta_r}{\eta_i}$ is a value less than 1.0. In fact, for the equation to even give a correct answer, the ratio of $\frac{\eta_r}{\eta_i}$ must be less than 1.0. Since TIR only occurs if the refractive medium is less dense than the incident medium, the value of η_i must be greater than the value of η_r. If at any time the values for the numerator and denominator become accidentally switched, the critical angle value cannot be calculated. Mathematically, this would involve finding the inverse-sine of a number greater than 1.00, which is not possible. Physically, this would involve finding the critical angle for a situation in which the light is traveling from the less dense medium into the more dense medium, which again, is not possible.

This equation for the critical angle can be used to predict the critical angle for any boundary, provided that the indices of refraction of the two materials on each side of the boundary are known. Examples of its use are shown below :

Critical Angle of Glass :

We know that the refractive index of glass, $\eta_i = 1.52$

And, the refractive index of air, $\eta_r = 1.00$

$$\theta_c = \sin^{-1}\frac{\eta_r}{\eta_i}$$

replacing values of η_i and η_r in formula

$$\theta_c = \sin^{-1}\frac{1.00}{1.52}$$

$$\theta_c = 41.1^o$$

Critical Angle of Diamond :

the refractive index of diamond, $\eta_i = 2.42$

the refractive index of air, $\eta_r = 1.00$

$$\theta_c = \sin^{-1}\frac{\eta_r}{\eta_i}$$

replacing values of η_i and η_r in formula

$$\theta_c = \sin^{-1}\frac{1.00}{2.42}$$

$$\theta_c = 24.4^o$$

Critical Angle of Water :

the refractive index of water, $\eta_i = 1.33$

the refractive index of air, $\eta_r = 1.00$

$$\theta_c = \sin^{-1}\frac{\eta_r}{\eta_i}$$

replacing values of η_i and η_r in formula

$$\theta_c = \sin^{-1}\frac{1.00}{1.33}$$

$$\theta_c = 48.75^o$$

4.2.3 Necessary Conditions for Total Internal Reflection :

The two necessary conditions for the total internal reflection are :

(i) The light must travel from an optically denser medium to an optically rarer medium.

(ii) The angle of incidence in denser medium must be greater than the critical angle for the pair of media.

4.3 Applications of Total Internal Reflection in Optical Fibers :

The bright glitter and sparkling of Crystal glass and diamond glitter are attributed to the total internal reflection. A total internal reflection in nature gives the illusion of a mirage in the desert. Similarly, looming occurs due to total internal reflection in the polar or extremely cold regions. That means sailors see the steamer or ship hanging upside down in the air. The optical fibres used in communication and the medical field works on the principle of total internal reflection.

One thing to note here is that the total internal reflection does not occur when any light ray enters from an optically rarer medium to an optically denser medium. For objects with a large refractive index, the critical angle is less. For example, the critical angle for the light ray going from diamond to air is $\theta_c = 24^o$. This phenomenon is the reason for sparkling glitter seen in diamonds and crystal glass.

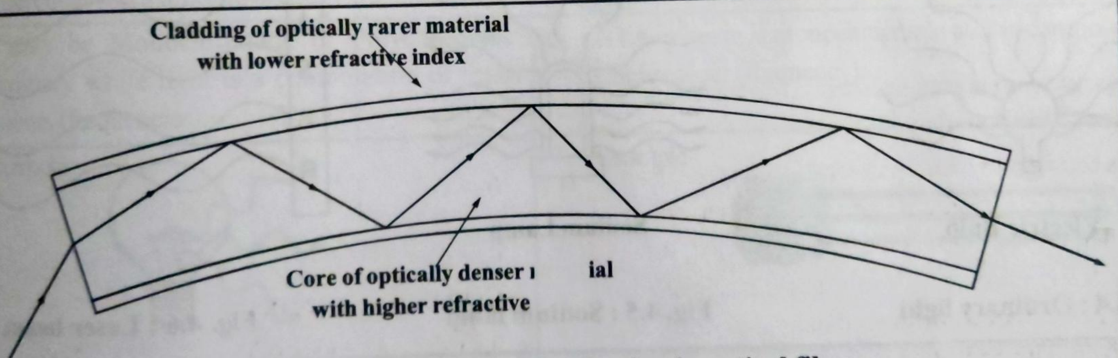


Fig. 4.3 : Total internal reflection in optical fiber

Optical fibres are now widely used to send audio or video signals over long distances. Optical fibres can transmit signals from one place to another using the phenomenon of total internal reflection. They are in the form of long and thin fibres of high-quality glass, quartz and plastic materials. Its diameter is about 0.0001 centimetres. The central-axial part of this fibre is called the core while the core is surrounded by the layer called cladding. In an optical fiber, the refractive index of the core is higher than that of cladding material.

As shown in the figure, when a light ray enters into one end of the optical fiber at a proper acceptance angle, it undergoes multiple total internal reflections and finally emerges out from the other end of the optical fiber. Even if the optical fiber is curved or twisted, the ray of light undergoes total internal reflection and passes through it.

Optical fiber is widely used in communication. In addition, it has various uses in various fields such as engineering field, medical, military field, etc.

4 LASER :

4.1 Introduction to LASER :

The year 2020 marks the 60th anniversary of the invention of the laser, the Diamond Jubilee of the laser. We don't even know and we have used laser technology unknowingly. When we shop in a big shopping mall, the laser-based bar code gun/scanner is used. The optical mouse, connected to a computer, is also an example of a laser device. The read write process of the CDs/DVDs used in a music system is done by a laser beam only. When we send an e-mail, the worldwide fiber optic network based on laser starts working. Laser technology has numerous applications in the present and is likely to lead to many more revolutionary discoveries in the future. What is this laser ?

LASER is the abbreviation of "**Light Amplification by Stimulated Emission of Radiation**".

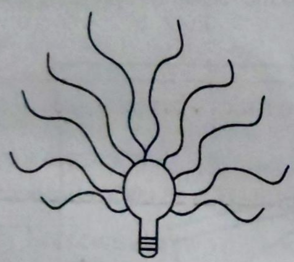
L – Light

A – Amplification

S – Stimulated

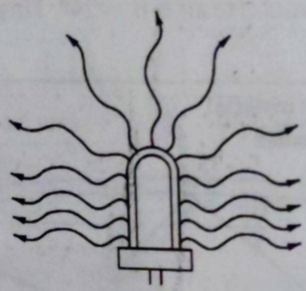
E – Emission

R – Radiation



Electric Bulb

Fig. 4.4 : Ordinary light



Sodium Lamp

Fig. 4.5 : Sodium lamp

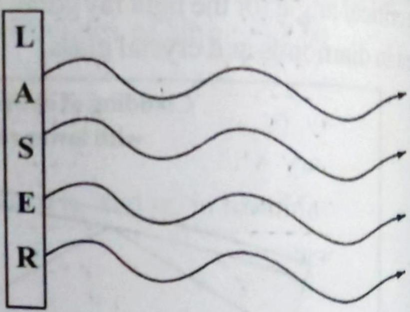


Fig. 4.6 : Laser beam

A laser is an electromagnetic, visible or invisible, ray of monochromatic light that consists of an extremely powerful, intense, bright, focused and coherent unidirectional beam of light rays that travels by tremendous velocity in air or vacuum. A laser beam is highly energetic and has unique properties over conventional ordinary light rays. The light of a normal bulb has all the wavelengths, as shown in **figure 4.4,** which propagates in all directions. The monochromatic (single wavelength) light of a sodium lamp has only one wavelength which spreads in all directions (**Figure 4.5**), while the laser light has only one wavelength, as shown in **figure 4.6**, which propagates in one direction.

4.4.2 Characteristics of Laser :

(1) A laser is an intense, powerful and coherent beam of light rays that travel at a tremendous speed.

(2) The laser light is highly directional, which means laser light is emitted as a relatively narrow beam in a specific direction.

(3) In a laser beam, the rays are parallel to each other.

(4) The laser beam propagates in only one straight direction without angular divergence, so even after reaching very long distances, there is hardly any change in the cross-section of its beam.

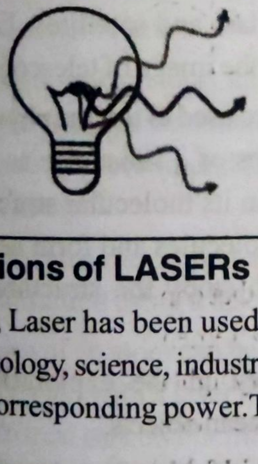
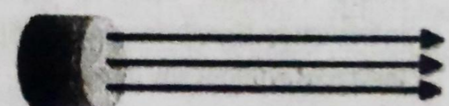
(5) Laser is a strong, concentrated and highly focused beam. It can deposit a lot of energy within a small area.

(6) Laser light is coherent, i.e. All photons in a laser beam are in the same phase.

(7) A laser beam contains only monochromatic light (Single wavelength).

(8) Laser light is usually emitted by intense pulses. Ruby and other solid crystal diodes produce lasers thro pulses. But, a gas laser can emit continuous waves.

4.3 The differences between LASER and ordinary light :

Ordinary Light Beam	LASER Light Beam
1. Spreads in all directions from the place of origin. (Divergent)	1. Spreads in the same direction. (Non-diverger Unidirectional)
2. Intensity decreases gradually as it travels long distances and spread with the distance.	2. Even travelling long distances rarely changes its cros section.
3. A convex lens or a concave mirror is needed to convert ordinary light into a parallel beam. However, its divergence is greater than that of laser light.	3. Laser light is made up of parallel rays.
4. Has low intensity and low brightness.	4. Has more intensity and has more brightness.
5. Not coherent, that is, the phase of all photons is different as it is a mixture of many wavelengths.	5. Coherent, meaning that all photons have the sam phase.
6. It may be Monochromatic or Polychromatic. Ordinary white light is a combination of many colours (frequencies).	6. A Laser beam is monochromatic as it is composed of single colour (frequency).
7. Example 	7. Example 

4.5 Applications of LASERs in Engineering and Medical field :

At present, Laser has been used in many ways in every field of modern society such as consumer electronic information technology, science, industry, entertainment, defence, medical etc. For different purposes, different lasers hav been used with corresponding power. The following table shows different laser power requirements corresponding t applications.

Laser Energy	Corresponding Application	Laser Energy	Corresponding Application
<1 mW	Laser Pointer	~ 5 mW	CD-ROM Drive
5 – 10 mW	DVD Player /DVD ROM Drive	~ 100mW	High Speed CD Burner
~250 mW	DVD burner/Writer	1W	Holographic Versatile Disc
1 W-20W	Micro-Machining	30 W –100W	Special types of CO_2 surgical lasers
100W–3000W	A special type of CO_2 laser, used in industrial laser cutting.	300W – 500W (Up to 1000 W)	Home use Laser Printer (Commercial Laser Printer)

4.5.1 Applications of Lasers in Engineering And Technology :

1. Industrial welding and drilling : Lasers are also used to make holes of a certain precise size in a given specific place or to make a series of such holes in any object, to cut and weld each type of sheet. Lasers are now widely used to make or weld metal tins. Lasers are also used to heat objects.
2. Civil engineering : Lasers are used in surveying. Engineers use lasers to align long tunnels in a straight path.
3. Precision marking involves "laser" marking where specific measurements are required. Lasers are used for everything from marking to measurement.
4. Laser hardening is done to harden the material.
5. In electronics :
   (i) In Consumer Electronics, Laser is used in barcode guns/ scanners used in supermarkets, CD players, DVD player/rewriters, laser printers, laser pointers, scanners, thermometers etc.
   (ii) The speed and efficiency of a computer can be increased by passing the laser through optical fibers. A Laser beam is used to transmit information signals into optical fibers over long distances without any distortion.
   (iii) It is widely used in fast and precision laser printers.
6. Communication : The laser beam is used for long-distance continuous transmission through optical fibers by converting information signals into optical signals. It is used in audio &/or video broadcasting like Television. Lasers are used to communicate messages on Earth and in space.
7. Environment engineering : Lasers are useful to measure and control air pollution as well as water pollution.
8. Chemical industry and material science :
   (i) In photo-chemistry, lasers are useful to monitor ultrafast chemical reactions.
   (ii) Laser can initiate and accelerate some chemical reactions and achieve more yield at low production cost.
   (iii) Small new molecules can be obtained by breaking large molecules with a laser.
9. Defence engineering :
   (i) Laser radar is used in the military. It can intercept the messages of the enemies and thus know the movements of the enemies. It can be used to know the exact location and distance of enemy cannons, missiles and submarines.
   (ii) The laser can also be used as a weapon, but because of the risk of severe disability such as blindness caused by the laser, it is a morally controversial non-lethal weapon and has led to a ban on the manufacture of such laser weapons by the "Protocol on Blinding Laser Weapons".
10. With the help of laser, photography producing three-dimensional colour images called Holography can be obtained, which has diversified the field of entertainment. This technology is currently used in "Laser Shows" in various locations.
11. Scientific research :
   (i) In Astronomy : The cross-section of the laser beam rarely changes even after reaching very long distances. So lasers are used to measure the exact distances of celestial objects like the sun, moon, stars and satellites. Lasers are used to sharpen the image of telescopes.
   (ii) Lasers are used to test the physical and chemical properties of a substance as well as to detect defects in its molecular structure. It is used to break molecules and form new materials. It is useful to study the structure of crystals and materials.
   (iii) It is used in the exploration of undersea-subterranean objects.
   (iv) To check whether the value of gravity constant "G" is constant, the laser is used.
   (v) For accurate measurement of light velocity, the laser beam is used.
   (vi) Lasers are used for high-speed photography.
   (vii) It is used to study the spectrum of objects. They are used to find out the fundamental properties of any material. It is used in laser fluorescence and laser spectroscopy. Lasers are used for spectroscopic analysis of materials. Thus, it is used to determine the atomic and molecular

configuration of materials. It is used to know the crystal structure.

(viii) To find and study the hidden or unseen fingerprint in forensic science.

(ix) Laser is useful in the nuclear fusion process, as it can create extreme temperature.

(x) In the study of the Raman phenomenon : Nobel Prize-winning Indian scientist C.V. Raman invented Raman spectroscopy based on the laser. Raman spectroscopy is based on the scattering of light after colliding with different atoms. This method is currently used by chemical and pharmaceutical companies. Raman lasers are used to answer questions like how fuel burns, how much energy is generated, how much pollution is spread, etc. Raman lasers are also used to obtain information about bones.

4.5.2 Applications of Lasers in the medical field :

In the medical field, laser is very useful. The laser beam can be used to take photos of the internal parts of the body with a micro camera, which can diagnose the disease and guide the surgery. Using laser, the surgery can be bloodless without any problems.

(i) The basic information and structure of many biomolecules can be understood with laser. The structure of proteins and DNA can be detected with a laser.

(ii) The structure and properties of microorganisms can be studied using a laser.

(iii) Particles of an atom can be accelerated at a high energy level with a laser beam. This concept is used to treat cancer. For this, the laser is focused on the tumour. When the photon of the laser passes through the body, its energy is given to the healthy cells as well as cancer cells, but all the energy is deposited at the endpoint i.e. the tumour. In simple terms, we call it the process of dissolving or burning a cancerous tumour.

(iv) In the operation of removing the eye number (Lasik surgery), as well as in repairing the broken retina, a laser beam of specific wavelength and power is used.

(v) In a cataract removal operation, a laser beam is used.

(vi) In an operation to remove the tumour, a laser beam is used.

(vii) Removal of kidney stones can be done by applying a laser beam.

(viii) In removing tooth decay, the laser is very useful.

(ix) A laser beam is used in cosmetic surgery, to beautify the skin, in the treatment of acne, to remove unwanted scars, warts and hair from the face and body.

(x) When a person becomes ill or is about to become ill, the patient's diseased organ have cells with changed chemical quality. They become chemically abnormal than healthy cells. Raman spectroscopy also changes as the cell-structure changes. Thus, information on the patient's diseased organs is obtained in a few seconds without taking a dose of dangerous X-rays. Thus, the symptoms of breast cancer, tooth decay and osteoporosis can be known in advance.

(xi) Cholesterol levels can be determined by laser testing of blood passing through the blood vessels above the armpits, without collecting a blood sample.

(xii) Using laser techniques, biological studies have been carried out in enzymes, proteins, cellular components and isolated cells, microorganisms, tissue culture, isolated physiological systems, individual organs etc. Lasers are used to prepare the dedicated instrument for genetic studies.

4.5.3 Hazards of Lasers :

Some lasers are completely non-hazardous, e.g.The CD player is safe as the laser is enclosed. Some lasers are safe during normal usage, e.g. Laser pointer, in which blinking eyes prevents damage. While some lasers should be used with extreme caution, otherwise a useful laser can be a harmful one. e.g. the retina of the eye is exposed to a laser beyond safe level, result in permanent damage in a few seconds. Many lasers (mostly industrial lasers) burn the skin and damage the eye. For such purposes, eye protection can be provided by goggles when working with a laser.

4.6 Fiber Optics :

4.6.1 Introduction - Fiber Optics :

When we use telephone, mobile phone, cable (D-to-H) TV or internet, knowingly or unknowingly we use fiber optic cable. Fiber optics is a branch of optics that studies the propagation of light waves by dielectric in a transparent medium optically denser than air. e.g. Optical fiber. In this chapter, we will look at how these tiny fibers of glass or plastic are made and how light is transmitted through them.

An optical fiber is a cylindrical dielectric waveguide as thick as human hair, made of glass and/or plastic. When a signal of information in the form of a light ray is inserted at one end, it exits at the other end, allowing the light waves to propagate along its length through the total internal reflections at its walls. During the continuous propagation within an optical fiber, the motion of a light ray follow the zig-zag path and a negligibly small portion of the light is likely to be dissipated through the sidewalls, but most of the light emerges at the other end.

4.6.2 Structure of Optical Fiber :

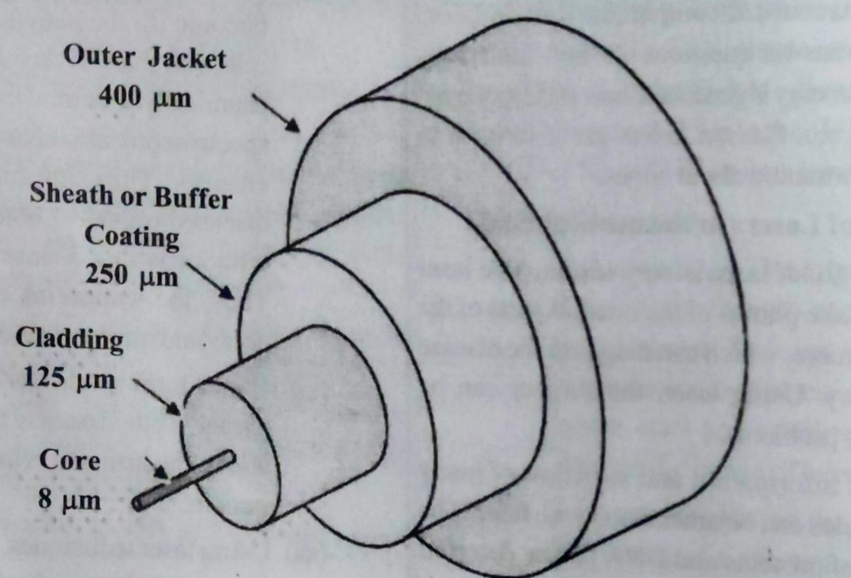


Fig. 4.7 : Constructional Structure of Optical Fiber

As shown in **Figure 4.7**, optical fibers are mainly consists of the following three parts :

Core : Core is the innermost cylindrical wire-like region. It is about 50 μm (50×10^{-6} m) in diameter. The core is made up of dielectric material like glass or plastic. The Refractive index of the core is greater than that of cladding. The light ray propagates through the core region undergoing a zigzag path due to the total internal reflection phenomenon.

Cladding : It is the middle part. The core is surrounded by an outer coaxial cylindrical layer of cladding, which is made up of optical material like glass or plastic. The refractive index of the cladding is always smaller than that of the core ($\eta_{core} > \eta_{cladding}$). The thickness of the cladding is equal to or greater than the wavelength of the light to be passed through it. It directs back the light ray into the core, results in total internal reflection phenomenon. Cladding is the middle layer, which serves to confine the light to the core.

Sheath or Buffer coating : It is the outermost protective part. It protects the core and cladding from damage due to moisture and wears by providing excellent mechanical strength. It is usually made up of opaque plastic material.

Optical fiber is formed as a single fiber or in the form of a flexible group of fibers i.e. in the form of a cable. The number of fibers in a single jacket is called a Fiber Bundle. Each of these fibers carries light independently. The entire structure is covered with a polyurethane or polyethylene jacket.

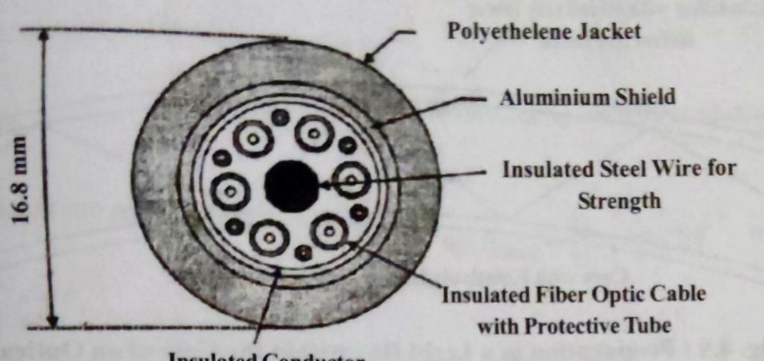


Fig. 4.8 : Optical Fibers Cable

The whole structure formed from the above sections is called cable. **Figure 4.8** shows the cross-section of a typical telecommunication cable. It features a bunch of 6 optical fibers and an insulated steel wire in the centre to give proper strength. Each optical fiber is made up of a core, cladding and insulating sheath. There are 6 wires of insulated copper in the space between 6 such optical fibers. An Aluminium sheath is applied to cover the whole structure. The outermost protective tube-like cylindrical jacket holds the cable of many optical fibers. This jacket is made of polyurethane or polyethylene material.

4.6.3 Total Internal Reflection :

You have studied total internal reflection in this Chapter. Here again, let's refresh it in terms of fiber optics. When light travels from one medium with a higher refractive index (η_1) to another with a lower refractive index (η_2), it moves away from an imaginary normal drawn at the interface. As the incident angle increases in medium having refractive index η_1, the refracted ray in medium having refractive index η_2 moves away from the normal.

The angle of incidence, for which the angle of refraction becomes 90°, is called the critical angle (θ_c).

For a particular angle (Critical angle) the refracted ray will not go into the medium of the refractive index η_2, but will go in the direction of the surface connecting the two media. Now if the angle of incidence from the medium of refractive index η_1 exceeds the critical angle, the refracted ray will go back completely to the medium of refractive index η_1, even though the medium of refractive index η_2 is transparent.

4.6.4 Propagation of light through fiber :

When light ray is incident to an optical fiber, it travels from one end to the other through total internal reflection within the core. The light entered into the core does not dissipate through its wall and reflected back into the core when the angle of incidence is greater than critical angle at the core-cladding interface. The cladding does not absorb light at all. Thus, the light entering the optical fiber is continuously reflected from the interface connecting the core-cladding as shown in **Figure 4.9** and carries it to the other end.

When a Light ray enters into the optical fiber core and striking the core-cladding interface at an angle of incidence greater than the critical angle, is reflected back into the core and light confines in the optical fiber due to the total internal reflection phenomenon. If the angle of incident and angle of reflection are equal (and both greater than the critical angle too), the light ray continues to follow the zig-zag path down the length of the fiber because the light ray is trapped within the core due to the total internal reflection. If the light ray striking the core-cladding interfaces at an angle less than the critical angle, it passes into the cladding and is transmitted out.

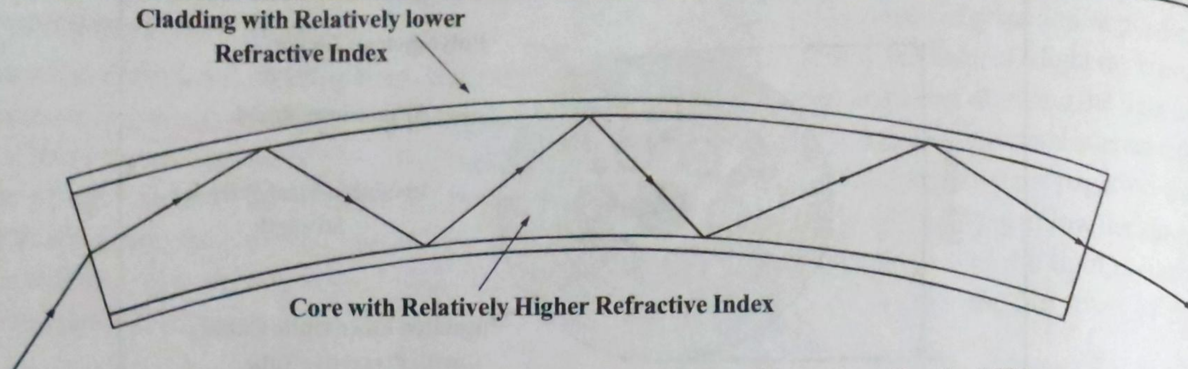


Fig. 4.9 : Propagation of a Light Ray within the Core of an Optical Fiber

The main function of optical fiber is to accept and transmit as much light as possible from the light source. Its light-gathering ability depends on its core size and numerical aperture. The numerical aperture of a fiber depends on its acceptance angle and fractional refractive index change.

4.6.5 Acceptance angle :

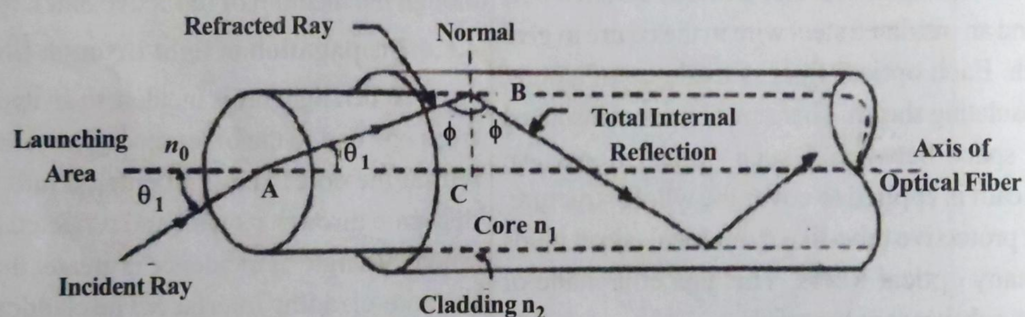


Fig. 4.10 Acceptance angle

As shown in figure 4.10, light is incident at the launching end of an optical fiber.

Suppose the refractive index of the core is η_1 and the refractive index of the cladding is η_2, where $\eta_1 > \eta_2$. The refractive index of the medium from which the light enters into the core is η_0. Suppose light-ray strikes along the axis of the optical fiber at an angle of incidence. The beam is refracted at the angle and make an angle ϕ with the core-cladding interface; with ϕ_c is the critical angle.

Here, $\eta_1 > \eta_2$ so if $\phi > \phi_c$ the interface has a total internal reflection of the beam. As long as $\phi > \phi_c$ the light will remain in the fiber. Now let's calculate the angle of incidence for which, $\phi \geq \phi_c$ and light ray remains within the fiber.

Applying snail rule to the surface of the optical fiber launching end,

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{\eta_1}{\eta_0} \quad \text{... (1)}$$

Now if we go on increasing the angle of incidence θ_i, one such value will be obtained that $\phi < \phi_c$ and the ray will escape out of the sidewall of the fiber. When $\phi < \phi_c$, the maximum value of θ_i is obtained.

It can be seen from ΔABC that,

$$\sin \theta_r = \sin (90^o - \phi) = \cos \phi \; .... \quad \text{... (2)}$$

Substituting $\sin \theta_r$ from equation (2) into equation (1) we have,

$$\frac{\sin \theta_i}{\cos \phi} = \frac{\eta_1}{\eta_0} \quad \text{... (3)}$$

$$\therefore \sin \theta_i = \frac{\eta_1}{\eta_0} \cos \phi$$

Now, θ_i becomes maximum when $\phi = \phi_c$

$$\text{So, } \sin \theta_{imax} = \frac{\eta_1}{\eta_0} \cos \phi_c \quad \text{... (4)}$$

Again, from Snell's law, $\sin \phi_c = \frac{\eta_2}{\eta_1}$

$$\text{And, } \cos \phi_c = (1 - \sin^2 \phi_c)^{1/2}$$
$$= [1 - (\eta_2/\eta_1)^2]^{1/2}$$

$$\text{So, } \cos \phi_c = \left(\frac{1}{\eta_1}\right) (\eta_1^2 - \eta_2^2)^{1/2} \quad \text{... (5)}$$

Substituting $\cos \phi$ from equation (5) into equation (4) gives,

$$\sin \theta_{imax} = \frac{\eta_1}{\eta_0} \left(\frac{1}{\eta_1}\right) (\eta_1^2 - \eta_2^2)^{1/2} \quad \text{... (6)}$$

$$\therefore \sin \theta_{i\,max} = \left(\frac{1}{\eta_0}\right) (\eta_1^2 - \eta_2^2)^{1/2} \quad \text{.... (7)}$$

Mostly the incident ray comes from air. So, applying $\eta_0 = 1$ and for air $\theta_{imax} = \theta_0$, we have,

$$\sin \theta_0 = ({\eta_1}^2 - {\eta_2}^2)^{1/2} \quad \text{.... (8)}$$

$$\text{And finally, } \theta_0 = \sin^{-1} ({\eta_1}^2 - {\eta_2}^2)^{1/2} \quad \text{.... (9)}$$

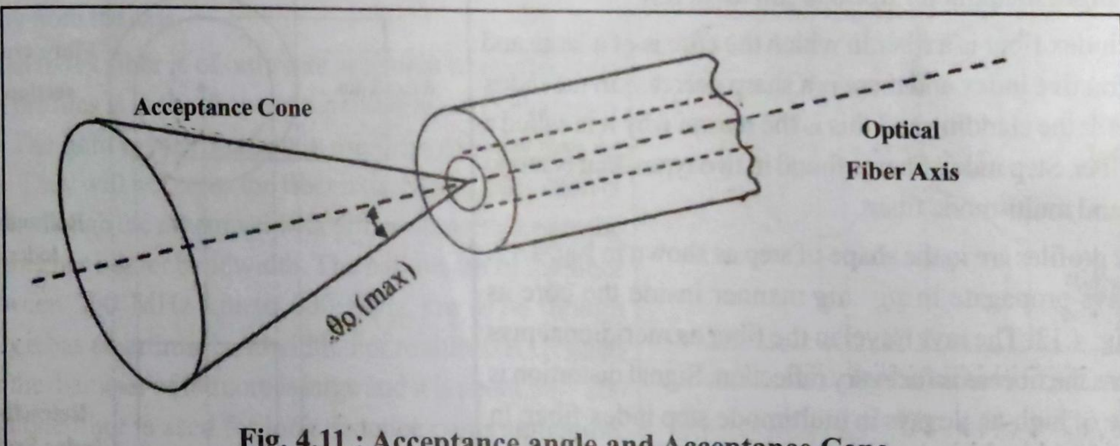


Fig. 4.11 : Acceptance angle and Acceptance Cone

This angle θ_0 is called the acceptance angle for optical fiber. The acceptance angle of an optical fiber is the maximum value of the angle at which the light ray travels through the fiber-core (without leaking) relative to the axis of the fiber. The light rays given at an angle of more than θ_0 values are refracted in the cladding and hence loses the corresponding light energy. The larger the diameter of the core, the higher the value of the acceptance angle. As shown in **Figure 4.11,** the rays of light at a solid angle $2\theta^o$ are acceptable and also transmitted to the fiber. Therefore, this cone is said to be an acceptance cone.

4.6.6 Numerical Aperture :

The sine value of the acceptance angle is known to be the numerical aperture.

Thus, $NA = \sin \theta_0$

$$\text{And, } NA = ({\eta_1}^2 - {\eta_2}^2)^{1/2} \quad \text{.... (10)}$$

$$\text{Also, } NA = \eta_1 \cdot \cos \phi_c \quad \text{.... (11)}$$

Numerical aperture determines the light gathering capacity of an optical fiber. A numerical aperture gives a measure of how much light an optical fiber can accept. It can be seen from **Equation (10)** that the numerical aperture (NA) depends only on the refractive indices of the core and the cladding. The higher the value of numerical aperture (NA), the greater its ability to accept light from a light source. Generally, NA ranges from 0.13 to 0.50. NA is unitless.

Here, the size of the optical fiber is written by placing a slash (/) between the diameters of core and cladding e.g. /125, i.e. 50 μm core diameter and 125 μm cladding diameter. Laser or LED is used as the light source.

Multimode Propagation : (Only for information)

If the light is propagated in more than one mode in an optical fiber, it is called multi-mode propagation. Due to many modes, the pulse that is carried in the fiber is slightly stretched as the distance increases. This is called dispersion. There are two types of multi-mode light rays propagation in optical fibers.

Multimode Step index Optical fibers :

The construction of both multimode step-index fiber and single-mode step-index fiber are mostly similar, but the main difference is that the core diameter of the multimode step-index fiber is relatively large. The core diameter in multimode optical fiber range from 50 μm to 200 μm, which is much larger than the wavelength of light they carry. Here, the light rays in the optical fiber occupy many zigzag paths. Light rays propagate from one end to the other by multiple total internal reflections. Multi-mode step-index optical fibers are used in data links where low bandwidth is required.

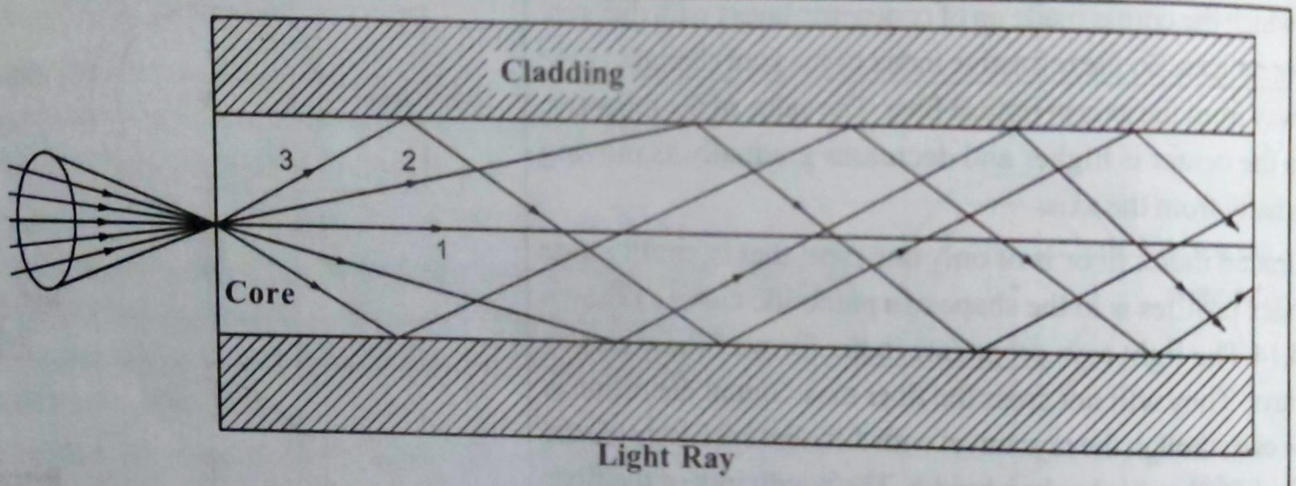


Fig. 4.16 : Light Propagation in the Multimode Step Index Optical Fibers

Multimode Graded Index Optical Fibers :

The diameter of core in graded-index multimode fiber is somewhat between 50 to 200 micrometer. The large diameter of the core allows multiple rays to propagate through the fiber.

The light wave that travels inside the fiber changes its behaviour with time while travelling inside it. As we have already discussed that the refractive index of the core at the axis is comparatively larger than at the other part inside it.

Thus when light is allowed is propagate inside the fiber, then it travels from less dense medium to more dense medium. However, we are aware of the fact that for TIR to take place the light must travel from denser to rarer medium. So, the light ray despite being reflected gets refracted inside the core.

Hence, the light on travelling gets continuously refracted and bends. Thus in case of graded-index multimode fiber, the light rays do not propagate by following a straight line, rather they propagate in the form of skew rays or helical rays. They will not cross the fiber axis. this is due to the gradually change in the refractive index of the core.

4.7.3 Difference between step-index fiber and graded-index fiber :

Basis of Comparison	Step Index Optical Fiber	Graded Index Optical Fiber
Description	Step index fiber is a fiber in which the core is of a uniform refractive index and there is a sharp decrease in the index of refraction at the cladding.	Graded index fiber is a type of fiber where the refractive index of the core is maximum at the center core and then it decreases gradually towards core-cladding interface.
Types	Step index fiber is found in two types, that is mono mode fiber and multi mode fiber.	Graded index fiber is of only one type, that is, multi mode fiber.
Index Profiles	Index profiles are in the shape of step.	Index profiles is in the shape of a parabolic curve
Light Rays Propagation	The light rays propagate in zig-zag manner inside the core.	The light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
Signal Distortion	Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion.	Signal distortion is very low even though the rays travel with different speeds inside the fiber.
Bandwidth Size	The fiber has lower bandwidth. The bandwidth of multi-mode step-index fiber is about 50 MHz, while the bandwidth of a single-mode step-index fiber is more than 1000 MHz.	The fiber has higher bandwidth. The bandwidth of this fiber is between 200 MHz to 600 MHz. However, theoretically, it is infinite bandwidth
Diameter Of The Core	The diameter of the core is between 50-200 μm in the case of multimode fiber and 10 μm in the case of single mode fiber.	The diameter of the core is about 50-200 μm in the case of multimode fiber.
Application	Used for short distance communication.	Used for long distance communication.
Attenuation Of Light Rays	Attenuation of light rays is more in multimode step index fibers but for single mode step index fibers, it is very less.	Attenuation of light rays is less in graded index fibers.
Cost	Less expensive	Highly expensive.
Numerical Aperture	Single-mode step-index fibers have a lower numerical aperture (NA), while multimode step-index fibers have a higher numerical aperture (NA).	NA of graded index fibers is less.

4.8 Advantages of optical fibers over Coaxial cables :

Radio waves and microwaves are used to carry information in electronic communication. Due to their limited bandwidth, their information (data) carrying capacity is low, so it is not sufficient for modern needs. If light waves are used instead of radio waves and microwaves, the number of signals increases considerably and can be transmitted simultaneously.

Optical fiber has many advantages over conventional Coaxial cables.

(1) **Optical fibers are cheaper.** Optical fiber is made from silica (SiO_2), which is found in abundance very cheaply.

(2) **Optical fiber is small in size, light in weight, flexible and has good mechanical strength.** Due to its small size, a cable of a given diameter can be bundled (in the form of a cable) with more optical fibers than a copper wire. Which allows more telephone lines from a single cable or more TV channels from a single cable to reach our TV.

(3) **Optical fiber is not harmful.** If a normal conductor wire breaks accidentally, a short circuit occurs in the high voltage line and the sparks cause great damage to the combustible gases in the area. While such accidents do not occur due to the insulating properties of optical fiber.

(4) **Electromagnetic radio frequency interferences (EMI) and radio frequency interferences (RFI) do not affect optical fibers.** Photons are electrically neutral and therefore do not experience the effects of background noise caused by disturbances of high voltage, electricity or electromagnetic **interference (EMI) or radio frequency interference (RFI) like plain conductive wires.**

(5) **Optical fiber reduces the possibility of background and cross-talks.** In communication through copper wire cable, the signal keeps moving from one circuit to another, resulting in other calls being heard in the background as well. The light waves passing through the optical fiber do not leak. Because of this, even if a lot of optical fiber clusters are taken as a cable, the possibility of cross-talk is less.

(6) **Optical fiber has higher bandwidth.** The rate of transmission of any information/data is related to its signal frequency. The frequency of light is very high i.e. of the order of 10^{14} to 10^{15} Hz. While the frequency of radio waves is in the order of 10^6 and the frequency of microwaves is 10^8 Hz - 10^{10}Hz. Therefore the rate of transmission of information by light is higher than that of radio waves or microwaves. A typical telephone cable, made up of 900 conducting wires, can handle 10,000 calls, while 1 mm optical fiber can handle 50,000 calls. Thus, optical fiber can carry large amounts of information.

(7) **Optical fiber has low transmission loss per unit length and noise-free transmission.**

(8) **In Optical fiber, light signals does not spread out much so signal safety is maintained.**

(9) **Optical fiber is more efficient than electrical conducting wire, as it requires fewer repeaters and saves both maintenance and costs.**

(10) **The tensile strength of the optical fiber is very high. And it can be bend.**

(11) **Optical fiber can be used for a long time.** Optical fiber lasts for 20-30 years, while copper wire lasts for 12-15 years.

(12) **Optical fiber is temperature resistant.** That is, unlike copper wire, it can withstand high temperatures.

(13) **Optical fiber transmits digital information through digital signals**, which is especially useful in computers.

Sr. No.	Optical Fiber Cables	Conventional Metallic Coaxial Cables
01	Raw materials SiO_2 is low cost and easily available everywhere on the earth.	Raw material metals are costly and restrictively available from mines.
02	Cheaper and economical production.	Costly production.
03	Smaller size & lighter in weight yet flexible and strong.	The diameter is higher than optical fiber. Not lighter in weight. Not so flexible & strong.
04	Signal degradation & transmission loss is negligible at long distances also.	Signal degradation and transmission loss are very considerable and heavier at long distances.
05	Less power loss. So, it requires low power to transmit the signals. Moreover, less number of repeaters is required.	Power loss is considerably heavy for long-distance transmission. So, repeaters are required at certain distances.
06	Optical fibres are immune to unaffected by induced coupling of electromagnetic signals and hence no cross talks possible.	The electromagnetic coupling or induced signals from nearby cables result in cross talks.
07	Large bandwidth is available. More communication channels are available & more data can be transferred at a larger speed. Data is travelled in form of light rays.	Little data can be transferred at lower speed requires heavy power input because data is carried in the form of electric signals .
08	The light signals in an optical fiber do not interfere with another optical fiber in the same cable due to good isolation among them. So, clearer reception of audio-video quality results.	In conventional metallic wires, data is transferred in the form of electrical signals which can interfere to the electrical signals of the nearest metallic wire by electromagnetic induction.
09	Optical fibers are made up of dielectric material hence no disturbances of electromagnetic or other kinds of disturbances.	Metallic conventional cables experience all kinds of disturbances like electromagnetic induction from electric field or lightning in sky etc..
10	Optical fiber cables assure speedy transfer and good reception of data.	The conventional metallic cable can transfer data speedy but reception quality is not satisfactory every time.
11	Fibre optics can tolerate large variations in temperature, humidity & atmospheric changes. They are less affected by gases & chemicals. They are corrosion resistive.	The conventional metallic cables are not corrosion resistive because they do not bear the effect of pollution, temperature- atmospheric changes.
12	The life span of optical fibers is 20 to 30 years.	The life span of conventional metallic cables is 10 to 15 years.
13	Optical fiber data communication is safe, inexpensive, easy, speedy and pollution-free. Does not require rare natural resources.	Data communication through conventional metallic cable is expensive, complex and not pollution-free. Requires rare natural resources like metal and plastic sometimes.

4.9 Applications of Optical Fibers In Different Fields :

There are many applications of optical fibers in different fields. Optical fibers have many versatile applications in different fields of science, technology and our day to day life.

4.9.1 Applications of Optical Fibers In Engineering Field :

Optical fiber sensors :

Optical fibers are used in thermometers (80°C – 700°C), smoke detectors, pollution detectors, liquid level detectors, security alarm systems, electronic instrumentation systems, industrial automation controls, pressure sensors for various uses, Current, Resistance and voltages Sensors, Electromagnetic field sensors, magnetic field sensors etc. Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fiber. Fibers have many uses in remote sensing. In some applications, the sensor is itself a modified optical fiber. In other cases, optical fibers are used to connect a non-fiber optic sensor to a measurement system. Optical fiber interferometers are used for measurements of heat flux and unsteady temperature in turbo-machinery test rigs.

Applications of optical fibers in mechanical fields :

Engineers use optical fibers to detect damages and faults which are hard to reach places. An optical endoscope is a long thin imaging diagnostic device made up of a coherent bundle of optical fibers with a lens and camera at one end and its other end is connected to computer system. It is used for visual inspection of internal parts of a human body through a small hole. The industrial endoscopes are used for inspecting anything difficult to reach such as jet engine interiors. It is used for mechanical imaging as inspecting mechanical welds in pipes and engines (of aeroplanes, rockets, space shuttles, cars, etc.).They are used for safety measures and lighting purposes in automobiles both in the interior and exterior. They are used in airbags and traction control. They are also used for research and testing purposes in industries.

Applications in communication systems :

The greatest impact of developments in fiber optics has been on telecommunication engineering and information technology. Optical fiber is widely used by cable television services, industrial plants and office buildings, university campuses and electric companies. Optical fiber provides large bandwidth for communication. It is therefore capable of handling a large number of channels. Optical fiber can be used for the transmission of digital data generated by devices such as computers and sensors.

Optical fiber communication is classified into two sections :

(1) Local and medium-range systems

(2) Long-haul systems

(1) Local and medium-range system : In a small business or bank-like organization where short-distance systems are used, information is delivered to different places through LAN (local area network). Many computers are networked by optical fiber through a common channel to transmit and process information. This is called optical fiber data bus, which is cheaper than a normal multi-wire data bus, as well as the ability to carry information is much higher.

(2) Long-haul system : Long haul systems are those where optical fiber networks spread across the city or telephone cables connecting different countries spread far and wide over long distances.

4.9.2 Applications of Optical Fibers in the Medical Field :

Optical fibers guided endoscope is used to inspect internal organs for diagnostic purposes. Also, it is used in Echo-Cardiogram.

In every laser surgery, optical fiber is used as a guiding medium. It is used to detect tumours, stone etc. in the body.

In ophthalmology, a laser beam guided by optical fibre is used to re-attach the detached retina or remove cataracts or correct the visual impairment of the eye by removing short/long sight numbers.

In cardiology, optical energy of a laser beam is transmitted through optical fiber and blockage or clotting in the artery is dissolved and evaporated.

They are used in the treatment of cancer by focusing rays direct to burn the cancer tumour.

Numericals based on refraction :

Example-1 : A light ray enters from the air into glass medium of a refractive index of 1.50. What will be the speed of light in the glass medium ? The velocity of light in air is 3×10^8 m / s.

Solution :

Data Given :

Refractive index of glass $\eta = 1.50$

Velocity of light $c = 3 \times 10^8$ m/s

Velocity of light in the glass medium $v = ?$

Absolute Refractive index of glass = c/v

$\therefore \quad v = c/\eta$

$v = 3 \times 10^8/1.50$

$v = 2 \times 10^8$ m/s

Example-2 : A light ray enters into medium of water with an absolute refractive index of 1.33 from the air. If the angle of refraction of light in water is 17°30', what will be the angle of incidence of light at the surface separating the two media ?

Solution :

Taking air as medium 1 and water as medium 2,

Data given :

Refractive index of air $= \eta_1 = 1$

Refractive index of water = 1.33

Angle of refraction $= \theta_r = 17^0 30'$

Angle of incidence $= \theta_i = ?$

Snell's law : $\eta_1 \sin \theta_i = \eta_2 \sin \theta_r$

$\therefore \quad 1 \times \sin \theta_i = 1.33 \times \sin 17^o 30'$

$\therefore \quad \sin \theta_i = 1.33 \times 0.3 = 0.4$

$\therefore \quad \theta_i = \sin^{-1}(0.4) = 23^o 36'$

Example-3 : If the relative refractive index of diamond with respect to glass is 1.62 and the absolute refractive index of glass is 1.5, then calculate the absolute refractive index of a diamond.

Solution :

Data given :

η_{dg} = Refractive index of diamond with respect to glass = 1.62

η_{ga} = Absolute refractive index of glass = 1.5

η_{ad} = Refractive index of air with respect to diamond

η_{da} = Absolute refractive index of diamond = ?

Now,

$\eta_{ga} \times \eta_{ad} \times \eta_{dg} = 1$

$\therefore \quad 1.5 \times \eta_{ad} \times 1.62 = 1$

$\therefore \quad 1.5 \times 1.62 = 1/\eta_{ad} = \eta_{da}$

$\therefore \quad \eta_{da} = 2.43$

Example-4 : The critical angle for the air-glass interface is 45°. Find the refractive index of the glass.

Solution :

Given : Critical angle $\theta_c = 45°$.

Refractive index of glass $\mu = ?$

$$\mu = \frac{1}{\sin\theta_c} = \frac{1}{\sin 45°} = \frac{1}{0.707} = 1.414$$

Ans : The refractive index of glass is 1.414

Example-5 : The critical angle for a medium is 40°. Find the refractive index of the medium.

Solution :

Given : Critical angle $\theta_c = 40°$.

Refractive index of medium $\mu = ?$

$$\mu = \frac{1}{\sin\theta_c} = \frac{1}{\sin 40°} = \frac{1}{0.6428} = 1.56$$

Ans. : The refractive index of medium is 1.56

Example-6 : Find critical angle of water air interface ${}_a\eta_w = 4/3$.

Solution :

Given : Refractive index of water w.r.t. air, ${}_a\eta_w = 4/3$

Critical angle $\theta_c = ?$

$${}_a\eta_w = 4/3 = \frac{1}{\sin\theta_c}$$

$$= \sin\theta_c = \frac{1}{\frac{4}{3}} = 3/4 = 0.75$$

$\theta_c = \sin^{-1}(0.75) = 48°36'$

Critical angle of water air interface $= 48°36'$

Example-7 : If the refractive indices of the core and cladding of an optical fiber are 1.563 and 1.498 respectively, calculate its acceptance angle.

Solution :

Data given :

Refractive index of the core $\eta_1 = 1.563$

Refractive index of cladding $\eta_2 = 1.498$

Numerical Aperture,

$$NA = (\eta_1^2 - \eta_2^2)^{1/2} = [(1.563)^2 - (1.498)^2]^{1/2}$$

$$= \sqrt{2.4430 - 2.2440} = \sqrt{0.199}$$

$$= 0.4460$$

Acceptance Angle,

$\theta_0 = \sin^{-1}(\eta_1{}^2 - \eta_2{}^2)^{1/2} = \sin^{-1}(NA)$

$= \sin^{-1}(0.4460)$

$= 26^\circ 30'$

mple-8 : If the refractive indices of the core and cladding of a step-index optical fiber are 1.48 and 1.45 pectively. Calculate its (1) acceptance angle (2) numerical aperture (3) critical angle at the core-cladding rface.

lution :

Data given :

Refractive index of core $\eta_1 = 1.48$

Refractive index of cladding $\eta_2 = 1.45$

Numerical Aperture,

$NA = (\eta_1{}^2 - \eta_2{}^2)^{1/2}$

$= [(1.48)^2 - (1.45)^2]^{1/2} = \sqrt{2.1904 - 2.1025} = \sqrt{0.879} = 0.2965$

Acceptance Angle, $\theta_0 = \sin^{-1}(\eta_1^2 - \eta_2^2)^{1/2} = \sin^{-1}(NA)$

$= \sin^{-1}(0.2965) = (17.24)^\circ = 17^\circ (0.24 \times 60)' = 17^\circ 24'$

We know that, $\sin \phi_c = \eta_2 / \eta_1$

$\therefore$ Critical Angle $\phi_c = \sin^{-1}(\eta_2/\eta_1)$

$= \sin^{-1}(1.445/1.48) = \sin^{-1}(0.97635)$

$= \sin^{-1}(\sin 77.51) = (77.51)^\circ = 77^\circ 30'$

Example-9 : If the refractive indices of the core and cladding of an optical fiber are 1.55 and 1.5 respectively. Calculate its NA.

Solution :

Data given :

Refractive index of core $\eta_1 = 1.55$

Refractive index of cladding $\eta_2 = 1.5$

Numerical Aperture, $NA = (\eta_1{}^2 - \eta_2{}^2)^{1/2}$

$= [(1.55)^2 - (1.50)^2]^{1/2} = \sqrt{2.4025 - 2.2500} = \sqrt{0.1525} = 0.3905$

Example-10 : The numerical aperture of an optical fiber is 0.39. If the difference between the refractive indices of its core and the cladding is 0.05, find the refractive index of the core.

Solution :

Data given :

The difference between refractive indices of core and cladding $= \eta_1 - \eta_2 = 0.05$

Numerical Aperture, $NA = 0.39$

Refractive index of core = ?

$\eta_1 = \eta_2 + 0.05$ .... (i)

Numerical aperture, $NA = (\eta_1{}^2 - \eta_2{}^2)^{1/2}$

$0.39 = (\eta_1 - \eta_2)^{1/2} (\eta_1 + \eta_2)^{1/2}$

Substituting from equation (i) in above result,

$$0.39 = (\eta_2 + 0.05 + \eta_2)^{1/2} (\eta_2 + 0.05 - \eta_2)^{1/2}$$

Squaring both sides,

$(0.39)^2 = (2\eta_2 + 0.05)(0.05)$

$0.1521/0.05 = 2\eta_2 + 0.05$

$3.042 = 2\eta_2 + 0.05$

$\eta_2 = (3.042 - 0.05)/2$

$\eta_2 = 1.496$ ... (ii)

Substituting from equation (ii) in equation (i) results in,

$\eta_1 = \eta_2 + 0.05 = 1.496 + 0.05 = 1.546$

$\eta_1 = \mathbf{1.546}$

Example-11 : If the core material of an optical fiber has a refractive index of 1.48 and the cladding material has a refractive index of 1.45, calculate its numerical aperture and acceptance angle.

Solution :

Data given :

Refractive index of core $\eta_1 = 1.45$

Refractive index of cladding $\eta_2 = 1.44$

Numerical Aperture, $NA = ({\eta_1}^2 - {\eta_2}^2)^{1/2} = [(1.45)^2 - (1.44)^2]^{1/2}$

$= \sqrt{2.1025 - 2.0736} = \sqrt{0.0289}$

$= 0.17$

Acceptance Angle, $\theta_0 = \sin^{-1}(\eta_1^2 - \eta_2^2)^{1/2} = \sin^{-1}(NA)$

$= \sin^{-1}(0.17)$

$= (9.78)^o = 9^o47'$

SUMMARY

- **Laws of Refraction :**

1. The incident ray, the refracted ray and the normal to the interface of two transparent media at the point of incidence, all are in the same plane.
2. Incident ray and refracted ray are in different optical media and on the opposite side of the normal.
3. When a light-ray passes through an optically rarer (thin) medium (like air) to an optically denser (thick) medium (like glass), the refracted ray bends towards the normal to the interface. Therefore, the angle of the incidence is greater than the angle of refraction ($i > r$).
4. When a light ray passes through a denser medium (like glass) to an optically rarer medium (like air), the refracted ray bends away from the normal to the interface. The angle of incidence is smaller than the angle of refraction ($i < r$).
5. The ray which incidents at the normal, returns in the same direction (but does not change direction).
6. **Snell's law :** Ratio of sine of the angle of incidence to the sine of the angle of refraction is always constant for the given two media. It is termed as refractive index. Its symbol is μ (Mu). Sometimes μ (Ita) is also written.

The refractive index of light can be represented as the ratio of the velocities of light in its two media. If the velocities of light in medium-1 and medium-2 are and v_2 respectively, then their ratio is called the refractive index of medium 1 relative to medium 2.