

Applications of Optical Fibers Applications

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. When a ray of light passes from one transparent medium to another transparent medium, its velocity changes. When a 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 media. 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 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 (the cuboid). Without repeating that experiment, let us once again understand the same phenomenon of refraction.

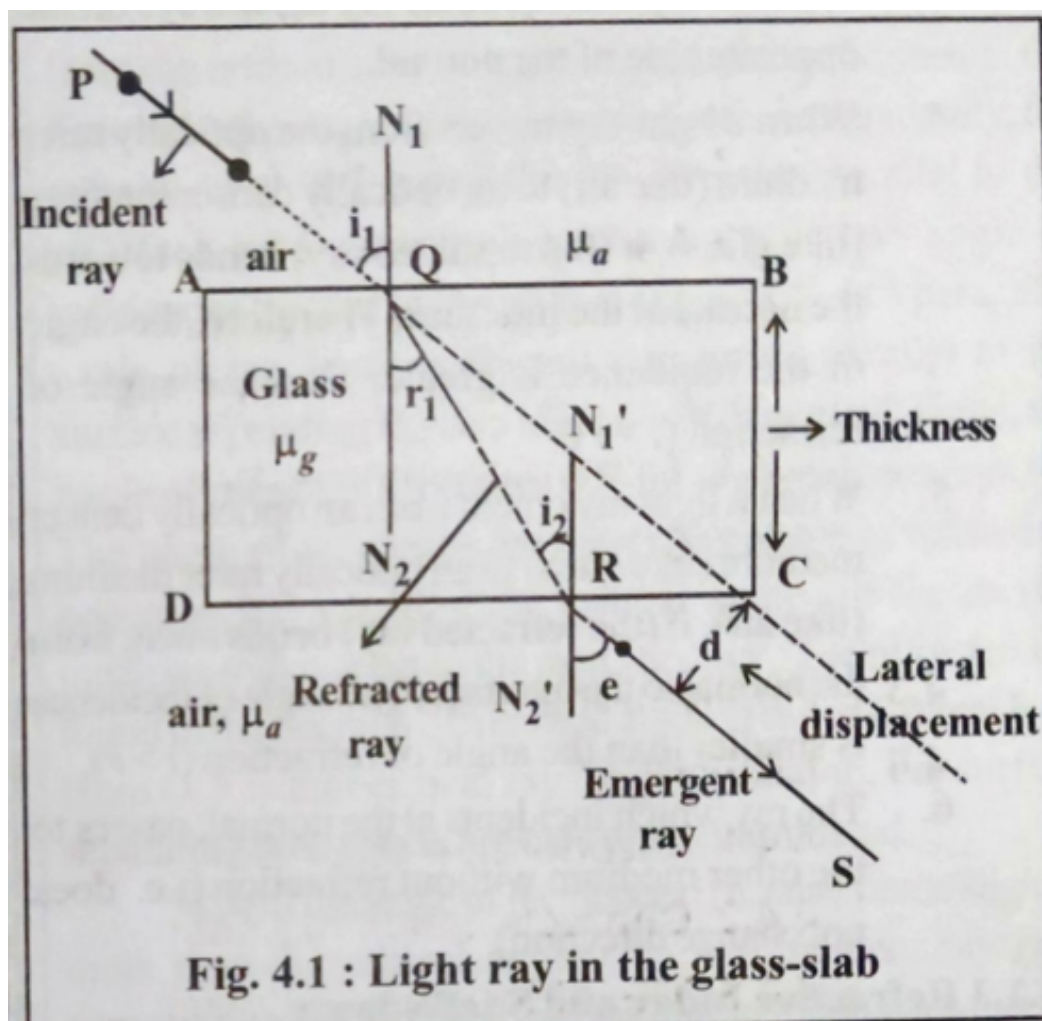


Fig. 4.1 : Light ray in the glass-slab

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

As shown in the figure 4.1. PO is an incident ray. It makes the angle of incidence i , 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. Its velocity decreases and it bends towards the normal and makes the angle of refraction r , 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 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. That is why it is called an Emergent Ray. In the figure, i is the angle of emergence.

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.

Refractive index with respect to that of the first medium (n_{21}) is defined as the ratio of the refractive index of the second medium to 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 NQ, 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 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 is incident 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 n (μ). Sometimes n_{21} is also written. It is known as Snell's law. It can be written in the form of a formula as follows:

4.1.4 Absolute Refractive Index

(4)

medium 1 relative to air. The refractive index of air (or vacuum) 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 (v) in the given medium. $n = \frac{c}{v}$.

- n = 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 =
- n_1 = Refractive index of medium-1
- v_2 = Velocity of light rays in medium-2 =
- n_2 = Refractive index of medium-2 Where, $n_1 = \frac{c}{v_1}$ and $n_2 = \frac{c}{v_2}$

Therefore, $n_2 = \frac{v_1}{v_2} n_1$

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GLYPH<26>

v_2

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

n_2

$n_1 =$

$\sin r \sin i = \frac{v_2}{v_1}$

$=$

v_2 Therefore, $n_2 \sin i = n_1 \sin r$ constant

i

... (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.

- n_{ga}

Suppose the refractive index of the first medium is n_1 and that of the second medium is n_2 . The refractive index of medium-2 relative to medium-1 is denoted by n_{21} or n_2/n_1 .

$n_{21} = \frac{n_2}{n_1}$ The optically denser a medium is, the more its refractive index is. The optically rarer a medium is, the lesser refractive index it has.

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.

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 optically denser, its refractive index increases 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

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f

Table 4.1 : Some established data regarding medium and its refractive index (20°C)

Glycerine 42 Total internal reflection and Critical | angle

Medium	Refractive Index	Medium	Refractive Index
Air Vacuum	1	Glass/Benzene	1.501
Ice [0°C]	1.31	Quartz	1.554
Water	1.333	Diamond	2.471
Ethyl Alcohol	1.362	Polystyrene	1.595
	1.473		

42.1 Total Internal Reflection

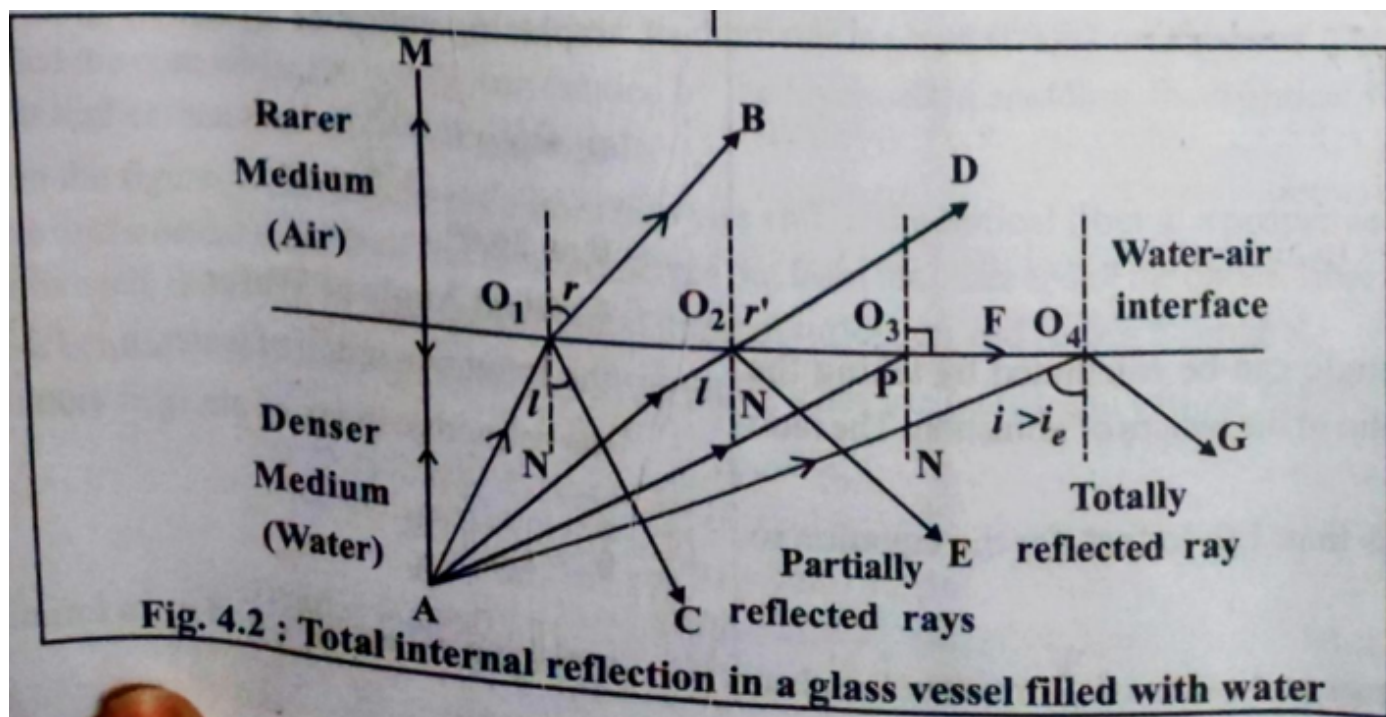
This phenomenon is based on the principle of refraction of light. The figure below will be helpful to understand the incidence of total internal reflection.

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 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 ray AO is a normal ray that comes out without being refracted. The ray AO forms the angle of incidence along the normal, which is slightly refracted and emitted in the form of ray OB (away from the normal) and partially reflected back to the water in the form of ray OC. The ray AO forms an angle of incidence (i) with the normal, which is slightly refracted and ray AO exits in the form of ray OD (away from the normal) and returns to the water in the form of ray OE after being refracted at a larger angle than 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 OF travels in the direction parallel to the interface separating both media for a certain angle of incidence equal to the critical angle (i_c). At a particular angle of incidence, the 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 OF. 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 is found in the position

of a critical angle is called Critical Ray. Here OF 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 this case. That is, here, as shown in the figure, incident ray, completely reflected back into the denser medium (water, in this case) and returned back to the water in the form of OG. This phenomenon is called total internal reflection. This phenomenon is true for any angle of incidence greater 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.



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 off the boundary.

In our introduction to TIR, we used the example of incident light traveling through water towards the boundary with less dense material such as air. When the angle of incidence along the boundary, having an angle of refraction of 90-degrees in water reaches a certain critical value, the refracted ray lies along the boundary. 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_c that gives a 90° value of refraction. 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.

$n_i \sin \theta_i = n_r \sin \theta_r$, $n_i \sin 0 = n_r \sin 90^\circ$

$n_i \sin \theta_i = n_r$

The critical angle can be calculated by taking the inverse-sine of the ratio of the indices of refraction. The ratio of is a value less than 1.0. In fact, for the equation to

even give a correct answer, the ratio of must be less than n_i

1.0. Since TIR only occurs if the refractive medium is denser than the incident medium, the value of n_i must be greater than the value of n_r . If at any time the values for 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 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, $n_g = 1.5$. And, the refractive index of air, $n_a = 1.00$.

Replacing values of n_r and n_i in formula

$\theta_c = 41.1^\circ$

Critical Angle of Diamond

The refractive index of diamond, $n_d = 2.42$. The refractive index of air, $n_a = 1.00$.

Replacing values of n_r and n_i in formula

$\theta_c = 24.4^\circ$

Critical Angle of Water :

The refractive index of water, $n_w = 1.33$. The refractive index of air, $n_a = 1.00$.

$$\theta_c = \sin^{-1} \frac{n_r}{n_i}$$

Replacing values of n_r and n_i in formula

$(\sin 90^\circ)$

ASER

\sin^{-1}

1.00

1.33

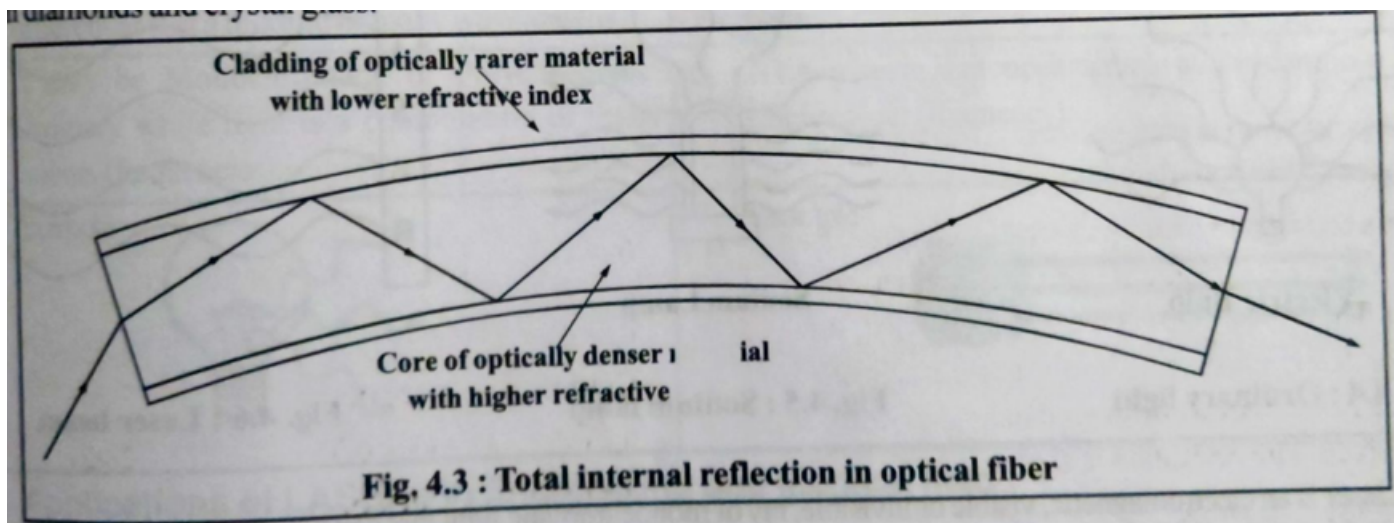
$\theta_c = 48.75^\circ$ Conditions for Total Internal Reflection

3 Necessary The two necessary conditions for the total internal reflection are:

- The light must travel from an optically denser medium to an optically rarer medium.
- The angle of incidence in denser medium must be greater than the critical angle for the pair of media.

I Applications of Total Internal Reflection in Optical Fibers

The bright glitter and sparkling of Crystal glasses and diamond glitter are attributed to the total internal reflection. An 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 sky. Optical fibers are used in communication and the medical field work on the principle of total internal reflection.



The optical fibres One thing to note here is that the total internal reflection does not occur when any light ray enters from an optically 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 $\theta_c = 24^\circ$. This phenomenon is the reason for sparkling glitter in diamonds and crystal glass.

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 made of long and thin rods of high-quality glass, quartz and plastic materials. Its diameter is about 0.001 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 cladding material

is curved or twisted, the ray of light Optical fiber is widely used in communication. In addition, it has various uses in various fields such as engineering field, medical, military field, etc.

of the core is higher than that of the cladding. 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 undergoes total internal reflection and passes through it.

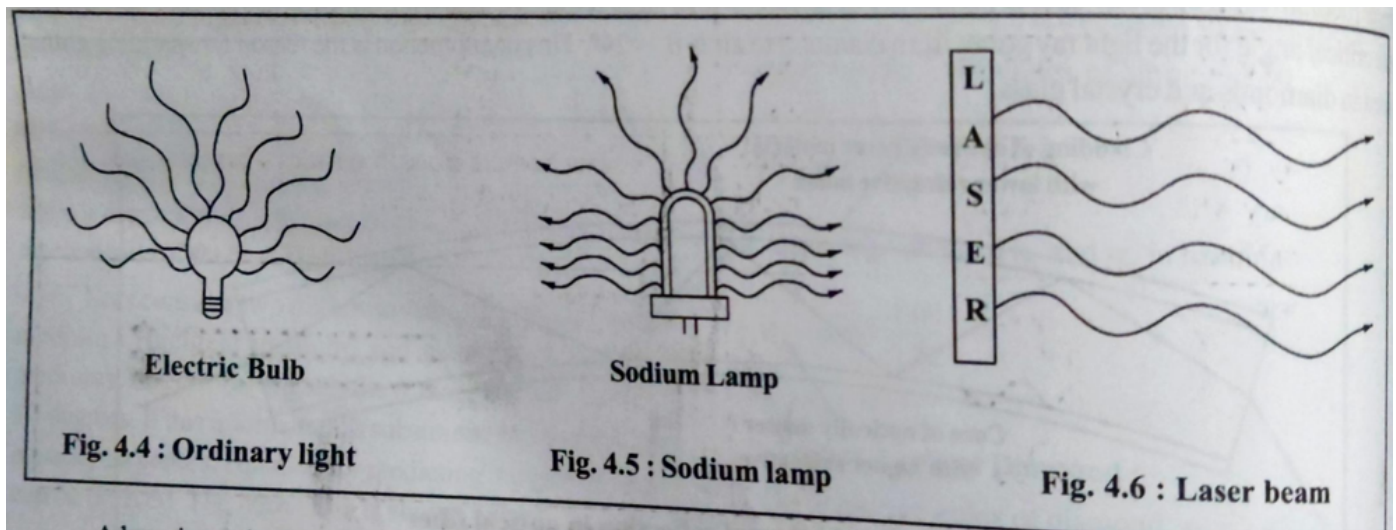
4 LASER

4.1 Introduction to LASER

invention of the laser, the Diamond Jubilee of the laser. When the year 2020 marks the 60th anniversary of the invention of the laser. When we shop in a big shopping mall, the laser-based code gun/scanner is used. The optical mouse, connected to a computer, is also an example of a laser device. The remote control, which we know and we have used laser technology unknowingly. When we send an e-mail, the transmission process of the CDs/DVDs used in a music system is done by a laser beam only. 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



4.4.2 Characteristics of Laser

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 an ordinary 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 powerful direction.

- (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 direction.

'specific

- (3) In a laser beam, the rays are

relatively narrow beam in a specific:

- parallel to each other. (4) The laser beam propagates in only one straight direction

- cross-section of its beam. (5) Laser is a strong, concentrated
- without angular divergence, so D even after reaching very long distances, there is hardly any change in the

and highly focused deposit

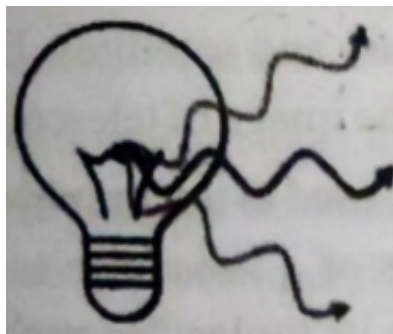
of a beam. It can

store energy within a

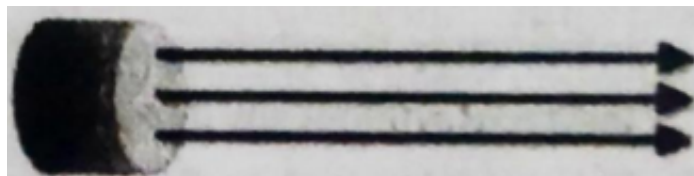
small area

- Laser light is coherent, i.e. All photons in a laser beam are in the same phase.
- laser beam contains only monochromatic light (Single wavelength).
- 8. Laser light is usually emitted by intense pulses. Ruby and other solid state lasers produce laser pulses. But, a gas laser can emit continuous waves. pulses:

The differences between LASER and ordinary light: differences



The differences LASER and ordinary light: Ordinary Light Beam	LASER Light Beam
Spreads in all directions from the place of origin. (Divergent)	1. Spreads in the same direction. (Non-divergent Unidirectional)
Divergent) Intensity decreases gradually as it travels long	2. Intensity and spread with the distance
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.
Has low intensity and low brightness.	4. Has more intensity and has more brightness.
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 same phase.
It may be Monochromatic or Polychromatic. 6. Ordinary white light is a combination of many colours (frequencies).	A Laser beam is monochromatic as it is composed of single colour (frequency).
1 Example	7. Example



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 electronics technology, science, industry, entertainment, defence, medical etc. For different purposes, different lasers are used with corresponding power. The following table shows different laser power requirements corresponding to applications.

Laser

Energy

Corresponding Application

Laser Energy

Corresponding Application

<1mW

5-10 mW

-250 mW

IW-20W

100W-3000W

LaserPointer

DVDPlayer/DVD ROM

Drive

DVDburner/Writer

Micro-Machining

Aspecial type ofCO, laser,

usedin industrial laser cutting.

~5mW

~100mW

1W

30 W -100W

300W -500W

(Up to

1000 W)

CD-ROM Drive

High Speed CD Burner

Holographic Versatile Disc

Special types ofCO, surgical

lasers

HomeuseLaser

Printer (Commercial LaserPrinter)

4.5.1 Applications of Lasers in Engineering And Technology

9.

1. Industrial welding and drilling:Lasers are also used to make holes ofa certain precise size in a given specific place orto make a series ofsuchholes in any object, to cut andweld each type of sheet. Lasers are now widelyused to make orweld metaltins. Lasers are also usedto heat objects.
2. Civil engineering : Lasers are used in surveying. Engineers use lasersto align long tunnels in a straight path.
3. Precision markinginvolves "laser" markingwhere specific measurementsare required. Lasers are

used | 10. for everything from marking to measurement.

4. Laser hardening is done to harden the material.
5. In electronics:
6. 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.
7.) 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.)
8. () It is widely used in fast and precision laser printers.
9. 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.
10. Environment engineering: Lasers are useful to measure and control air pollution as well as water pollution.
11. Chemical industry and material science:) In photo-chemistry, lasers are useful to monitor ultrafast chemical reactions.
12. () Laser can initiate and accelerate some chemical reactions and achieve more yield at low production Cost.
13. (i) Small new molecules can be obtained by breaking large molecules with a laser.

Defence engineering

-) 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.
 - (i) 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 the ban on the manufacture of such laser weapons by the "Protocol on Blinding Laser Weapons"
 - 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:
-) 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.
 - () 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.
 - (m) It is used in the exploration of underground subterranean objects.
 - (iv) To check whether the value of gravity constant "G" is constant, the laser is used.
 - (v) For accurate measurement of flight velocity, the laser beam is used.

- (vi) Lasers are used for high-speed photography
- (vi) 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 structure of materials.

LASER

- configuration of materials. It is used to know the crystal structure.
- (v) To find and study the hidden or unseen fingerprint in forensic science.
- (x) Laser is useful in the nuclear fusion process, as it can create extreme temperature.
- 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.

452 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 microcamera, which can diagnose the disease and guide the surgery. Using laser, the surgery can be bloodless without any problems.

- 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.
- The structure and properties of microorganisms can be studied using a laser.
- (v) In a cataract removal operation, a laser beam is used.
- (vi) In an operation to remove the tumour, a laser beam is used.
- (vi) Removal of kidney stones can be done by applying a laser beam.
- (viü) 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 has 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.
- (i) 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.

the laser is focused4.5.3 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 broken 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.

- (m) 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, 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 dissolving or burning a cancerous tumour.
- (N) In the operation of removing the eye number (Lasik surgery), as well as in repairing the retina, a laser beam of specific wavelength and power is used.

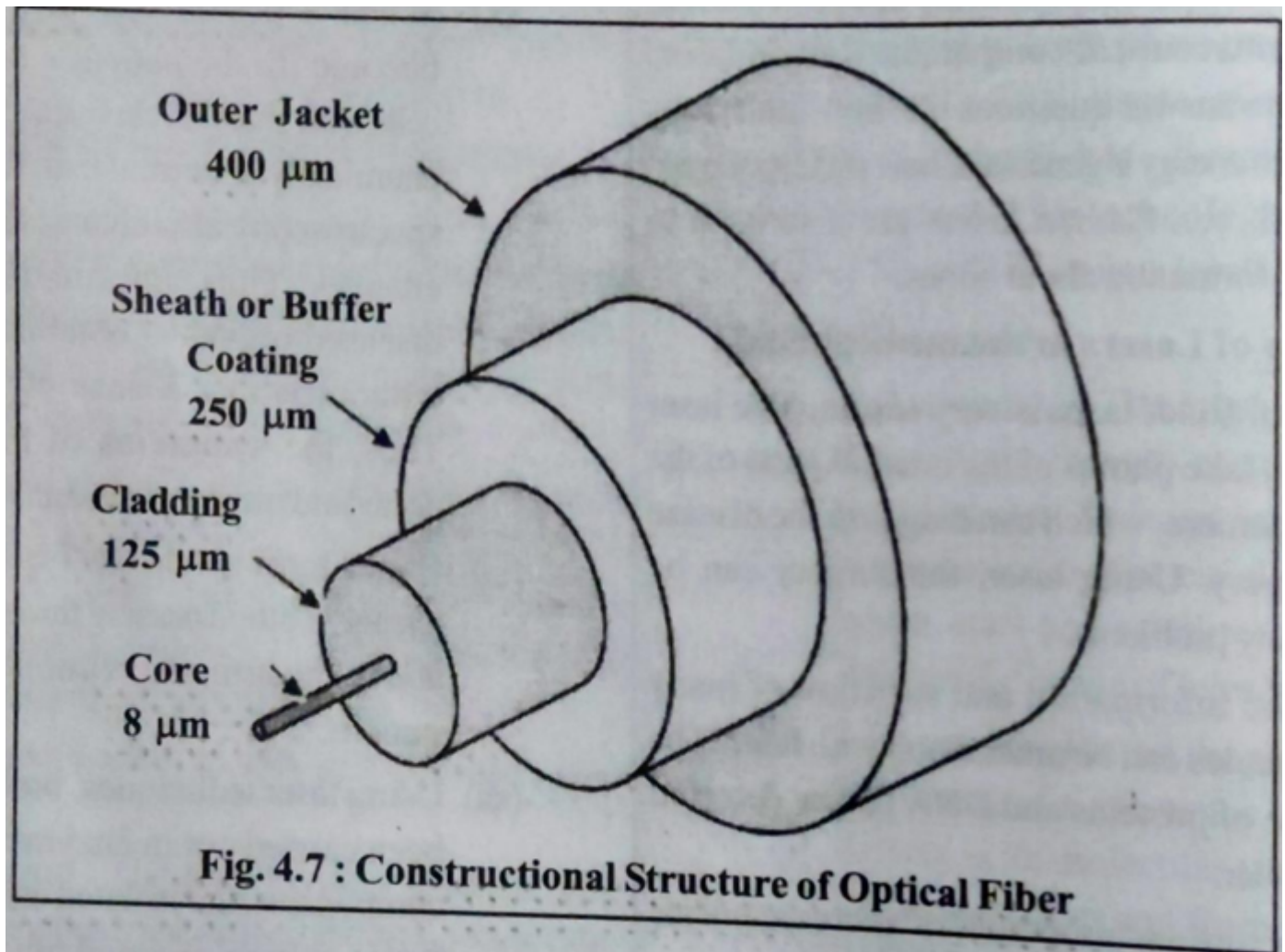
4.6 Fiber Optics

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. A signal of information in the form of a light ray is sent at one end, exits at the other end, allowing the light waves to propagate along its length through the total internal reflection at its walls. During the continuous propagation within an optical fiber, the motion of a light ray follows 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



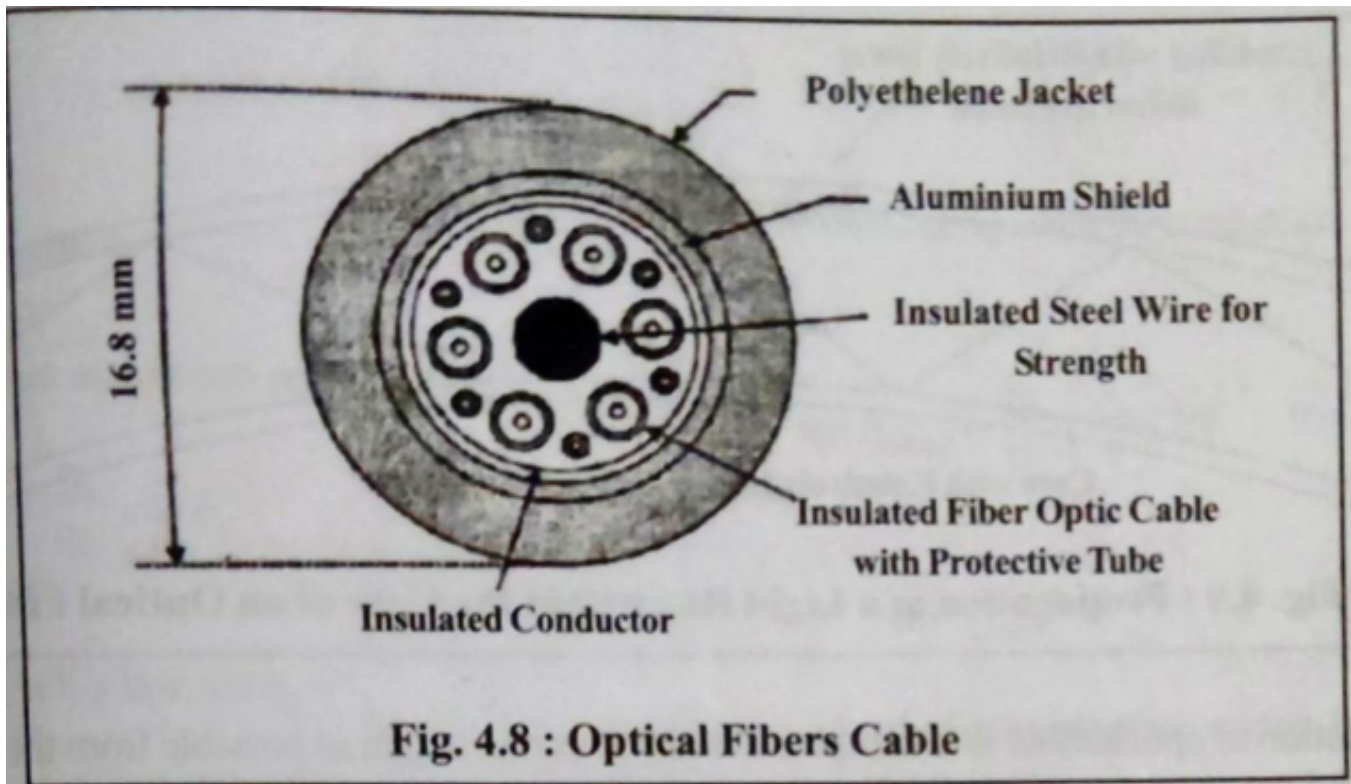
As shown in Figure 4.7, optical fibers are mainly consists of the following three parts:

Core: Core is the innermost cylindrical wire-like region. It is about 50 μm (50 x 10⁻⁶m) 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 ($n_{\text{core}} > n_{\text{cladding}}$). The thickness of the cladding is equal to or greater than the wavelength of the light to be carried.

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 passed through it. It directs back the light ray into the core, results in total internal reflection phenomenon.

Outer Jacket: The entire structure is covered with a polyurethane or polyethylene jacket. The number of fibers in a single jacket is called a Fiber Bundle. Each of these fibers carries light independently.



n , exceeds the critical angle, the refracted ray will go back completely to the medium of refractive index n_1 , even index n_1 is transparent.

4.6.4 Propagation of light through fiber

3 Total Internal Reflection

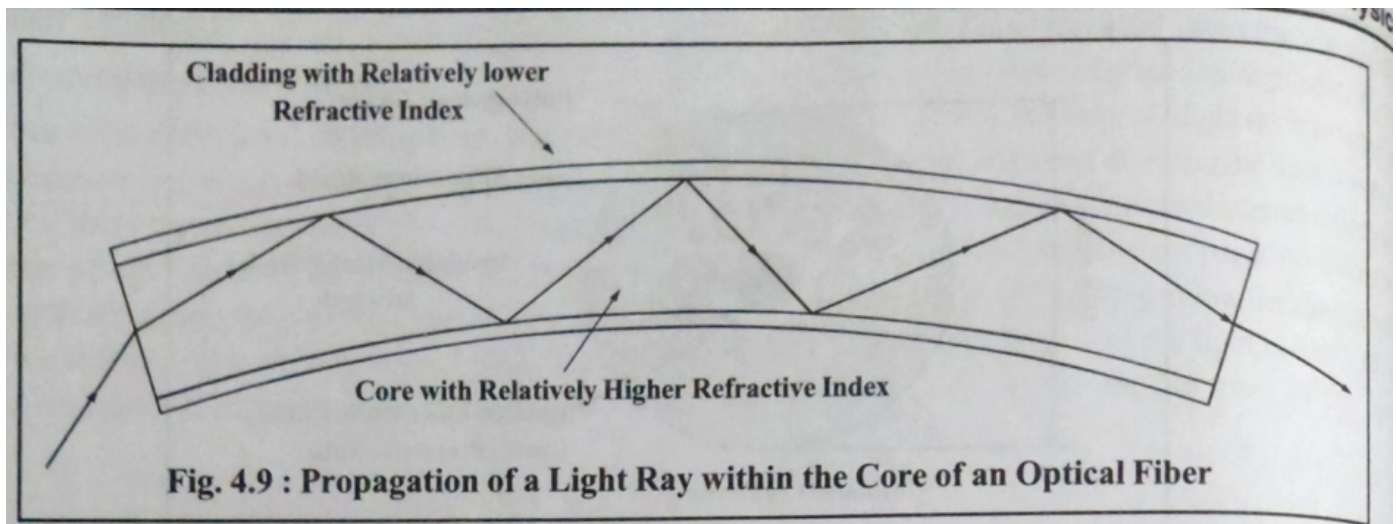
The whole structure formed from the above sections is called cable. Figure 4.8 shows the cross-section of a typical telecommunication cable. It features a bunch of 6 though the medium of refractive material fibers and an insulated steel wire in the center to give proper strength. Each optical fiber is made up of a core, cladding and insulating sheath. There are 6 wires of insulated per 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 cable of many optical fibers. This jacket is made of polyurethane or polyethylene material.

You have studied total internal reflection in this Chapter. Again, let's refresh it in terms of fiber optics. When light enters from one medium with a higher refractive index (n_1) to a medium with a lower refractive index (n_2), an imaginary normal is drawn at the interface. As the angle of incidence increases in the medium having refractive index n_1 , the refracted ray in the medium having refractive index n_2 bends away from the normal.

When a light ray is incident on an optical fiber, it travels from one end to the other through total internal reflection within the core. The light entering into the core does not dissipate through its wall and is reflected back into the core when the angle of incidence is greater than the 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. The angle of incidence, for which the angle of refraction becomes 90° , is called the critical angle (θ_c).

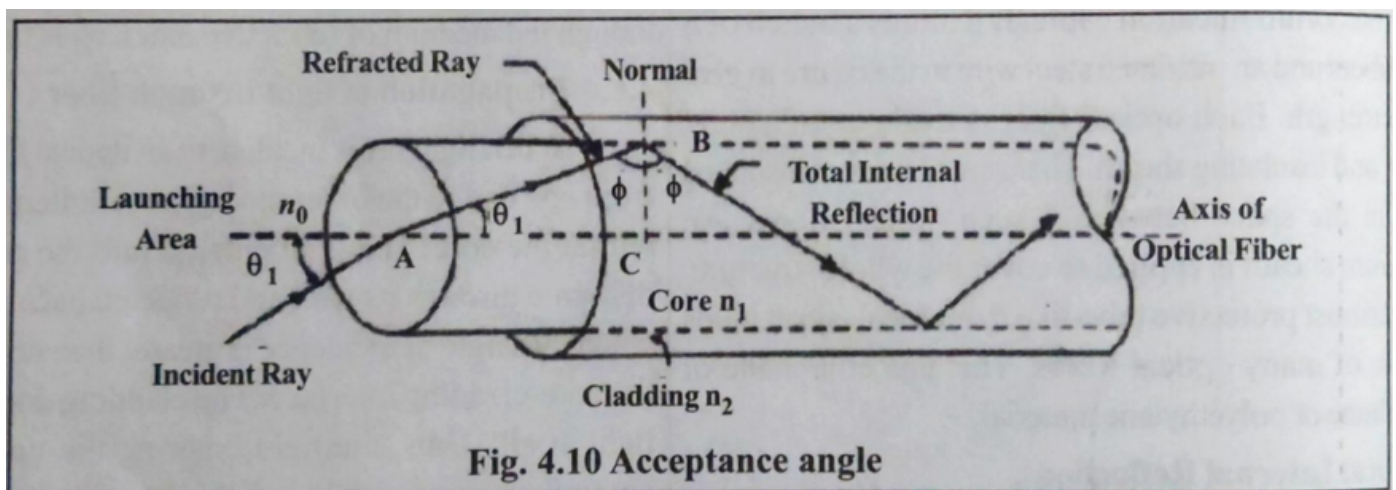
For a particular angle (Critical angle) the refracted ray goes into the medium of the refractive index n , but will be in the direction of the surface connecting the two if the angle of incidence from the medium of refractive

When a light ray enters into the optical fiber core and index (n), it moves away striking the core-cladding interface at an angle of incidence, is reflected back into the core and light confines in the optical fiber due to the total internal reflection phenomenon. If the angle of incidence 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 total internal reflection. If the light ray striking the core-cladding interface at an angle less than the media critical angle, it passes into the cladding and is transmitted out.



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

4.6.5 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 n and the refractive index of the cladding is n_c , where $n > n_c$. Suppose the refractive index of the medium from which the light enters into the core is n_0 . Suppose a light ray strikes along the axis of the optical fiber at an angle of incidence. The beam is refracted at the angle and makes an angle with the core-cladding interface; with is the critical angle. core-cladding

Applying Snell's rule to the surface of the optical fiber launching end, $\sin \theta_i = n_2 \sin \theta_t$. (1) $\sin \theta_i$, now if we go on increasing the angle of incidence one such value will be obtained that $\theta_i = \theta_c$, and the ray escapes out of the sidewall of the fiber. When $\theta_i = \theta_c$, the maximum value of θ_i is obtained.

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

Here, $n_1 > n_2$, so if $\theta_i > \theta_c$, the interface has a total internal reflection of the beam. As long as $\theta_i > \theta_c$, the ray will remain in the fiber. Now let's calculate the angle of incidence for which, $\theta_i = \theta_c$, and light ray remains within the fiber.

It can be seen from $\triangle ABC$ that, $\sin \theta_c = \sin (90^\circ) = \cos \theta_t$

or

,

\therefore

cos θ_t no

Now, θ_t becomes maximum when $\theta_t = 90^\circ$.

Again, from Snell's law, $\sin \theta_i = n_2 \sin \theta_t$

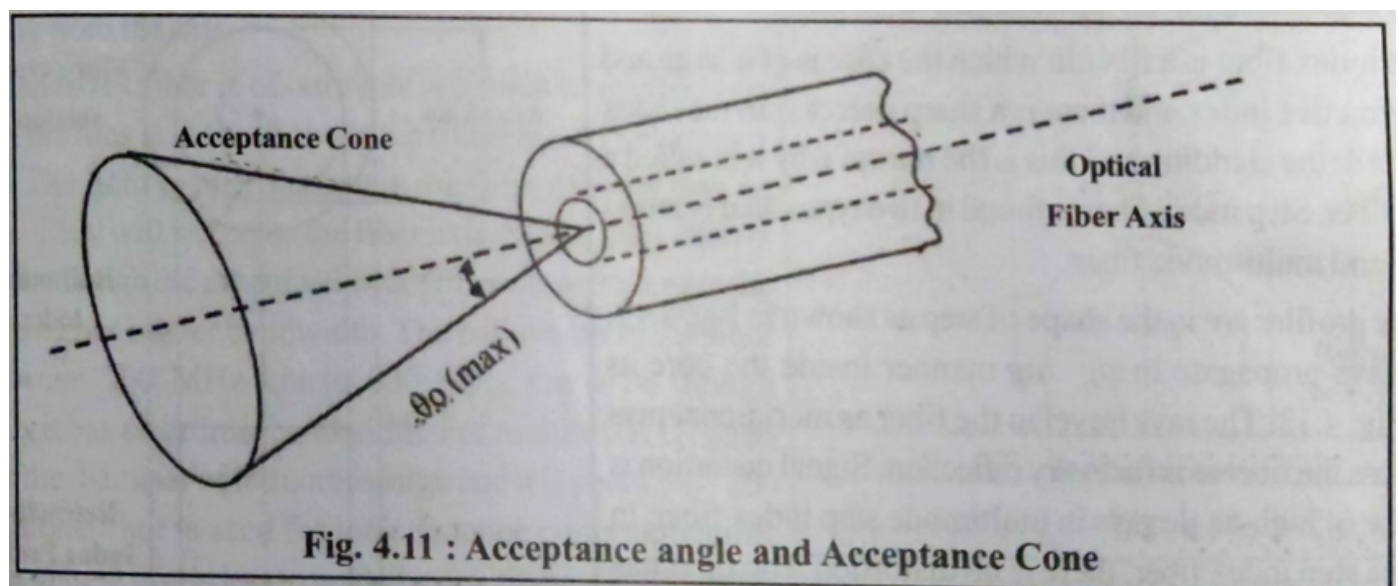
And, $\cos \theta_t = \sqrt{1 - \sin^2 \theta_t}$

$= \sqrt{1 - (n_2/n_1)^2}$

And finally, $\sin \theta_c = \sqrt{1 - (n_2/n_1)^2}$

Substituting $\cos \theta_t$ from equation (5) into equation (4)

Mostly the incident ray comes from air. So, applying Snell's law for air, $n_1 = 1$, max we have, θ_c



Thus, $NA = \sin \theta_0$

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

.. (10)

Also, $NA = n_1 \cos \theta_c$

...(11)

This angle θ_a 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_a are refracted in the cladding and hence lose 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 $2\theta_a$ 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.

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.

(3)

gives,

3

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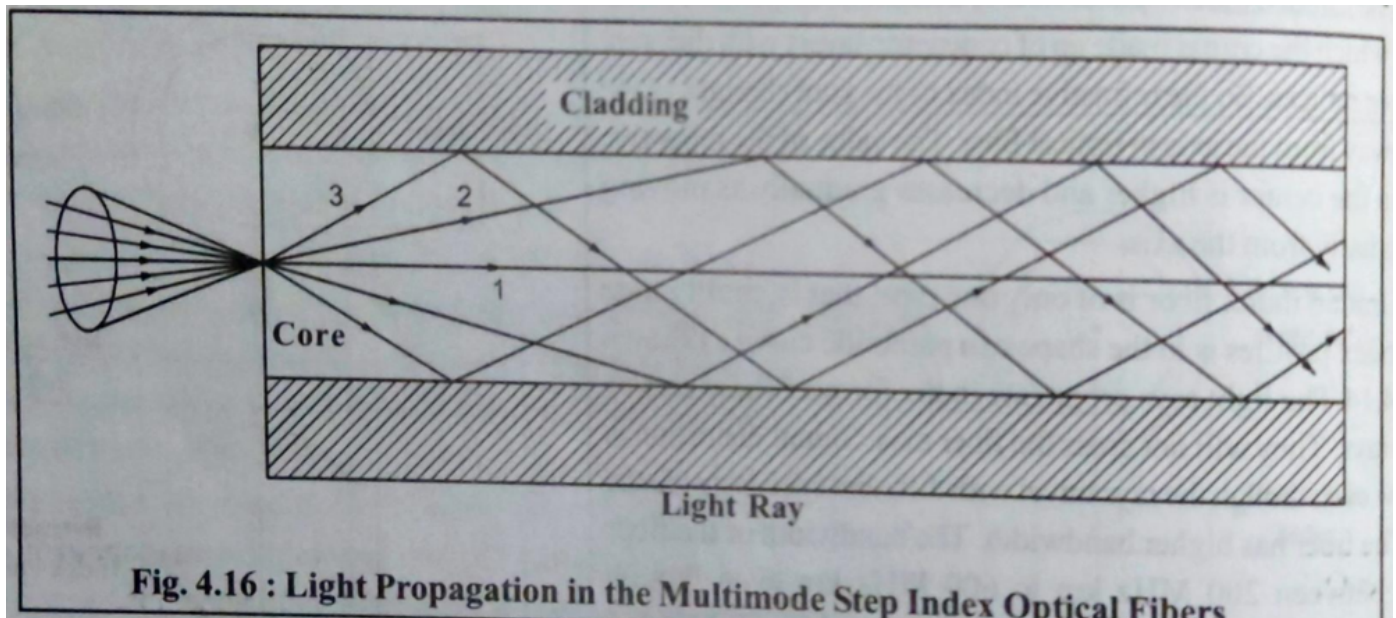
Physi of the optical fiber is written by placing a slash (/) between the diameters of core and cladding. Here, the size of the core is 50 μm and 125 μm cladding diameter. Laser or LED is used as the light source.

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 ray 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 of multimode optical fiber ranges 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.



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 to 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 propagate in the form of skew rays or helical rays the light rays do not propagate by following a straight line, rather they propagate in a helical path. They will not cross the fiber axis. This is due to the gradual change in the

1 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	Graded index is mono mode fiber and multi mode fiber.
Index Profiles	Index profiles are in the shape of step.	Index profiles are 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. single mode step index fiber, there is no distortion.	Signal distortion is very low even though the light 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 200 μm in the case of multimode fiber and 10 μm in the case of single mode 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 NA numerical aperture (NA), while multimode step-index fibers have a higher numerical aperture (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

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- moving from one circuit to another, resulting other calls being heard in the background well. The light waves passing through the optical fiber do not leak. Because of this, even if all 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 microwave is 10^8 to 10^{11} 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 a single 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
- safety is maintained. (9) Optical fiber is more efficient than electrical conducting wire, as it requires fewer repeaters and saves both maintenance and costs.
- transmission. (8) In Optical fiber, light signals do not spread out much so signal
- (10) The tensile strength of the optical fiber is very high. And it can be bent.
- years. (12) Optical fiber is temperature resistant. That is, unlike copper wire, it can withstand high
- (11) Optical fiber can be used for a long time. Optical fiber lasts for 20-30 years, while copper wire lasts for 12-15
- temperatures. (13) Optical fiber transmits digital information through digital signals, which is especially useful in computers. especially

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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 strong.	flexible and The diameter is higher than optical fiber. Not lighter in weight. Not so flexible & strong.
04	Signal degradation & transmission loss is Signal negligible at long distances also.	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 transmission repeaters is required.	Power loss is considerably heavy for long-distance. 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	Little communication channels are available & more data can be transferred at a larger speed. Data is travelled in form of light rays.
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 The conventional metallic good reception of data.	cable can transfer data speedy but reception quality is not satisfactory every time.
	Fibre optics can tolerate large variations in temperature, humidity & atmospheric changes. They are less affected by gases & chemicals. They are corrosion resistant,	The conventional metallic cables are not corrosion resistant because they do not bear the effect of pollution,
12	The lifespan of optical	fibres is 20 to 30 years. The lifespan of conventional metallic cables is 10 to 15
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

Applications of Fibers In Different

4.9 Optical | Fields

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

Physic 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.

4.9.1 Applications of Optical Field

Fibers In Engineering

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.

Optical fiber communication is classified into two sections:

- (1) Local and medium-range systems: Local and medium-range system: In a small business or bank-like organization where short distances systems are used, information is delivered to different places through LAN (local area network). Many computers are networked through 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 endoscopy is used to inspect 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 correct the visual impairment of the eye by removing short/long sight numbers.

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

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 or 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 and endoscopy. They are used in the treatment of cancer by focusing rays directly on the cancer tumour.

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Numericals based on refraction: Example-1 A : 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 $n = 1.50$

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

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

Absolute Refractive index of glass $= \frac{c}{v}$

..

$$v = \frac{c}{n} = \frac{3 \times 10^8}{1.50}$$

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

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 $17^\circ 30'$, 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 $= n_1 = 1$

Angle of refraction $= \theta_2 = 17^\circ 30'$

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$,

- $1 \times \sin \theta_1 = 1.33 \times \sin 17^\circ 30'$
- $\sin \theta_1 = 1.33 \times 0.3 = 0.4$
- $\theta_1 = 23^\circ 36'$

.. $\theta_c = \sin^{-1}(0.4)$ 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:

of diamond with respect to glass

Refractive index of air with respect to diamond n_{da} = Refractive index Absolute refractive index of glass = 1.5

n_{ad} = Refractive index Absolute refractive index of diamond = ?

n_{dg}

Now, n_{dg}

- $1.5 \times 1.62 = 1$
- $1.5 \times 1.62 = 1/n_{ad} n_{da}$
- $\therefore n_{ad} = 2.43$

Refractive index of water = 1.33

Angle of incidence = , -?

1.62

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

Solution:

Given: Critical angle $\theta_c = 45^\circ$.

Refractive index of glass = ?

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 $\theta_c = 40^\circ$.

Ans.

: The refractive index of medium is 1.56

Example-6: Find the critical angle of water-air interface

Solution:

Given: Refractive index of water w.r.t. air, $n_{wa} = 4/3$

Critical angle $\theta_c = ?$

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

$$\theta_c = \sin^{-1}(0.75) = 48^\circ 36'$$

Critical angle of water air interface = $48^\circ 36'$

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 $n_1 = 1.563$

Refractive index of cladding $n_2 = 1.498$

Numerical Aperture,

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.563)^2 - (1.498)^2}$$

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

$$= 0.4460$$

Acceptance Angle,

$$\theta_a = \sin^{-1}(NA)$$

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

$$= 26^\circ 30'$$

$$\sin \theta_a = NA$$

$$\sin \theta_a = 0.4460$$

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

$$\theta_a = 26^\circ 30'$$

$$\theta_a = 26^\circ 30'$$

$$\sin \theta_a = NA$$

- $26^\circ 30'$: If the refractive indices of the core and cladding of a step-index optical fiber are 1.48 and 1.45 respectively, Calculate its (1) acceptance angle (2) numerical aperture (3) critical angle at the core-cladding interface.

rtice.

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Data given:

Refractive index

of core $n_1 = 1.48$

Refractive index of cladding $n_2 = 1.45$ Refractive

Aperture,

$$\sin^{-1} \left(\frac{n_2}{n_1} \right) = \sin^{-1} \left(\frac{1.45}{1.48} \right) = \sin^{-1}(0.9797) = 0.2965 \text{ Acceptance Angle, } \theta_a = \sin^{-1}(\text{NA})$$

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

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

We know that, $\sin \theta_c = n_2 / n_1$

Critical Angle θ_c

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

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

$$= \sin^{-1}(0.97635) = 77.51^\circ$$

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 $n_1 = 1.55$

Refractive index of cladding $n_2 = 1.5$

Numerical Aperture, NA $= \sqrt{n_1^2 - n_2^2}$

$$= \sqrt{(1.55)^2 - (1.5)^2} = \sqrt{2.4025 - 2.25} = \sqrt{0.1525} = 0.3905$$

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

Data given:

The difference between refractive indices of core and cladding $= n_1 - n_2 = 0.05$

Numerical Aperture, NA = 0.39

Refractive index of core = ?

, +0.05

...)

Numerical aperture, NA $= \sqrt{n_1^2 - n_2^2}$

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$$0.39 = \sqrt{n_1^2 - n_2^2} \quad (n_1 - n_2 = 0.05) \quad | \quad 15$$

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Substituting from equation (i) in above result,

$$0.39 = (n_1 + 0.05 + n_2)^2 (n_1 + 0.05 - n_2)^2$$

Squaring both sides,

$$(0.39)^2 = (2n_1 +$$

$$0.05)(0.05)$$

$$0.1521/0.05 = 2n_1 + 0.05$$

$$3.042 = 2n_1 + 0.05$$

$$n_1^2(3.042 - 0.05)/2$$

$$n_1^2 1.496$$

$$\therefore (1)$$

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

$$n_1 = n_1 + 0.05 = 1.496 + 0.05 = 1.546$$

$$n_1 = 1.546$$

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 $n_1 = 1.45$

Refractive index of cladding $n_2 = 1.44$

Numerical Aperture, $NA = (n_1^2 - n_2^2)^{1/2} = [(1.45^2 - 1.44^2)]^{1/2}$

$$= [2.1025 - 2.0736]^{1/2} = \sqrt{0.0289}$$

$$= 0.17 \text{ Acceptance Angle, } \sin \theta_c = NA$$

$$= \sin(0.17)$$

$$= (9.78)^\circ = 9.78^\circ$$

SUMMARY

Laws of Refraction

refracted ray bends away from the normal to the interface. The angle of incidence is smaller than angle of refraction ($i < r$).

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 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
 5. The ray which is incident at the normal, returns in the same direction (but does not change direction).
- O. 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 n (Ita) is also written. 6

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