Fiber Optics and Holography

INTRODUCTION

The field of fiber optics communications has exploded over the past two decades. Fiber is an integral part of modern day communication infrastructure and can be found along roads, in buildings, hospitals and machinery.

An optical fiber is a glass or plastic fiber designed to guide light along its length. Fiber optics is the overlap of applied science and engineering concerned. Optical fibers are widely used in fiber-optic communication which permits transmission over longer distances and at higher data rates than other forms of wired and wireless communications. Fibers are used instead of metal wires because signals propagate along them with less loss and they are immune to electromagnetic interferences. Optical fibers are also used to form sensors, and in a variety of other applications.

The use of optical fibers for information transmission has become widespread and it is evident from the installation of fiber optic telecommunication networks throughout the world. In India millions of kilometers of fiber have been installed due to progressive privatization of its telecommunication industry. Other than communication, optical fiber finds application in medical science, illumination technology, instrumentation etc.

The optical fiber is simply a cylindrical waveguide system operating at optical frequencies. It consists of a core at the centre and a cladding outside the core. The core is generally cylindrical dielectric glass with a refractive index and cladding is second dielectric sheath or cover usually of glass with a lower refractive index.

This chapter covers the physical nature and various characteristics of optical fiber with some of the applications.

FIBER BASICS

Fiber Structure

The diagram shows the typical structure of a fiber used for communication links. It has an inner glass core with an outer cladding. This is covered with a protective buffer and outer jacket. This design of fiber is light and has a very low loss, making it ideal for the transmission of information over long distances.

Physically a fiber optics is a very thin flexible medium having a cylindrical shape that consists of three sections, core, cladding and protective jacket.

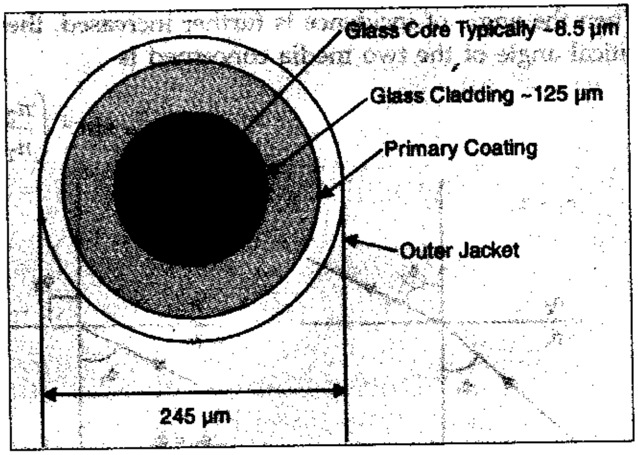

Fig. 6.1. *Structure of a fiber.*

The core is the innermost section having diameter approximately 5 μm - 100 μm and is made up of glass or plastic. This core is surrounded by cladding of slightly lower refractive index with a diameter ~ 125 μm which is of glass or plastic (Fig. 6.1.). The outermost section is made of plastic or polymer or some other suitable material and is used for the protection against moisture, crushing, abrasion or any other environmental dangers. A small impurity in the fiber optic cable could cause the light pulse to lose some of the information that it is carrying. Because of this reason, ultrapure glass is required as it allows the light pulses to flow through the long strands of fiber optic cable without being distorted. Sometimes plastic fibers or plastic clad silica fibers are also used. Plastic fiber is inexpensive, has some limitations considering UV resistance, life expectancy, humidity resistance, heat, bending sensitivity, compatibility with environment.

Advantages of the Cladding

The cladding serves the following useful purposes:

1. It adds mechanical strength to the fiber and protects the fiber from absorbing surface contaminants with which it may come in contact.
2. The cladding is capable of reducing the scattering loss of light resulting from dielectric discontinuities at the core surface.

BASIC PRINCIPLE OF OPTICAL FIBER

The purpose of optical fibers is to carry light from one place to another, as the conducting wire carries electrical current. Fiber optics are based on the principle of refraction. Refraction governs the behaviour of light as it passes from one transparent medium to another and is described by Snell's law. The refractive index of a medium is defined as

$$n = \frac{c}{v}$$

where c is velocity of light in vacuum and v is velocity of light in the medium.

When light passes from denser to rarer medium, it bends away from the normal as shown in Fig. 6.2 (*a*). According to Snell's law

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

where ϕ_1 and ϕ_2 represent the angles of incidence and refraction respectively. If the angle of incidence ϕ_1 is increased, the refracted ray bends more and more away from the normal and at a particular angle of incidence, the refracted ray passes perpendicular to the normal *i.e.*, grazing along the interface (Fig. 6.2 *b*). This particular angle of incidence is known as critical angle (ϕ_c).

When the angle of incidence is further increased, there is total internal reflection. The value of critical angle of the two media concerned is

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

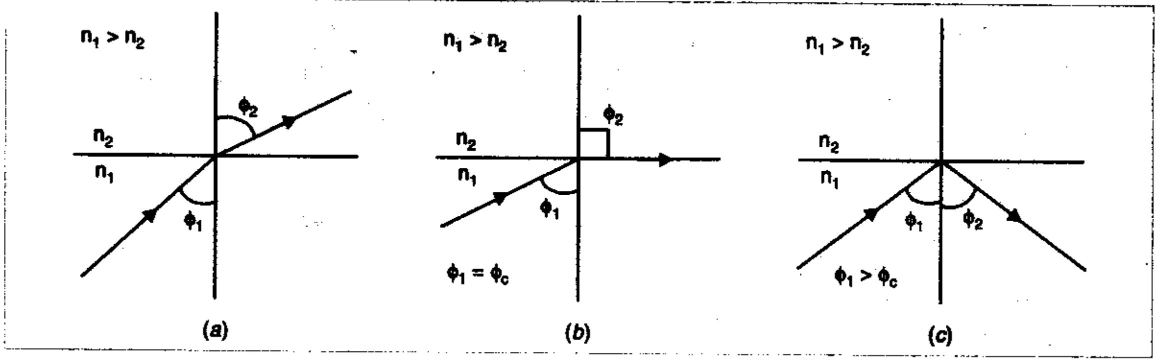

Fig. 6.2. *Different cases of refraction*

(*a*) ray of light passes from optically denser to rarer medium.

(*b*) angle of incidence in denser medium is equal to critical angle.

(*c*) angle of incidence in denser medium is greater than critical angle.

In optical fiber, refractive index n_1 of the core region is slightly more than the refractive index of the cladded material. Figure 6.3 (*a*) shows longitudinal cross-section of a fiber with $n_2 < n_1$. For a ray entering the fiber, if the angle of incidence ϕ (at the core-cladding interface) is greater than the critical angle ϕ_c, then there is total internal reflection at the interface. Because of cylindrical symmetry in the fiber structure, this ray will suffer total internal reflection at the lower interface also and therefore get guided through the core by repeated total internal reflection as if the core of the fiber acts like a continuous layer of two parallel mirrors. Because of total internal reflection, light beam can propagate through a long optical fiber even around gentle curves. Thus an optical fiber acts as a 'light guide' and is also known as an optical 'waveguide'.

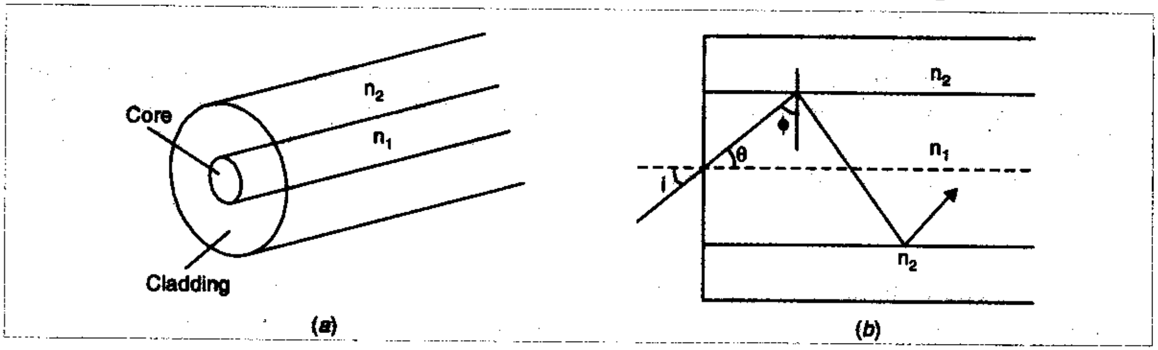

Fig. 6.3. *(a) Optical fiber with cylindrical core cladded by a material with $n_2 < n_1$.*
(b) Light guidance at the core-cladding interface.

FIBER CLASSIFICATION

The optical fiber can be classified mainly based on refractive index profile and modes of propagation.

REFRACTIVE INDEX PROFILE

Considering the refractive index of the core and cladding materials, fiber can be classified as

(i) Step Index Fiber (SI)

(ii) Graded Index Fiber (GI).

Step Index Fiber

In step index fiber, core is of constant refractive index n_1 and cladding is of slightly lower refractive index n_2 (Fig. 6.4 (a)). Thus, for this type of fiber, there is a step change at core cladding interface. The refractive index profile may be defined as

$$n(r) = n_1 \text{ for } r < a \text{ (core)}$$
$$= n_2 \text{ for } r > a \text{ (cladding)}$$

Graded Index Fiber

Graded index fibers have decreasing core index $n(r)$ with radial distance from maximum value of n_1 at the axis to a constant value n_2 beyond the core radius (a) Fig. 6.4 (b). The index variation may be given as

$$n(r) = n_1 \left[1 - 2\Delta \left(\frac{r}{a}\right)^2\right]^{1/2} \qquad \text{for } r < a \text{ (core)}$$
$$n_2 [1 - 2\Delta]^{1/2} \qquad \text{for } r > a \text{ (cladding)}$$

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

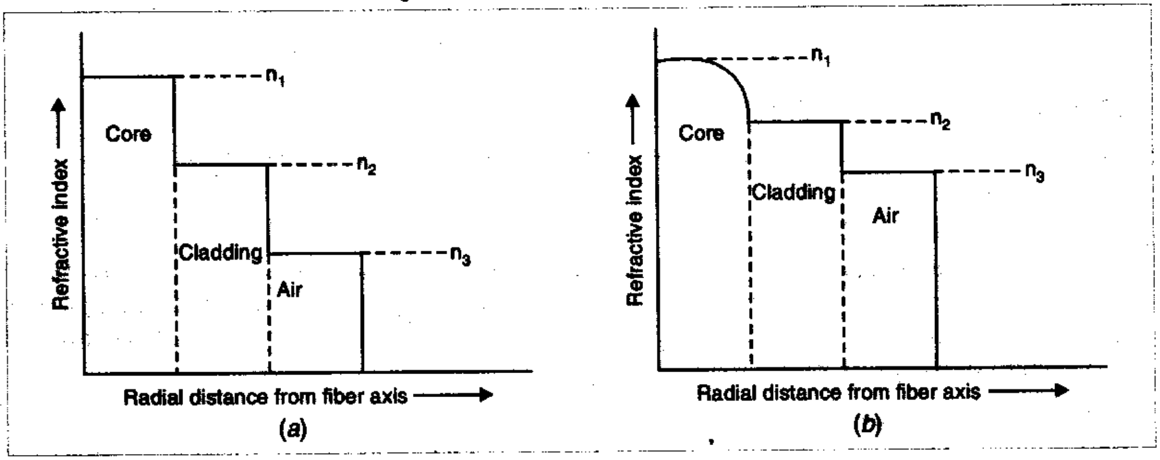

Fig. 6.4. (a) Step index fiber (b) Graded index fiber.

W-Index Fiber

This type of fiber is shown in Fig. 6.5. In this case, the width of the cladding is made thick. The first cladding with refractive index n_2 is surrounded by a second thicker cladding layer with refractive index n_3 where $n_1 > n_3 > n_2$. This produces W-shaped refractive index profile.

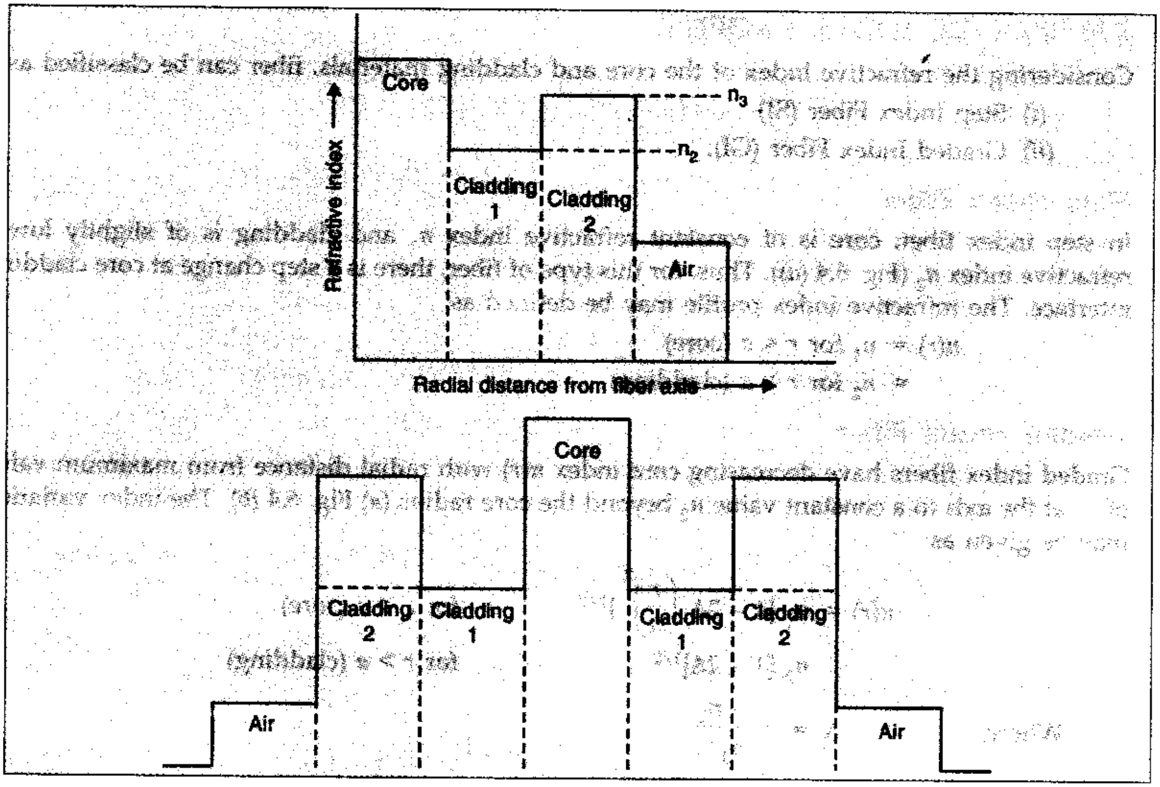

Fig. 6.5. *Refractive index profile for W-index fiber.*

MODAL CLASSIFICATION

Two basic types of fibers are considered on the basis of mode of transmission.

(*i*) Multimode (MM)

(*ii*) Singlemode (SM)

In multimode fiber, core diameter is greater than 10 μm, the light can travel many different paths through the core of the fiber and can enter and leave the fiber at various angles. Single mode propagation can be achieved by reducing core diameter less than about ten times the wavelength of the propagating light.

Difference between Single Mode and Multimode

With copper cables larger size means less resistance and therefore more current but with fiber the opposite is true. To explain this we first need to understand how the light propagates within the fiber core.

Light Propagation

Light travels along a fiber cable by a process called 'Total Internal Reflection' (TIR), this is made possible by using two types of glass which have different refractive indexes. The inner core has a high refractive index and the outer cladding has a low index. In multimode fibers, as the name suggests, there are multiple modes of propagation for the rays of light. These range from low order modes which take the most direct route straight down the middle, to high order modes which take the longest route as they bounce from one side to the other all the way down the fiber (Fig. 6.6).

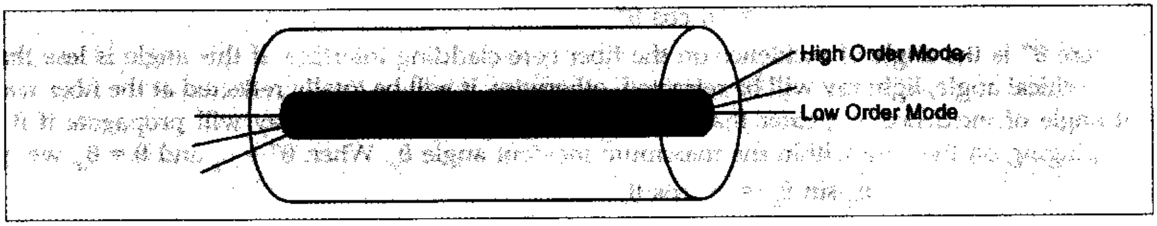

Fig. 6.6. *Low and high order mode.*

Advantages of Multimode Fibers

Multimode fibers possess several advantages as compared to single mode fibers which are as follows:

1. The larger radii of the multimode fibers make it easier to launch the optical power into the fiber.
2. Light can be launched in a multimode fiber with the help of light emitting diode (LED) source, whereas in a single mode fiber light can only be launched by a laser. Although the LEDs have lesser power output than the laser, LEDs are easier to manufacture, less expensive, requires less complex electronic circuitry and have a longer lifetime.

The intermodal dispersion in multimode fibers which distorts the shape of the propagating light pulses may be considered the only disadvantage.

Acceptance Angle, Acceptance Cone and Numerical Aperture of a Fiber

We input the light into the core of the optical fiber within a cone to get the light into the core of the fiber. Not all rays entering the fiber core will continue to be propagated down the length. Only those rays which will have angle of incidence greater than critical angle at the core cladding interface are transmitted by total internal reflection. The light rays should impinge the core of the optical fiber within a maximum external incident angle $\theta = \theta_a$ to have the condition for propagating down the core length. The path of a ray entering the fiber core at an angle $\theta = \theta_a$ for which the ray propagate grazing the core-cladding interface is shown in Fig. 6.7 (*a*). This angle θ_a is known as the angle of acceptance for the fiber.

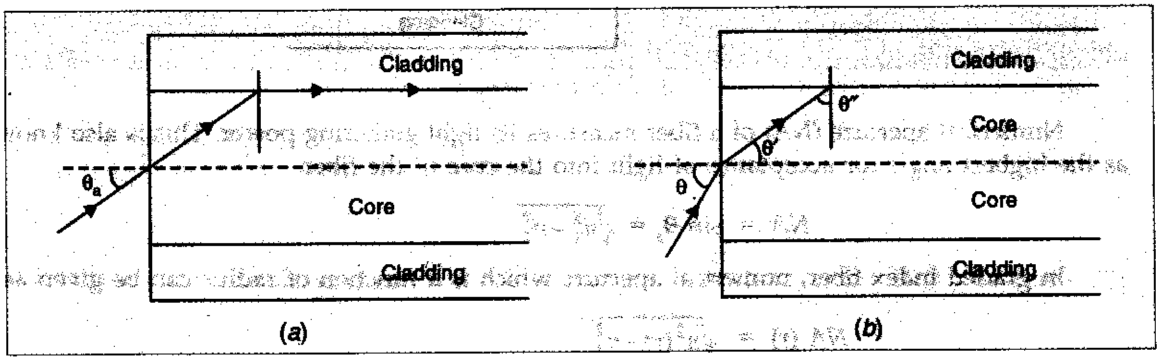

Fig. 6.7. *(a) Angle of incidence $\theta = \theta_a$ (b) at an angle θ at the fiber face.*

Angle θ_a can be derived using Snell's law. Let us consider the ray from air (refractive index n_0) is incident at an angle θ onto the perpendicular end face of the fiber for which the angle of refraction is θ'. Using Snell's law, we get

$$n_0 \sin\theta = n_1 \sin\theta'$$
$$= n_1 \sin(90 - \theta'')$$

$$= n_1 \cos \theta''$$

where θ'' is the angle of incidence on the fiber core-cladding interface. If this angle is less than the critical angle, light ray will be refracted, otherwise, it will be totally reflected at the fiber wall, if angle of incidence is greater than critical angle θ_c. Thus, the light ray will propagate if it is impinging on the core within the maximum incident angle θ_a. When $\theta'' = \theta_c$ and $\theta = \theta_a$, we get

$$n_0 \sin \theta_a = n_1 \cos \theta_c$$
$$= n_1 (1 - \sin^2 \theta_c)^{1/2}$$

Since we know that $\sin \theta_c = \dfrac{n_2}{n_1}$

$$n_0 \sin \theta_a = n_1 \left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}$$

$$= \left[n_1^2 - n_2^2\right]^{1/2}$$

$$\theta_a = \sin^{-1} \sqrt{(n_1^2 - n_2^2)} \qquad [n_0 = 1 \text{ for air}]$$

Thus, if the rays are incident at an angle greater than θ_a on the fiber would be refracted in cladding. All the rays falling within the cone formed with acceptance angle θ_a as vertex angle would be transmitted down the fiber and this cone as shown in the Fig. 6.8 is known as acceptance cone for the fiber.

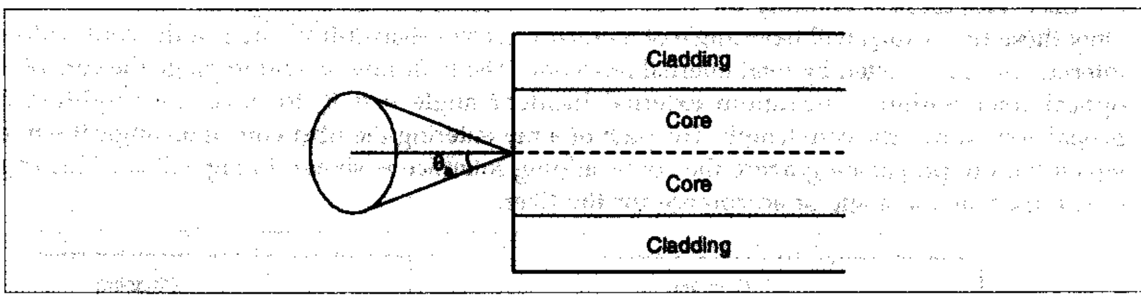

Fig. 6.8. *Light acceptance cone*

Numerical aperture (*NA*) of a fiber measures its light gathering power. This is also known as the highest angle for acceptance of light into the core of the fiber.

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

In graded index fiber, numerical aperture which is a function of radius can be given as

$$NA\,(r) = \sqrt{n^2(r) - n_2^2}$$

$NA\,(r)$ is numerical aperture at a distance r from the centre.

If we denote $n_1 - n_2 = \Delta n$, $n_1 + n_2 = 2n$

We get $\sin \theta_a = (2n\,\Delta n)^{1/2}$

Numerical aperture (*NA*) of the fiber = $\sin \theta_a = (2n\,\Delta n)^{1/2}$ and the acceptance angle

$$\theta_a = \sin^{-1} (2n\,\Delta n)^{1/2}$$
$$= \sin^{-1} (NA)$$

It can be shown that when a light is emitted from a diffuse source situated on the fiber axis near the end face, only a fraction $(NA)^2$ of the total amount of light emitted can be collected by the fiber and propagated along the fiber.

Thus $\sin^2 \theta_a = (NA)^2 = 2n\,\Delta n$

Thus, to collect as much light as possible it is necessary to make n and Δn large and the best we can do is to use a glass with high refractive index as core without any cladding.

Advantages of Optical Fiber over Copper Wire

The advantages of optical fiber transmission over conventional copper wire system can be given as:

1. Optical fibers have lower transmission losses and thus more data can be sent over the long distance.
2. The light weight and the small hair thin sized dimension of the fibers offer a distinct advantage. It is important in aircraft where small light weight cables are advantageous.
3. Dielectric nature of optical fiber is an important advantageous feature. This provides optical immunity to the electromagnetic interferences.
4. Silica, which is principal material for optical fiber is abundantly available, since the main source of silica is sand.

PRINCIPLE OF OPERATION

An optical fiber is a cylindrical dielectric waveguide that transmits light along its axis, by the process of total internal reflection. The fiber consists of a *core* surrounded by a cladding layer. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The boundary between the core and cladding may either be abrupt, in *step-index fiber*, or gradual, in *graded-index fiber*.

Multimode Fiber

Fiber with large (greater than 10 μm) core diameter may be analyzed by geometric optics. Such fiber is called *multimode fiber*, from the electromagnetic analysis (Fig. 6.9). In a step-index multimode fiber, rays of light are guided along the fiber core by total internal reflection. Rays that meet the core-cladding boundary at a high angle (measured relative to a line normal to the boundary), greater than the critical angle for this boundary, are completely reflected. The critical angle (minimum angle for total internal reflection) is determined by the difference in index of refraction between the core and cladding materials. Rays that meet the boundary at a low angle are refracted from the core into the cladding, and do not convey light and hence information along the fiber. The critical angle determines the acceptance angle of the fiber, often reported as a numerical aperture. A high numerical aperture allows light to propagate down the fiber in rays both close to the axis and at various angles, allowing efficient coupling of light into the fiber. However, this high numerical aperture increases the amount of dispersion as rays at different angles have different path lengths and therefore take different times to traverse the fiber. A low numerical aperture may therefore be desirable.

In graded-index fiber, the index of refraction in the core decreases continuously between the axis and the cladding. This causes light rays to bend smoothly as they approach the cladding, rather than reflecting abruptly from the core-cladding boundary. The resulting curved paths reduce multipath dispersion because high angle rays pass more through the lower-index periphery of the core, rather than the high-index center. The index profile is chosen to minimize the difference in axial propagation speeds of the various rays in the fiber. This ideal index profile is very close to a parabolic relationship between the index and the distance from the axis.

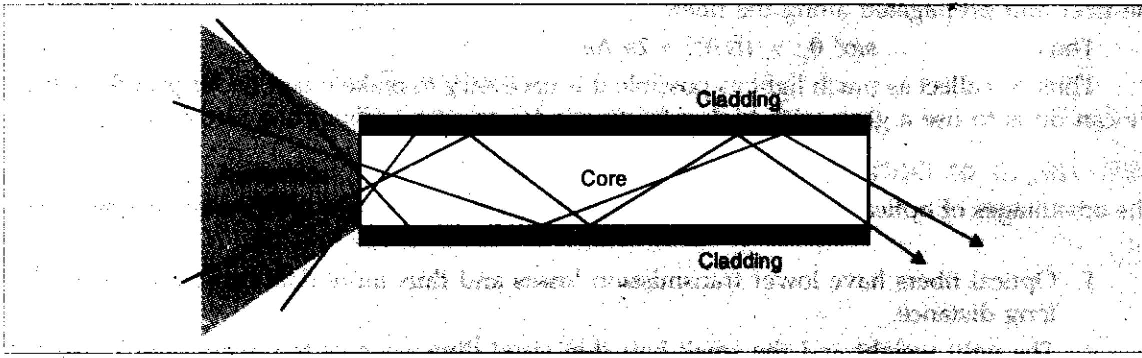

Fig. 6.9. *The propagation of light through a multi-mode optical fiber.*

Single-mode Fiber

Fiber with a core diameter less than about ten times the wavelength of the propagating light cannot be modelled using geometric optics. Instead, it must be analyzed as an electromagnetic structure, by solution of Maxwell's equations as reduced to the electromagnetic wave equation. Fiber supporting only one mode is called single-mode or *mono-mode* fiber (Fig. 6.10).

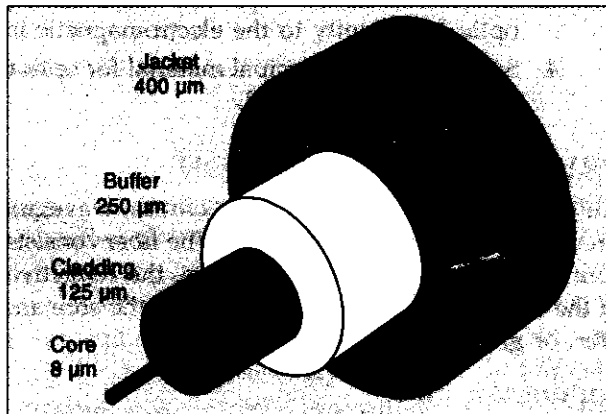

Fig. 6.10. *A typical single-mode optical fiber, showing diameters of the component layers.*

The most common type of single-mode fiber has a core diameter of 8 to 10 μm and is designed for use in the near infrared. The mode structure depends on the wavelength of the light used, so that this fiber actually supports a small number of additional modes at visible wavelengths. Multimode fiber, by comparison, is manufactured with core diameters as small as 50 microns and as large as hundreds of microns.

CUT-OFF WAVELENGTH

The various structural parameter of the fiber responsible for propagation characteristics can be combined into a normalised parameter known as V number.

$$V = \left(\frac{2\pi}{\lambda}\right) \cdot a \cdot \sqrt{n_1^2 - n_2^2}$$

where a = core radius

n_1 and n_2 are refractive indices of core and cladding materials.

λ = wavelength of wave propagating through it.

Depending on the value of V-number and refractive index variation, a fiber can support specific number of guided modes. Each mode has a minimum V-value below which it can not propagate. This V-value is called cut-off V-value, V_c of the mode.

For a fiber, we can obtain cut-off wavelength λ_c and for fiber operation $\lambda > \lambda_c$

$$\lambda_c = \left(\frac{2\pi}{V_c}\right) \cdot a \sqrt{n_1^2 - n_2^2}$$

$$= \left(\frac{2\pi}{V_c}\right) \cdot a \cdot n_2 \sqrt{(2\Delta)}$$

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

Cable Design

Fiber optic cables are required instead of fiber bundles in telephone communication system. A fiber cable installed can work at any transmission rate whether 1 Mbps, 10 Mbps, 100 Mbps or 1 Gbps. A cable design is an important aspect to be considered because once a cable has been installed, it is difficult and expensive to recover it. An ideal cable should be mechanically indestructible, chemically inert, fire proof and should also be unaffected by moisture.

Fiber Attenuation (Losses)

To discuss the design of any communication system, signal losses are an important factor to be considered. The losses in ion optical communication system may be due to channel input coupler, splices, connectors and within fiber itself. Inside the fiber, losses are due to material absorption and scattering. In addition to the losses discussed, there may be losses due to geometrical effect of fiber and splicing.

Details of various sources of attenuation are being discussed in the following section.

Material Absorptions

The light waves are attenuated because of absorption even if we use purified fiber glass. Purest glass also absorbs light within specific wavelength regions. Absorption is strong in short wavelength ultraviolet region and it is also present in infrared region. Because of absorption due to impurity within the fiber, there is heating effect. Two types of impurities are usually present. Impurities are due to transition metals such as iron, cobalt-nickel, vanadium, manganese, chromium and also due to presence of OH^- ion. OH^- ion is the main fiber impurity and creates an attenuation peak around 1430 nm. Therefore, precautions should be taken at the stage of manufacturing to ensure very low percentage level of OH impurity.

Scattering

Scattering is one of the important parameter for optical attenuation. It is because of local variations in refractive index of the manufactured glass which may be considered as small scattering objects. This is known as Rayleigh scattering loss which increases with decrease in wavelength according to the relation $\frac{1}{\lambda^4}$. In optical telecommunication we use infrared light to minimise scattering loss. Rayleigh scattering loss can be approximated by the relation

$$\text{Loss} = 1.7\left(\frac{0.85}{\lambda}\right)^4$$

λ is in micrometer and loss is in dB/km.

Losses due to Geometrical Effect

There is an additional radiation loss because of the stress created by bending of the fiber. In fiber, we consider micro and macro bending. Micro bending is due to deformation of fiber axis during cable processing. Micro bending loss can be eliminated by using loose tube cable construction.

Macro bending loss occurs due to pulling the fiber cable round the corner. A single mode fiber of 125 μm diameter can be bent with a radius of curvature of 10 cm with negligible loss but for lower radii, losses increases exponentially with increasing curvature. There is breaking if the bend radius is less than 150 times the fiber diameter.

Splice Losses

In fiber optic transmission system for long transmission, we use various types of connectors, couplers and splices. In single mode fiber link, splice loss is the main source of loss. This loss is at the fiber joint due to imperfectly formed splices or imperfectly aligned connectors.

DECIBEL (DB)

Decibel is the unit of attenuation

$$\text{Attenuation} = 10 \log (P_0/P_{in})\text{dB}$$

Attenuation means loss of optical power in the fiber or in a pair of connectors or splice. It is expressed in dB where–10 dB means reduction in power by 10 times, –20 dB means reduction in power by 100 times and similarly –30 dB means 1000 times loss.

Mathematically we can write

$$P_0 = P_{in}\, 10^{-\alpha L/10}$$

where P_0 = Power at a distance L from the input

P_{in} = Amount of power coupled into the fiber

α = Fiber attenuation in dB/km

Thus, attenuation is defined as the ratio of the optical power output P_0 obtained from a fiber of length L to the optical power input P_{in} led to the fiber.

$$\alpha = 10 \log [(P_{in}/P_0)/L] \text{ in dB/km}$$

For an ideal fiber $P_{in} = P_0$ and there is no loss of optical power *i.e.*, attenuation is 0 dB. But practically we do not get this ideal condition and it has been found that minimum attenuation of a standard telecommunication fiber is of the order of 0.2 dB/km at 1550 nm wavelength.

dBm is decibel measure of power relative to 1 mW. The power in dBm is an absolute value of power and can be given as

$$\text{Power level} = 10 \log P/1 \text{ mW}$$

$$P \text{ (in dBm)} = 10 \log P \text{ (in mW)}$$

Thus for 0 dBm we have 1 mW

The neper (N) is another unit of attenuation.

$$\text{Power} = \frac{1}{2} \ln \frac{(P_2)}{P_1}\ N.$$

Where P_2 and P_1 are two power levels with $P_2 > P_1$. To convert neper to decibel, the value in neper multiplied by 20 log e = 8.686 as ln e = 1.

Dispersion

Light from a typical optical source will contain a finite spectrum. The different wavelength components in this spectrum will propagate at different speeds along the fiber eventually causing the pulse to spread. When the pulses spread to the degree where they "collide" it causes detection problems at the receiver resulting in errors in transmission. This is called Intersymbol Interference (ISI). Dispersion (sometimes called *chromatic dispersion)* is a limiting factor in fiber bandwidth, since the shorter the pulses the more susceptible they are to ISI.

Dispersion in Optical Fiber

Dispersion is the spreading of light pulse as it travels down along the length of the fiber causing the pulses to overlap and thus making the pulses undetectable at the receiving end. Dispersion is of three types which are as follows:

1. Modal or intermodal dispersion
2. Material dispersion
3. Waveguide dispersion

1. **Modal or Intermodal Dispersion**

   This type of dispersion we get in multimode fiber. It arises due to different velocities of different modes.

2. **Material Dispersion**

   It is caused due to property of materials *i.e.,* due to variation of velocity with the wavelength. We do not have absolute monochromatic light and different wavelength travel with different velocity even when all the light follow the same path. Thus, pulses reaches at the end of the fiber at slightly different times. Thus, output signal is lengthened relative to the input signal.

3. **Waveguide Dispersion**

   Waveguide dispersion is important for transmission rate in the case of single mode. It occurs because guided optical energy is divided between core and cladding. Energy travels with slightly different velocity in cladding. The wavelength 1.5 μm is the present day choice of fiber optic communication because distortion is much less at this wavelength.

THE ADVANTAGES OF USING FIBER OPTICS

Because of the low loss, high bandwidth properties of fiber cable they can be used over greater distances than copper cables, in data networks this can be as much as 2 km without the use of repeaters. Their light weight and small size also make them ideal for applications where running copper cables would be impractical, and by using multiplexors one fiber could replace hundreds of copper cables. This is pretty impressive for a tiny glass filament, but the real benefits in the data industry are its immunity to Electro Magnetic Interference (EMI), and the fact that glass is not an electrical conductor. Because fiber is non-conductive, it can be used where electrical isolation is needed, for instance between buildings where copper cables would require cross bonding to eliminate differences in earth potentials. Fibers also pose no threat in dangerous environments such as chemical plants where a spark could trigger an explosion. Last is the security aspect, it is very, very difficult to tap into a fiber cable to read the data signals.

APPLICATIONS

Optical Fiber Communication

Optical fiber can be used as a medium for telecommunication and networking because it is flexible and can be bundled as cables. It is especially advantageous for long-distance communications, because light propagates through the fiber with little attenuation compared to electrical cables. This allows long distances to be spanned with few repeaters. Additionally, the light signals propagating in the fiber can be modulated at rates as high as 40 Gb/s and each fiber can carry many independent channels, each by a different wavelength of light. In total, a single fiber-optic cable can carry data at rates as high as 14.4 Pb/s (circa 14 million Gb/s). Over short distances, such as networking within a building, fiber saves space in cable ducts because a single fiber can carry much more data than a single electrical cable. Fiber is also immune to electrical interference, which prevents cross-talk between signals in different cables and pick up of environmental noise. Also, wiretapping is more difficult compared to electrical connections, and there are concentric dual core fibers that are said to be tap-proof. Because they are non-electrical, fiber cables can bridge very high electrical potential differences and can be used in environment where explosive fumes are present, without danger of ignition.

Although fibers can be made out of transparent plastic, glass, or a combination of the two, the fibers used in long-distance telecommunications applications are always glass, because of the lower optical attenuation. Both multi-mode and single-mode fibers are used in communications, with multi-mode fiber used mostly for short distances (up to 500 m), and single-mode fiber used for longer distance *links*. Because of the tighter tolerances required to couple light into and between single-mode fibers (core diameter about 10 micrometers), single-mode transmitters, receivers, amplifiers and other components are generally more expensive than multi-mode components.

Fiber Optic Sensors

Optical fibers can be used as sensors to measure strain, temperature, pressure and other parameters. The small size and the fact that no electrical power is needed at the remote location gives the fiber optic sensor advantages to conventional electrical sensor in certain applications.

Optical fibers are used as hydrophones for seismic or SONAR applications. Hydrophone systems with more than 100 sensors per fiber cable have been developed. Hydrophone sensor systems are used by the oil industry. Both bottom mounted hydrophone arrays and towed streamer systems are in use. The German company Sennheiser developed a microphone working with a laser and optical fibers.

Optical fiber sensors for temperature and pressure have been developed for downhole measurement in oil wells. The fiber optic sensor is well suited for this environment as it is functioning at temperatures too high for semiconductor sensors.

Another use of the optical fiber as a sensor is the optical gyroscope which is in use in the Boeing 767 and in some car models (for navigation purposes) and the use in Hydrogen microsensors.

Fiber optic sensors have been developed to measure co-located temperature and strain simultaneously with very high accuracy. This is particularly useful to acquire information from small complex structures.

Other Uses of Optical Fibers

Fibers are widely used in illumination applications. They are used as light guides in medical and other applications where bright light needs to be shone on a target without a clear line-of-sight path. In some buildings, optical fibers are used to route sunlight from the roof to other parts of the building. Optical fiber illumination is also used for decorative applications, including signs, art, and artificial Christmas trees. Swarovski boutiques use optical fibers to illuminate their crystal showcases from many different angles while only employing one light source. Optical fiber is an intrinsic part of the light transmitting concrete building product, LiTraCon.

Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory of surgical procedures (endoscopy). Industrial endoscopes are used for inspecting anything hard to reach, such as jet engine interiors.

An optical fiber doped with certain rare-earth elements such as erbium can be used as the gain medium of a laser or optical amplifier. Rare-earth doped optical fibers can be used to provide signal amplification by splicing a short section of doped fiber into a regular (undoped) optical fiber line.

HOLOGRAPHY

The image of a three dimensional object is recorded on a two dimensional photographic plate. When a photograph is recorded, the phase distribution at the plane of the photograph is lost because emulsion on the photographic plate is sensitive only to the intensity variations. Hence, three dimensional character is lost.

A new method of recording optical images is known as holography. Holography means complete recording. In 1948, Dennis Galior gave an entirely new idea and proposed a method of recording not only the amplitude but also the phase of the wave. During recording process, there is superimposition of two waves, one emanating from the object and another coherent wave called the reference waves. The two waves produce interference fringes in the plane of the recording medium. The record is called a hologram. It memorizes, an encoded image of the object and contains much more information than ordinary photograph can record.

Now the hologram is illuminated by the wave which is very much similar to the reference wave known as reconstruction wave. When the hologram is illuminated by the reconstruction wave and one views this wave (emerging from the hologram), then one sees a reconstructed image of the object in its true three dimensional form. In addition to the virtual image, the reconstruction process generates another image which is a real image. This real image can also be photographed by placing a photographic plate at the position where the real image is formed.

The principle of holography was laid down by Gabor and attained practical importance due to lasers in 1960. Before the advent of lasers, one had to employ the method of in-line holography in which the reference beam is approximately parallel to the object wave and path traversed by reference wave and object wave are almost equal. This was required because sources used such as mercury lamps had small coherence length. The in-line technique has associated with it the disadvantage that while viewing the virtual image one is faced with an unfocused real image because the waves that form the virtual and real images travel along the same direction.

In the year 1962, Leith and Upatneiks introduced the technique of off-axis holography which removed the difficulty associated with the in-line technique. Laser holograms were prepared for the first time by Leith and Upatneiks.

Principle of Holography

The basic principle of holography can be explained in two steps

(*i*) Recording of the hologram and

(*ii*) Reconstructing the image.

(*i*) Recording of the Hologram

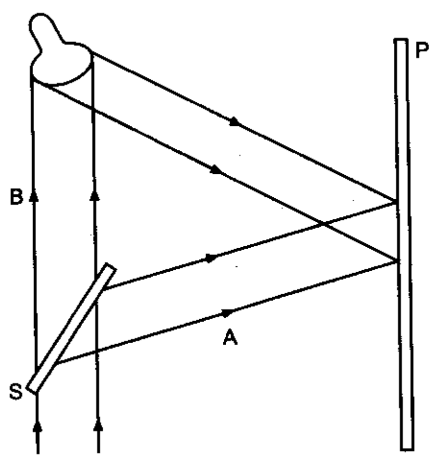

Fig. 6.14. *Recording of a hologram*

Splitter S is used to divide a laser beam into two beams A and B (Fig. 6.14). The transmitted beam illuminates the object and the light scattered by the object impinges on a photographic plate. The reflected beam A falls on to the photographic plate. This beam is known as reference beam. An interference pattern which we get due to superposition of two beams is recorded on the plate. The developed plate is known as hologram. The hologram contains enough information to produce complete reconstruction of the object and it is quite unintelligible and gives no hint of the image embedded in it.

(*ii*) Reconstructing the Image

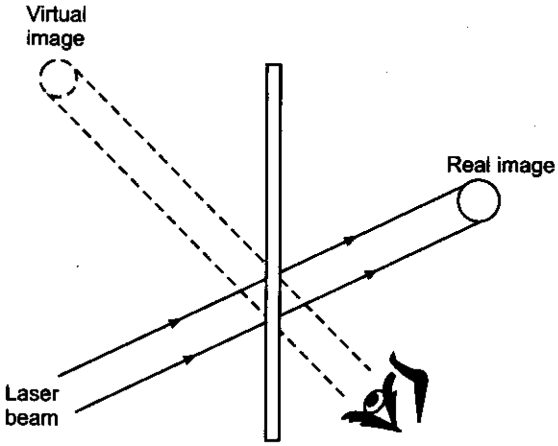

Fig. 6.15. *Reconstruction of the image*

In the reconstruction process, the hologram is illuminated by a reconstruction wave, which in most cases is identical to the reference wave used for forming hologram. The reconstruction wave after passing through the hologram produces two images. One of them appears at the original position occupied by the object (virtual image) and the other (real image) which can be photographed directly without using a lens. The virtual image which is seen by looking through the hologram appears in complete three dimensional form. If one moves his eyes, it is possible to see the other sides of the object. The real image has all the properties as in the case of virtual image and is found between the observes and the plate as shown in Fig. 6.15. However, the real image reverse foreground and background, so the interest of the observer lies in the virtual image.

Characteristics of Hologram

1. The virtual image produced by a hologram appears in complete three dimensional form.
2. Each point on the hologram receives light from all parts of the object and therefore contains information about the geometrical characteristics of the entire image. Thus, each part of the hologram can reproduce entire image. Consequently destruction of a part of a hologram does not erase a specific portion of the image. It may be noted that reduction in size affects resolution. Thus, hologram is a reliable method of data storage.
3. A hologram may contain a number of consecutively recorded scenes that can be recorded independently. Different scenes can be recorded on a hologram by rotating the plate. By rotating the plate, the angle at which reference wave is incident on the photographic plate is changed. Reconstruction of a specific scene only requires that the hologram be properly oriented with respect to the reference wave.

4. A hologram copied from another by contact printing would be identical in all respects to that produced by the original.

SOLVED EXAMPLES

1. *A silica glass optical fiber has a core refractive index of 1.500 and the cladding refractive index of 1.450. Calculate*
   (i) Critical angle for core-cladding interface.
   (ii) The acceptance angle in air for fiber and the corresponding angle of obliqueness.
   (iii) The numerical aperture (NA) of the fiber
   (iv) The percentage of light collected by the fiber with respect to incident light (It is given that the core diameter of the fiber is greater than the diameter of the light source).

Sol. (*i*) $\sin\theta_c = \dfrac{n_2}{n_1}$ where θ_c is critical angle

$$n_1 = 1.500 \text{ and } n_2 = 1.450$$

$$\sin\theta_c = \frac{1.450}{1.500} = 0.966$$

$$\theta_c = \sin^{-1} 0.966 = 75°$$

Angle of obliquence $\theta' = 90 - \theta_c = 90 - 75° = 15°$

(*ii*) $n_a \sin\theta_a = n_1 \sin\theta' = n_1 \sin(90 - \theta_c) = n_1 \cos\theta_c$

$$\frac{\sin\theta_a}{\sin\theta'} = \frac{n_1}{n_a}$$

$$\sin\theta_a = \frac{n_1}{n_a}\sin\theta' = \frac{1.5}{1}\sin\theta' = 1.5\sin 15°$$

$$= 1.5 \times 0.26 = 0.39$$

$$\theta_a = \sin^{-1} 0.39$$

$$\theta_a = 23°$$

The acceptance angle θ_a of the fiber is 23°

(*iii*) Numerical aperture $NA = \left[(n_1+n_2)(n_1-n_2)\right]^{\frac{1}{2}}$

$$= \left[(1.500+1.450)(1.500-1.450)\right]^{\frac{1}{2}}$$

$$= \left[2.95\times 0.050\right]^{\frac{1}{2}} = (0.1475)^{\frac{1}{2}}$$

$$= 0.3481$$

The numerical aperture of the fiber is 0.3841

(*iv*) Percentage of light collected $= (NA)^2 \times 100 = 0.1475 \times 100$

$$= 14.7\%$$

2. *The refractive index of the core of W-step index fiber is 1.46 and the relative refractive index difference between the core and the cladding of the fiber is 2%. Estimate*
   (i) Numerical aperture
   (ii) The critical angle at the core cladding interface within the fiber.

Sol. (*i*)
$$\Delta = \frac{n_1 - n_2}{n_1} = 0.02 \text{ and } n_1 = 1.46$$

Thus,
$$n_1 - n_2 = 0.02 \times 1.46 \text{ and } n_2 = 1.46 - 0.02 \times 1.46$$
$$= 1 - 0.0292$$
$$= 1.43$$

$$NA = \left[(n_1 + n_2)(n_1 - n_2)\right]^{\frac{1}{2}} = (2.89 \times 0.03)^{\frac{1}{2}}$$
$$= (0.0867)^{\frac{1}{2}} = 0.29$$

(*ii*)
$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1.43}{1.46} \text{ or } \theta_c = \sin^{-1}\frac{1.43}{1.46} = \sin^{-1} 0.98$$
$$= 78°$$

The critical angle at the core cladding interface is 78°.

3. *A multimode fiber has a core diameter of 70 μm and the relative refractive index difference of 1.5 percent. It operates at the wavelength of 0.85 μm. The refractive index of the fiber is 1.46. Calculate*

   (a) The refractive index of the cladding.

   (b) The normalized frequency V-number of the fiber and

   (c) The total number of guided modes in the fiber.

Sol.
$$a = \frac{70}{2} = 35\ \mu\text{m},\ \Delta = \frac{n_1 - n_2}{n_1} = 1.5\%$$
$$n = 1.46\ \lambda = 0.85\ \mu\text{m}$$

(*a*)
$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.5}{100} = 0.015$$
$$n_1 - n_2 = 0.015\ n_1$$
$$n_2 = n_1 - 0.015\ n_1 = 1.46\ (1 - 0.015) = 1.438$$

(*b*) V-number can be calculated as

$$V = \frac{2\pi a}{\lambda}\left[n_1^2 - n_2^2\right]^{\frac{1}{2}} = \frac{2\pi a}{\lambda}\left[(n_1 + n_2)(n_1 - n_2)\right]^{\frac{1}{2}}$$
$$= \frac{2\pi a}{\lambda}(2n_1)^{\frac{1}{2}}(n_1 - n_2)^{\frac{1}{2}} \qquad [\text{Putting } n_1 + n_2 = 2n_1]$$
$$= \frac{2\pi a}{\lambda} n_1 \left[\frac{2(n_1 - n_2)}{n_1}\right]^{1/2} = \frac{2\pi a}{\lambda} n_1 (2\Delta)^{1/2}$$
$$2\Delta = \frac{2 \times 1.5}{100} = 0.03$$
$$(2\Delta)^{\frac{1}{2}} = (0.03)^{\frac{1}{2}} = 0.173$$
$$V = \frac{2\pi \times 35 \times 10^{-6} \times 1.46 \times 0.173}{0.85 \times 10^{-6}} = 65.3$$

(*c*) Total number of guided modes in the step-index fiber is

$$M = \frac{V^2}{2} = \frac{(65.3)^2}{2} = 2132 \text{ modes.}$$

4. *A single mode step index fiber is operating in the guided mode. The core refractive index and radius are 1.46 and 5 μm respectively. The refractive index difference between the core and cladding is 0.25 per cent. Calculate the cut-off wavelength of the fiber. (Cut-off value of V-parameter for single mode operation is V_c = 2.405).*

Sol.
$$(2\Delta)^{\frac{1}{2}} = \left(2\,\frac{n_1-n_2}{n_1}\right)^{\frac{1}{2}} = \left(\frac{2\times 0.25}{100}\right)^{\frac{1}{2}}$$
$$= (0.005)^{\frac{1}{2}} = 0.071$$

The cut-off wavelength

$$\lambda_c = \frac{2\pi a}{V_c} n_1 (2\Delta)^{\frac{1}{2}} = \frac{2\times 3.14\times 5\times 10^{-6}\times 1.46\times 0.071}{2.405}$$
$$= 1.48\ \mu\text{m}$$

The cut-off wavelength for the single mode step index fiber is 1.48 μm.

5. *The core and cladding refractive indices of a step index fiber are 1.6 and 1.44 μm respectively. An electromagentic wave having wavelength of 0.8 μm is propagating through the fiber in guided mode through the core of the fiber. Find out maximum and minimum value of phase constant.*

Sol. The maximum value of phase constant

$$= \frac{2\pi}{\lambda} n_1 = \frac{2\pi}{0.8} \times 1.6 = 12.56\ \text{rad}/\mu\text{m}$$

The minimum value of phase constant

$$= \frac{2\pi}{\lambda} n_2 = \frac{2\pi}{0.8} \times 1.44 = 11.33\ \text{rad}/\mu\text{m}$$