UNIT - 1
OVERVIEW OF OPTICAL FIBER COMMUNICATION

Historical Development

- Fiber optics deals with study of propagation of light through transparent dielectric wageguides. The fiber optics are used for transmission of data from point to point location. Fiber optic systems currently used most extensively as the transmission line between terrestrial hardwired systems.
- The carrier frequencies used in conventional systems had the limitations in handlinmg the volume and rate of the data transmission. The greater the carrier frequency larger the available bandwith and information carrying capacity.

First generation

- The first generation of lightwave systems uses GaAs semiconductor laser and operating region was near 0.8 μm. Other specifications of this generation are as under:

i) Bit rate : 45 Mb/s

ii) Repeater spacing : 10 km

Second generation

i) Bit rate : 100 Mb/s to 1.7 Gb/s

ii) Repeater spacing : 50 km

iii) Operation wavelength : 1.3 μm

iv) Semiconductor : In GaAsP

Third generation

i) Bit rate : 10 Gb/s

ii) Repeater spacing : 100 km

iii) Operating wavelength : 1.55 μm

Fourth generation

Fourth generation uses WDM technique.

Bit rate	: 10 Tb/s
Repeater spacing	: > 10,000 km
Operating wavelength	: 1.45 to 1.62 µm

Fifth generation

Fifth generation uses Roman amplification technique and optical solitiors.

Bit rate	: 40 - 160 Gb/s
Repeater spacing	: 24000 km - 35000 km
Operating wavelength	: 1.53 to 1.57 µm

Need of fiber optic communication

- Fiber optic communication system has emerged as most important communication system. Compared to traditional system because of following requirements :

  1. In long haul transmission system there is need of low loss transmission medium
  2. There is need of compact and least weight transmitters and receivers.
  3. There is need of increase dspan of transmission.
  4. There is need of increased bit rate-distrance product.

- A fiber optic communication system fulfills these requirements, hence most widely acception.

General Optical Fiber Communication System

- Basic block diagram of optical fiber communication system consists of following important blocks.

  1. Transmitter
  2. Information channel
  3. Receiver.

Fig. 1.2.1 shows block diagram of OFC system.

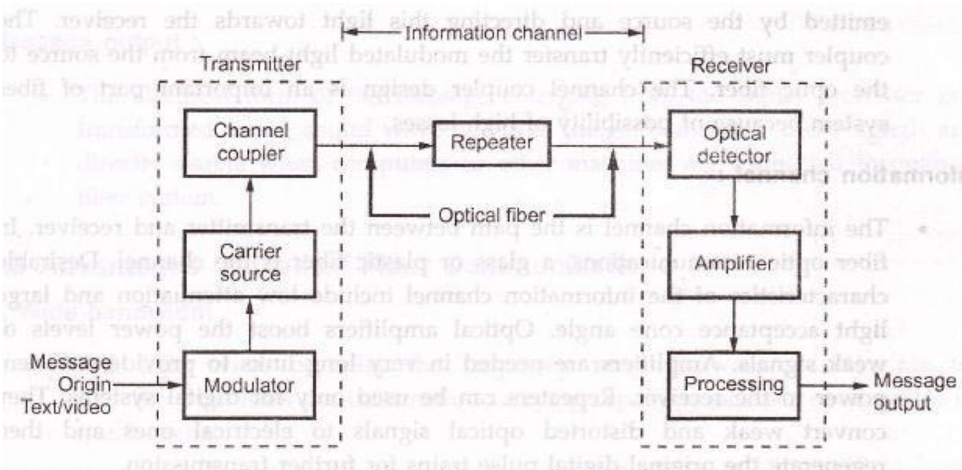

Fig. 1.2.1 Block diagram of OFC systems

Message origin :

- Generally message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound waves into currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator :

- The modulator has two main functions.

  1) It converts the electrical message into the proper format.

  2) It impresses this signal onto the wave generated by the carrier source.

  Two distinct categories of modulation are used i.e. analog modulation and digital modulation.

Carrier source :

- Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) is used. They can be called as optic oscillators, they provide stable, single frequency waves with sufficient power for long distance propagation.

Channel coupler :

- Coupler feeds the power into the information channel. For an atmospheric optic system, the channel coupler is a lens used for collimating the light emitted by the source and directing this light towards the receiver. The coupler must efficiently transfer the modulated light beam from the source to the optic fiber. The channel coupler design is an important part of fiber system because of possibility of high losses.

Information channel :

- The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate the original disgital pulse trains for further transmission.

- Another important property of the information channel is the propagation time of the waes travelling along it. A signal propagating along a fiber normally contains a range of optic frequencies and divides its power along several ray paths. This results in a distortion of the propagating signal. In a digital system, this distortion appears as a spreading and deforming of the pulses. The spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.

Optical detector :

- The information being transmitted is detector. In the fiber system the optic wave is converted into an electric current by a photodetector. The current developed by the detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and thn amplified.

- The important properties of photodetectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power.

Signal processing :

- Signal processing includes filtering, amplification. Proper filtering maximizes the ratio of signal to unwanted power. For a digital system decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

Message output :

- The electrical form of the message emerging from the signal processor are transformed into a soud wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

Advantages of Optical Fiber Communications

1. Wide bandwidth

- The light wave occupies the frequency range between 2 x 1012 Hz to 3.7 x 1012 Hz. Thus the information carrying capability of fiber optic cables is much higher.

2. Low losses

- Fiber optic cables offers bery less signal attenuation over long distances. Typically it is less than 1 dB/km. This enables longer distance between repeaters.

3. Immune to cross talk

- Fiber optic cables has very high immunity to electricaland magnetic field. Since fiber optic cables are non-conductors of electricity hence they do not produce magnetic field. Thus fiber optic cables are immune to cross talk between cables cause dby magnetic induction.

4. Interference immune

- Fiber optic cable sar eimmune to conductive and radiative interferences caused by electrical noise sources such as lighting, electric motors, fluorescent lights.

5. Light weight

- As fiber cables are made of silica glass or plastic which is much lighter than copper or aluminium cables. Light weight fiber cables are cheaper to transport.

6. Small size

- The diameter of fiber is much smaller compared to other cables, therefore fiber calbe is small in size, requires less storage space.

7. More strength

- Fiber cables are stronger and rugged hence can support more weight.

8. Security

- Fiber cables are more secure than other cables. It is almost impossible to tap into a fiber cable as they do n ot radiate signals.

No ground loops exist between optical fibers hence they are more secure.

9. Long distance transmission

- Becaujse of less attenuation transmission at a longer distance is possible.

10. Environment immune

- Fiber calbes are more immune to environmental extremes. They can operate over a large temperature varioations. Also they are not affected by corrosive liquids and gases.

11. Sage and easy installation

- Fiber cables are safer and easier to install and maintain. They are non-conductors hence there is no shock hazards as no current or voltage is associated with them. Their small size and light weight feature makes installation easier.

12. Less cost

- Cost of fiber optic system is less compated to any other system.

Disadvantages of Optical Fiber Communicaitons

1. High initial cost

- The intial cost of installation or setting up cost is very high compared to all other system.

2. Maintenance and repaiding cost

- The maintenance and repaiding of fiber optic systems is not only difficult but expensive also.

3. Jointing and test procedures

- Since optical fibers are of very small size. The fiber joining process is very constly and requires skilled manpower.

4. Tensile stress

- Optical fibers are more susceptible to buckling, bending and tensile stress than copper cables. This leades to restricted practice to use optical fiber technology to premises and floor backbones with a few interfaces to the copper cables.

5. Short links

- Eventhough optical fiber calbes are inexpensive, it is still not cost effective to replace every small conventional connector (e.g. between computers and peripherals), as the price of optoelectronic transducers are very high.

6. Fiber losses

- The amount of optical fiber available to the photodetector at the end of fiber length depends on various fiber losses such as scattering, dispersion, attenuation and reflection.

Applications of Optical Fiber Communicaitons

- Applications of optical fiber communications include telecommunications, data communications, video control and protection switching, sensors and power applications.

1. Telephone networks

- Optical waveguide has low attenuation, high transmission bandwidth compated to copper lines, therefore numbers of long haul co-axial trunks l;links between telephone exchanges are being replaced by optical fiber links.

2. Urban broadband service networks

- Optical waveguide provides much larger bandwidth than co-axial calbe, also the number of repeaters required is reduced considerably.

- Modern suburban communications involves videotext, videoconferencing videotelephony, switched broadband communication network. All these can be supplied over a single fiber optic link. Fiber optic calbes is the solution to many of today's high speed, high bandwidth data communication problems and will continue to play a large role in future telecom and data-com networks.

Optical Fiber Waveguides

- In free space light ravels as its maximum possible speed i.e. 3×10^8 m/s or 186×10^3 miles/sec. When light travels through a material it exnibits certain behavior explaned by laws of reflection, refraction.

Electromagnetic Spectrum

- The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3×10^8 m/sec. The distance travelled during each cycle is called as wavelength (λ)

$$\text{Wavelength } (\lambda) = \frac{\text{Speed of light}}{\text{Frequency}} = \frac{c}{f}$$

- In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies, wavlengfth is often stated in microns or nanometers.

1 micron (μ) = 1 Micrometre (1×10^{-6})

1 nano (n) = 10^{-9} metre

Fig. 1.6.1 shows electromagnetic frequency spectrum.

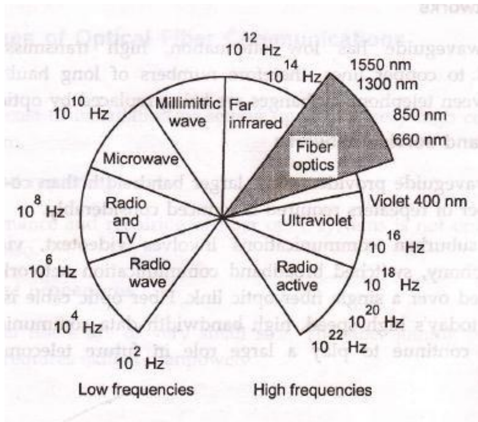

Fig. 1.6.1 Electromagnetic spectrum

- Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber.

Ray Transmission Theory

- Before studying how the light actually propagates through the fiber, laws governing the nature of light m ust be studied. These was called as **laws of optics (Ray theory).** There is conception that light always travels at the same speed. This fact is simply not true. The speed of light depends upon the material or medium through which it is moving. In free space light travels at its maximum possible speed i.e. 3 x 108 m/s or 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction.

Reflection

- The law of reflection states that, when a light ray is incident upon a reflective surface at some incident angle ϕ_1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle ϕ_2 from normal which is equal to the angle of incidence.

Fig. 1.6.2 shows law of relection.

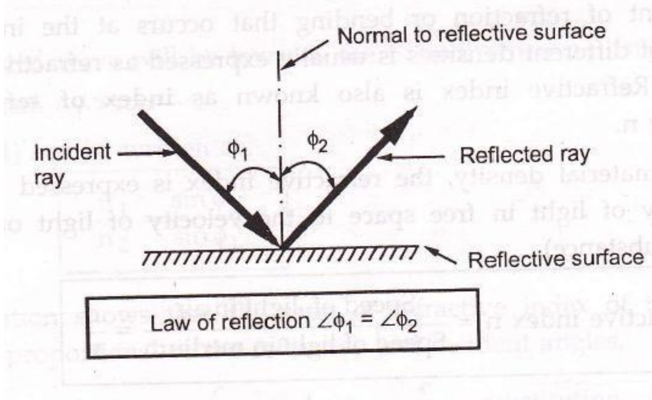

Fig. 1.6.2 Reflection

Refraction

- Refraction occurs when light ray passes from one medium to another i.e. the light ray changes its direction at interface. Refractio occurs whenever density of medium changes. E.g. refraction occurs at air and water interface, the straw in a glass of water will appear as it is bent.

The refraction can also observed at air and glass interface.

- When wave passes through less dense medium to more dense medium, the wave is refracted (bent) towards the normal. Fig. 1.6.3 shows the refraction phenomena.
- The refraction (bending) takes place because light travels at different spped in different mediums. The speed of light in free space is higher than in water or glass.

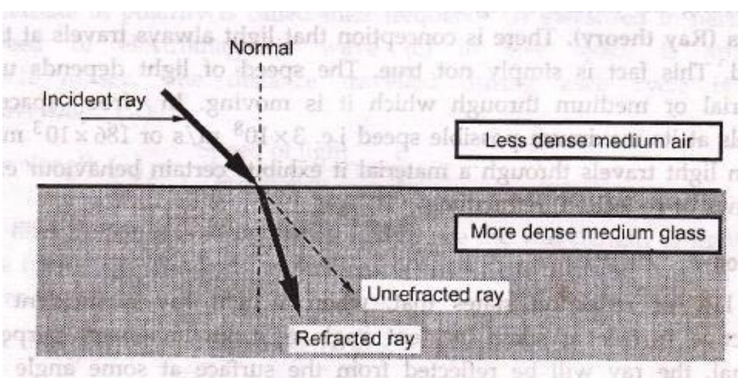

Fig. 1.6.3 Refraction

Refractive Index

- The amount of refraction or bending that occurs at the interface of two materials of different densities is usually expressed as refractive index of two materials. Refractive index is also known as **index of refraction** and is denoted by n.

- Based on material density, the refractive index is expressed as the ratio of the velocity of light in free space to the velocity of light of the dielectric material (substance).

$$\boxed{\text{Refractive index } n = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}} = \frac{c}{v}}$$

The refractive index for vacuum and air os 1.0 for water it is 1.3 and for glass refractive index is 1.5.

Snell’s Law

- Snell’s law states how light ray reacts when it meets the interface of two media having different indexes of refraction.

- Let the two medias have refractive indexes n1 and n_2 where $n_1 > n_2$.

$\phi 1$ and $\phi 2$ be the angles of incidence and angle of refraction respectively. Then according to Snell’s law, a relationship exists between the refractive index of both materials given by,

$$\boxed{n_1 \sin \phi_1 = n_2 \sin \phi_2} \quad \dots (1.6.1)$$

- A refractive index model for Snell’s law is shown in Fig. 1.6.4.

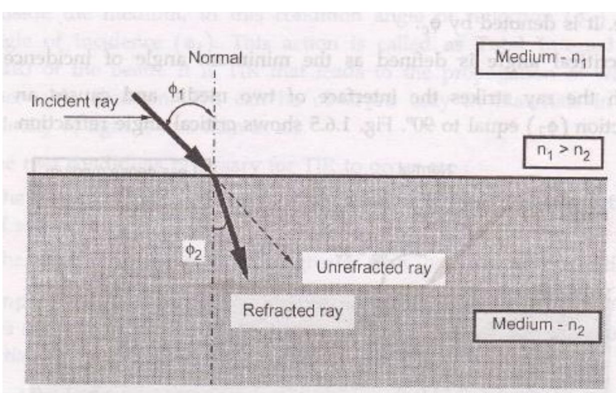

Fig. 1.6.4 Refractive model for Snell's law

- The refracted wave will be towards the normal when $n_1 < n_2$ and will away from it when $n_1 > n_2$.

Equation (1.6.1) can be written as,

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

- This equation shows that the ratio of refractive index of two mediums is inversely proportional to the refractive and incident angles.

As refractive index $n_1 = \frac{c}{v_1}$ and $n_2 = \frac{c}{v_2}$ substituting these values in equation (1.6.2)

$$\frac{c / v_1}{c / v_2} = \frac{\sin \phi_2}{\sin \phi_1}$$

$$\frac{v_2}{v_1} = \frac{\sin \phi_2}{\sin \phi_1}$$

Critical Angle

- When the angle of incidence (ϕ_1) is profressively increased, there will be progressive increase of refractive angle (ϕ_2). At some condition (ϕ_1) the refractive angle (ϕ_2) becomes 90o to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence (ϕ_1) at the point at which the refractive angle (ϕ_1) becomes 90^o is called the critical angle. It is denoted by ϕ_c.

- The **critical angle** is defined as the minimum angle of incidence (ϕ_1) at which the ray strikes the interface of two media and causes an agnle of refraction (ϕ_2) equal to 90^o. Fig 1.6.5 shows critical angle refraction.

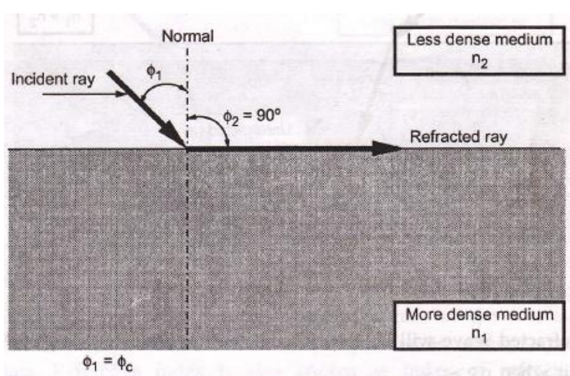

Fig. 1.6.5 Critical angle

Hence at critical angle $\phi_1 = \phi_c$ and $\phi_2 = 90^o$

Using Snell's law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90^o$$

∵ $\sin 90^o = 1$

Therefore, $\sin \phi_c = \frac{n_2}{n_1}$

$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)} \quad \ldots (1.6.3)$$

- The actual value of critical angle is dependent upon combination of materials present on each side of boundary.

Total Internal Refleciton (TIR)

- When the incident angle is increase dbeyond the critical angle, the light ray does not pass through the interface into the other medium. This gives the effect of mirror exist at the interface with no possibility of light escaping outside the medium. In this condition angle of reflection (ϕ_2) is equal to angle of incidence (ϕ_1). This action is called as **Total Internal Reflection (TIR)** of the beam. It is TIR that leads to the propagation of waves within fiber-cable medium. TIR can be observed only in materials in which the velocity of light is less than in air.

- The two conditions necessary for TIR to occur are :

1. The refractive index of first medium must be greater than the refractive index of second one.
2. The angle of incidence must be greater than (or equal to) the critical angle.

Example 1.6.1 : A light ray is incident from medium-1 to medium-2. If the refractive indices of medium-1 and medium-2 are 1.5 and 1.36 respectively then determine the angle of refraction for an angle of incidence of 30°.

Solution : Medium-1 n1 = 1.5

Medium-2 n2 = 1.36

Angle of incidence $\phi_1 = 30^o$.

$$\boxed{\text{Snell'slaw}: n_1 \sin \phi_1 = n_2 \sin \phi_2}$$

Angle of incident ϕ_2 = ?

$$1.5 \sin 30^o = 1.36 \sin \phi_2$$

$$\sin \phi_2 = \frac{1.5}{1.36} \sin 30^o$$

$$\sin \phi_2 = 0.55147$$

∴ $$\phi_2 = 33.46^o$$

Angle of refraction 33.46^o from normal. **… Ans.**

Example 1.6.2 : A light ray is incident from glass to air. Calculate the critical angle (ϕ_c).

Solution : Refractive index of glass n_1 = 1.50

Refrative indes of air n_2 = 1.00

$$\boxed{\text{Snell'slaw}: n_1 \sin \phi_1 = n_2 \sin \phi_2}$$

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

From definition of critical angle, ϕ_2 = 90^o and $\phi_1 = \phi_c$.

∴ $$\sin \phi_1 = \frac{n_2}{n_1} \sin 90^o$$

$$\sin \phi_c = \left(\frac{1.0}{1.5}\right) x\, 1 = 0.67$$

∴ $$\phi_c = \sin^{-1} 0.67$$

$$\phi_c = 41.81^o$$

Critical angle $\phi_c = \mathbf{41.81^o}$ **… Ans.**

Example 1.6.3 : Calculate the NA, acceptance angle and critical angle of the fiber having n_1 (Core refractive index) = 1.50 and refractive index of cladding = 1.45.

Soluiton : $n_1 = 1.50$, $n_2 = 1.45$

$$\Delta = \frac{(n_1 - n_2)}{(n_1)} = \frac{1.50 - 1.45}{1.50} = 0.033$$

Numerical aperture, $NA = n_1 \sqrt{2\Delta}$

$$NA = 1.50\sqrt{2 \text{ x } 0.033}$$

$$NA = 0.387$$

Acceptance angle $\phi_0 = \sin^{-1} NA$

$$\phi_0 = \sin^{-1} 0.387$$

$$\phi_0 = 22.78^o$$

Critical angle $\phi_c = \sin^{-1} \frac{n_2}{n_1}$

$$\phi_c = \sin^{-1} \frac{1.45}{1.50}$$

$$\phi_c = 75.2^o$$

Optical Fiver as Waveguide

- An optical fiber is a cylindrical dielectric waveguide capable of conveying electromagnetic waves at optical frequencies. The electromagnetic energy is in the form of the light and propagates along the axis of the fiber. The structural of the fiver determines the transmission characteristics.
- The propagation of light along the waveguide is decided by the modes of the waveguides, here mode means path. Each mode has distict pattern of electric and magnetic field distributions along the fiber length. Only few modes can satisfy the homogeneous wave equation in the fiver also the boundary condition a waveguide surfaces. When there is only one path for light to follow then it is called as single mode propagation. When there is more than one path then it is called as multimode propagation.

Single fiber structure

- A single fiber structure is shown in Fig. 1.6.6. It consists of a solid dielectric cylinder with radius 'a'. This cylinder is called as **core** of fiber. The core is surrounded by dielectric, called **cladding**. The index of refraction of core (glass fiber) is slightly greater than the index of refraction of cladding.

If refractive index of core (glass fiver) = n_1

and refractive index of cladding = n_2

then $n_1 > n_2$.

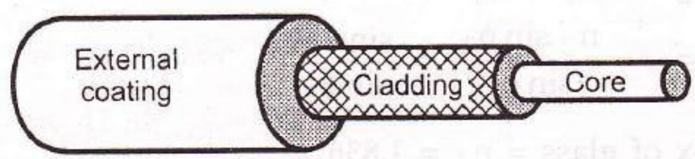

Fig. 1.6.6 Single optical fiber structure

Propagation in Optical Fiber

- To understand the general nature of light wave propagation in optical fiber. We first consider the construction of optical fiber. The innermost is the glass core of very thin diameter with a slight lower refractive index n2. The light wave can propagate along such a optical fiber. A single mode propagation is illustrated in Fig. 1.6.7 along with standard size of fiber.

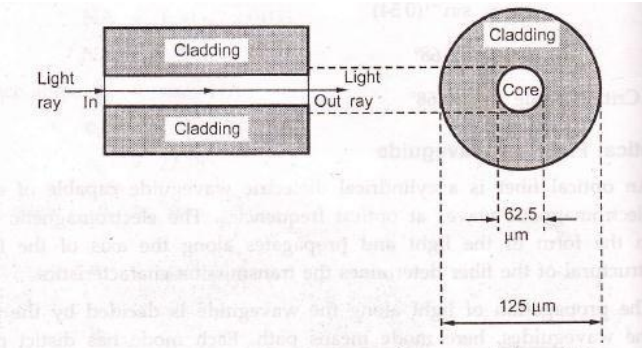

Fig. 1.6.7 Single mode propagation and standard size of fiber

- Single mode fibers are capable of carrying only one signal of a specific wavelength.
- In multimode propagation the light propagates along the fiber in zigzag fashion, provided it can undergo total internal reflection (TIR) at the core cladding boundaries.
- Total internal reflection at the fiber wall can occur only if two conditions are satisfied.

Condition 1:

The index of refraction of glass fiber must be slightly greater than the index of refraction of material surrounding the fiber (cladding).

If refractive index of glass fiber = n_1

and refractive index of cladding = n_2

then $n_1 > n_2$.

Condition 2 :

The angle of incidence (ϕ_1) of light ray must be greater than critical angle (ϕ_c).

- A light beam is focused at one end of cable. The light enters the fibers at different angles. Fig. 1.6.8 shows the conditions exist at the launching end of optic fiber. The light source is surrounded by air and the refractive index of air is $n_0 = 1$. Let the incident ray makes an angle ϕ_0 with fiber axis. The ray enters into glass fiber at point P making refracted angle ϕ_1 to the fiber axis, the ray is then propagated diagonally down the core and reflect from the core wall at point Q. When the light ray reflects off the inner surface, the angle of incidence is equal to the angle of reflection, which is greater than critical angle.
- In order for a ray of light to propagate down the cable, it must strike the core cladding interface at an angle that is greater than critical angle (ϕ_c).

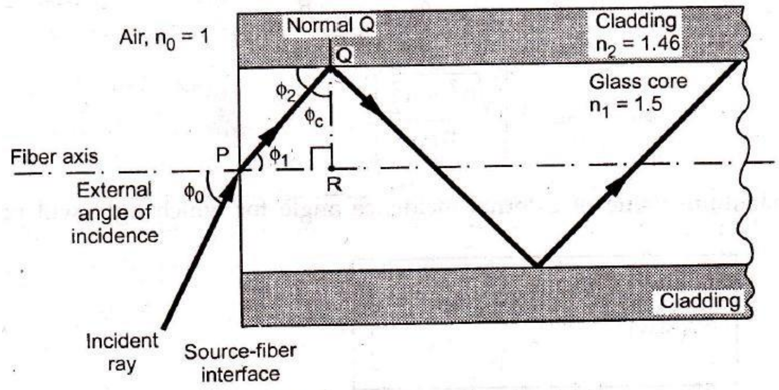

Fig. 1.6.8 Ray propagation by TIR

Acceptance Angle

Applying Snell's law to external incidence angle.

$$n_0 \sin \phi_0 = n_1 \sin \phi_1$$

But $\phi_1 = (90 - \phi_c)$

$$\sin \phi_1 = \text{sing } (90 - \phi_c) = \cos \phi_c$$

Substituting $\sin \phi_1$ in above equation.

$$n_0 \sin \phi_0 = n_1 \cos \phi_c$$

$$\sin \phi_c = \frac{n_1}{n_0} \cos \phi_c$$

Applying Pythagorean theorem to ΔPQR.

$$\cos \phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\sin \phi_0 = \frac{n_1}{n_0}\left[\frac{\sqrt{n_1^2 - n_2^2}}{n_1}\right]$$

$$\sin \phi_0 = \left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]$$

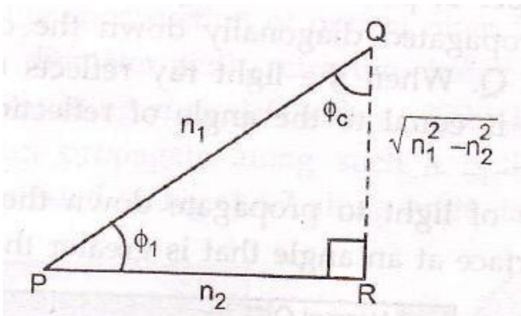

Fig. 1.6.9

$$\phi_0 = \sin^{-1}\left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]$$

The maximum value of external incidence angle for which light will propagate in the fiber.

$$\boxed{\phi_{0(max)} = \sin^{-1}\left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]}$$

When the light rays enters the fivers from an air medium $n_0 = 1$. Then above equation reduces to,

$$\phi_{0(max)} = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

The angle ϕ_0 is called as **acceptance angle** and $\phi_{0(max)}$ defines the maximum angle in which the light ray may incident on fiber to propagate down the fiber.

Acceptance Cone

- Rotating the acceptance angle $\phi_{0(max)}$ around the fiber axis, a cone shaped pattern is obtained, it is called as **acceptance cone** of the fiber input. Fig 1.6.10 shows formation of acceptance cone of a fiber cable.

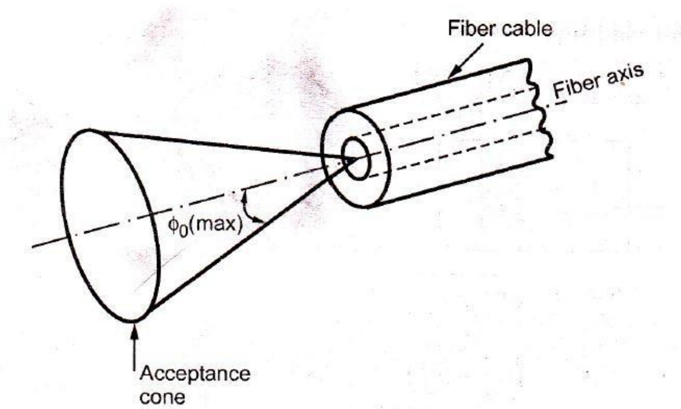

Fig. 1.6.10 Acceptance cone of a fiber cable

- The Cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber. The launching of light wave becomes easier for large acceptance come.
- The angle is measured from the axis of the positive cone so the total angle of convergence is actually twice the stated value.

Numerical Aperture (NA)

- The **numerical aperture** (NA) of a fiber is a figure of merit which represents its light gathering capability. Larger the numerical aperture, the greater the amount of light accepted by fiber. The acceptance angle also determines how much light is able to be enter the fiber and hence there is relation between the numerical aperture and the cone of acceptance.

Numerical aperture (NA) = sin $\phi_{0(\max)}$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

For air $n_o = 1$

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

$$\boxed{NA = \sqrt{n_{core}^2 - n_{cladding}^2}} \qquad \ldots (1.6.4)$$

Hence acceptance angle = $\sin^{-1}$ NA

By the formula of NA note that the numerical aperture is effectively dependent only on refractive indices of core and cladding material. NA is not a function of fiber dimension.

- The index difference (Δ) and the numerical aperture (NA) are related to the core and cladding indices:

$$\Delta = \frac{(n_1 - n_2)}{n_1} \quad (1.6.5\ (a))$$

$$\boxed{\Delta = \frac{NA^2}{2n_1^2}} \quad ...\ (1.6.5\ (b))$$

Also

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

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

$$\boxed{NA = n_1 (2\Delta)^{1/2}}$$

Example 1.6.5 : Calculate the numerical aperture and acceptance angle for a fiber cable of which $n_{core} = 1.5$ and $n_{cladding} = 1.48$. The launching takes place from air.

Solution :

$$\boxed{NA = \sqrt{n_{core}^2 - n_{cladding}^2}}$$

$$NA = \sqrt{1.5^2 - 1.48^2}$$

NA = **0.244** **…Ans.**

$$\boxed{\text{Acceptance angle} \sin^{-1}\sqrt{n_{core}^2 - n_{cladding}^2} = \sin^{-1} NA}$$

Acceptance angle = $\sin^{-1} 0.244$

ϕ_0 = **14.12º** **…Ans.**

Types of Rays

- If the rays are launched within core of acceptance can be successfully propagated along the fiber. But the exact path of the ray is determined by the position and angle of ray at which it strikes the core.
  There exists three different types of rays.
  i) Skew rays ii) Meridional rays iii) Axial rays.
- **The skew rays** does not pass through the center, as show in Fig. 1.6.11 (a). The skew rays reflects off from the core cladding boundaries and again bounces around the outside of the core. It takes somewhat similar shape of spiral of helical path.

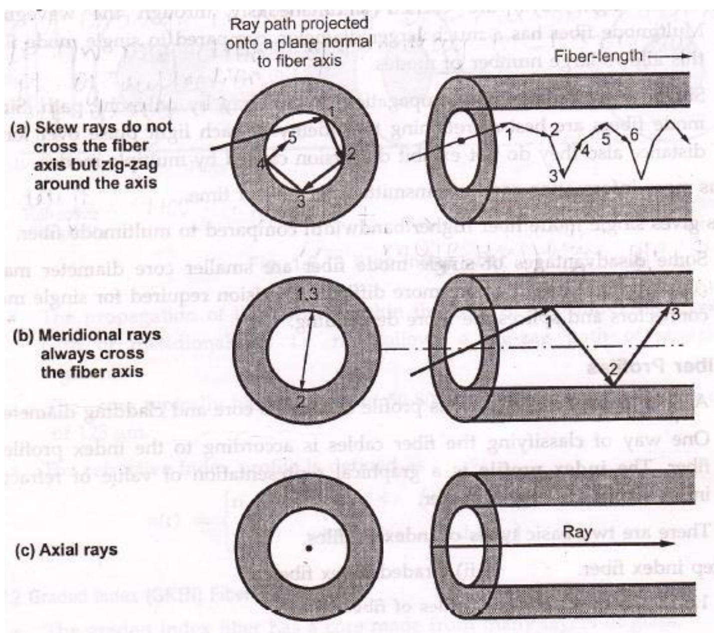

Fig. 1.6.11 Different ray propagation

- The **meridional** ray enters the core and passes through its axis. When the core surface is parallel, it will always be reflected to pass through the enter. The meridional ray is shown in fig. 1.6.11 (b).
- The **axial ray** travels along the axis of the fiber and stays at the axis all the time. It is shown in fig. 1.6.11 (c).

Modes of Fiber

- Fiber cables cal also be classified as per their mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called **modes** of transmission. The **mode** of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types.
  i) Single mode fiber ii) Multimode fiber.
- Multimode fiber was the first fiber type to be manufactured and commercialized. The term multimode simply refers to the fact that numerous modes (light rays) are carried simultaneously through the waveguide. Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.
- Single mode fiber allows propagation to light ray by only one path. Single mode fibers are best at retaining the fidelity of each light pulse over longer distance also they do not exhibit dispersion caused by multiple modes.

Thus more information can be transmitted per unit of time.

This gives single mode fiber higher bandwidth compared to multimode fiber.

- Some disadvantages of single mode fiber are smaller core diameter makes coupling light into the core more difficult. Precision required for single mode connectors and splices are more demanding.

Fiber Profiles

- A fiber is characterized by its profile and by its core and cladding diameters.
- One way of classifying the fiber cables is according to the index profile at fiber. The **index profile** is a graphical representation of value of refractive index across the core diameter.
- There are two basic types of index profiles.

i) Step index fiber. ii) Graded index fiber.

Fig. 1.6.12 shows the index profiles of fibers.

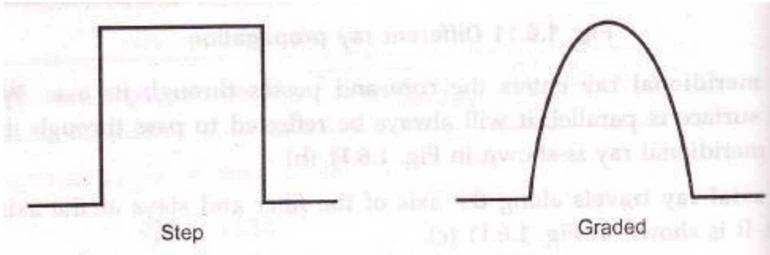

Fig. 1.6.12 Index profiles

Step Index (SI) Fiber

- The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2. The cladding refractive index (n_2) is less than the core refractive index (n_1). But there is an abrupt change in the refractive index at the core cladding interface. Refractive index profile of step indexed optical fiber is shown in Fig. 1.6.13. The refractive index is plotted on horizontal axis and radial distance from the core is plotted on vertical axis.

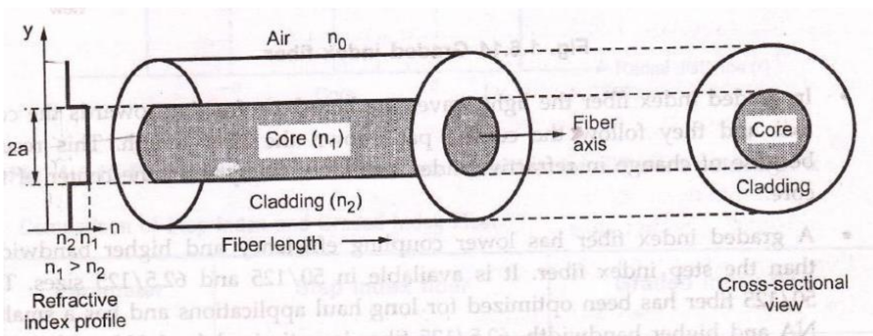

Fig. 1.6.13 Step index fiber

- The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight line segments.
  The core typically has diameter of 50-80 μm and the cladding has a diameter of 125 μm.
- The refractive index profile is defined as –

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

Graded Index (GRIN) Fiber

- The graded index fiber has a core made from many layers of glass.
- In the **graded index (GRIN)** fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. The refractive index profile across the core takes the parabolic nature. Fig. 1.6.14 shows refractive index profile of graded index fiber.

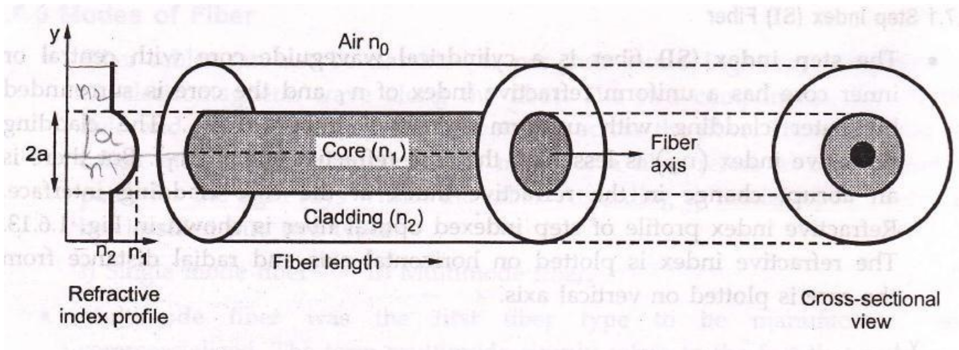

Fig. 1.6.14 Graded index fiber

- In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.
- A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber. It is available in 50/125 and 62.5/125 sizes. The 50/125 fiber has been optimized for long haul applications and has a smaller NA and higher bandwidth. 62.5/125 fiber is optimized for LAN applications which is costing 25% more than the 50/125 fiber cable.
- The refractive index variation in the core is giver by relationship

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) & \text{when } r < a \ (core) \\ n_1(1-2\Delta)^{\frac{1}{2}} \approx n_2 & when\ r \geq a \ (\text{cladding}) \end{cases}$$

where,

r = Radial distance from fiber axis

a = Core radius

n_1 = Refractive index of core

n_2 = Refractive index of cladding

α = Shape of index profile.

- Profile parameter α determines the characteristic refractive index profile of fiber core. The range of refractive index as variation of α is shown in Fig. 1.6.15.

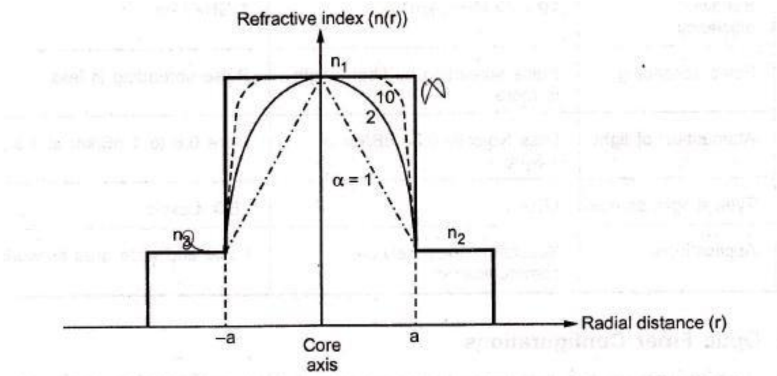

Fig. 1.6.15 Possible fiber refractive index profiles for different values of α

Comparison of Step Index and Graded Index Fiber

Sr. No.	Parameter	Step index fiber	Graded index fiber
1.	Data rate	Slow.	Higher
2.	Coupling efficiency	Coupling efficiency with fiber is higher.	Lower coupling efficiency.
3.	Ray path	By total internal reflection.	Light ray travels in oscillatory fashion.
4.	Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
5.	Numerical aperture	NA remains same.	Changes continuously with distance from fiber axis.
6.	Material used	Normally plastic or glass is preferred.	Only glass is preferred.
7.	Bandwidth efficiency	10 – 20 MHz/km	1 GHz/km
8.	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9.	Attenuation of light	Less typically 0.34 dB/km at 1.3 µm.	More 0.6 to 1 dB/km at 1.3 µm.

10.	Typical light source	LED.	LED, Lasers.
11.	Applications	Subscriber local network communication.	Local and wide area networks.

Optic Fiber Configurations

- Depending on the refractive index profile of fiber and modes of fiber there exist three types of optical fiber configurations. These optic-fiber configurations are -

  i) Single mode step index fiber.
  ii) Multimode step index fiber.
  iii) Multimode graded index fiber.

Single mode Step index Fiber

- In single mode step index fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light ray is propagated in the fiber through reflection. Typical core sizes are 2 to 15 µm. Single mode fiber is also known as fundamental or monomode fiber.

Fig. 1.6.16 shows single mode fiber.

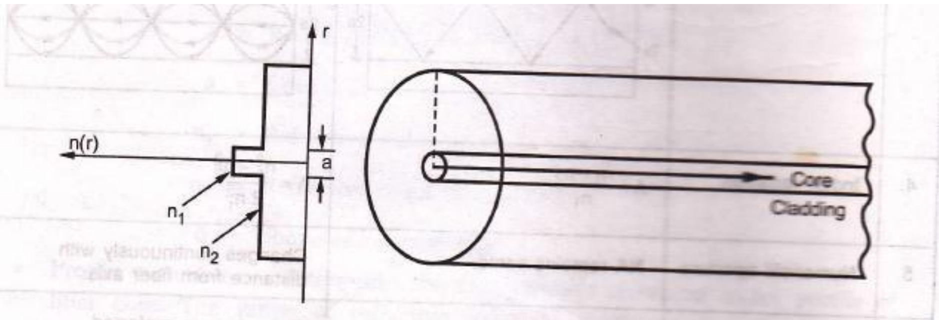

Fig. 1.6.16 The refractive index profile and ray transmission in single mode step index fiber

- Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. These are primarily developed for the 1300 nm window but they can be also be used effectively with time division multiplex (TDM) and wavelength division multiplex (WDM) systems operating in 1550 nm wavelength region.
- The core fiber of a single mode fiber is very narrow compared to the wavelength of light being used. Therefore, only a single path exists through the cable core through which light can travel. Usually, 20 percent of the light in a single mode cable actually

travels down the cladding and the effective diameter of the cable is a blend of single mode core and degree to which the cladding carries light. This is referred to as the 'mode field diameter', which is larger than physical diameter of the core depending on the refractive indices of the core and cladding.

- The disadvantage of this type of cable is that because of extremely small size interconnection of cables and interfacing with source is difficult. Another disadvantage of single mode fibers is that as the refractive index of glass decreases with optical wavelength, the light velocity will also be wavelength dependent. Thus the light from an optical transmitter will have definite spectral width.

Multimode step Index Fiber

- **Multimode step index fiber** is more widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 μm i.e. large aperture and allows more light to enter the cable. The light rays are propagated down the core in zig-zag manner. There are many many paths that a light ray may follow during the propagation.
- The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.

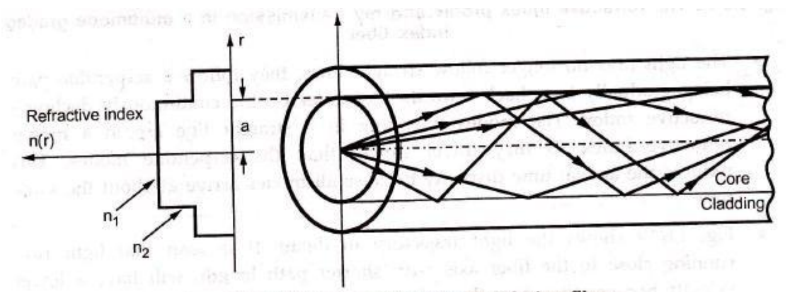

Fig. 1.6.17 TIR in multimode step index fiber

- Light rays passing through the fiber are continuously reflected off the glass cladding towards the centre of the core at different angles and lengths, limiting overall bandwidth.
- The disadvantage of multimode step index fibers is that the different optical lengths caused by various angles at which light is propagated relative to the core, causes the transmission bandwidth to be fairly small. Because of these limitations, multimode step index fiber is typically only used in applications requiring distances of less than 1 km.

Multimode Graded Index Fiber

- The core size of **multimode graded index fiber** cable is varying from 50 to 100 μm range. The light ray is propagated through the refraction. The light ray enters the fiber at many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication.

Fig 1.6.18 shows multimode graded index fiber.

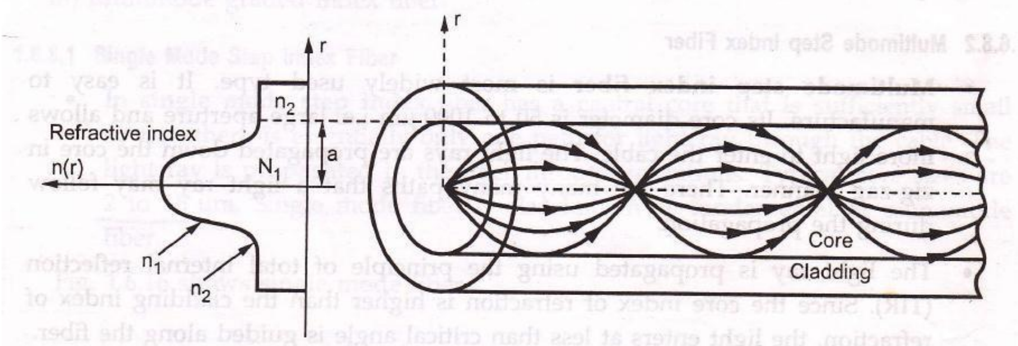

Fig. 1.6.18 The refractive index profile and ray transmission in a multimode graded index fiber

- The light rays no longer follow straight lines, they follow a serpentine path being gradually bent back towards the center by the continuously declining refractive index. The modes travelling in a straight line are in a higher refractive index so they travel slower than the serpentine modes. This reduces the arrival time disparity because all modes arrive at about the same time.
- Fig 1.6.19 shows the light trajectory in detail. It is seen that light rays running close to the fiber axis with shorter path length, will have a lower velocity because they pass through a region with a high refractive index.

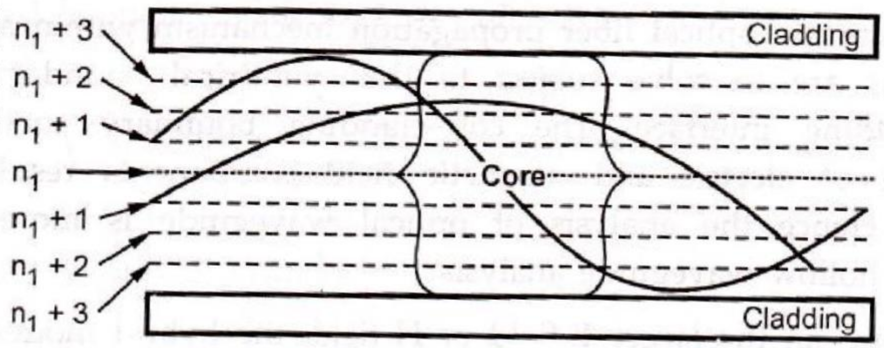

Fig. 1.6.19 Light trajectories in a graded index fiber

- Rays on core edges offers reduced refractive index, hence travel more faster than axial rays and cause the light components to take same amount of time to travel the length of fiber, thus minimizing dispersion losses. Each path at a different angle is termed as 'transmission mode' and the NA of graded index fiber is defined as the maximum value of acceptance angle at the fiber axis.
- Typical attenuation coefficients of graded index fibers at 850 nm are 2.5 to 3 dB/km, while at 1300 nm they are 1.0 to 1.5 dB/km.
- The main advantages of graded index fiber are:

1. Reduced refractive index at the centre of core.
2. Comparatively cheap to produce.

Standard fibers

Sr. No.	Fiber type	Cladding diameter (μm)	Core diameter (μm)	Δ	Applications
1.	Single mode (8/125)	125	8	0.1% to 0.2%	1. Long distance 2. High data rate
2.	Multimode (50/125)	125	50	1% to 2%	1. Short distance 2. Low data rate
3.	Multimode (62.5/125)	125	62.5	1% to 2%	LAN
4.	Multimode (100/140)	140	100	1% to 2%	LAN

Mode Theory for Cylindrical Waveguide

- To analyze the optical fiber propagation mechanism within a fiber, Maxwell equations are to solve subject to the cylindrical boundary conditions at core-cladding interface. The core-cladding boundary conditions lead to coupling of electric and magnetic field components resulting in hybrid modes. Hence the analysis of optical waveguide is more complex than metallic hollow waveguide analysis.
- Depending on the large E-field, the hybrid modes are HE or EH modes. The two lowest order does are HE_{11} and TE_{01}.

Overview of Modes

- The order states the number of field zeros across the guide. The electric fields are not completely confined within the core i.e. they do not go to zero at core-cladding interface and extends into the cladding. The low order mode confines the electric field near the axis of the fiber core and there is less penetration into the cladding. While the high order mode distribute the field towards the edge of the core fiber and penetrations into the cladding. Therefore cladding modes also appear resulting in power loss.
- In leaky modes the fields are confined partially in the fiber core attenuated as they propagate along the fiber length due to radiation and tunnel effect.
- Therefore in order to mode remain guided, the propagation factor β must satisfy the condition

$$\boxed{n_2 k < \beta < n_1 k}$$

where, n_1 = Refractive index of fiber core

n_2 = Refractive index of cladding

k = Propagation constant = $2\pi / \lambda$

- The cladding is used to prevent scattering loss that results from core material discontinuities. Cladding also improves the mechanical strength of fiber core and reduces surface contamination. Plastic cladding is commonly used. Materials used for fabrication of optical fibers are silicon dioxide (SiO_2), boric oxide-silica.

Summary of Key Modal Concepts

- Normalized frequency variable, V is defined as

$$\boxed{V = \frac{2\pi a(n_1^2 - n_2^2)^{1/2}}{\lambda}} \quad \ldots (1.7.1)$$

where, a = Core radius

λ = Free space wavelength

$$\boxed{V = \frac{2\pi a}{\lambda} NA}$$ Since $(n_1^2 - n_2^2)^{1/2}$ = NA ... (1.7.2)

- The total number of modes in a multimode fiber is given by

$$M = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

$$M = \frac{1}{2}\left[\frac{2\pi\ a}{\lambda}\ NA\right]^2 = \frac{[V]^2}{2}$$

$$M = \frac{1}{2}\left[\frac{\pi d}{\lambda}.NA\right]^2$$ 'd' is core diameter ... (17.3)

Example 1.7.1 : Calculate the number of modes of an optical fiber having diameter of 50 μm, n_1 = 1.48, n_2 = 1.46 and λ = 0.82 μm.

Solution : d = 50 μm

n_1 = 1.48

n_2 = 1.46

λ = 0.82 μm

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

NA = $(1.48^2 – 1.46^2)^{1/2}$

NA = 0.243

Number of modes are given by,

$$M = \frac{1}{2}\left[\frac{\pi\, d}{\lambda}.NA\right]^2$$

$$M = \frac{1}{2}\left[\frac{\pi\,(50\,X\,10^{-6})}{0.82\,X\,10^{-6}} X\,0.243\right]^2$$

M = 1083 …Ans.

Example 1.7.2 : A fiber has normalized frequency V = 26.6 and the operating wavelength is 1300nm. If the radius of the fiber core is 25 μm. Compute the numerical aperture.

Solution : V = 26.6

λ = 1300 nm = 1300 X 10^{-9} m

a = 25 μm = 25 X 10^{-6} m

$$\boxed{V = \frac{2\pi a}{\lambda} NA}$$

$$NA = V.\frac{\lambda}{2\pi a}$$

$$NA = 26.6\ \frac{1300\ X\ 10^{-9}}{2\pi\ X\ 25\ X\ 10^{-6}}$$

NA = **0.220** **… Ans.**

Example 1.7.3 : A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5 % is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate the normalized frequency for the fiber and number of guided modes.

[July/Aug.-2008, 6 Marks]

Solution : Given : MM step index fiber, 2 a = 80 μm

∴ Core radians a = 40 μm

Relative index difference, Δ = 1.5% = 0.015

Wavelength, λ = 0.85μm

Core refractive index, n1 = 1.48

Normalized frequency, V = ?

Number of modes, M = ?

Numerical aperture $\boxed{NA = n_1 (2\Delta)^{1/2}}$

$= 1.48 \, (2 \text{ X } 0.015)^{1/2}$

$= 0.2563$

Normalized frequency is given by,

$$\boxed{V = \frac{2\pi a}{\lambda} NA}$$

$$V = \frac{2\pi \text{ X } 40}{0.85} \text{ x } 0.2563$$

V = 75.78 **… Ans.**

Number of modes is given by,

$$\boxed{M = \frac{V^2}{2}}$$

$M = \frac{(75.78)^2}{2} = \mathbf{2871.50}$ **…Ans.**

Example 1.7.4 : A step index multimode fiber with a numerical aperture of a 0.20 supports approximately 1000 modes at an 850 nm wavelength.

i) What is the diameter of its core?
ii) How many modes does the fiber support at 1320 nm?
iii) How many modes does the fiber support at 1550 nm? **[Jan./Feb.-2007, 10 Marks]**

Solution : i) Number of modes is given by,

$$\boxed{M = \frac{1}{2}\left[\frac{\pi\, a}{\lambda}.NA\right]^2}$$

$$1000 = \frac{1}{2}\left[\frac{\pi\, a}{850\ X\ 10^{-9}}\ X\ 0.20\right]^2$$

$$2000 = 5.464\ X\ a^2$$

a = **60.49 µm** **… Ans.**

ii)

$$M = \frac{1}{2}\left[\frac{\pi\ X\ 60.49\ X\ 10^{-6}}{1320\ X\ 10^{-9}}\ X\ 0.20\right]^2$$

M = $(14.39)^2$ = **207.07** **… Ans.**

iii)

$$M = \frac{1}{2}\left[\frac{\pi\ X\ 6.49\ X\ 10^{-6}}{1320\ X\ 10^{-9}}\ X\ 0.20\right]^2$$ **… Ans.**

M = **300.63** **… Ans.**

Wave Propagation

Maxwell's Equations

Maxwell's equation for non-conducting medium:

∇ X E = - ∂B /

∇ X H = - ∂D /

∇. D = 0

∇. B   0

where,

E and H are electric and magnetic field vectors.

D and B are corresponding flux densities.

- The relation between flux densities and filed vectors:

$D = \varepsilon_0 E + P$

$B = \mu_0 H + M$

where,

ε_0 is vacuum permittivity.

μ_0 is vacuum permeability.

P is induced electric polarization.

M is induced magnetic polarization (M = 0, for non-magnetic silica glass)

- P and E are related by:

$$P(r, t) = \varepsilon_0 \int_{-\infty}^{\infty} X\,(r, t - t')E\,(r, t')dt'$$

Where,

X is linear susceptibility.

- Wave equation:

$$\nabla \times \nabla \times E = \frac{-1}{c^2}\frac{\partial^2 E}{\partial E^2} - \mu_0 \frac{\partial^2 P}{\partial t^2}$$

Fourier transform of E (r, t)

$$\tilde{E}\,(r, \omega) = \int_{-\infty}^{\infty} E\,(r, t)e^{i\omega t}\,dt$$

$$\nabla \times \nabla \times \tilde{E} = -\varepsilon\,(r, \omega)\frac{\omega^2}{c^2}\tilde{E}$$

where,

$$\varepsilon = \left(n + \frac{i\alpha c}{2\omega}\right)^2$$

n is refractive index.

α is absorption coefficient.

$$n = \sqrt{(1 + R_e\chi)}$$

$$\alpha = \left(\frac{\omega}{nc}\right) I_m\, \chi$$

- Both n and α are frequency dependent. The frequency dependence of n is called as chromatic dispersion or material dispersion.
- For step index fiber,

$$\nabla \times \nabla \times \tilde{E} = \nabla (\nabla . \tilde{E}) - \nabla^2 . \tilde{E} = -\nabla^2 \tilde{E}$$

Fiber Modes

Optical mode : An optical mode is a specific solution of the wave equation that satisfies boundary conditions. There are three types of fiber modes.

a) Guided modes
b) Leaky modes
c) Radiation modes

- For fiber optic communication system guided mode is sued for signal transmission.
  Considering a step index fiber with core radius ‘a’.
  The cylindrical co-ordinates ρ, ϕ and can be used to represent boundary conditions.

$$\frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho} . \frac{\partial E_z}{\partial \rho} + \frac{1}{\rho^2} . \frac{\partial^2 E_z}{\partial \phi^2} + \frac{\partial^2 E_z}{\partial z^2} + n^2 k_0^2 E_z = 0$$

- The refractive index ‘n’ has values

$$n = \begin{cases} n_1; & \rho \leq a \\ n_2; & \rho > a \end{cases}$$

- The general solutions for boundary condition of optical field under guided mode is infinite at $\rho = 0$ and decay to zero at $\rho = \infty$. Using Maxwell’s equation in the core region.

$$E_\rho = \frac{i}{p^2}\left(\beta \frac{\partial E_z}{\partial \rho} + \mu_0 \frac{\omega}{\rho} . \frac{\partial H_z}{\partial \phi}\right)$$

$$E_\phi = \frac{i}{p^2}\left(\frac{\beta}{\rho}\frac{\partial E_z}{\partial \phi} - \mu_0 \omega . \frac{\partial H_z}{\partial \rho}\right)$$

$$H_\rho = \frac{i}{p^2}\left(\beta \frac{\partial E_z}{\partial \rho} + \varepsilon_0 n^2 \frac{\omega}{\rho}\frac{\partial H_z}{\partial \rho}\right)$$

$$H_\phi = \frac{i}{p^2}\left(\frac{\beta}{\rho}\frac{\partial E_z}{\partial \phi} + \varepsilon_0 n^2 \omega \frac{\partial H_z}{\partial \rho}\right)$$

- The **cut-off condition** is defined as –

$$V = k_0 a \sqrt{(n_1^2 - n_2^2)}$$

$$\mathrm{V} = \left(\frac{2\pi}{\lambda}\right) a\, n_1 \sqrt{2\Delta}$$

It is also called as **normalized frequency**.

Graded Index Fiber Structure

- The Refractive index of graded index fiber decreases continuously towards its radius from the fiber axis and that for cladding is constant.
- The refractive index variation in the core is usually designed by using power law relationship.

$$\mathrm{n(r)} = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{1}{2}}, & when\ 0 \le r \le a \\ n_1(1-2\Delta)^{\frac{1}{2}} \approx n_1(1-\Delta) = n_2, & when\ r \ge a \end{cases} \qquad \textbf{... (1.7.4)}$$

Where, r = Radial distance from fiber axis

a = Core radius

n_1 = Refractive index core

n_2 Refractive index of cladding and

α = The shape of the index profile

- For graded index fiber, the index difference Δ is given by,

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

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

- In graded index fiber the incident light will propagate when local numerical aperture at distance r from axis, NA® is axial numerical aperture NA(0). The local numerical aperture is given as,

$$\mathrm{NA(r)} = \begin{cases} [n^2(r) - n_2^2]^{\frac{1}{2}} \approx NA(0)\sqrt{1 - \left(\frac{r}{a}\right)^{\alpha}}, & for\ r \leq a \\ 0, & for\ r > a \end{cases}$$

- The axial numerical aperture NA(0) is given as,

$$\mathrm{NA(0)} = [\mathrm{n}^2(0) - \mathrm{n}_2^2]^{1/2}$$

$$\mathrm{NA(0)} = [\mathrm{n}_1^2 - \mathrm{n}_2^2]^{1/2}$$

$$\mathrm{NA(0)} = \mathrm{n}_1\sqrt{2\Delta} \approx \mathrm{n}_1(2\Delta)^{1/2}$$

Hence Na for graded index decreases to zero as it moves from fiber axis to core-cladding boundary.

- The variation of NA for different values of α is shown in Fig. 1.7.1.

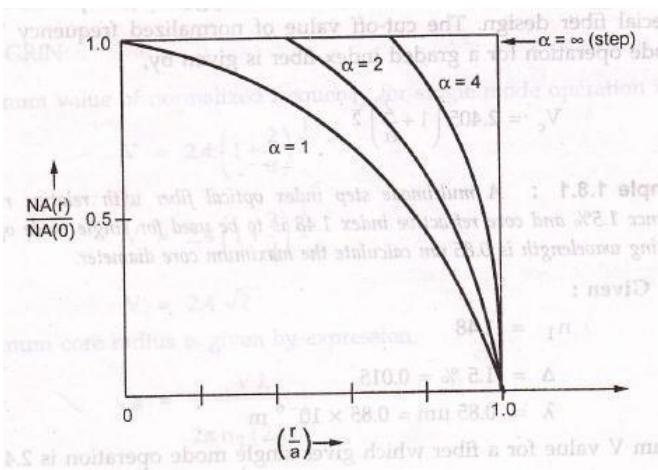

Fig. 1.7.1 Variation of NA for different α

- The number of modes for graded index fiber in given as,

$$\boxed{M = \frac{\alpha}{\alpha + 2} a^2 k^2 n_1^2 \Delta} \qquad \dots (1.7.6)$$

Single Mode Fibers

- Propagation in single mode fiber is advantageous because signal dispersion due to delay differences amongst various modes in multimode is avoided. Multimode step index fibers cannot be used for single mode propagation due to difficulties in maintaining single mode operation. Therefore for the transmission of single mode the fiber is designed to allow propagation in one mode only, while all other modes are attenuated by leakage or absorption.
- For single mode operation, only fundamental LP_{01} mode many exist. The single mode propagation of LP_{01} mode in step index fibers is possible over the range.

$0 \leq V < 2405$

- The normalized frequency for the fiber can be adjusted within the range by reducing core radius and refractive index difference < 1%. In order to obtain single mode operation with maximum V number (2.4), the single mode fiber must have smaller core diameter than the equivalent multimode step index fiber. But smaller core diameter has problem of launching light into the fiber, jointing fibers and reduced relative index difference.
- Graded index fibers can also be sued for single mode operation with some special fiber design. The cut-off value of normalized frequency Vc in single mode operation for a graded index fiber is given by,

$$V_c = 2.405\left(1 + \frac{2}{\propto}\right)^{\frac{1}{2}}$$

Example 1.8.1 : A multimode step index optical fiber with relative refractive index difference 1.5% and core refractive index 1.48 is to be used for single mode operation. If the operating wavelength is 0.85μm calculate the maximum core diameter.

Solution : Given :

$n_1 = 1.48$

$\Delta = 1.5\ \% = 0.015$

$\lambda = 0.85\ \mu m = 0.85 \times 10^{-6}$ m

Maximum V value for a fiber which gives single mode operations is 2.4.

Normalized frequency (V number) and core diameter is related by expression,

$$V = \frac{2\pi}{\lambda} a\ (NA)$$

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

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

$$a = \frac{2.4 \times (0.85 \times 10^{-6})}{2\pi \times (1.48) \times (0.03)^{\frac{1}{2}}}$$

a = **1.3 µm** **… Ans.**

Maximum core diameter for single mode operation is 2.6 µm.

Example 1.8.2 : A GRIN fiber with parabolic refractive index profile core has a refractive index at the core axis of 1.5 and relative index difference at 1%. Calculate maximum possible core diameter that allows single mode operations at $\lambda = 1.3\ \mu m$.

Solution : Given :

$$n_1 = 1.5$$

$$\Delta = 1\ \% = 0.01$$

$$\lambda = 1.3\ \mu m = 1.3 \times 10^{-6} m$$

for a GRIN

Maximum value of normalized frequency for single mode operation is given by,

$$V = 2.4 \left(1 + \frac{2}{\alpha}\right)^{\frac{1}{2}}$$

$$V = 2.4\left(1 + \frac{2}{2}\right)^{\frac{1}{2}}$$

$$V = 2.4\sqrt{2}$$

Maximum core radius is given by expression,

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

$$a = \frac{24\sqrt{2} \text{ x } 1.3 \text{ x } 10^{-6}}{2\pi \text{ x } 1.5 \text{ x } (0.02)^{\frac{1}{2}}}$$

a = 3.3 μm **… Ans.**

∴ Maximum core diameter which allows single mode operation is 6.6 μm.

Cut-off Wavelength

- One important transmission parameter for single mode fiber us cut-off wavelength for the first higher order mode as it distinguishes the single mode and multim0de regions.
- The effective cut-off wavelength λ_c is defined as the largest wavelength at which higher order $(L_{P_{11}})$ mode power relative to the fundamental mode $(L_{P_{01}})$ power is reduced to 0.1 dB. The range of cut-off wavelength recommended to avoid modal noise and dispersion problems is : 1100 to 1280 nm (1.1 to 1.28μm) for single mode fiber at 1.3 μm.
- The cut-off wavelength λ_c can be computed from expression of normalized frequency.

$$V = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{\frac{1}{2}} \Rightarrow \lambda = \frac{2\pi a n_1}{V}(2\Delta)^{\frac{1}{2}} \qquad \text{…. (1.8.1)}$$

∴

$$\lambda = \frac{2\pi a n_1}{V}(2\Delta)^{\frac{1}{2}} \qquad \text{…. (1.8.2)}$$

where,

V_c is cut-off normalized frequency.

- λ_c is the wavelength above which a particular fiber becomes single moded. For same fiber dividing λ_c by λ we get the relation as:

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

$$\lambda = \frac{v\lambda}{v_C} \qquad \text{… (1.8.3)}$$

But for step index fiver $V_c = 2.405$ then

$$\lambda_c = \frac{v\lambda}{2.405} \qquad \text{… (1.8.4)}$$

Example 1.8.3 : Estimate cut-off wavelength for step index fiber in single mode operation. The core refractive index is 1.46 and core radius is 4.5 μm. The relative index difference is 0.25 %.

Solutions : Given :

$n_1 = 1.46$

$a = 4.5$ μm

$\Delta = 0.25\ \% = 0.0025$

Cut-off wavelength is given by,

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{\frac{1}{2}}}{V_c}$$

For cut-off wavelength, $V_c = 2.405$

$$\lambda_c = \frac{2\pi \text{ x } 4.5 \text{ x } 1.46\ (0.005)^{\frac{1}{2}}}{2.405}$$

$$\lambda_c = 1.214\ \mu\text{m}$$

… Ans.

Mode Field Diameter and Spot Size

- The mode filed diameter is fundamental parameter of a single mode fiber. This parameter is determined from mode field distributions of fundamental LP_{01} mode.
- In step index and graded single mode fibers, the field amplitude distribution is approximated by Gaussian distribution. The **mode Field diameter** (MFD) is distance between opposite 1/e – 0.37 times the near field strength)amplitude) and power is $1/e^2$ = 0.135 times.
- In single mode fiber for fundamental mode, on field amplitude distribution the mode filed diameter is shown in fig. 1.8.1.

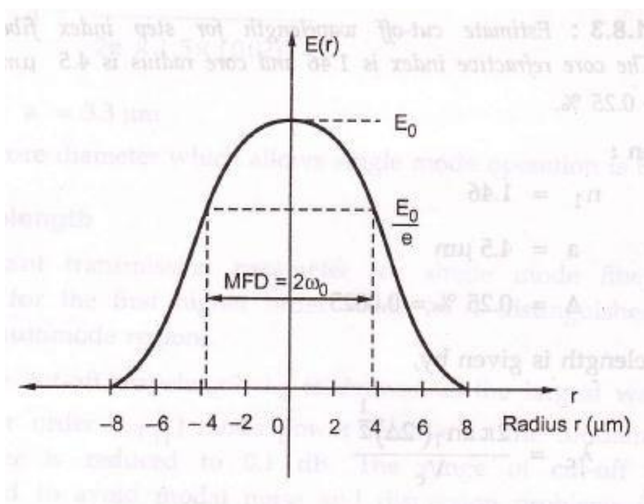

Fig. 1.8.1 Mode field diameter

- The spot size ω_0 is gives as –

$$\omega_0 = \frac{\text{MFD}}{2}$$

$$\text{MFD} = 2\,\omega_0$$

The parameter takes into account the wavelength dependent filed penetration into the cladding. Fig. 1.8.2 shows mode field diameters variation with λ.

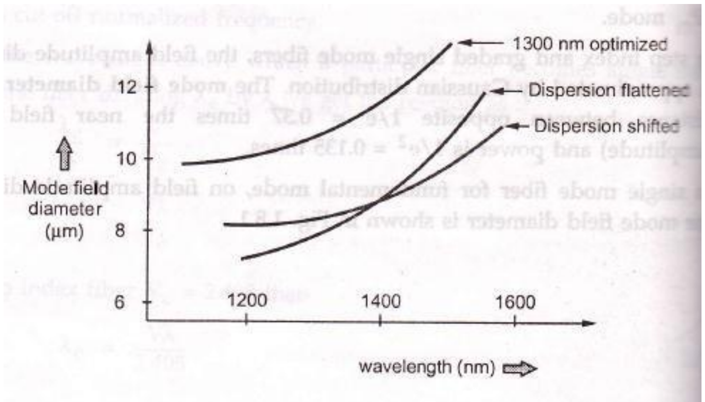

Fig. 1.8.2 Mode field diameter variations

Fiber Materials

Requirements of Fiber Optic Material

1. The material must be transparent for efficient transmission of light.
2. It must be possible to draw long thin fibers from the material.
3. Fiber material must be compatible with the cladding material.

Glass and plastics fulfills these requirements.

- Most fiber consists of silica (SiO_2) or silicate. Various types of high loss and low loss glass fibers are available to suit the requirements. Plastic fibers are not popular because of high attenuation they have better mechanical strength.

Glass Fibers

- Glass is made by fusing mixtures of metal oxides having refractive index of 1.458 at 850 nm. For changing the refractive index different oxides such as B_2O_3, GeO_2 and P_2O_5 are added as dopants. Fig. 1.8.3 shows variation of refractive index with doping concentration.

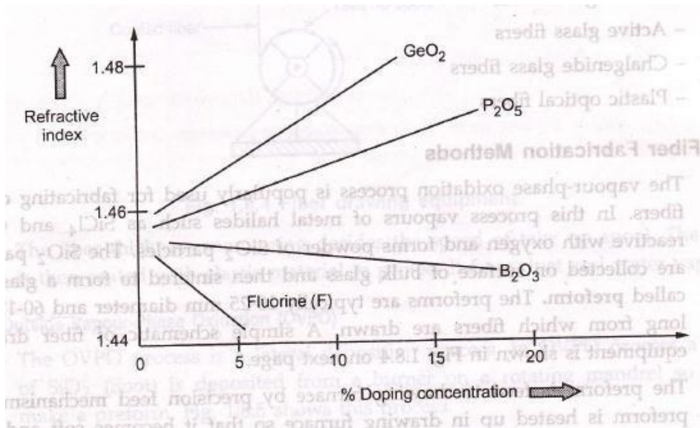

Fig. 1.8.3 Variation of refractive index with doping concentration

- Fig 1.8.3 shows addition of dopants $Ge0_2$ and P_2O_5 increases refractive index, while dopants Fluorine (F) and B_2O_3 decreases refractive index. One important criteria is that the refractive index of core is greater than that of the cladding, hence some important

Composition	Core	Cladding
1	$GeO_2 – SiO_2$	SiO_2
2	$P_2O_5 – SiO_2$	SiO_2
3	SiO_2	$B_2O_3 – SiO_2$
4	$GeO_2 – B_2O_3 – SiO_2$	$B_2O_3 – SiO_2$

compositions are used such as

- The principal raw material for silica is sand and glass. The fiber composed of pure silica is called as silica glass. The desirable properties of silica glass are :-
  - Resistance to deformation even at high temperature.
  - Resistance to breakage from thermal shocks (low thermal expansion).
  - Good chemical durability.
  - Better transparency.
- Other types of glass fibers are :
  - Halide glass fibers
  - Active glass fibers
  - Chalgenide glass fibers
  - Plastic optical fibers

Fiber Fabrication Methods

- The vapor-phase oxidation process is popularly used for fabricating optical fibers. In this process vapours of metal halides such as $SiCl_4$ and $Gecl_4$ reactive with oxygen and forms powder of SiO_2 particles. The SiO_2 particles are collected on surface of bulk glass and then sintered to form a glass rod called **Preform**. The preforms are typically 10-25 mm diameter and 60-120 cm long from which fibers are drawn. A simple schematic of fiber drawing equipment is shown in Fig. 1.8.4 on next page.
- The preform is feed to drawing furnace by precision feed mechanism. The preform is heated up in drawing furnace so that it becomes soft and fiber can be drawn easily.

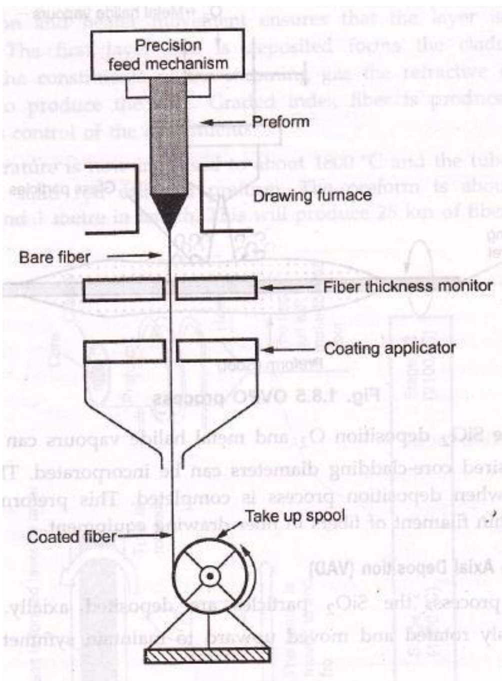

Fig. 1.8.4 Fiber drawing equipment

- The fiber thickness monitoring decides the speed of take up spool. The fiber is then coated with elastic material to protect it from dust and water vapour.

Outside Vapour-Phase Oxidation (OVPO)

- The OVPO process is a lateral deposition process. In OVPO process a layer of SiO_2 (Soot) is deposited from a burner on a rotating mandrel so as to make a perform. Fig, 1.8.5 shows this process.

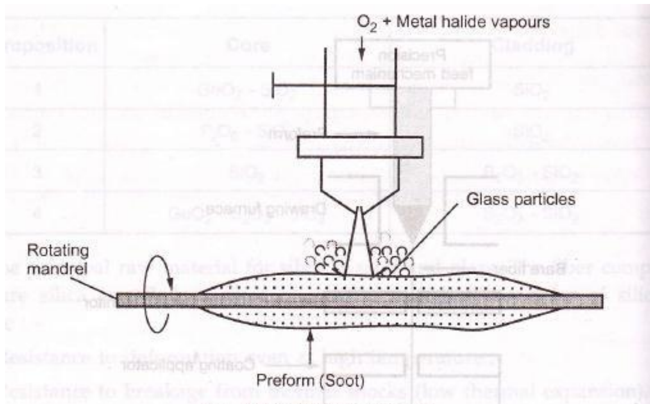

Fig. 1.8.5 OVPO process

- During the SiO_2 deposition O_2 and metal halide vapours can be controlled so the desired core-cladding diameters can be incorporated. The mandrel is removed when deposition process is completed, This preform is used for drawing thin filament of fibers in fiber drawing equipment.

Vapour-Phase Axial Deposition (VAD)

- In VADprocess, the SiO2 particles are deposited axially. The rod is continuously rotated and moved upward to maintain symmetry of particle deposition.
- The advantages of VAD process are
  - Both step and graded index fibers are possible to fabricate in multimode and single mode.
  - The preforms does not have the central hole.
  - The performs can be fabricated in continuous length.
  - Clean environment can be maintained.

Modified Chemical Vapour Deposition (MCVD)

- The MCVD process involves depositing ultra fine, vapourized raw materials into a pre-made silica tube. A hollow silica tube is heated to about 1500 ^{o}C and a mixture of oxygen and metal halide gases is passed through it. A chemical reaction occurs within the gas and glass '500t' is formed and deposited on the inner side of the tube. The soot that develops from this deposition is consolidated by heating. The tube is rotated while the heater is moved to and along the tube and the soot forms a thin layer of silica glass. The rotation and heater movement ensures that the layer is of constant thickness. The first layer that is deposited forms the cladding and by changing the constituents of the incoming gas the refractive index can be modified to produce the core. Graded index fiber is produced by careful continuous control of the constituents.

- The temperature is now increased to about 1800 ^{o}C and the tube is collapsed to form a solid rod called a preform. The preform is about 25 mm in diameter and 1 metre in length. This will produce 25 km of fiber.

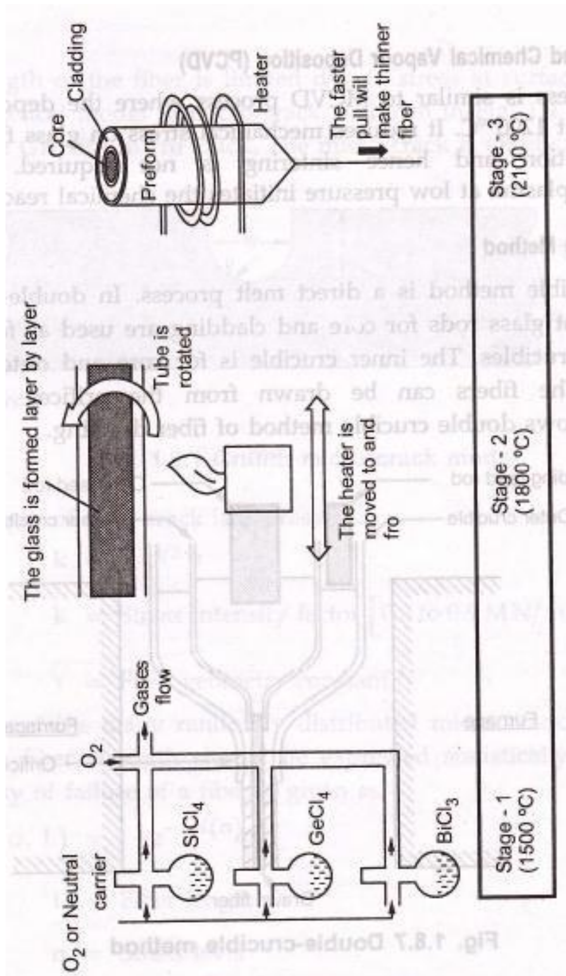

Fig. 1.8.6 MCVD process

- The preform is placed at a height called a pulling tower and its temperature is increased to about 2100 ^{o}C. To prevent contamination, the atmosphere is kept dry and clean. The fiber is then pulled as a fine strand from the bottom, the core and cladding flowing towards the pulling point. Laser gauges continually monitor the thickness of the fiber and automatically adjust the pilling rate to maintain required thickness. After sufficient cooling the primary buffer is applied and the fiber is drummed.
- Fig. 1.8.6 (Refer Fig. 1.8.6 on previous page) shows the overall MCVD process.

Plasma-Activated Chemical Vapour Deposition (PCVD)

- PCVD process is similar to MCVD process where the deposition occurs on silica tube at 1200 ^{o}C. It reduces mechanical stress on glass films. There is no soot formation and hence sintering is not required. Non-isothermal microwave plasma at low pressure initiates the chemical reaction.

Double-Crucible Method

- Double-crucible method is a direct melt process. In double-crucible method two different glass rods for core and Cladding are used as feedstock for two concentric crucibles. The inner crucible is for core and outer crucible is for cladding. The fibers can be drawn from the orifices in the crucible. Fig. 1.8.7 shows double crucible method of fiber drawing.

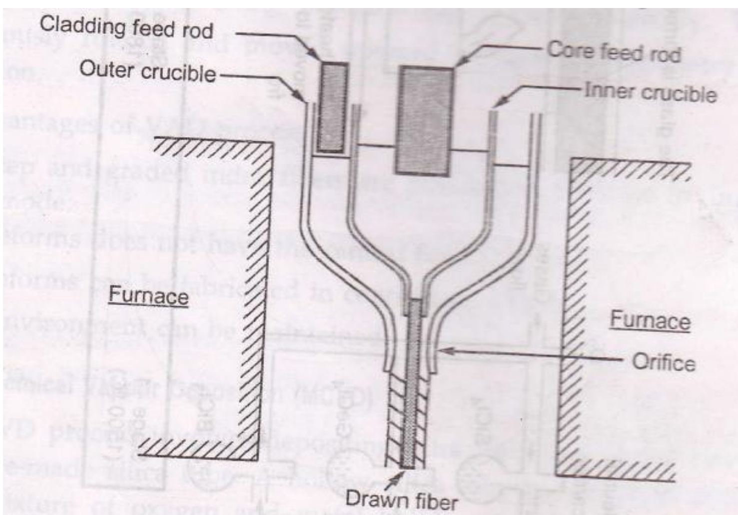

Fig. 1.8.7 Double-crucible method

Major advantages of double crucible method is that it is a continuous production process.

Mechanical Properties of Fibers

- The mechanical properties of fibers are equally important as that of transmission properties. The fibers must be able to sustain stresses and strains exerted during the cabling process.

Two basic mechanical properties of glass fibers are identified.

1. Strength
2. Static fatigued

1. Strength

- The strength of the fiber is limited due to stress at surfaces or micro cracks. A hypothetical model of micro crack is shown in Fig. 1.9.1. This is popularly known as Griffith micro crack. The micro crack is elliptical shaped.

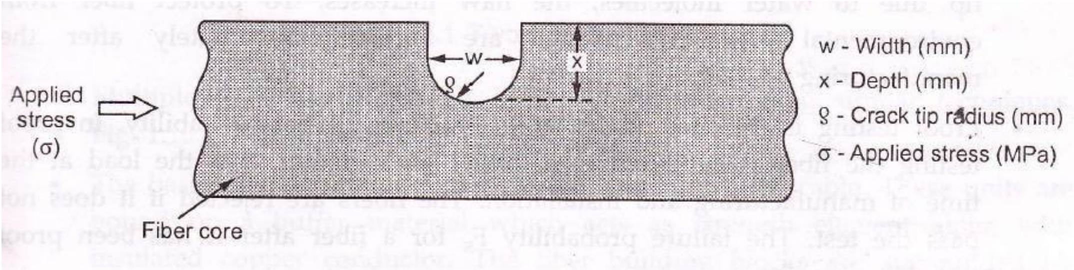

Fig. 1.9.1 Griffith micro crack model

- The strength of fiber crack is expressed as,

$$k = Y\, x1/2\, \sigma$$

where, k = Stress intensity factor [0.6 to 0.9 MN/$m^{3/2}$]

Y = Flaw geometry constant

- A fiber contains many randomly distributed micro cracks of different sizes. Therefore fiber strength should be expressed statistically. The commutative probability of failure of a fiber is given as,

$$F(\sigma, L) = 1 - e^{-LN(\sigma)}$$

where, L = Fiber length

σ = Stress level

N(σ) = Total cracks per unit length

- The expression for N(σ) is given by Weibull

$$N(\sigma) = \frac{1}{L_0}\left(\frac{\sigma}{\sigma_0}\right)^m$$

where L_0, σ_0 and m are constant relating to initial inert strength distribution. The Weibull expression is given by

2. Static fatigue

- The static fatigue is the process of slowly growing micro cracks (flaws) due to humid conditions and tensile stress. There is possibility of fiber failure due to growing micro crack. Also because of chemical erosion at the flaw tip due to water molecules, the flaw increases. To protect fiber from environmental erosion, coatings are applied immediately after the manufacturing of fiber.
- Proof testing is the method for high assurance of fiber reliability. In proof testing the fiber is subjected to a tensile load greater than the load at the time of manufacturing and installation. The fibers are rejected if it does not pass the test. The failure probability F_s for a fiber after it has been proof tested is given as,

$$F_s = 1- e^{-L(N_S - N_P)}$$

Fiber Optic Cables

- The fiber optic cable are to be used under variety of situations such as underground, outdoor poles or submerged under water. The structure of cable depends on the situation where it is to be used, but the basic cable design principles remains same.
- Mechanical property of cable is one of the important factor for using any specific cable. Maximum allowable axial load on cable decides the length of the cable be reliably installed.
- Also the fiber cables must be able to absorb energy from impact loads. The outer sheath must be designed to protect glass fibers from impact loads and from corrosive environmental elements.

Fiber Arrangements

- Several arrangements of fiber cables are done to use it for different applications. The most basic form is two fiber cable design. Fig. 1.10.1 shows basic two fiber cable design. It is also known as basic building block of fiber cable.
- For providing strength to the core several coatings of different materials are applied as shown in fig 1.10.1.

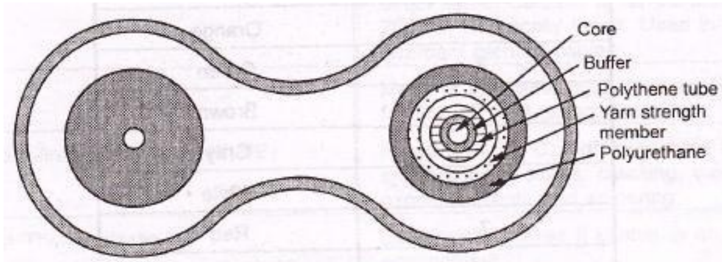

Fig. 1.10.1 Two fiber cable design

- Multiple fiber cable can be combined together using similar techniques. Fig. 1.10.2 shows commonly used six fiber cable.
- The basic fiber building blocks are used to form large cable. These units are bound on a buffer material which acts as strength element along with insulated copper conductor. The fiber building blocks are surrounded by paper tape, PVC jacket, yarn and outer sheath.

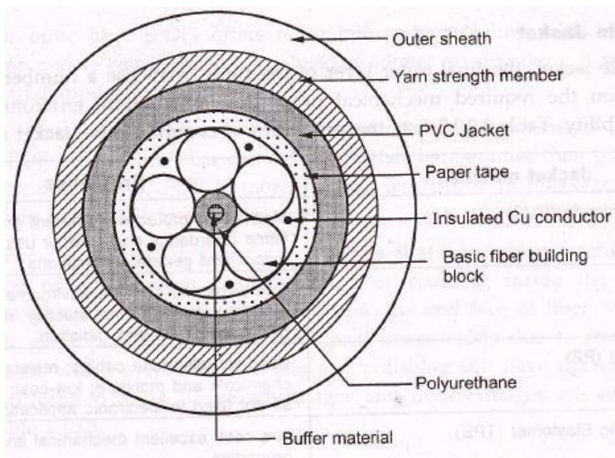

Fig. 1.10.2 Six fiber cable

Fiber Optic Cable Ducts

- Number of cores are bundled in plastic ducts. To ease identification, individual fibers are colour coded Table 1.10.1 shows an example of the colour coding used by manufacturers.

Fiber number	Colour
1	Blue
2	Orange

3	Green
4	Brown
5	Grey
6	White
7	Red
8	Black
9	Yellow
10	Violet
11	Pink or light blue
12	Tur quoise or neutral

Table 1.10.1 Fiber colour coding

- If there are more than 12 fibers in a tube they are usually bundled together in quantities of 12 and held together with a coloured binding yarn.

Cable Jacket

The cable jacket, the final outer layer of the cable, may use a number of materials depending on the required mechanical properties, attenuation, environmental stress and flammability. Table 1.10.2 lists the properties of common cable jacket materials.

Jacket material	**Properties**
Polyvinyl Chloride (PVC)	Mechanical protection; different grades offer flame retardancy and outdoor use. Also for indoor and general applications.
Gypalon ®	Can withstand extreme environments; flame retardant; good thermal stability; resistant to oxidation, ozone and radiation.
Polyethylene (PE)	Used for telephone cables; resistant to chemicals and moisture; low-cost; flammable, so not used in electronic application.
Thermoplastic Elastomer (TPE)	Low-coast; excellent mechanical and chemical properties.
Nylon	Used over single conductors to improve physical properties

Kynar ® (Polyvinylidene Fluoride)	Resistant to abrasions, cuts; thermally stable; resistant to most chemicals; low smoke emission; self-extinguishing. Used in highly flame retardant plenum cables.
Teflon ® FEP	Zero smoke emission, even when exposed to direct flame. Suitable to temperatures of 200 ^{o}C; chemically insert. Used in highly flame retardant plenum cables.
Tefzel ®	Many of the same properties as Teflon; rated for 150 ^{o}C; self-extinguishing.
Irradiated cross-linked Polyolefin (XLPE)	Rated for 150 ^{o}C; high resistance to environmental stress, cracking, cut-through, ozone, solvents and soldering.
Zero Halogen Thermoplastic	Low toxicity makes it usable in any enclosed
Kevlar, Hyplon, Tefzel and Teflon are registered trademarks of E.I. Du Pont Nemours and Company. Kynar is a registered trademark of Pennwalt, Inc.	

Table 1.10.2 Properties of cable jacket material

Plastic Fiber Optic Cables

- Fibers can also be manufactured from transparent plastic which offers advantages of larger diameter (1 mm), increased flexibility, can be cut using a hot razor blade, ease of termination. But because of high intrinsic loss use of plastic fibers is normally restricted to only few metres.
- Plastic optic fiber (POF) offers noise immunity and low cable weight and volume and is competitive with shielded copper wire making it suitable for industrial applications.
- Silica (glass) optical fiber has better transmission characteristics (Low loss) than POF. Also, silica fiber can tolerate higher temperature than plastic fiber. On the other hand, POF is more flexible, less prove to breakage, easier to fabricate and cost is low than glass fibers.
- Another advantages of glass/glass fiber is that very clean fracture surface can be obtained which ensures that fiber cladding inside the connector retains its optical characteristics right upto the end face to fiber. Whereas in plastic glass/plastic fiber some additional losses exists due to fracture zone of plastic which even after grinding and polishing still have microscope end face absorption areas. These advantages and disadvantages are summarized in Table 1.10.3.

Types of cladding	Advantages	Disadvantages
Glass/glass fiber	• Clean fracture surface. • Retention of optical characteristics.	• Less flexible than plastic fiber. • Prone to damage.
Transparent plastic/plastic fiber	• Large diameter. • Increased flexibility. • Ease of termination.	• High intrinsic loss. • Additional losses at the fracture zone. • Limited distances of a few metres and to environments protected from temperature extremes.

Table 1.10.3 Advantages and disadvantages of different fiber claddings

Recommended Questions

1. State and explain the advantages and disadvantages of fiber optic communication systems.
2. State and explain in brief the principle of light propagation.
3. Define following terms with respect to optical laws –
   A) Reflection
   B) Refraction
   C) Refractive index
   D) Snell's law
   E) Critical angle
   F) Total internal reflection (TIR)
4. Explain the important conditions for TIR to exit in fiber.
5. Derive an expression for maximum acceptance angle of a fiber.
6. Explain the acceptance come of a fiber.
7. Define numerical aperture and state its significance also.
8. Explain the different types of rays in fiber optic.
9. Explain the following –

A) Step index fiber

B) Graded index fiber

10. What is mean by mode of a fiber?
11. Write short notes on following –

    A) Single mode step index fiber

    B) Multimode step index fiber

    C) Multimode graded index fiber.
12. Explain the fiber materials used in fabrication requirements.
13. In case of glass fibers how the refractive index can be varied?
14. Briefly explain following techniques of fabrication.

    i) OVPO ii) VAD

    iii) MCVD iv) PCVD

    v) Double crucible technique.
15. Comment on major mechanical properties of a fiber.
16. Write a note on fiber arrangements.