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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – I

INTRODUCTION TO OPTICAL FIBER COMMUNICATION

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UNIT - I

INTRODUCTION TO OPTICAL FIBERS

1.1 INTRODUCTION

♣ The communication medium in most electronic communications systems are either a wire conductor cable or the free space. But recently, a new medium is growing in popularly named, ***the fiber – optic cable.***

Definition of Fiber Optic Cable:

*A fiber – optic cable is essentially **a light pipe** that is used to **carry a light beam** from one place to another which is used for long distance communication.*

♣ Light is an ***electromagnetic signal*** like a radio wave. It can be modulated by an information signal and sent over the fiber – optic cable.

♣ The frequency of light is ***extremely high,*** it can accommodate ***wider bandwidths*** of information and thus extremely ***high data rates*** can be achieved with an excellent reliability.

☑ Advantages

The primary advantages of fiber – optic cables over conventional cables are,

- ***Wider bandwidth,***
- ***Lower loss,***
- ***Light weight,***
- ***Small size,***
- ***Strength, security,***
- ***Interference immunity, and***
- ***Safety.***

Disadvantages:

The main disadvantages of fiber – optic cable is that its ***small size*** and ***brittleness*** which makes ***more difficult*** to work with.

1.1.1 Spectrum of Light

- Light is a kind of ***electromagnetic radiation***. All kind of electromagnetic waves are made up of both ***electric*** and ***magnetic fields*** that can travel through space from one place to another.
- The basic characteristics of electromagnetic radiation are its ***frequency*** or ***wavelength***.

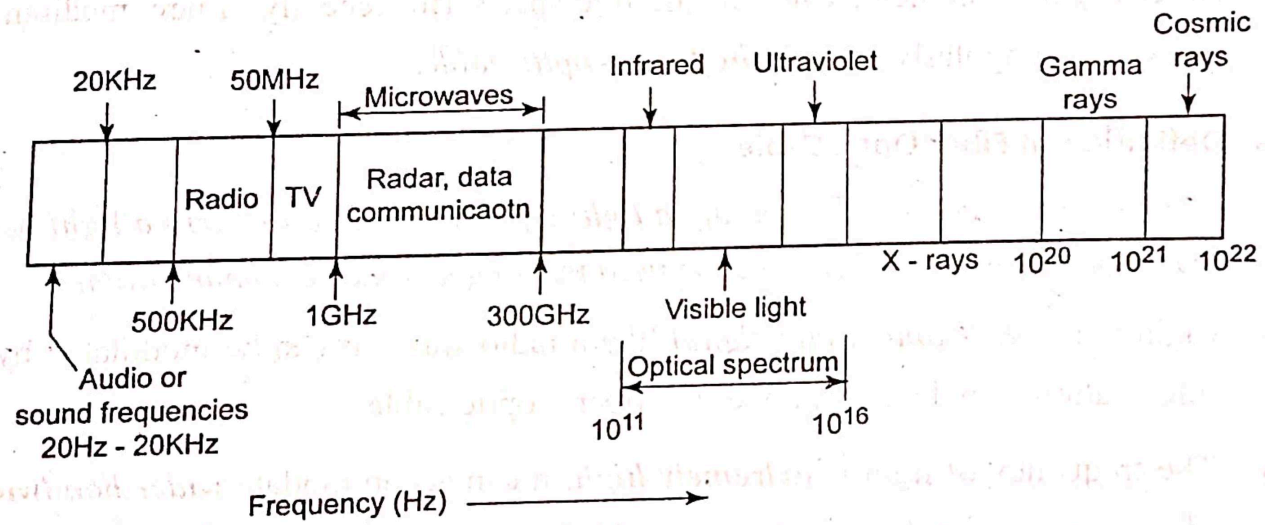


Fig 1.1 Electromagnetic frequency spectrum

- The frequency of the optical spectrum is in the range of 3×10^{11} *to* 3×10^{16} *Hz.* This includes both ***infrared*** and ***ultraviolet*** as well as the ***visible parts*** of the spectrum.
- *Light frequencies used in optical fiber communication systems are between* 1×10^{14} *Hz and* 4×10^{14} *Hz (100,000 GHz to 400,000 GHz).*

Wavelength (λ)

Wavelength is the length that one cycle of an electromagnetic wave occupies in space. It is measured in the unit of metres.

1.1.2 Advantages of Optical Fiber Communication

Communication using an optical carrier wave guided along a glass fiber has a number of extremely attractive features as follows:

(1) Wider Bandwidth and Greater Information Capacity

- Optical fibers have ***greater information capacity*** than metallic cables because of the inherently ***wider bandwidths*** available with ***optical frequencies.***
- Optical fibers are available with bandwidths upto ***several thousand Giga Hertz (GHz),*** which provides higher ***information – carrying capability.***

  Transmission capacity of optical fiber links = $B \times L$

  where,

  B - Transmission bit rate, and

  L - Repeater spacing (distance between repeaters) in an optical network.

(2) Lower Transmission Losses

- In the fiber – optic cables, there is a ***less signal attenuation*** ($\approx$ 0.2dB/km) over long distances.
- This feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics), thus ***reducing both system cost and complexity.***

(3) Small Size and Light Weight

- Optical fibers have very small diameters which often no greater than the diameter of a human hair, therefore the fiber cable is small in size and thus provides less storage space.
- ***Glass or plastic*** optical cables are much ***lighter*** than the copper cables. Thus, the small size and light weight makes them especially attractive for use in aircrafts, satellites and ships.

(4) Signal Security

Fiber – optic cables cannot be ***"tapped"*** as easily as electrical cables. This feature makes it attractive for ***military, banking,*** and ***general data transmission (i.e. Computer network) applications.***

(5) Repeaters Spacing

- *Repeater is a re-generator of the original signal which can be affected by the noise and it is **not an amplifier**.*
- Using an optical fiber without these repeaters we can transmit the signal at a maximum data rate of ***5Gbps*** over a distance of ***111 kms***. But co-axial, twisted systems generally have repeaters for every ***few kilometers.***

(6) Environmental Immunity

- Optical fiber cables are more resistant to an environment extreme (including weather variations) than the metallic cables.
- Optical cables can also operate over a wider temperature range and are less affected by the corrosive liquids and gases.

(7) Low Cost and Ease of Maintenance

- The cost of optical fiber cables are approximately the same as metallic cables.
- The lower loss property of optical fiber cables will reduce the need for ***intermediate repeaters*** or ***line amplifiers*** to boost the transmitted signal strength. These factors tend to reduce both the maintenance time and costs.

(8) Electrical Isolation

- Optical fibers are mostly fabricated from glass, or sometimes a plastic polymer, both are electrical insulators which do not exhibit ***earth loop*** and ***interface problems.***

(9) Immunity to Interference and Crosstalk

- Optical fibers form a dielectric waveguide and therefore free from ***Electromagnetic Interference (EMI)*** and ***Radio Frequency Interference (RFI).***

- The optical inference between these individual fibers in an optical fiber cable is also absent and as a result there is no cross-talk effect which is quite common in the conventional electrical communication that uses metal cables.

(10) System Reliability

Due to the reliability of the optical components, their predicted lifetimes are about 20 to 30 years.

(11) Long Distance Transmission

Because of ***less attenuation*** (≈ 0.2dB/km), optical transmission at a longer distance is possible with the help of few repeaters.

(12) Safe and Easy Installation

Fiber cables are safer and easier to both install and maintain. Its small size and light weight feature makes the installation easier.

1.1.3 Disadvantages of Optical Communication

(1) High Initial Cost

The initial cost of installation or setting up cost of optical fiber is very high when compared to all other system.

(2) Joining and Test Process

Since optical fibers are of very small size, the fiber joining process is not only very difficult and also costly. It requires skilled manpower.

1.1.4 Optical Communication Applications

(i) Telecommunications:

In the area of telecommunications, the small size and large information carrying capacity of an optical fibers make them attractive as alternatives to the conventional copper twisted pair cables in ***telephone systems.***

(ii) Cable TV Network:

The applications of the optical fiber communication that are mainly video includes broadcast television, cable television (CATV), remote monitoring and surveillance.

CATV has a coverage range from a few tens of meters to several kilometers.

(iii) Data Transmission and Distribution:

Optical fiber communication system is also used for transmitting digital data generated by computers between CPU and peripherals, between CPU and the memory and between CPU's.

(iv) Data Communication:

Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs) have revolutionized the computer technology. To make a LAN work effectively, a huge amount of information need to be transmitted over the network at a high speed by using fiber optics.

1.2 GENERAL OPTICAL FIBER COMMUNICATION SYSTEM

1.2.1 Generalized Optical Communication System

- A generalized optical fiber communication system is shown in Fig 1.2. The major elements of this system are shown in Fig 1.2 by individual blocks.

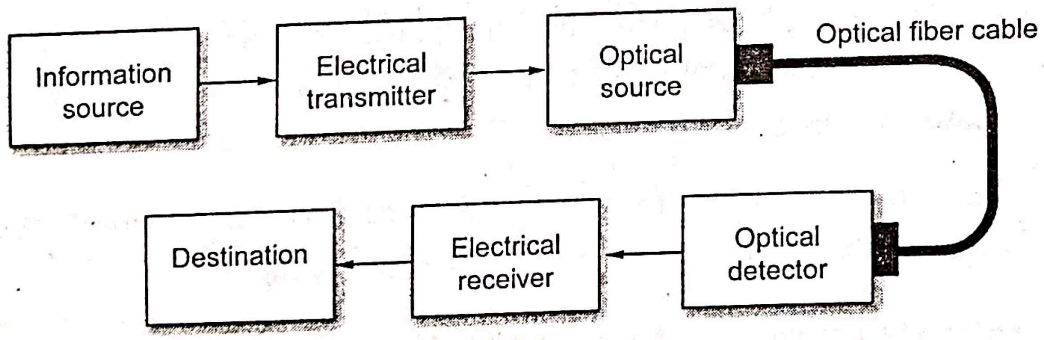


Fig 1.2 Block diagram of an optical fiber communication system

(1) Information Source

- The information signal to be transmitted may be ***voice, video,*** or ***computer data***. The first step is to ***convert*** an ***information signal*** into a form compatible with the communications medium.
- In optical communication, an information source provides an ***electrical signal*** as an input signal to the transmitter.

- If it is a non-electrical signal, then the transducer is used in the optical transmitter that converts the ***non-electrical signal*** into an ***electrical signal.***

(2) Electrical Transmitter

The electrical signal from an information source is fed to a transmitter that comprising an electrical stage which is called as ***drive circuit*** which is used to drive an ***electrical signal into the light source.***

(3) Light Source (or) Optical Source

- The light source has two main functions as,
  - (i) *It generates the optical (light) signal.*
  - (ii) *It modulates the light wave carrier signal by using an information signal to propagate the information signal to a long distance.*
- The electric input signals to the transmitter can be either an ***analog*** or of a ***digital form.*** The transmitter circuitry converts these ***electrical signals to an optical signal*** by varying the current flow through the light source.
- The optical source which provides an electrical – optical conversion may be either a ***semiconductor laser*** or ***Light Emitting Diode (LED).***

(4) Optical Fiber Cables: Transmission Medium

- The modulated light wave output from the optical source is coupled to the transmission medium which is consisting of optical fiber cables.
- The information channel is a medium which is used for bridging the distance between transmitter and receiver.

Plastic vs Glass:

Fiber – optic cables are made of ***glass and plastic. Glass*** has the ***lowest loss*** but it is ***brittle*** whereas, ***plastic*** is ***cheaper*** and ***more flexible,*** but has ***high attenuation.***

- The optical signal propagates through the fiber by ***Total Internal Reflection (TIR).*** As the optical signal propagates down the fiber length, it gets attenuated due to absorption and scattering.

(5) Optical Receiver:

- *The receiver consists of a detector that will detect the **optical signal** and **convert them** into an electrical current (signal).*
- The ***electrical current*** developed by the detector is ***proportional to the power in the incident optical signal.*** The detector output current contains the transmitted information.
- ***Photo diodes (p – n, p– i – n or avalanche)*** and, in some instances, ***photo transistors*** and ***photo conductors*** are utilized for the detection of the signal and an ***optical – electrical*** conversion.
- The electrical signal is then amplified and restores it to its ***original form*** by an electrical receiver before passing it onto the signal destination.

1.2.2 Practical Optical Communication System

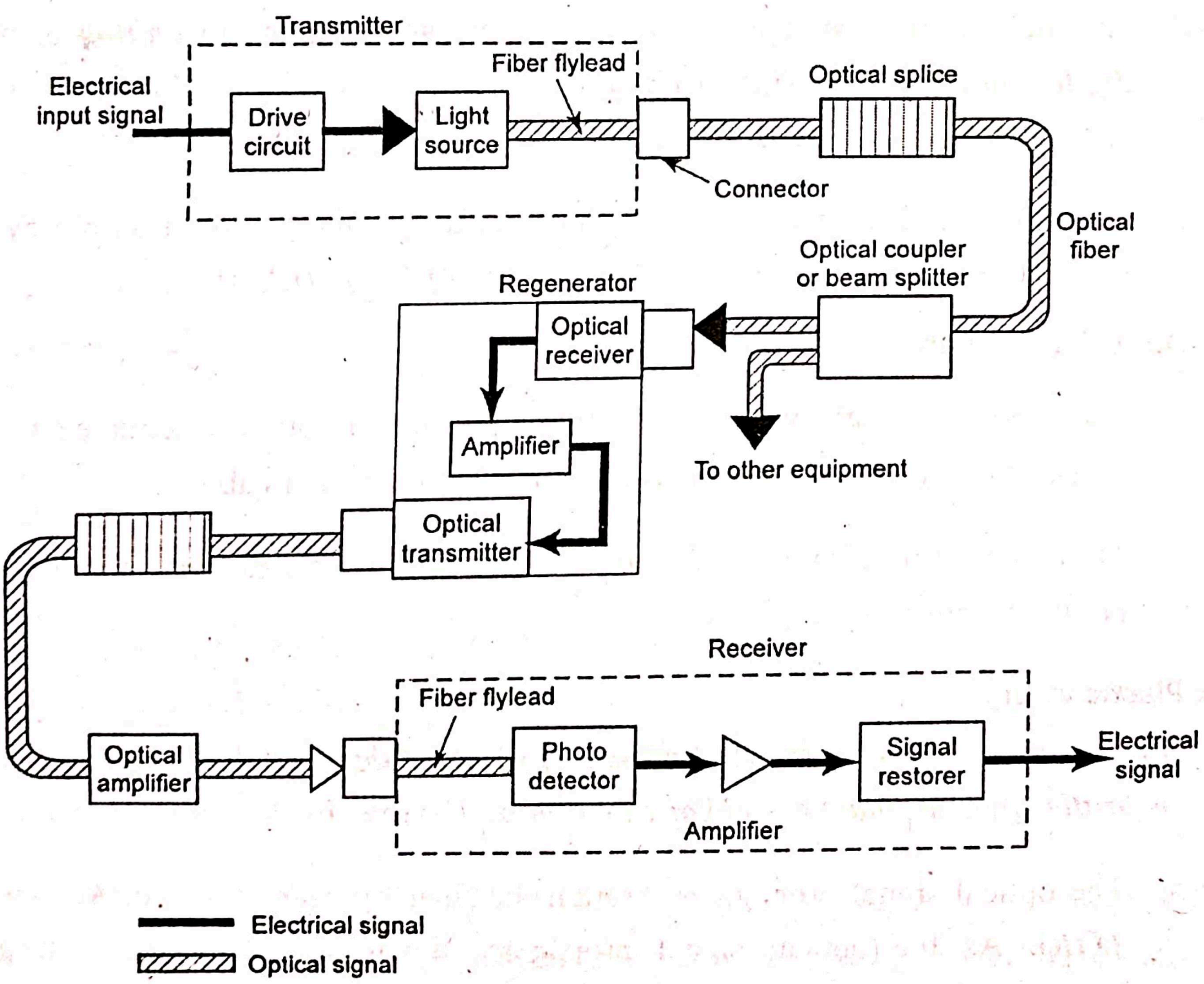


Fig 1.3 Major elements of an optical fiber transmission link

- A practical optical communication system shown in Fig 1.3 is actually much more complex than the generalized optical fiber communication system which is shown in Fig 1.2.
- The basic components in the optical fiber communication are the ***light source,*** the ***optical transmitter,*** the ***optical fiber*** and the ***optical receiver.*** Additional elements used in optical link are ***fiber and cable splices, connectors, regenerators, beam splitters,*** and ***optical amplifiers.***

Fiber Pigtail Flylead

- The manufacturers generally provide optical sources with a small portion of an optical fiber (1-2 m length) attached to it in an optimum fashion. This is called fiber pigtail flylead.
- This can be easily plugged in for connection with the line fiber by using a demountable connector.

(1) Repeaters

For the long distance optical communication, we use ***repeaters*** to compensate the ***attenuation loss.*** The repeater contains optical receiver, optical transmitter and amplifier.

(i) Optical Receiver

An optical receiver detects an ***optical signal*** and converts it into an ***electrical signal,*** which is amplified, reshaped and sent to the electric input of the amplifier.

(ii) Amplifier

The amplifier receives an electrical signal from the optical receiver and ***amplifies*** the signal and also sends it into optical transmitter.

(iii) Optical Transmitter

An optical transmitter converts the ***electrical signal*** back to an ***optical signal*** and sends it down the optical fiber waveguide.

(2) Optical Amplifiers

- Optical amplifiers provide on-line amplification to the propagating optical signal. Such amplifiers are useful for compensating the attenuation caused by an optical fiber during propagation of the signal.

- Both ***Semiconductor Laser Amplifier (SLA)*** and ***Erbium Doped Fiber Amplifier (EDFA)*** are used for providing amplification of the signal in the optical domain.

1.2.3 Digital Optical Communication System

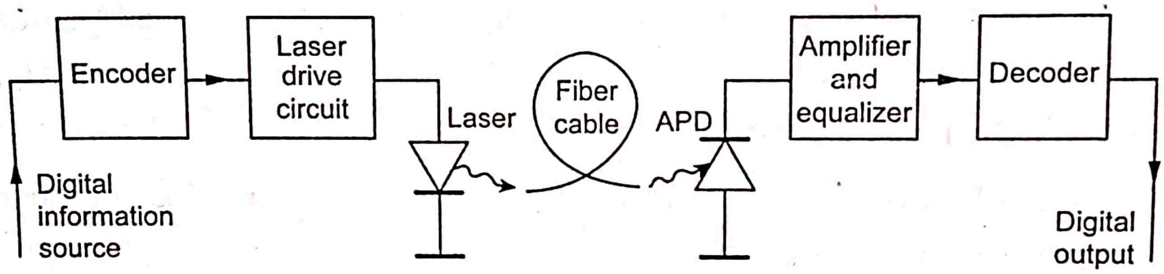


Fig 1.4 Digital optical system

- The working principle of the digital optical system as shown in Fig 1.4. The input digital signal from an information source is suitably encoded for optical transmission.

- The *laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal.* Hence a digital optical signal is launched into the optical fiber cable.

- The ***Avalanche Photo Diode (APD)*** detector is followed by a front-end amplifier and equalizer or filter to provide the gain as well as linear signal processing and noise bandwidth reduction.

- Finally, the signal obtained is decoded to give the original digital information.

1.3 OPTICAL COMMUNICATIONS APPLICATIONS

*Optical fibers are used in **telecommunications, instrumentation, cable TV network and data transmission and distribution*** as,

(i) In the area of telecommunications, the small size and large information carrying capacity of an optical fibers make them attractive as alternatives to the conventional copper twisted pair cables in ***telephone systems.***

(ii) The applications of optical fiber communication that are mainly video include broadcast television, cable television (CATV), remote monitoring and surveillance. CATV has a coverage range from a few tens of meters to several kilometers.

(iii) Optical fiber communication system are also used for transmitting digital data generated by computers between CPU and peripherals, between CPU and the memory and between CPU's.

(iv) ***Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs)*** have revolutionized tne computer technology. To make a LAN work effectively, a huge amount of information has to be transmitted over the network at high speed by using fiber optics.

1.4 CHARACTERISTICS AND BEHAVIOUR OF LIGHT

1.4.1 Introduction

- Light waves travel in a ***straight line.*** The light rays travel at the speed of light, which is generally considered to be ***300,000,000 m/s*** ($3 \times 10^8 m/s$) or ***186,000 mile / sec*** (186×10^3 *miles / sec*) in free space.

- The speed of light ***depends upon the medium*** through which the light passes and it is related to the frequency υ and the wavelength λ by $c = \upsilon\lambda$.

1.4.2 Reflection

- The reflection of light from a mirror follows a simple physical law, which is called as ***law of reflection.***

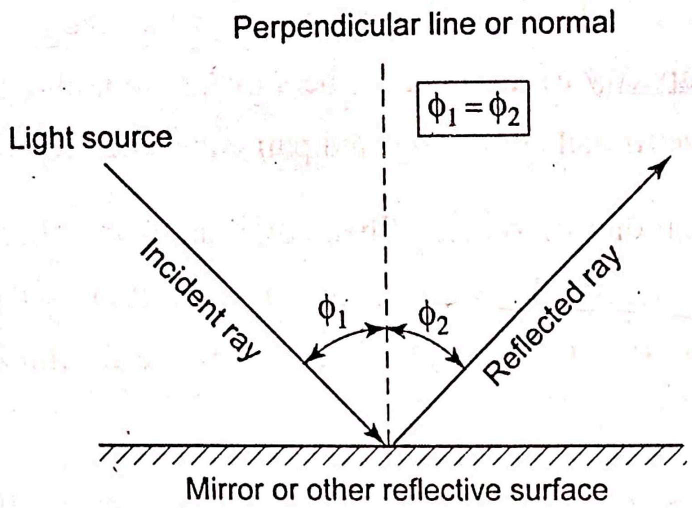


Fig 1.5 Law of reflection

- Assume an imaginary line that is perpendicular to the flat mirror surface, which is referred to as the ***normal.*** The normal is usually drawn at the point where the mirror reflects the light beam.

(i) Angle of Incidence (ϕ_1)

- *The angle at which the light strikes a surface with respect to the normal is called the **angle of incidence.***
- The angle of the incident light ray determines whether the ray will be ***reflected*** or ***refracted.***

(ii) Angle of Reflection (ϕ_2)

*The angle at which light is reflected from a surface is called the **angle of reflection.***

Law of Reflection:

The angle of incidence is equal to the angle of reflection.

$$\text{Angle of incidence } (\phi_1) = \text{Angle of reflection } (\phi_2)$$

1.4.3 Refraction

- When waves passes from less dense medium to more dense medium, the wave is refracted (bent) towards the normal.

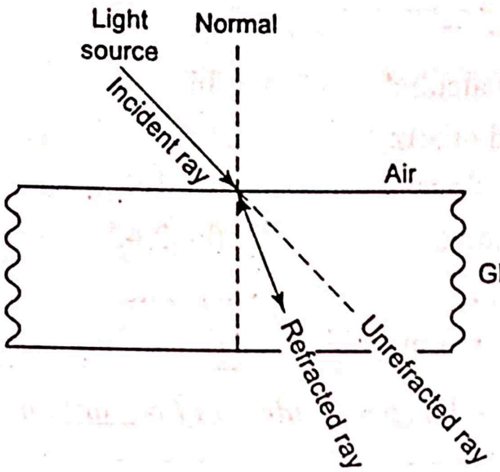


Fig 1.6 Refraction

Definition of Refraction:

Refraction is the bending of a light ray that occurs when the light rays passes from one medium to another.

(i) Index of Refraction

- The ***amount of refraction*** is called the ***index of refraction (n)*** and it is defined as, ***"the ratio of the speed of light in air to the speed of light in another medium**, such as water, glass or plastic".*
- Mathematically, refractive index is expressed as,

$$\text{Index of refraction } (n) = \frac{\text{Speed of light in air } (c)}{\text{Speed of light in substance } (v)}$$

where,

n – Refractive index,

c – Speed of light in free space (3×10^8 meters per second), and

v – Speed of light in a given material (meters per second).

(ii) Typical Indexes of Refraction

Sl. No.	Material	Index of refraction (n)
1.	Vacuum	1.0
2.	Air	1.0003 (≈1)

3.	Water	1.33
4.	Ethyl alcohol	1.36
5.	Fused quartz	1.46
6.	Glass fiber	1.5 – 1.9
7.	Diamond	2.0 – 2.42
8.	Silicon	3.4
9.	Gallium - arsenide	2.6

Table 1.1 Typical indexes of refraction

1.5 RAY THEORY TRANSMISSION

1.5.1 Total Internal Reflection (TIR)

- To consider the propagation of light in an optical fiber, utilizing the ray theory model is necessary to take an account of the refractive index of the dielectric medium.
- The refractive index of a medium is defined as, *"the ratio of the velocity of the light in a vacuum to the velocity of light in the medium"*.

(1) Partial Internal Reflection

- Let the two media have refractive indexes n_1 and n_2, where $n_2 < n_1$ and ϕ_1 *and* ϕ_2 be the ***angles of incidence*** and ***angle of refraction*** respectively, where ϕ_2 is greater than ϕ_1.

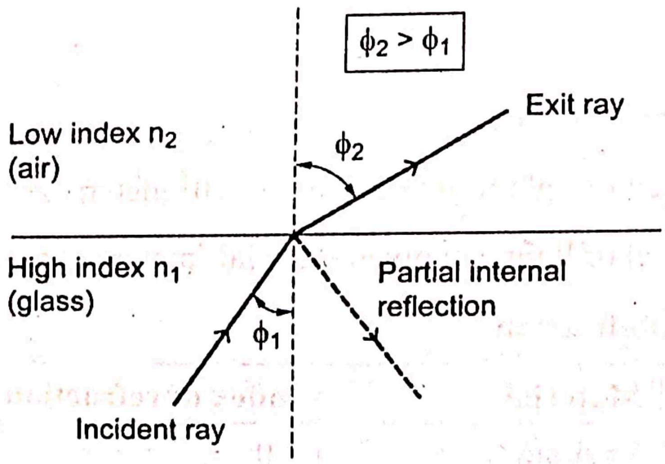


Fig 1.7 Partial internal reflection

- It is observed that a small amount of light is reflected back into the originating dielectric medium, that is, ***partial internal reflection***.

Snell's Law

Snell's law states that "***how light ray reacts when it meets the interface of two media having difference indexes of refraction***". Snell's law stated mathematically as,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

(2) Critical Angle (ϕ_c)

- Consider n_1 is greater than n_2 and the angle of refraction (ϕ_2) is always greater than the angle of incidence(ϕ_1), that is, $(\phi_2 > \phi_1)$
- The critical angle is occur, when the angle of refraction (ϕ_2) is 90^0 and the angle of incidence (ϕ_1) at the interface between dielectrics must be less than 90^0.

Definition

The critical angle is defined as "***angle of incidence that causes the refracted light to travel along the interface between the two different media***".

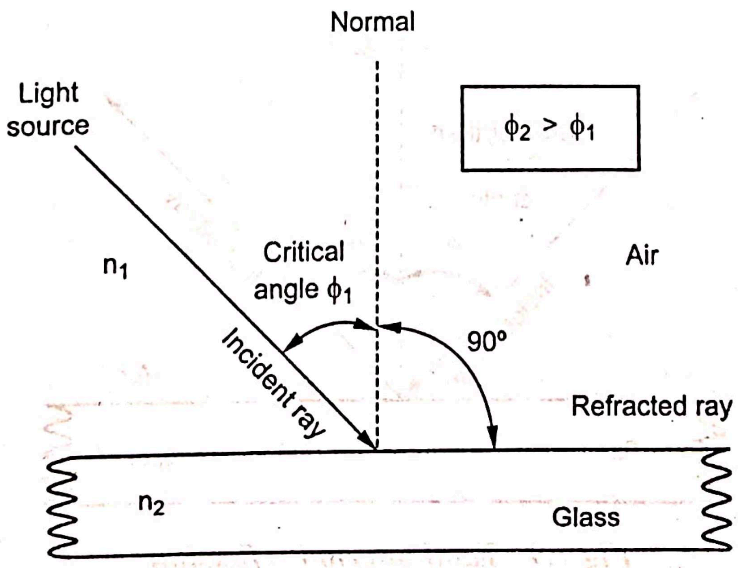


Fig 1.8 Critical angle

- Critical angle (ϕ_c) can be represented mathematically by using Snell's law as,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\sin \phi_1 = \frac{n_2}{n_1} \sin \phi_2 \qquad \text{...... (1)}$$

When $\phi_2 = 90°$, ϕ_1 becomes the critical angle (ϕ_c) and thus equation (1) becomes,

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90°$$

$$= \frac{n_2}{n_1} (1) \qquad [\because \sin 90° = 1]$$

$$\boxed{\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)} \qquad \text{...... (2)}$$

- When the light ray strikes the interface at an angle (incident angle) greater than the critical angle ($\phi_1 > \phi_c$), the light ray does not pass through the interface into the glass, a mirror effect is existed at the interface, that is, ***reflection*** occurs instead of ***refraction***.
- When this occurs, the angle of reflection ϕ_2 is equal to the angle of incidence ϕ_1 as ***if a real mirror were*** used. This action is known as ***total internal reflection***.

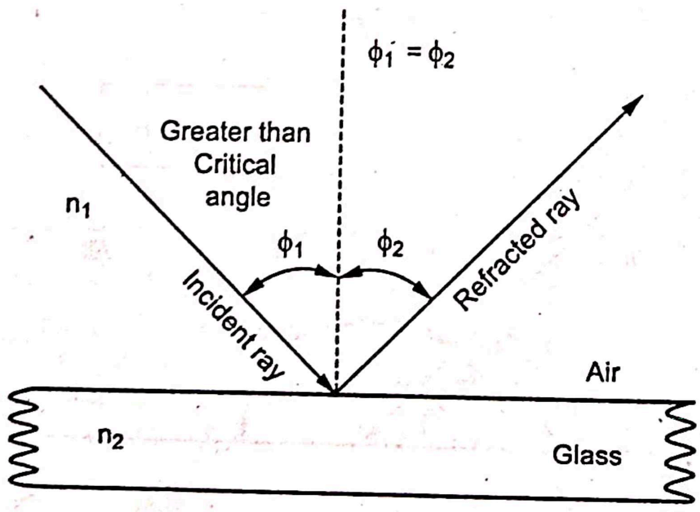


Fig 1.9 Total internal reflection.

- Total internal reflection occurs only in ***materials in which the velocity of light is slower than in air.***

Definition

*The ray has an angle of incidence at the interface which is greater than the critical angle ($\phi_1 > \phi_c$) and is totally reflected back into the air at the same angle ($\phi_1 = \phi_2$) to the normal. This action is known as **Total Internal Reflection (TIR).***

Two necessary Conditions :

The necessary conditions for TIR to occur are,

(i) *The refractive index of first medium (n_1) must be greater than the refractive index of second one (n_2).i.e., $n_1 > n_2$.*

(ii) *The angle of incidence of the ray exceeds the critical value ($\phi_1 > \phi_c$).*

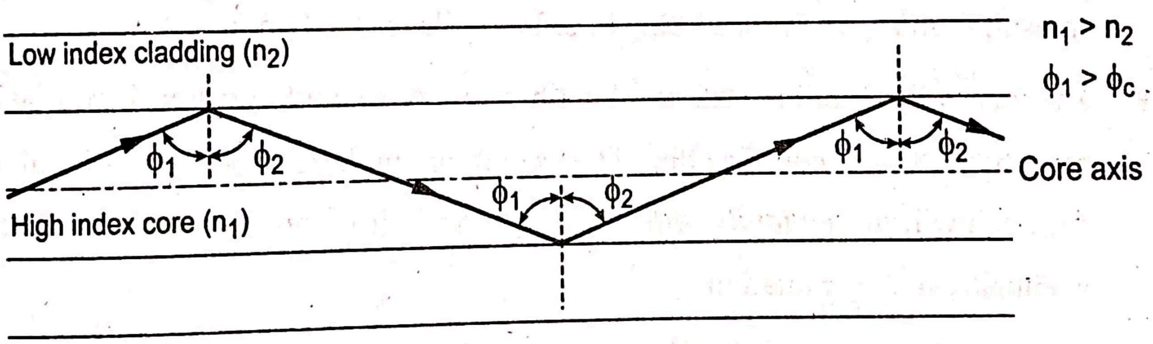


Fig 1.10 Transmission of a light ray using TIR in a perfect optical fiber

1.5.2 Acceptance Angle (θ_a)

Definition:

Acceptance angle (θ_a) is the "***maximum angle to the fiber axis at which the light may enter the fiber axis in order to be propagated***".

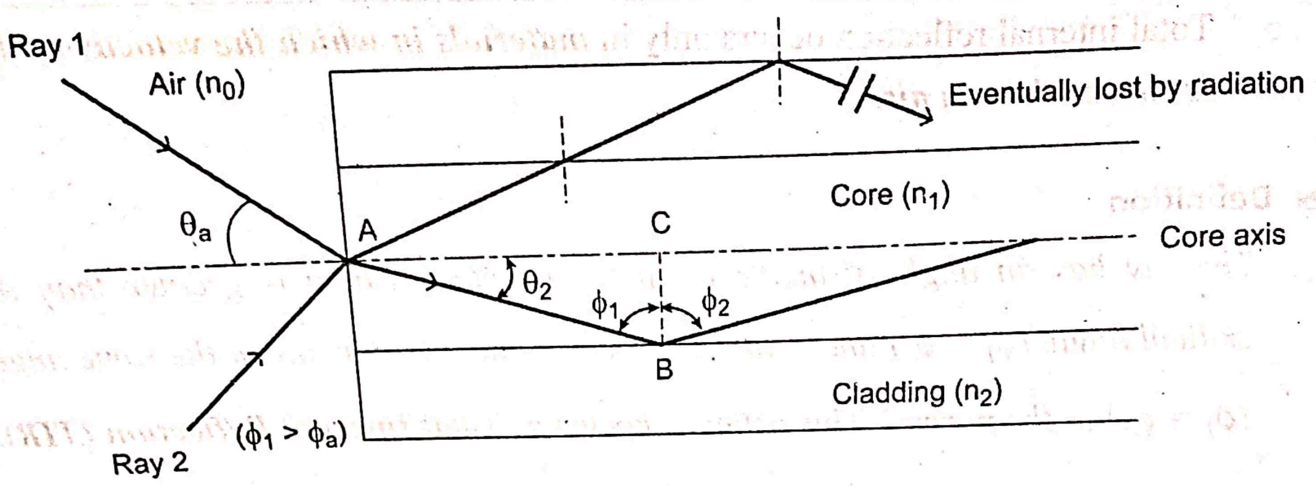


Fig 1.11 The acceptance angle (θ_a) when launching light into an optical fiber

- The Figure 1.11 shows a light ray incident on the fiber core at an angle (θ_a) which is the maximum angle to the axis at which light may enter the fiber in order to be propagated , and is often referred to as the ***acceptance angle*** for the fiber.

- It may be observed that this ray is refracted at the air –core interface before transmission to the core-cladding interface at the critical angle.

- Any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core-cladding interface at an angle less than the critical angle (ϕ_c), and will ***not be totally internally reflected.*** It is refracted into cladding and eventually lost by radiation.

- Consider, the ray enters the fiber from a medium (air) of refractive index n_0, and the fiber core has a refractive index n_1, which is slightly greater than the cladding refractive index n_2.

By applying Snell's law to external incidence angle,

$$n_0 \sin \theta_a = n_1 \sin \theta_2 \qquad \ldots\ldots (3)$$

Considering the right-angled triangle ABC, then the critical angle (ϕ_c) becomes,

$$\phi_c = \frac{\pi}{2} - \theta_2 \Rightarrow \theta_2 = \frac{\pi}{2} - \phi_c \qquad \ldots\ldots (4)$$

By substituting equation (4) in equation (3), we get

$$\sin \theta_2 = \sin\left(\frac{\pi}{2} - \phi_c\right) = \cos \phi_c \quad \text{...... (5)}$$

Then the equation (3) becomes,

$$n_0 \sin \theta_a = n_1 \cos \phi_c \quad \text{...... (6)}$$

Using the trigonometrical relationship,

$$\sin^2 \phi + \cos^2 \phi = 1$$

$$\cos \phi = (1 - \sin^2 \phi)^{1/2}$$

Then the equation (3) may be written in the form as follows,

$$n_0 \sin \theta_a = n_1 (1 - \sin^2 \phi_c)^{1/2} \quad \text{...... (7)}$$

Already we know that, the critical angle is expressed as,

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad \text{...... (8)}$$

By substituting equation (8) in equation (7), we get

$$n_0 \sin \theta_a = n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$= n_1 \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} \quad \text{...... (9)}$$

Equation (9), in terms of acceptance angle (θ_a) is expressed as,

$$\boxed{\theta_{a\,(max)} = \sin^{-1} \frac{\sqrt{n_1^2 - n_2^2}}{n_0}} \quad \text{...... (10)}$$

n_0 – Refractive index of air ($n_0 = 1$). So equation, (10) becomes

$$\boxed{\theta_{a\,(max)} = \sin^{-1} \sqrt{n_1^2 - n_2^2}} \quad \text{...... (9)}$$

1.5.3 Numerical Aperture (N_a)

Definition:

*Numerical aperture is used to describe **the light-gathering or light–collecting ability of an optical fiber.*** It is also referred as ***figure of merit*** which is commonly used to measure the ***magnitude*** of acceptance angle.

- The numerical aperture for light entering the glass fiber from an air medium is described mathematically as,

$$\boxed{NA = \sin\theta_a} \quad \ldots\ldots (10)$$

By substituting equation (9) for the acceptance angle (θ_a) in equation (10) , we get

$$NA = \sqrt{n_1^2 - n_2^2} \quad \ldots\ldots (11)$$

- From equation (11), the ***acceptance angle*** in ***terms*** of ***numerical aperture*** is given as,

$$\boxed{\theta_a = \sin^{-1}(NA)} \quad \ldots\ldots (12)$$

- From equations (10) and (11), the numerical aperture in terms of refractive index is expressed as,

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

$$= \sqrt{(n_1 + n_2)(n_1 - n_2)} \quad [n_1 \approx n_2]$$

$$= \sqrt{2n_1 (n_1 - n_2)} \quad \ldots\ldots (13)$$

Refractive Index Difference:

- The numerical aperture may also be given in terms of the ***relative refractive index difference*** Δ between the core and the cladding which is defined as,

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

$$= \frac{n_1 - n_2}{n_1} \quad \textit{for } \Delta << 1$$

$$\Delta n_1 = n_1 - n_2 \qquad \ldots\ldots (14)$$

- By substituting equation (14) in equation (13), we get

$$\text{NA} = \sqrt{2\, n_1 \,(n_1\, \Delta)}$$

$$\boxed{\text{NA} = n_1 \sqrt{2\,\Delta}} \qquad \ldots\ldots (15)$$

1.5.4 Ray Optics Representation

- The light ray propagation in a fiber can be analyzed by two methods:
  - (i) Ray theory approach, and
  - (ii) Mode theory approach.
- Mode theory approach deals with the number of light propagation path used within an optical fiber cable.

Ray Theory Approach

- *A ray of light is the **one dimensional approach** and indicates the direction of propagation of light through the fiber.*
- The ray theory is otherwise known as ***tracing approach*** or ***geometrical optics representation.***

(1) Types of Rays

- If the rays are launched within core, it can be successfully propagated along the fiber. But an exact path of the ray is determined by the position and an angle of ray at which it strikes the core.
- The light ray which is ***passing*** through the fiber is classified as shown in Fig 1.12.

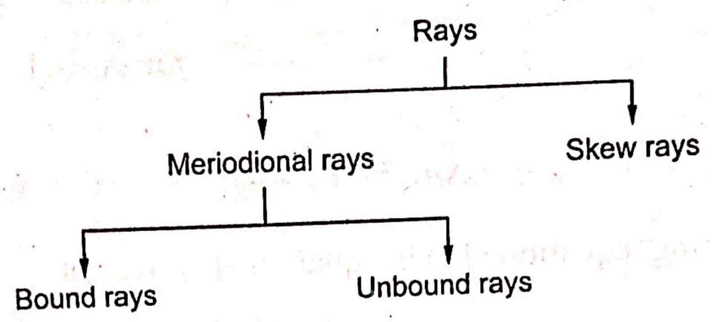


Fig 1.12 Types of rays

Meridional Rays

Meridional rays are passes through the fiber (core) axis after each total internal reflection from the core cladding boundaries.

- Meridional ray lies in a single plane, its path is easy to track as ***it travels along*** the fiber. The main classifications of meridional rays are,

  (i) Bound rays, and

  (ii) Unbound rays.

- Bound rays that are trapped in the core and propagate along the fiber axis according to the laws of ***geometrical optics.*** Unbound rays that are ***refracted out*** of the fiber core.

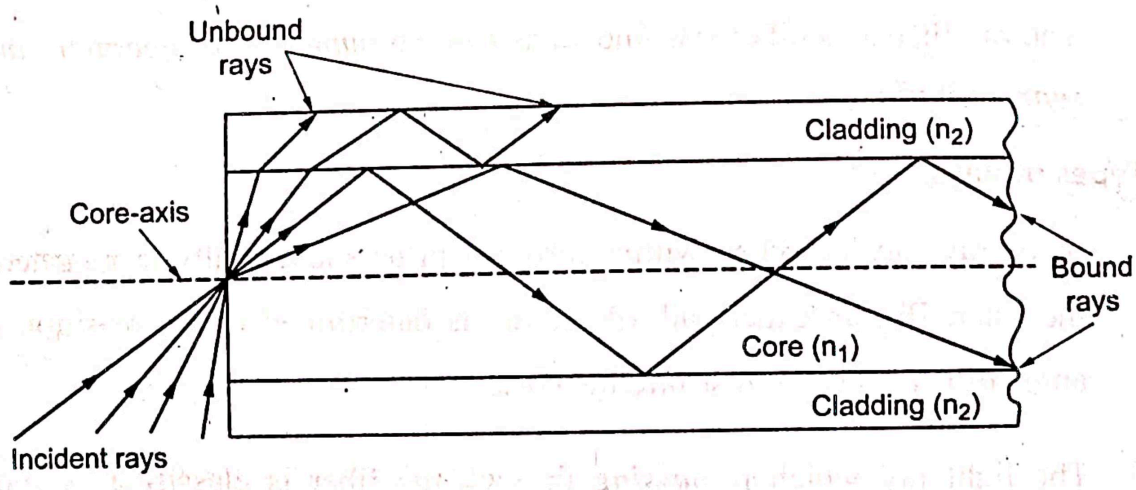


Fig 1.13 Bound and unbound rays in an SI optical fiber in ray representation

(2) Skew Rays

Definition:

- *Skew rays are **not transmitted through** the fiber axis and it simply follows a **helical path** in a fiber.*
- *The skew rays reflect off from the core cladding boundaries and again bounces around the outside surface of the core.*

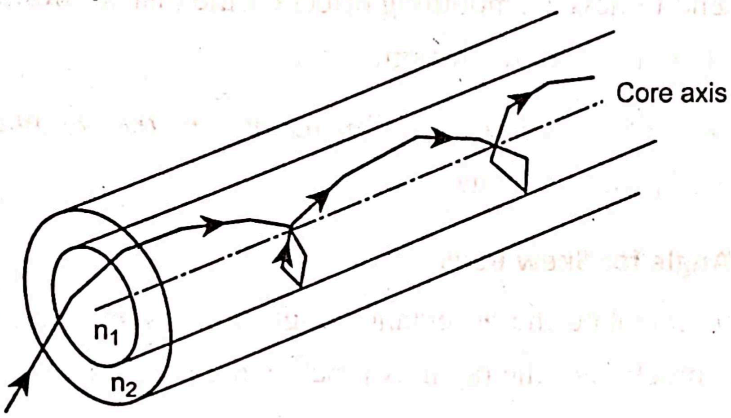


Fig 1.14 Helical path taken by a skew ray in an optical fiber

- These rays are ***more difficult*** to track as they travel along the fiber, since they do not lie in a single plane.
- Skew rays will change the ***light – acceptance ability of the fiber*** and ***power losses*** of light traveling along a waveguide.
- When the light input to the fiber is non-uniform, the skew rays will therefore tend to have smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output.

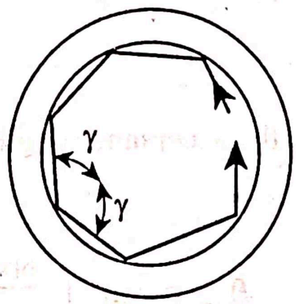


Fig 1.15 Cross-sectional view of the fiber

- The helical path traced through the fiber gives a change in direction of 2γ at ***each reflection***. The reflection is based on 'γ' which is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection.
- Skew rays from the fiber in air will depend upon the number of reflections they undergo rather than the input conditions of the fiber. Therefore, skew rays will tend to have a smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output.
- *The amount of smoothing is dependent on the number of reflections encountered by the skew rays.*

Acceptance Angle for Skew Rays

- In order to calculate the acceptance angle for a skew ray, it is necessary to define the direction of the ray in two perpendicular planes.
- Consider the angles of incidence and the reflection at the point reflection inside the fiber, which is greater than the critical angle for the core-cladding interface. Then the acceptance conditions for skew rays are,

$$n_0 \sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{1/2} = \text{NA} \quad \text{...... (16)}$$

where, θ_{as} represents the ***maximum input angle or acceptance angle for skew rays.***

- In the case of fiber in air ($n_0 = 1$), the numerical aperture is given as,

$$\boxed{\sin \theta_{as} \cos \gamma = \text{NA}} \quad \text{...... (17)}$$

Thus from equation (17), the acceptance angle for skew rays is expressed as,

$$\theta_{as} = \sin^{-1}\left(\frac{\text{NA}}{\cos \gamma}\right) \quad \text{...... (18)}$$

ELECTROMAGNETIC MODE THEORY FOR OPTICAL PROPAGATION

2.1 INTRODUCTION

- This analysis is based on the particular nature of light which treats light as an electromagnetic wave and allows to apply Maxwell's equations to explain its propagation through the dielectric waveguides.
- An electromagnetic wave comprises of two fields, that is, an ***electric field*** and a ***magnetic field.*** Both are vectors having both the ***direction*** and a ***magnitude*** i.e., ***amplitude.***
- These two fields are orthogonal to each other and moves with the speed of light. The electric and magnetic field distribution of a train of plane of linearly polarized electromagnetic wave is shown in Fig 2.1.

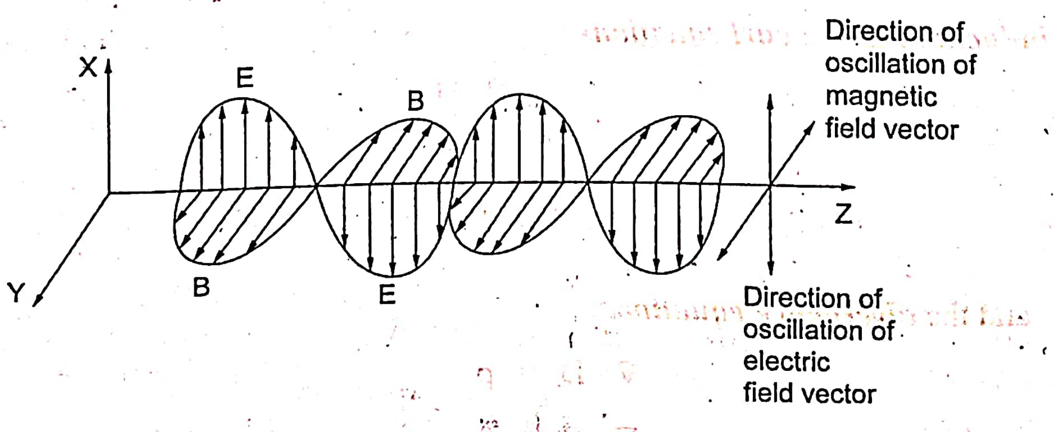


Fig 2.1 EM wave propagation in the z-direction

- Assume, that an electric field is oriented along the x-axis, and the magnetic field along the y-axis. Under this condition, the direction of propagation of light will be along the z- direction.
- The electric field vector always oscillates in the x-z plane. i.e., ***vertical polarization***, while the magnetic field vector is confined in x-y plane. i.e., ***horizontal polarization***.

Polarization

- *Polarization refers to an orientation of an electromagnetic field with respect to some plane or boundary towards which the wave advances.*
- *It is a property which is applying to the transverse waves that specifies the geometrical orientation of an oscillation. In a transverse wave, the direction of the oscillation is perpendicular to the direction of motion of the wave.*

2.1.1 Electromagnetic(EM) Wave Equation

- In order to obtain an improved model for the propagation of light in an optical fiber, an electromagnetic wave theory must be considered.
- The mode analysis is based on an electromagnetic wave equations which is derived on the basis of ***Maxwell's equations***.
- Maxwell's equations involving an ***electric field E***, ***magnetic field H***, ***electric flux density D (electric displacement)*** and ***magnetic flux density B (magnetic induction)*** as the ***curl equations***:

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \ldots (1)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad \ldots (2)$$

and the ***divergence equations***:

$$\nabla \cdot D = \rho \quad \ldots (3)$$

$$\nabla \cdot B = 0 \quad \ldots (4)$$

where Δ – *Vector operator,*

$J = \sigma E$ = *Conduction current density,*

σ – *Conductivity of the medium, and*

ρ – *Volume density of electric charge.*

- The electric and the magnetic flux density vectors are related with their corresponding field vectors as:

$$D = \epsilon E \quad \text{... (5)}$$

and

$$B = \mu H \quad \text{... (6)}$$

where ϵ – *Dielectric permittivity, and*

μ – *Magnetic permeability of the medium.*

- For a pure dielectric medium, the ***conductivity is zero*** ($\sigma = 0$). Assuming, that no electric charge is enclosed, then equations (1) to (4) can be rewritten as:

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} \quad \text{... (7)}$$

$$\nabla \times H = \epsilon \frac{\partial E}{\partial t} \quad \text{... (8)}$$

$$\nabla \cdot E = 0 \quad \text{... (9)}$$

$$\nabla \cdot H = 0 \quad \text{... (10)}$$

Taking the curl on both sides of equation (7), we get

$$\nabla \times (\nabla \times E) = -\mu \frac{\partial (\nabla \times H)}{\partial t} \quad \text{... (11)}$$

By substituting equation (8) in equation (11), we get

$$\nabla \times (\nabla \times E) = -\mu \frac{\partial \left(\epsilon \frac{\partial E}{\partial t} \right)}{\partial t}$$

$$\nabla \times (\nabla \times E) = -\mu \epsilon \frac{\partial^2 E}{\partial t^2} \quad \text{...(12)}$$

- Then, use the ***vector identity*** in LHS of equation (12), we get

$$\nabla \times (\nabla \times E) = \nabla (\nabla \cdot E) - \nabla^2 (E) \quad \text{... (13)}$$

where ∇^2 is the ***Laplacian operator.***

$$\nabla(\nabla \cdot E) - \nabla^2(E) = -\mu \in \frac{\partial^2 E}{\partial t^2} \quad \text{... (14)}$$

- Now, by using the divergence condition of equation (9) in equation (14), we get

$$\nabla^2 E = \mu \in \frac{\partial^2 E}{\partial t^2} \quad \text{... (15)}$$

- Similarly, by taking the curl on both sides of equation (8) and using equation (10), we get,

$$\nabla^2 H = \mu \in \frac{\partial^2 H}{\partial t^2} \quad \text{... (16)}$$

Equations (15) and (16) are the ***standard non-dispersive wave equations.***

- For rectangular Cartesian and cylindrical polar coordinates, the above wave equations hold for each component of the field vector, every component satisfying the scalar wave equation:

$$\nabla^2 \psi = \frac{1}{v_p^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{... (17)}$$

where ψ corresponds to anyone of the components of E or H field.

- v_p is the ***phase velocity*** which corresponds to the velocity of propagation of a point of constant phase on the wave in the dielectric medium and it is given by,

$$\boxed{v_p = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}}} \quad \text{... (18)}$$

where μ_r and ε_r are the ***relative permeability*** and ***permittivity for the dielectric medium.*** μ_0 and ε_0 are the ***permeability*** and ***permittivity of free space.***

- The ***velocity of light in free space*** is given by,

$$\boxed{c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}} \quad \text{... (19)}$$

- If planar waveguides, described by rectangular Cartesian coordinates (x, y, z), or circular fibers, described by cylindrical polar coordinates (r, ϕ, z), are considered, then the Laplacian operator takes the form

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2} \quad \ldots (20)$$

or

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2}+\frac{\partial^2\psi}{\partial z^2} \quad \ldots (21)$$

- It is necessary to consider both these forms for a complete treatment of optical propagation in the fiber.
- The basic solution of the wave equation is a sinusoidal wave and the most important form of a uniform plane wave is given by,

$$\psi = \psi_0\, exp\,[\,j\,(\,\omega t - k \cdot r)\,] \quad \ldots (22)$$

where,

ω - Angular frequency of the field.

t - Time.

k - Propagation vector which gives the direction of propagation and the rate of change of phase with distance.

- The components of 'r' specify the coordinate point at which the field is observed. The magnitude of the propagation vector or the vacuum phase propagation constant k is given by,

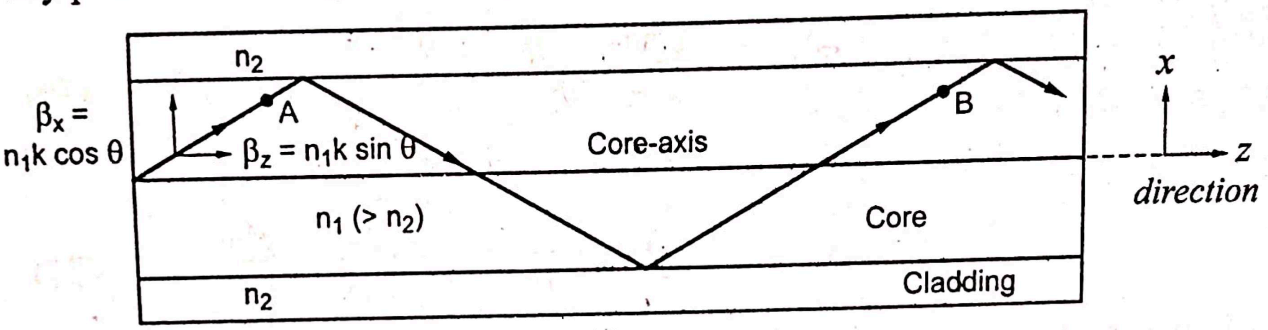
$$k = \frac{2\pi}{\lambda} \quad \ldots (23)$$

k is also referred to as the ***free space wave number***.

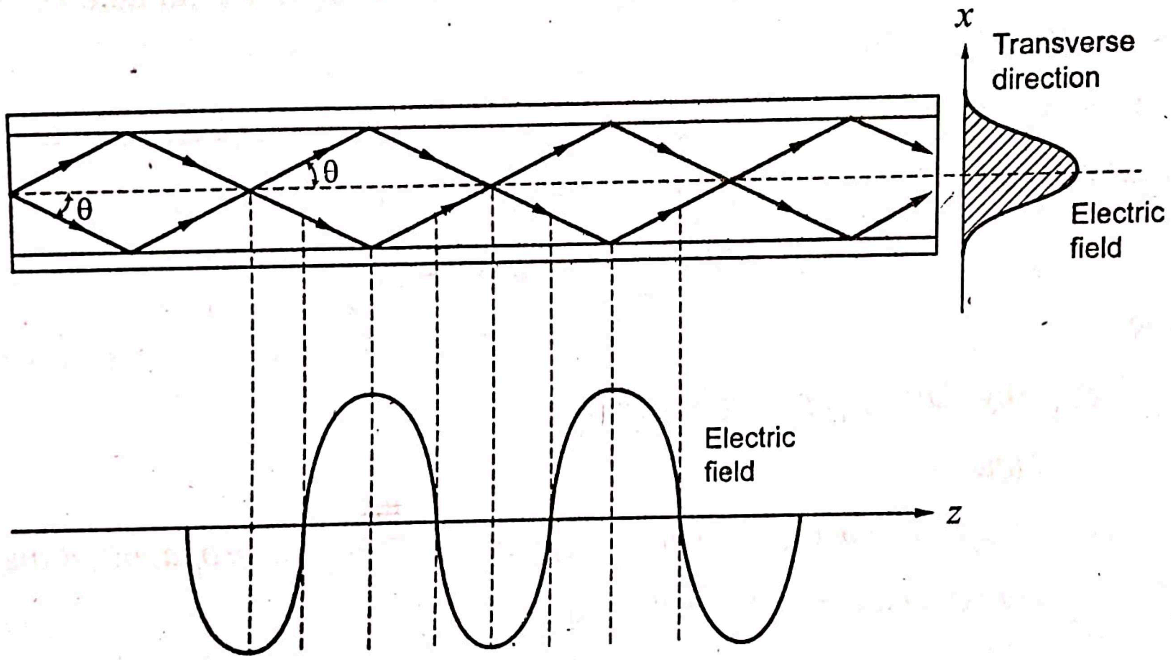
2.1.2 Modes in a Planar Waveguide

- The planar waveguide is the simplest form of an optical waveguide. Its structure consists of a slab of dielectric with refractive index 'n_1' sandwiched between two regions of lower refractive index 'n_2', that is $n_2 < n_1$ as shown in Fig 2.2.

♣ The conceptual transition from the ray to wave theory may be aided by consideration of a plane monochromatic wave propagating in the direction of the ray path within the guide in Fig 2.2(a).



(a)



(b)

Fig 2.2 The formation of a mode in a planar dielectric guide:

(a) ***Plane wave propagating through the guide shown in the form of equivalent ray which corresponds to the wave vector.***

(b) ***Formation of the lowest order mode through superposition of plane waves in the transverse direction.***

♣ The plane wave associated with the ray *(considered as the wave propagation vector)* can be resolved into two orthogonal component plane waves propagating in both the *z (horizontal)* and *x (vertical)* directions, as shown in Fig.2.2.

♣ The component of the phase propagation constant in the '*z*' direction is given by,

$$\beta_z = n_1 k \cos\theta \qquad \text{... (24)}$$

- On the other hand, the component of the phase propagation constant in the 'x' direction is :

$$\beta_x = n_1 k \sin\theta \qquad \dots (25)$$

where, $k = \frac{2\pi}{\lambda}$ is the ***free space propagation constant*** which increases in an optically denser medium with refractive index n_1 (> 1) as the free space wave length is reduced to $\frac{\lambda}{n_1}$.

- The component of the plane wave in the x direction is total internally reflected at an interface between the central core region and the outer cladding region of lower refractive index.
- When the total phase change after two successive reflections at the upper and lower interfaces *(between points A and B)* it is equal to $2\pi m$ ***radians***, where 'm' is an integer, then constructive interference of the wave occurs and a standing wave is obtained in the x direction.
- This is illustrated in Fig 2.2(b). In this illustration, it is assumed that the constructive interference of the waves form the lowest order standing wave ($m = 0$) in which an electric field is maximum at the center.
- The electric field is effectively confined in the central region but decays exponentially towards zero in the cladding region beyond the interfaces on both the sides.
- The variation of an electric field in the transverse x-direction for the lowest order mode is shown in Fig 2.2(a).
- The wave advances in the z-direction, an electric field distribution does not change in the transverse x-direction. This stable field distribution in the x-direction with periodic z dependence is called a ***mode***. The variation of an electric field in the z-direction is shown in Fig 2.2(b).
- A particular mode is obtained only when the plane waves making a specific angle (θ) with the core-cladding interface or the axis of the fiber. The light propagating

through a waveguide thus forms a discrete number of modes corresponding to a discrete value of 'θ'.

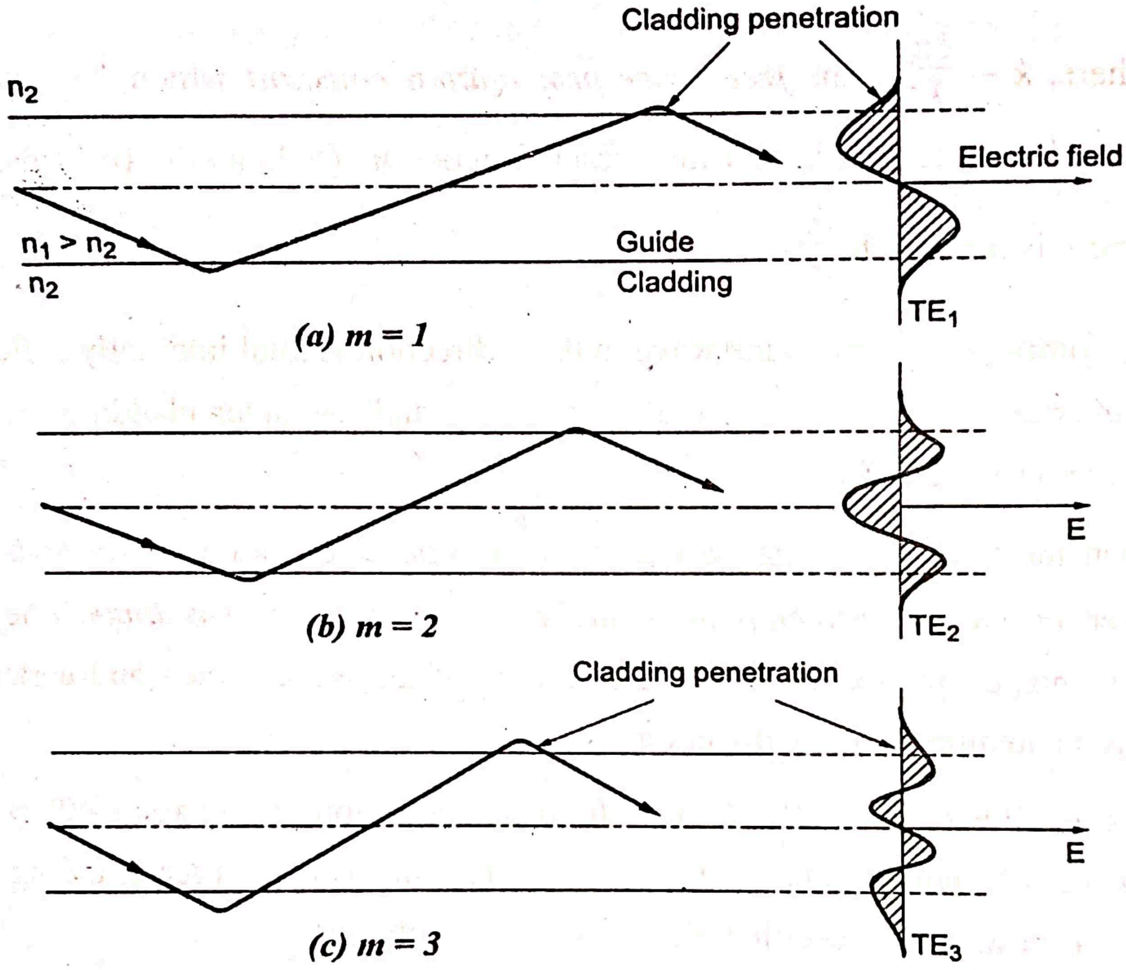


Fig 2.3 Illustrating transverse electric modes TE_m (m = 1, 2, 3) along with ray paths showing penetration in the cladding region.

- A few higher order modes with the electric field distributions in the transverse direction (x-direction) for different modes corresponding to $m = 1, 2, 3$ are shown in Fig 2.3. The penetrating of the field in the cladding region increases with the order of the mode.
- It may be observed that 'm' denotes the number of zeros in the transverse direction. In this way 'm' signifies the order of the modes and it is known as the ***mode number.***
- In the mode analysis, light is considered as electromagnetic waves with E and H fields varying periodically in orthogonal directions.

Transverse Electric (TE_m) Modes

The electric field is considered to be perpendicular to the direction of propagation that is, $E_z = 0$ while the magnetic field is non-zero in the z-direction i.e., ($H_z \neq 0$). These modes are designated as TE_m modes.

Transverse Magnetic (TM_m) Modes

When an electric field is in the direction of propagation, i.e., in the z-direction ($E_z \neq 0$) and the magnetic field is perpendicular to the direction of propagation ($H_z = 0$). These modes are called TM_m modes.

Transverse Electro Magnetic (TEM) Modes

When $E_z = 0$ and $H_z = 0$, then the total field lies in the transverse plane and the mode is called TEM mode and they are rarely found in optical waveguides.

- The field pattern of a particular mode is invariant in the transverse direction while it has a ***periodic z-dependence*** of the form:

$$exp\,(-j\,\beta_z\,z) \qquad \ldots (26)$$

- The direction of propagation of light is considered conventionally along the z-axis, and so it is customary to represent β_z as β.
- Considering the time dependence of the monochromatic electromagnetic field in the form exp ($j\,\omega\,t$), then the propagating mode can be expressed as,

$$exp\,[\,j(\omega t - \beta z)\,] \qquad \ldots (27)$$

2.1.3 Phase and Group Velocity

- *Within all EM waves, whether plane or otherwise, there are points of constant phase. For plane waves these constant phase points form a surface which is referred to as a* ***wavefront.***

♣ As a monochromatic light wave propagates along a waveguide in the 'z' direction these points of constant phase travel at a phase velocity:

$$v_p = \frac{\omega}{\beta} \quad \text{... (28)}$$

where, ω is the ***angular frequency of the wave.***

♣ A group of waves with closely similar frequencies propagate and their resultant forms a packet of waves. The formation of such a wave packet resulting from the combination of two waves of slightly different frequency propagating together is illustrated in Fig 2.4.

♣ This wave packet does not travel at the phase velocity of the individual waves but is observed to move at a group velocity v_g :

$$v_g = \frac{\delta\omega}{\delta\beta} \quad \text{... (29)}$$

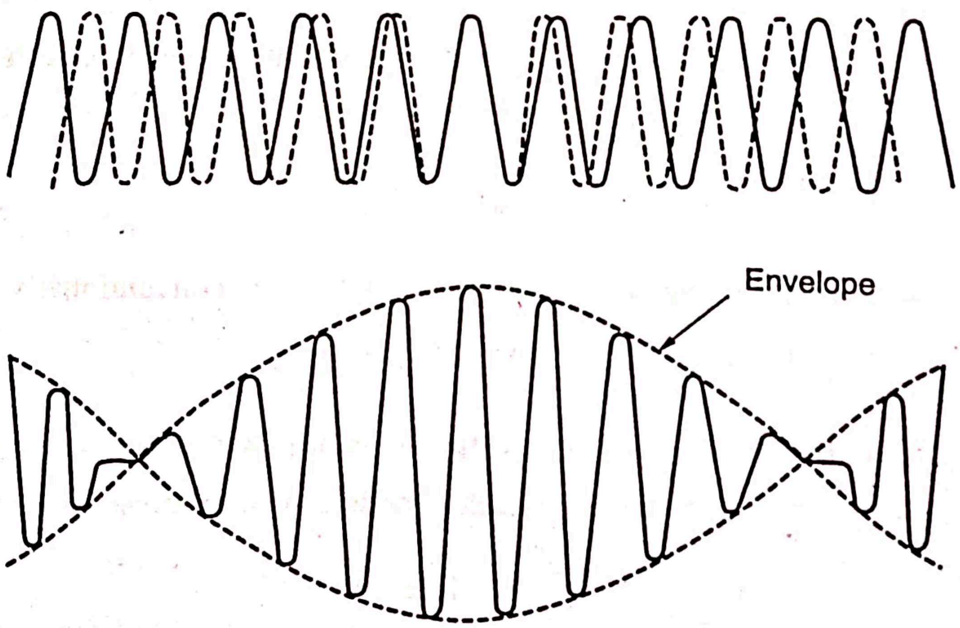


***Fig 2.4** The formation of a wave packet and the envelope of the wave package or group of waves travels at a group velocity v_g.*

- Consider, if the propagation in an infinite medium of refractive index n_1, then the propagation constant may be written as,

$$\beta = n_1 \frac{2\pi}{\lambda} \qquad \left(\lambda = \frac{c}{f} \ \& \ \omega = 2\pi f\right)$$

$$= n_1 \frac{2\pi f}{c} = \frac{n_1 \omega}{c} \qquad \text{... (30)}$$

Where, c is the ***velocity of light in free space.*** Equation (30) follows from equations (23) and (24) where we assume propagation in the 'z' direction only and hence $\cos\theta$ is equal to unity.

- By using equation (28), we obtain the following relationship for the phase velocity as,

$$v_p = \frac{c}{n_1} \qquad \text{... (31)}$$

- Similarly, in equation (29) the limit $\frac{\delta\omega}{\delta\beta}$ becomes $\frac{d\omega}{d\beta}$, then the group velocity becomes,

$$v_g = \frac{d\lambda}{d\beta} \cdot \frac{d\omega}{d\lambda}$$

$$= \frac{d}{d\lambda}\left(n_1 \frac{2\pi}{\lambda}\right)^{-1} \left(-\frac{\omega}{\lambda}\right) \qquad \left[\beta = n_1 \frac{2\pi}{\lambda}\right]$$

$$= \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1}$$

$$= \frac{c}{\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)} = \frac{c}{N_g} \qquad \text{... (32)}$$

The parameter N_g is known as the ***group index of the guide.***

2.2 OPTICAL FIBER MODES AND CONFIGURATIONS

2.2.1 Introduction

- An optical fiber is a ***dielectric waveguide*** that ***operates at the optical frequencies.*** This fiber waveguide is normally ***cylindrical inform.***

♣ Light can be propagated down an optical fiber cable using either ***reflection*** or ***refraction.*** The propagation of light along a waveguide can be described in terms of a ***set of guided electromagnetic waves*** called the ***modes of the waveguide.***

Guided Mode

*Each guided mode is a **pattern of electric and magnetic field distributions** that is **repeated along the fiber at an equal interval.***

Modes

*Simply modes are referred to the **number of paths for the light rays in the cable.*** Only a ***certain discrete number*** of modes are capable of ***propagating along*** the guide.

2.2.2 Basic Construction of a Fiber – Optic Cable

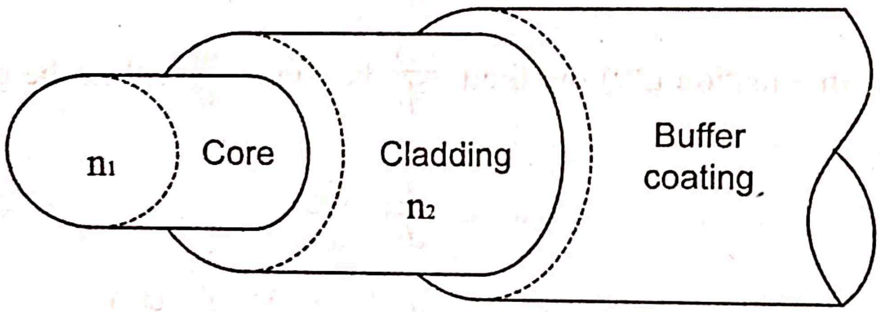


Fig 2.5 Schematic of a single – fiber structure

Core

The fiber which is the single solid dielectric cylinder of ***radius 'a'*** and the index of refraction is 'n_1'.

Cladding

The core is usually surrounded by a solid dielectric cladding and it has a refractive index 'n_2' which is less than n_1 that is, $n_1 > n_2$.

☑ **Advantages**

The advantages of cladding are,

(i) The cladding reduces the ***scattering loss*** which occurs due to ***dielectric discontinuities*** at the core surface.

(ii) It adds ***mechanical strength*** to the fiber, and

(iii) It protects the core from absorbing ***surface contaminants*** with which it would come in contact.

Classification of Fiber – Optic Cables

There are two basic ways of classifying fiber – optic cables:

(i) Based on the varied ***index of refraction across*** the ***cross section of the cable,***

(a) Step index, and

(b) Graded index.

(ii) Based on modes,

(a) Mono-mode or single mode, and

(b) Multimode.

Index Profile of the Fiber

The ***index profile*** *of an optical fiber is a* ***graphical representation of the magnitude of the refractive index across the fiber.*** There are two basic ways of defining the index of ***refraction variation*** across a cable as,

(a) Step index fiber, and

(b) Graded index fiber.

2.2.3 Modes of Fiber

Mode refers to the ***number of paths*** *for the light rays in the cable.* There are two classifications as ***single mode*** and ***multimode.***

(1) Single Mode Fiber

In single mode, light follows a single path (one mode of propagation) through the core.

☑ Advantages

(i) No ***intermodal dispersion.***

(ii) ***Information capacity*** of single mode fiber is large.

☒ Disadvantages

(i) ***Launching*** of light into single mode and joining of two fibers are ***very difficult.***

(ii) Fabrication is ***very difficult*** and hence the fiber is ***so costly.***

(2) Multimode Fiber

*In multimode, the **light takes many paths** through the core.*

☑ Advantages

Multimode fibers offer ***several advantages*** when compared to ***single mode fibers*** as,

(i) The larger ***core radii*** as well as ***numerical apertures*** of multimode fibers makes it ***easier*** to ***launch optical power*** into the fiber.

(ii) Connecting together of similar fibers is easy.

(iii) Light can be launched into a multimode fiber by using LED which is easier to make and ***less expensive*** and have ***longer life times.***

(iv) Fabrication is less difficult and so fiber is not costly.

(v) The tolerance requirements on this fiber are also low.

☒ Disadvantages

(i) Multimode fibers are suffered from ***intermodal dispersion.***

(ii) They are much more limited in both speed and distance. For instance, the maximum speed of a multimode cable is 10 GB, but only up to a distance of 300 meters.

Intermodal Dispersion (or) Intermodal Distortion

- *When an optical pulse is launched into a fiber, the optical power in the **pulse is distributed over** the modes of the fiber. Each of the modes that can propagate in a multimode fiber travels at a slightly different velocity. So the optical pulses arrive **at the fiber ends at slightly different times,** thus causing the pulse to spread out in time as it travels along the fiber.*

CYLINDRICAL AND SINGLE MODE (SM) FIBERS

3.1 STEP INDEX FIBERS

Definition:

The refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary. This is called a ***step-index fiber.***

Step index sharply defined ***"a step in the index of refraction where the fiber core and cladding interface".***

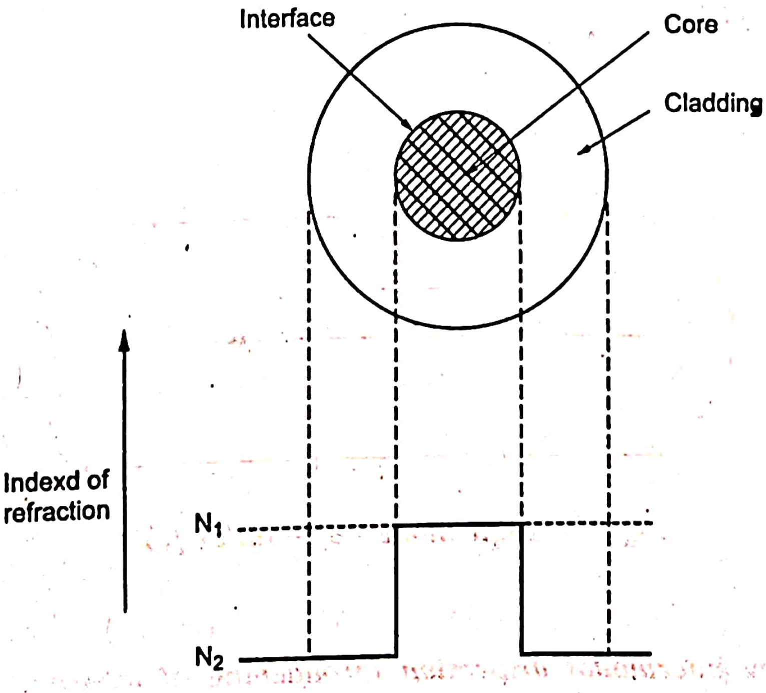


Fig 3.1 A step-index cable cross section

- As shown in Fig 3.1, here refractive index n_1 of the core is uniform (constant) and refractive index n_2 of a cladding is slightly lower than n_1. The refractive index profile for this type of fiber makes a step change at the core-cladding interface.
- ***Refractive index profile*** *n(r)* may be defined as,

$$n(r) = \begin{cases} n_1 & r < a \ (core) \\ n_2 & r \geq a \ (cladding) \end{cases} \quad \ldots (1)$$

where,

r - Radial distance from the fiber axis, and

a - Core radius.

(1) Single Mode or Mono Mode Step – Index Fiber

- Single mode step – index fibers are the dominant fibers used in today's ***telecommunications*** and ***data networking*** industries.
- It has a central core that is significantly ***smaller in diameter*** than any of the multimode cables, with a typical core size of ***8 to 12 μm.*** As the diameter is sufficiently small therefore, ***only one path*** that light may take as it propagates down the cable.

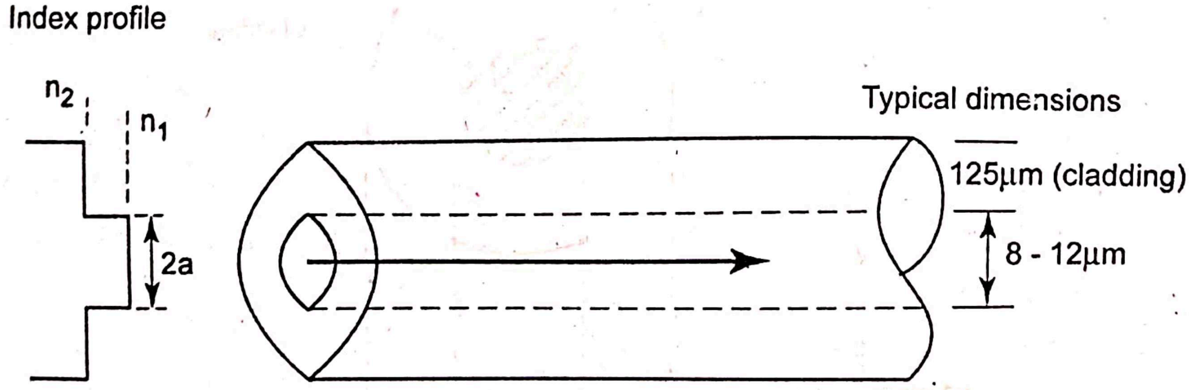


Fig 3.2 Single mode step – index fiber

☑ Advantages

(i) It has ***low intermodal dispersion*** *(broadening of transmitted light pulses) which is due to one mode propagation.*

(ii) ***For very long distance transmission and maximum information content, this cable should be used.***

(2) Multimode Step – Index Fiber

- Multimode step – index are similar to the single mode step – index except the diameter of the ***center core,*** which is much larger with the ***multimode configuration.***

- It is easy to manufacture and its core diameter is varying from ***50 – 200μm*** and the cladding is from ***125-400μm.***

- The light rays are propagated down the core in a ***zig-zag*** manner. There are ***many paths*** that a light ray may follow during the propagation. It allows the propagation of a finite number of guided modes along the channel.

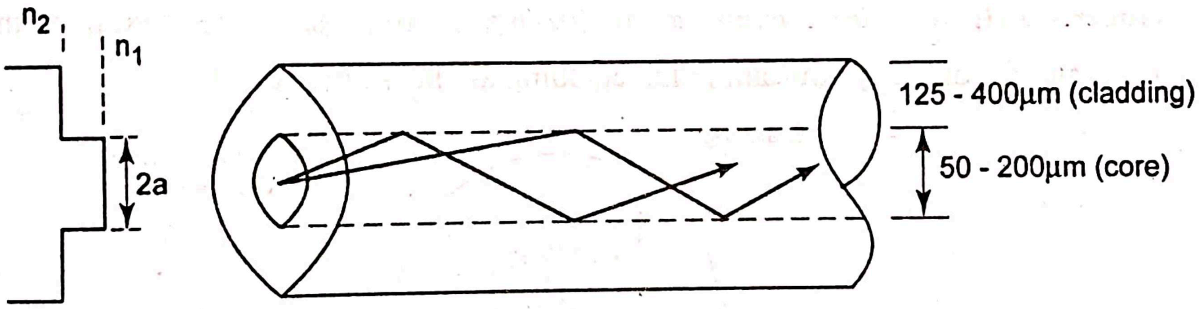


Fig 3.3 Multimode step – index fiber.

♣ The number of guided modes is dependent upon the physical parameters *(i.e., relative index difference, core radius)* of the fiber and the wavelengths of the transmitted light which are included in the ***normalized frequency*** 'V' for the fiber.

$$V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{1/2} \qquad \dots (2)$$

♣ The ***total number of guided modes*** or mode volume M for a step index fiber is related to the V value for the fiber by the approximate expression.

$$M \approx \frac{V^2}{2} \qquad \dots (3)$$

- In multimode step index fiber, considerable dispersion may occur due to the differing group velocities of the propagation modes.

3.2 GRADED INDEX FIBER

3.2.1 Introduction

Definition:

*Graded index fiber do not have a constant refractive index in the core. But the **core refractive index n(r) is made to vary as a function of the radial distance from the center** of the fiber.*

*The index of **refraction varies smoothly and continuously** over the diameter of the core.*

- In the graded – index fiber design, the core refractive index $n(r)$ ***decreases continuously*** with ***increasing radial distance*** r from the center (axis) of the fiber, but is generally constant in the cladding as shown in Fig 3.4.

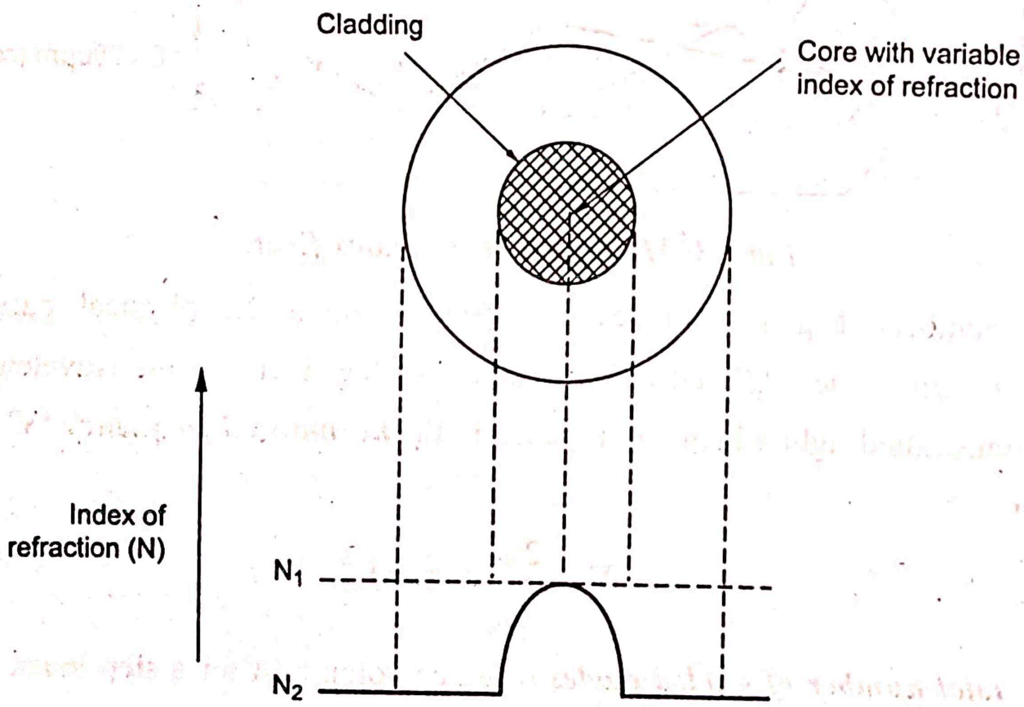


Fig 3.4 Graded – index cable cross section

- The graded-index refractive – index variation may be represented as,

$$n(r) = \begin{cases} n_1 \left[1-2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right]^{1/2} & for\ 0 \le r \le a\ (core) \\ n_1 (1-2\Delta)^{1/2} \approx n_1 (1-\Delta) = n_2 & for\ r \ge a\ (cladding) \end{cases} \quad \dots (1)$$

where,

r - Radial distance from the fiber axis,

a - Core radius,

n_1 - Refractive index at the core axis,

n_2 - Refractive index of the cladding,

α - ***Profile parameter*** which gives the ***characteristic refractive index profile of the fiber core,*** and

Δ - Relative refractive index difference.

♣ The ***index difference*** Δ for the graded – index fiber is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \quad \dots (2)$$

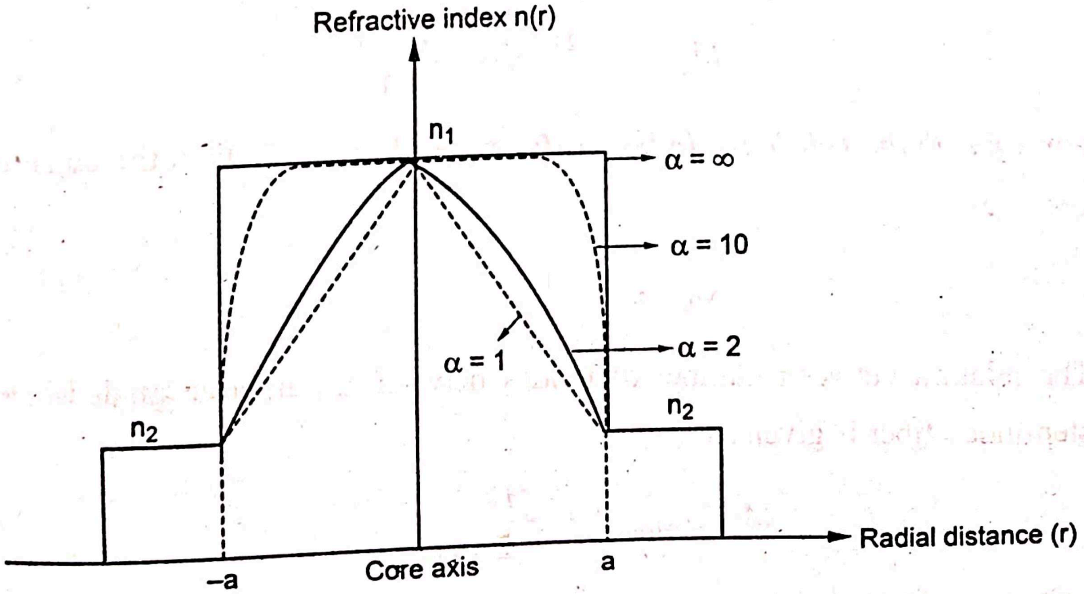


Fig 3.5 Possible fiber refractive index profiles for different value of α

- For multimode optical propagation, in a graded index fiber best suitable is parabolic refractive index profile core with $\alpha = 2$.
- Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile.

3.2.2 Total Number of Guided Modes

- The ***total number*** of guided modes or ***mode volume*** 'M' supported by the graded index fiber is given by,

$$M = \left(\frac{\alpha}{\alpha+2}\right)(n_1 ka)^2 \Delta \qquad \text{...... (3)}$$

- The ***normalized frequency V*** for the fiber, when $\Delta \ll 1$ is approximately given by,

$$V = n_1 k a (2\Delta)^{1/2} \qquad \text{...... (4)}$$

By substituting the equation (4) into equation (3), we will get

$$M_{GI} \approx \left(\frac{\alpha}{\alpha+2}\right)\left(\frac{V^2}{2}\right) \qquad \text{...... (5a)}$$

$$M_{GI} = a^2 k^2 n_1^2 \Delta \left(\frac{\alpha}{\alpha+2}\right) \qquad \text{...... (5b)}$$

- For a ***parabolic refractive index profile*** core fiber $\alpha = 2$, then the equation (5a) becomes,

$$M_{GI} \approx \frac{V^2}{4} \qquad \text{...... (6)}$$

- The relation between number of modes between a parabolic graded-index and step-index fiber is given as,

$$M_{GI\,(parabolic)} = \frac{M_{SI}}{2} \qquad \text{...... (7)}$$

where, $M_{SI} = \frac{V}{2}$

3.2.3 Numerical Aperture (NA) of the Graded-Index Fiber

- Determining the NA for graded-index fibers is more complex than for step index fibers, since it is a function of ***position across the core end face.***
- ***Geometrical optics considerations*** shows that light incident on the fiber core at position '*r*' will propagate as a guided mode only if it is within the ***local numerical aperture NA(r)*** at that point.

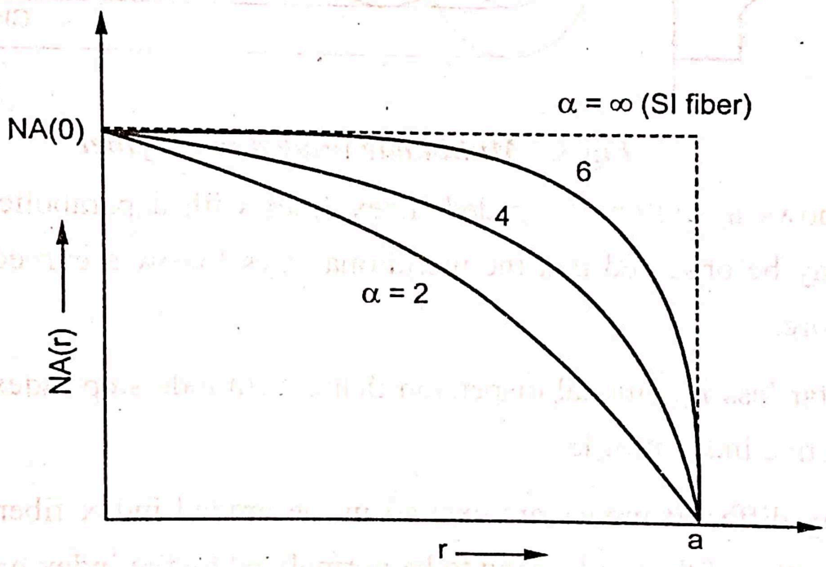


Fig 3.6 Variation of numerical aperture of a GI fiber with radial distance from the center of the core

- The ***local numerical aperture*** is defined as,

$$NA(r) = \begin{cases} \left[n^2(r) - n_2^2\right]^{1/2} \approx NA(0)\sqrt{1-(r/a)^\alpha} & \text{for } r \le a \\ 0 & \text{for } r > a \end{cases} \quad \ldots\ldots (8)$$

- The ***axial numerical aperture*** is defined as,

$$NA(0) = \left[n^2(0) - n_2^2\right]^{1/2} = \left(n_1^2 - n_2^2\right)^{1/2} \approx n_1\sqrt{2\Delta} \quad \ldots\ldots (9)$$

- Thus, the NA of a graded-index fiber ***decreases from NA (0) to zero*** as ***r moves*** from the ***fiber axis to the core – cladding boundary.***

3.2.4 Multimode Graded Index Fiber

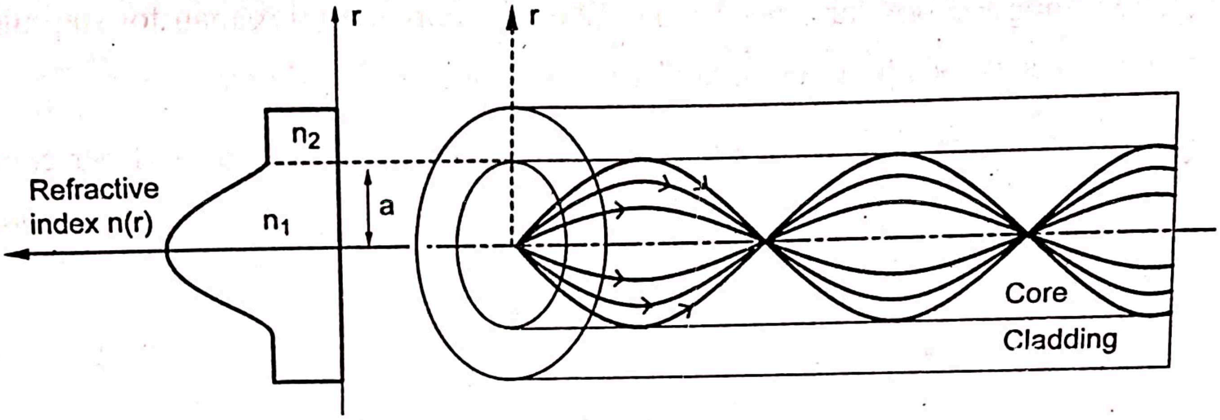


Fig 3.7 Multimode graded index fiber

- Fig 3.7 shows a multimode graded index fiber with a parabolic index profile core. It may be observed that the meridional rays follow a curved path through the fiber core.
- It exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile.
- Thus, many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalized by the index grading.

3.3 SINGLE MODE(SM) FIBERS

3.3.1 Introduction

- Single mode fibers are designed to ***allow only one mode of propagation.*** All other modes are attenuated by ***leakage*** or ***absorption.***
- The core diameter of the single mode fiber ranges from ***8 – 12μm*** and it has very ***small index differences*** between the core and the cladding with normalized frequency V = 2.405.
- The core – cladding index difference varies between ***0.2 and 1.0 percent,*** and the core diameter should be chosen to be just ***below the cutoff*** of the ***first higher – order mode.***

- For the single mode fiber operation, only ***LP_{01} mode*** can exist, also known as the fundamental mode of the fiber. Single mode propagation of the LP_{01} mode in step – index fiber is possible over the range.

$$0 \leq V < 2.405$$

- The fundamental mode has no cutoff and is always supported by a fiber.

Graded Index Fiber for Single Mode Operation:

- Graded index fibers may also be designed for single – mode operation and some specialist designs fiber, to adopt the non-step index profiles. The cutoff value of normalized frequency V_c to support a single mode in a graded index fiber is given by

$$V_c = 2.405\left(1 + \frac{2}{\alpha}\right)^{1/2} \quad \ldots (1)$$

- Using this expression, it is possible to determine the fiber parameters which give single-mode operation.

Why single mode fiber is widely used in telecommunications?

(i) Single mode fiber utilize transmission bandwidth effectively and have lowest losses in the transmission medium.

(ii) They have a superior transmission quality over other fiber types because of the absence of modal noise.

(iii) They offer a substantial upgrade capability for future wide bandwidth services using either faster optical transmitters or receivers or advanced transmission techniques.

(iv) They are compatible with the developing integrated optics technology.

(v) The installation of single-mode fiber will provide a transmission medium which will have adequate performance such that it will not require replacement over its twenty-plus anticipated lifetime.

Single-Mode W Fiber:

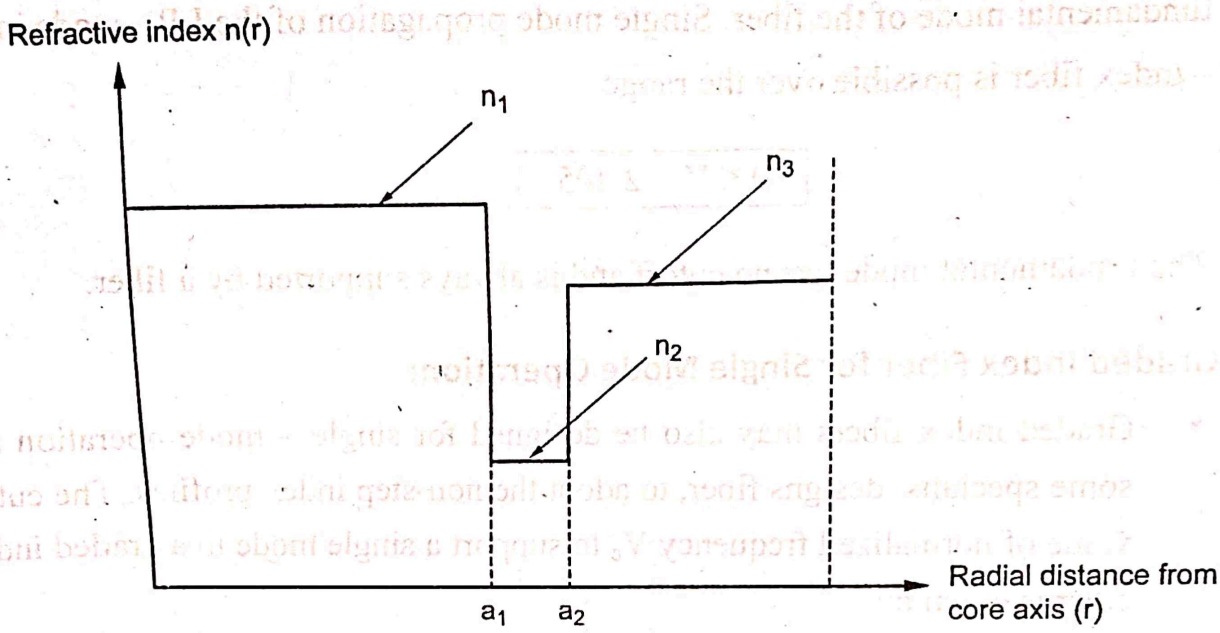


Fig 3.8 The refractive index profile for a single –mode W fiber

- Another approach to single-mode fiber design which allows the V value to be increased above 2.405 is the W fiber. The refractive index profile for this fiber is illustrated in Fig 3.8 where two cladding regions may be observed.
- Use of such two-step cladding allows the loss threshold between the desirable and undesirable modes to be substantially increased.

3.3.2 Cutoff Wavelength

- One of the important transmission parameter for single – mode fibers, is ***cut-off wavelength*** for the first higher – order mode (LP_{11}). It separates ***the single – mode and multimode regions.***
- The theoretical cut off wavelength of a single – mode operation is given by

$$\lambda_{c;th} = \frac{2\pi a}{V_c}\left(n_1^2 - n_2^2\right)^{\frac{1}{2}} \qquad \dots (2)$$

Equation (2) in another form

$$\lambda_{c;th} = \frac{2\pi a n_1}{V_c}(2\Delta)^{\frac{1}{2}} \qquad \dots (3)$$

Cutoff normalized frequency $V_c = 2.405$ for step-index fiber.

- At this wavelength, only ***the LP_{01} mode*** (i.e., the HE_{11} mode) should ***propagate in the fiber.*** *λ_c is the wavelength above which a particular fiber becomes single-moded.*
- The relation between cutoff wavelength (λ_c) and cutoff normalized frequency (V_c) is given as

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \quad \text{.....(4)}$$

- For step index fiber $V_c = 2.405$, the cutoff wavelength is given by

$$\lambda_c = \frac{V\lambda}{2.405}$$

- The cutoff wavelength is an important parameter, when we estimate the ***radius of curvature*** for a single – mode fiber and it is given as:

$$R_{CS} = \frac{20\lambda}{(n_1 - n_2)^{3/2}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3} \quad \text{....(5)}$$

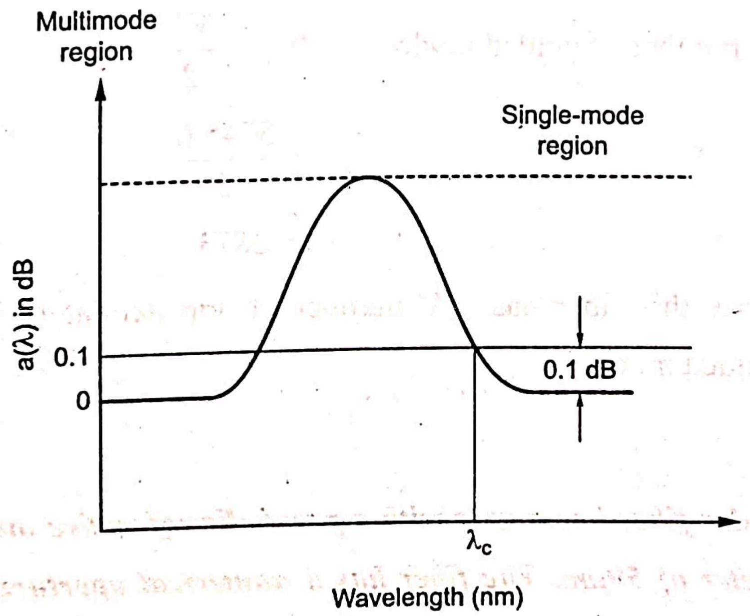


Fig 3.9 Typical attenuation – ratio versus wavelength plot for determining cutoff wavelength