1. **With the help of block diagrams explain the general optical fibre communication system. Also mention the advantages and disadvantages of optical fibre communication systems.**

An optical fibre communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 1.2(a), the function of which is to convey the signal from the information source over the transmission medium to the destination. The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a carrier, which, as mentioned previously, may be an electromagnetic wave. The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination. However, it must be noted that in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself. Therefore, in any communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication.

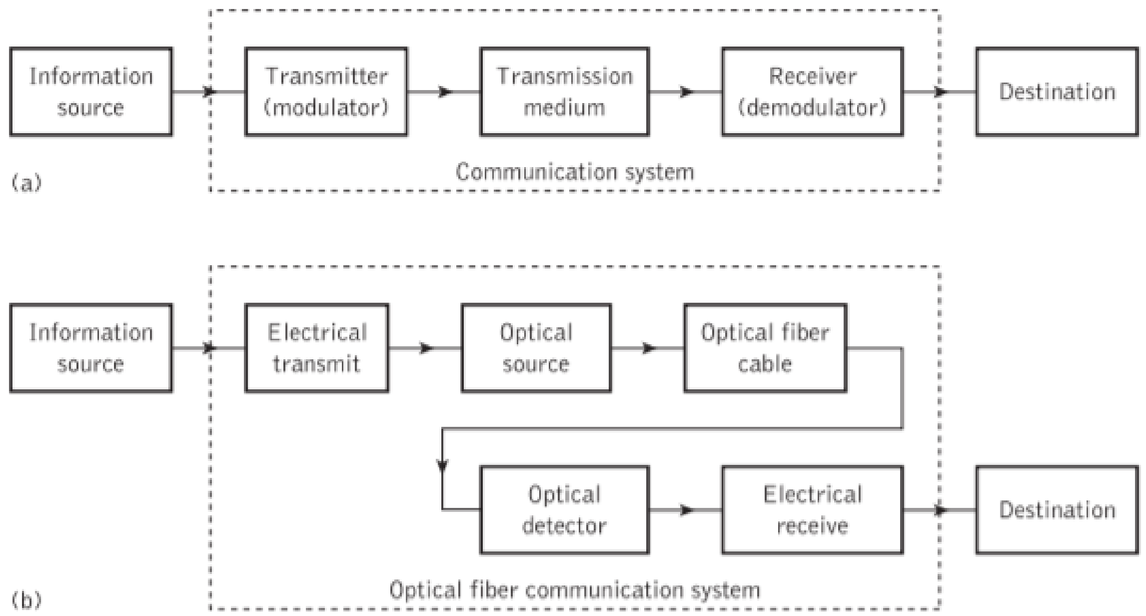


Figure 1 : General Optical Fibre Communication System

In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (p–n, p–i–n or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically. The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Figure 1.2(b) analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal-to-noise ratio at the receiver than digital modulation. Also, the linearity needed for analog modulation is not always provided by semiconductor optical sources, especially at high modulation frequencies. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidth operation than digital links.

Initially, the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction.

Advantages•

Wide Bandwidth

•Small Size & Light Weight

•Electrical isolation

•Immunity to interference and crosstalk

•Signal Security

•Low transmission Loss

•Ruggedness & Flexibility

•Reliability & ease of maintenance

•Long Distance Transmission

•Low Cost

Disadvantages

- High Initial Cost
- Maintenance & Repairing Cost
- Jointing & Test Procedure
- Splicing
- Fragility
- Short Links

2. **Define the following terms with respect to optical fiber waveguides:Reflection, Refraction, Refractive index, Critical angle, Total Internal reflection. Make use of necessary figures.**

Refraction

Refraction is the change in the direction of a wave passing from one medium to another. Refraction is the bending of a wave when it passes from one medium to another. The bending is caused due to the differences in density between the two substances. A light ray refracts whenever it travels at an angle into a medium of different refractive index. This change in speed results in a change in direction. As an example, consider air travelling into water. The speed of light decreases as it continues to travel at a different angle.

When the ray approaching the interface is propagating in a dielectric of refractive index n1 and is at an angle φ1 to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n2 which is less than n1, then the refraction is such that the ray path in this lower index medium is at an angle φ2 to the normal, where φ2 is greater than φ1. The angles of incidence φ1 and refraction φ2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction

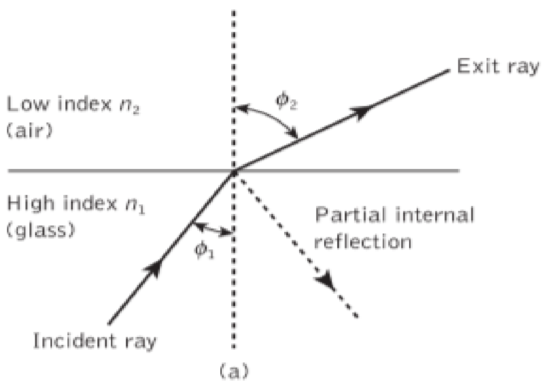


Figure 2: Refraction of Light

Reflection-

- As n1 is greater than n2, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°. This is the limiting case of refraction and the angle of incidence is now known as the critical angle φc, as shown in Figure 2.2(b). From Eq. (2.1) the value of the critical angle is given by: sin φc = (2.2) At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency.

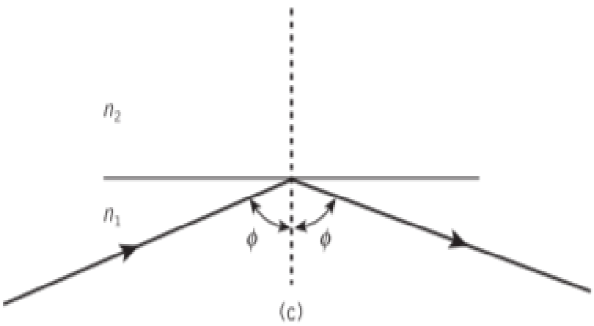


Figure 3 : Reflection of Light

Critical Angle –

The limiting case of refraction and the angle of incidence is now known as the critical angle φc,

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

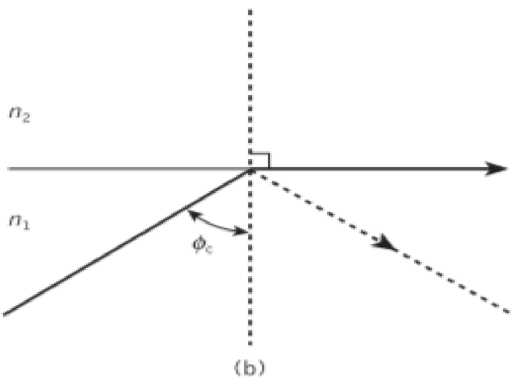


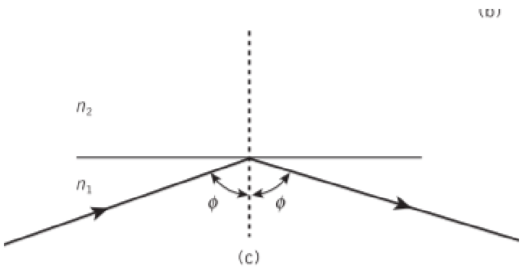
Figure 3 : Critical Angle

Total Internal Reflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium.

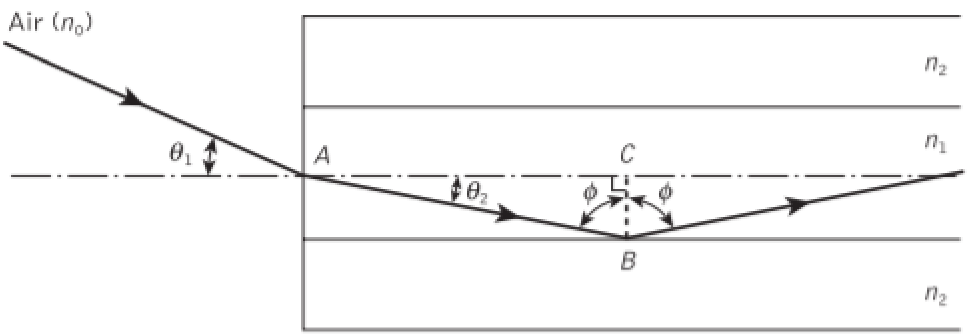
The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 2.2(a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n1 and is at an angle φ1 to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n2 which is less than n1, then the refraction is such that the ray path in this lower index medium is at an angle φ2 to the normal, where φ2 is greater than φ1. The angles of incidence φ1 and refraction φ2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that:

$$n1 \sin \varphi 1 = n2 \sin \varphi 2$$



3. (a) Derive the expression for Numerical Aperture (NA).

The acceptance angle for an optical fiber was defined in the preceding section. However, it is possible to continue the ray theory analysis to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, cladding and air. This leads to the definition of a more generally used term, the numerical aperture of the fiber. It must be noted that within this analysis, as with the preceding discussion of acceptance angle, we are concerned with meridional rays within the fiber. Figure 2.5 shows a light ray incident on the fiber core at an angle θ1 to the fiber axis which is less than the acceptance angle for the fiber θa. The ray enters the fiber from a



Medium (air) of refractive index n0, and the fibre core has a refractive index n1, which is slightly greater than the cladding refractive index n2.

Assuming the entrance face at the fibre core to be normal to the axis, then considering the refraction at the air–core interface and using Snell's law given by Eq.:

n0 sin θ1 = n1 sin θ2 ………………… (1)

Considering the right-angled triangle ABC indicated in Figure, then:

ϕ = − θ2 ,………………..(2) where ϕ is greater than the critical angle at the core–cladding interface.

Hence equation 1 becomes: n0 sin θ1 = n1 cos ϕ

Using the trigonometrically relationship sin2 ϕ + cos2 ϕ = 1, may be written in the form:

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{\frac{1}{2}}$$

When the limiting case for total internal reflection is considered, ϕ becomes equal to the critical angle for the core–cladding interface and is given by

. Also in this limiting case θ1 becomes the acceptance angle for the fibre θa.

Combining these limiting cases gives:

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

Apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the numerical aperture (NA). Hence the NA is defined as: NA = n0 sin θa = $(n1^2 - n2^2)^{1/2}$.

3.(b)A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47. Determine: (a) the critical angle at the core–cladding interface; (b) the NA for the fiber; (c) the acceptance angle in air for the fiber.

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50}$$
$$= 78.5°$$

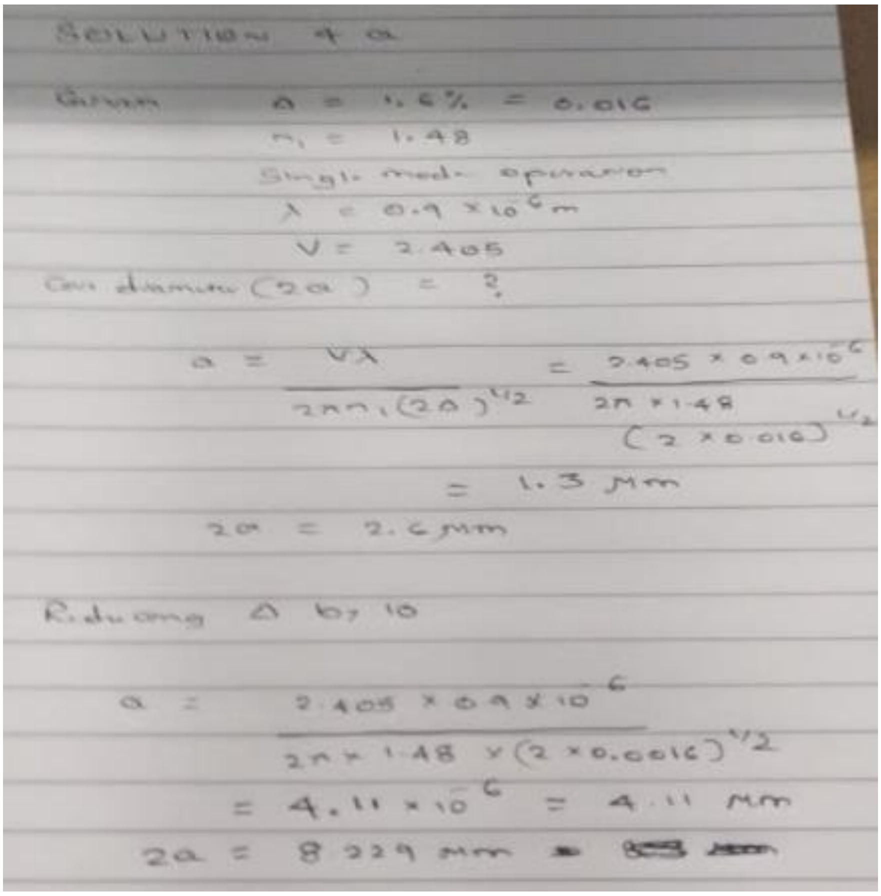
(b) From Eq. (2.8) the *NA* is:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.50^2 - 1.47^2)^{\frac{1}{2}}$$
$$= (2.25 - 2.16)^{\frac{1}{2}}$$
$$= 0.30$$

(c) Considering Eq. (2.8) the acceptance angle in air θ_a is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30$$
$$= 17.4°$$

4.(a) Estimate the maximum core diameter for an optical fiber with refractive index difference of 1.6% and a core refractive index of 1.48, in order that it may be suitable for single mode operation for an operating wavelength of 0.9 µm. Further estimate the maximum core diameter for a single mode operation when the relative refractive index difference is reduced by a factor of 10. Assume V number as 2.405.


SOLUTION 4 a

Given $\Delta = 1.6\% = 0.016$

$n_1 = 1.48$

Single mode operation

$\lambda = 0.9 \times 10^{-6}$ m

$V = 2.405$

Core diameter $(2a)$ = ?

$$a = \frac{V\lambda}{2\pi n_1 (2\Delta)^{1/2}} = \frac{2.405 \times 0.9 \times 10^{-6}}{2\pi \times 1.48 \, (2 \times 0.016)^{1/2}}$$

$= 1.3$ Mm

$2a = 2.6$ Mm

Reducing Δ by 10

$$a = \frac{2.405 \times 0.9 \times 10^{-6}}{2\pi \times 1.48 \times (2 \times 0.0016)^{1/2}}$$

$= 4.11 \times 10^{-6} = 4.11$ Mm

$2a = 8.229$ Mm ≈ [redacted]

4.(b)A Multimode graded index fiber has a core with a parabolic refractive index profile, with a diameter of 50 µm. The fiber has an NA of 0.2. Estimate the total number of propagating modes at a wavelength of 1µm.

Core diameter = 50 micrometer

core radius= 25 micrometer

N.A. = 0.2

Mg= V2/2

V= 2xpi x 25x10-6 x 0.2 /(1x10-6) = 31.41

Mg= (31.41)2 / 2 = 246.64= 247

5. (a) Explain modes of optical fiber and different types of optical fiber based upon fiber profile.

2.3.2 Modes in a planar guide

The planar guide is the simplest form of optical waveguide. We may assume it consists of a slab of dielectric with refractive index n_1 sandwiched between two regions of lower refractive index n_2. In order to obtain an improved model for optical propagation it is useful to consider the interference of plane wave components within this dielectric waveguide.

The conceptual transition from ray to wave theory may be aided by consideration of a plane monochromatic wave propagating in the direction of the ray path within the guide (see Figure 2.8(a)). As the refractive index within the guide is n_1, the optical wavelength in this region is reduced to λ/n_1, while the vacuum propagation constant is increased to n_1k. When θ is the angle between the wave propagation vector or the equivalent ray and the

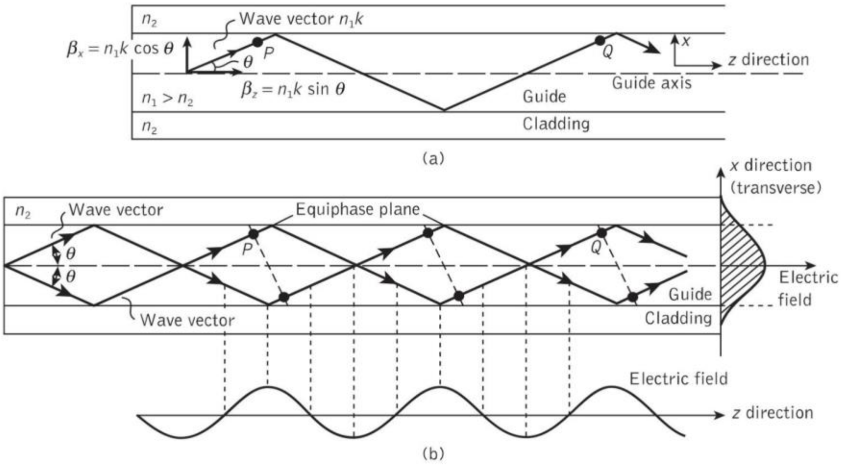


Figure 2.8 The formation of a mode in a planar dielectric guide: (a) a plane wave propagating in the guide shown by its wave vector or equivalent ray – the wave vector is resolved into components in the *z* and *x* directions; (b) the interference of plane waves in the guide forming the lowest order mode ($m = 0$)

guide axis, the plane wave can be resolved into two component plane waves propagating in the z and x directions, as shown in Figure 2.8(a). The component of the phase propagation constant in the z direction β_z is given by:

$$\beta_z = n_1 k \cos\theta \quad (2.34)$$

The component of the phase propagation constant in the x direction β_x is:

$$\beta_x = n_1 k \sin\theta \quad (2.35)$$

The component of the plane wave in the x direction is reflected at the interface between the higher and lower refractive index media. When the total phase change* after two successive reflections at the upper and lower interfaces (between the points P and Q) is equal to $2m\pi$ radians, where m is an integer, then constructive interference occurs and a standing wave is obtained in the x direction. This situation is illustrated in Figure 2.8(b), where the interference of two plane waves is shown. In this illustration it is assumed that the interference forms the lowest order (where $m = 0$) standing wave, where the electric field is a maximum at the center of the guide decaying towards zero at the boundary between the guide and cladding. However, it may be observed from Figure 2.8(b) that the electric field penetrates some distance into the cladding, a phenomenon which is discussed in Section 2.3.4.

Nevertheless, the optical wave is effectively confined within the guide and the electric field distribution in the x direction does not change as the wave propagates in the z direction. The sinusoidally varying electric field in the z direction is also shown in Figure 2.8(b). The stable field distribution in the x direction with only a periodic z dependence is known as a mode. A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface have a particular value, as indicated in Figure 2.8(b). In effect, Eqs (2.34) and (2.35) define a group or congruence of rays which in the case described represents the lowest order mode. Hence the light propagating within the guide is formed into discrete modes, each typified by a distinct value of θ. These modes have a periodic z dependence of the form $\exp(-\mathrm{j}\beta_z z)$ where β_z becomes the propagation constant for the mode as the modal field pattern is invariant except for a periodic z dependence. Hence, for notational simplicity, and in common with accepted practice, we denote the mode propagation constant by β, where $\beta = \beta_z$. If we now assume a time dependence for the monochromatic electromagnetic light field with angular frequency ω of $\exp(\mathrm{j}\omega t)$, then the combined factor $\exp[\mathrm{j}(\omega t - \beta z)]$ describes a mode propagating in the z direction.

To visualize the dominant modes propagating in the z direction we may consider plane waves corresponding to rays at different specific angles in the planar guide. These plane waves give constructive interference to form standing wave patterns across the guide following a sine or cosine formula. Figure 2.9 shows examples of such rays for $m = 1, 2, 3$, together with the electric field distributions in the x direction. It may be observed that m

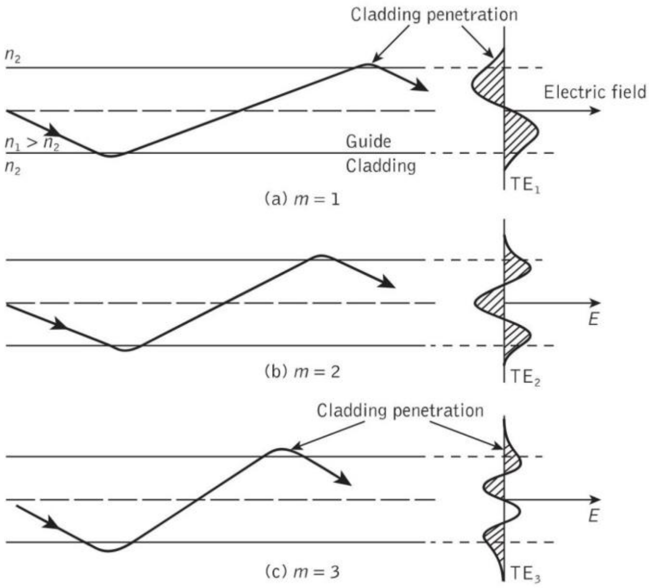


Figure 2.9 Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models ($m = 1, 2, 3$) in the planar dielectric guide

denotes the number of zeros in this transverse field pattern. In this way m signifies the order of the mode and is known as the mode number.

When light is described as an electromagnetic wave it consists of a periodically varying electric field **E** and magnetic field **H** which are orientated at right angles to each other. The transverse modes shown in Figure 2.9 illustrate the case when the electric field is perpendicular to the direction of propagation and hence $E_z = 0$, but a corresponding component of the magnetic field **H** is in the direction of propagation. In this instance the modes are said to be transverse electric (TE). Alternatively, when a component of the **E** field is in the direction of propagation, but $H_z = 0$, the modes formed are called transverse magnetic (TM). The mode numbers are incorporated into this nomenclature by referring to the TE_m and TM_m modes, as illustrated for the transverse electric modes shown in Figure 2.9. When the total field lies in the transverse plane, transverse electromagnetic (TEM) waves exist where both E_z and H_z are zero. However, although TEM waves occur in metallic conductors (e.g. coaxial cables) they are seldom found in optical waveguides.

2.4 Cylindrical fiber

2.4.1 Modes

The exact solution of Maxwell's equations for a cylindrical homogeneous core dielectric waveguide* involves much algebra and yields a complex result [Ref. 15]. Although the

presentation of this mathematics is beyond the scope of this text, it is useful to consider the resulting modal fields. In common with the planar guide (Section 2.3.2), TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder. The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, l and m, are necessary in order to specify the modes, in contrast to the single integer (m) required for the planar guide. For the cylindrical waveguide we therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays (see Section 2.2.1) traveling within the fiber. However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide. These modes, which result from skew ray propagation (see Section 2.2.4) within the fiber, are designated HE_{lm} and EH_{lm} depending upon whether the components of **H** or **E** make the larger contribution to the transverse (to the fiber axis) field. Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.

Fortunately, the analysis may be simplified when considering optical fibers for communication purposes. These fibers satisfy the weakly guiding approximation [Ref. 16] where the relative index difference $\Delta \ll 1$. This corresponds to small grazing angles θ in Eq. (2.34). In fact Δ is usually less than 0.03 (3%) for optical communications fibers. For weakly guiding structures with dominant forward propagation, mode theory gives dominant transverse field components. Hence approximate solutions for the full set of HE, EH, TE and TM modes may be given by two linearly polarized components [Ref. 16]. These linearly polarized (LP) modes are not exact modes of the fiber except for the fundamental (lowest order) mode. However, as Δ in weakly guiding fibers is very small, then HE–EH mode pairs occur which have almost identical propagation constants. Such modes are said to be degenerate. The superpositions of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations. This linear combination of degenerate modes obtained from the exact solution produces a useful simplification in the analysis of weakly guiding fibers.

The relationship between the traditional HE, EH, TE and TM mode designations and the LP_{lm} mode designations is shown in Table 2.1. The mode subscripts l and m are related to the electric field intensity profile for a particular LP mode (see Figure 2.15(d)). There are in general $2l$ field maxima around the circumference of the fiber core and m field

Table 2.1 Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

Linearly polarized	*Exact*
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1,m}$, $EH_{l-1,m}$

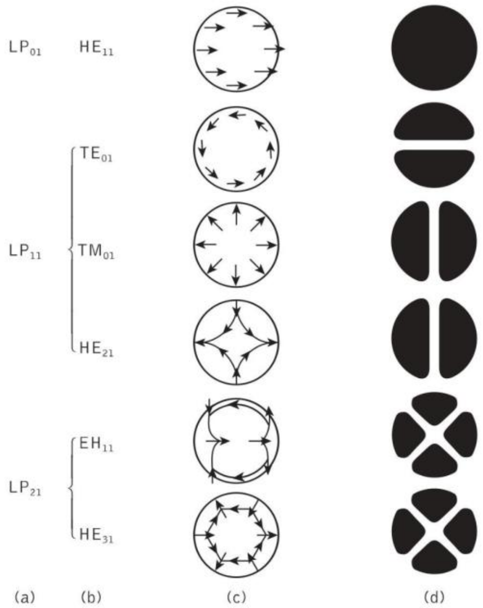


Figure 2.15 The electric field configurations for the three lowest LP modes illustrated in terms of their constituent exact modes: (a) LP mode designations; (b) exact mode designations; (c) electric field distribution of the exact modes; (d) intensity distribution of E_x for the exact modes indicating the electric field intensity profile for the corresponding LP modes

maxima along a radius vector. Furthermore, it may be observed from Table 2.1 that the notation for labeling the HE and EH modes has changed from that specified for the exact solution in the cylindrical waveguide mentioned previously. The subscript l in the LP notation now corresponds to HE and EH modes with labels $l+1$ and $l-1$ respectively.

The electric field intensity profiles for the lowest three LP modes, together with the electric field distribution of their constituent exact modes, are shown in Figure 2.15. It may be observed from the field configurations of the exact modes that the field strength in the transverse direction (E_x or E_y) is identical for the modes which belong to the same LP mode. Hence the origin of the term 'linearly polarized'.

5. (b) 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: (a) the normalized frequency for the fiber; (b) the number of guided modes.

Solution: (a) The normalized frequency may be obtained from Eq. (2.70) where:

$$V \simeq \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = \frac{2\pi \times 40 \times 10^{-6} \times 1.48}{0.85 \times 10^{-6}} (2 \times 0.015)^{\frac{1}{2}} = 75.8$$

(b) The total number of guided modes is given by Eq. (2.74) as:

$$M_s \simeq \frac{V^2}{2} = \frac{5745.6}{2}$$

$$= 2873$$

Hence this fiber has a V number of approximately 76, giving nearly 3000 guided modes.

6. A step index multimode fiber with a numerical aperture of 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?

Solution : i) Number of modes is given by,

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

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

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

a = **60.49 μm**

ii)

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

M = $(14.39)^2$ = **207.07**

iii)

$$M = \frac{1}{2}\left[\frac{\pi \times 6.49 \times 10^{-6}}{1320 \times 10^{-9}} \times 0.20\right]^2$$

M = **300.63**

7. (a) Explain photonic crystal fiber.

Photonic Crystal Fibers

A new class of microstructured optical fiber containing a fine array of air holes running longitudinally down the fiber cladding has been developed. Since the microstructure within the fiber is often highly periodic due to the fabrication process, these fibers are usually referred to as photonic crystal fibers (PCFs), or sometimes just as holey fibers. Whereas in conventional optical fibers electromagnetic modes are guided by total internal reflection in the core region, which has a slightly raised refractive index, in PCFs two distinct guidance mechanisms arise. Although the guided modes can be trapped in a fiber core which exhibits a higher average index than the cladding containing the air holes by an effect similar to total internal reflection, alternatively they may be trapped in a core of either higher, or indeed lower, average index by a photonic bandgap effect. In the former case the effect is often termed modified total internal reflection and the fibers are referred to as index guided, while in the latter they are called photonic bandgap fibers. Furthermore, the existence of two different guidance mechanisms makes PCFs versatile in their range of potential applications. For example, PCFs have been used to realize various optical components and devices including long period gratings, multimode interference power splitters, tunable coupled cavity fiber lasers, fiber amplifiers, multichannel add/drop filters, wavelength converters and wavelength demultiplexers. As with conventional optical fibers, however, a crucial issue with PCFs has been the reduction in overall transmission losses which were initially several hundred decibels per kilometer even with the most straightforward designs. Increased control over the homogeneity of the fiber structures together with the use of highly purified silicon as the base material has now lowered these losses to a level of a very few decibels per kilometre for most PCF types, with a loss of just 0.3 dB km^{-1} at 1.55 μm for a 100 km span being recently reported.

Index-guided microstructures

Although the principles of guidance and the characteristics of index-guided PCFs are similar to those of conventional fiber, there is greater index contrast since the cladding contains air holes with a refractive index of 1 in comparison with the normal silica cladding index of 1.457 which is close to the germanium-doped core index of 1.462. A fundamental physical difference, however, between index-guided PCFs and conventional fibers arises from the manner in which the guided mode interacts with the cladding region. Whereas in a conventional fiber this interaction is largely first order and independent of wavelength, the large index contrast combined with the small structure dimensions cause the effective cladding index to be a strong function of wavelength. For short wavelengths the effective cladding index is only slightly lower than the core index and hence they remain tightly confined to the core. At longer wavelengths, however, the mode samples more of the cladding and the effective index contrast is larger. This wavelength dependence results in large number of unusual optical properties which can be tailored. For example, the high index contrast enables the PCF core to be reduced from around 8 μm in conventional fiber to less than 1 μm, which increases the intensity of the light in the core and enhances the nonlinear effects.


(a)


(b)

Two common index-guided PCF designs are shown diagrammatically in Figure. In both cases a solid-core region is surrounded by a cladding region containing air holes. The cladding region in Figure(a) comprises a hexagonal array of air holes while in Figure (b) the cladding air holes are not uniform in size and do not extend too far from the core. It should be noted that the hole diameter d and hole to hole spacing or pitch Λ are critical design parameters used to specify the structure of the PCF. For example, in a silica PCF with the structure depicted in Figure (a) when the air fill fraction is low (i.e. $d/\Lambda < 0.4$), then the fiber can be single-moded at all wavelengths.

This property, which cannot be attained in conventional fibers, is particularly significant for broadband applications such as wavelength division multiplexed transmission. As PCFs have a wider range of optical properties in comparison with standard optical fibers, they provide for the possibility of new and technologically important fiber devices. When the holey region covers more than 20% of the fiber cross-section, for instance, index-guided PCFs display an interesting range of dispersive properties which could find application as dispersion-compensating or dispersion-controlling fiber components. In such fibers it is possible to produce very high optical nonlinearity per unit length in which modest light intensities can induce substantial nonlinear effects. For example, while several kilometers of conventional fiber are normally required to achieve 2R data regeneration, it was obtained with just 3.3 m of large air-filling fraction PCF. In addition, filling the cladding holes with polymers or liquid crystals allows external fields to be used to dynamically vary the fiber properties. The temperature sensitivity of a polymer within the cladding holes may be employed to tune a Bragg grating written into the core. By contrast, index-guided PCFs with small holes and large hole spacings provide very large mode area (and hence low optical nonlinearities) and have potential applications in high-power delivery (e.g. laser welding and machining) as well as high-power fiber lasers and amplifiers. Furthermore, the large index contrast between silica and air enables production of such PCFs with large multimoded cores which also have very high numerical aperture values (greater than 0.7). Hence these fibers are useful for the collection and transmission of high optical powers in situations where signal distortion is not an issue. Finally, it is apparent that PCFs can be readily spliced to conventional fibers, thus enabling their integration with existing components and subsystems.

Photonic bandgap fibers

Photonic bandgap (PBG) fibers are a class of microstructured fiber in which a periodic arrangement of air holes is required to ensure guidance. This periodic arrangement of cladding air holes provides for the formation of a photonic bandgap in the transverse plane of the fiber. As a PBG fiber exhibits a two-dimensional bandgap, then wavelengths within this bandgap cannot propagate perpendicular to the fiber axis (i.e. in the cladding) and they can therefore be confined to propagate within a region in which the refractive index is lower than the surrounding material. Hence utilizing the photonic bandgap effect light can, for example, be guided within a low-index, air-filled core region creating fiber properties quite different from those obtained without the bandgap. Although, as with index-guided PCFs, PBG fibers can also guide light in regions with higher refractive index, it is the lower index region guidance feature which is of particular interest. In addition, a further distinctive feature is that while index-guiding fibers usually have a guided mode at all wavelengths, PBG fibers only guide in certain wavelength bands, and furthermore it is possible to have wavelengths at which higher order modes are guided while the fundamental mode is not.

Two important PBG fiber structures are displayed in Figure. The honeycomb fiber design shown in Figure (a) was the first PBG fiber to be experimentally realized in 1998. A triangular array of air holes of sufficient size as displayed in Figure (b), however, provides for the possibility, unique to PBG fibers, of guiding electromagnetic modes in air. In this case a large hollow core has been defined by removing the silica around seven air holes in the center of the structure. These fibers, which are termed air-guiding or hollow-core PBG fibers, enable more than 98% of the guided mode field energy to propagate in the air regions. Such air-guiding fibers have attracted attention because they potentially provide an environment in which optical propagation can take place with little attenuation as the localization of light in the air core removes the limitations caused by material absorption losses. The fabrication of hollow-core fiber with low propagation losses, however, has proved to be quite difficult, with losses of the order of 13 dB km−1. Moreover, the fibers tend to be highly dispersive with narrow transmission windows and while single-mode operation is possible, it is not as straightforward to achieve in comparison with index-guiding PCFs.

More recently, the fabrication and characterization of a new type of solid silica-based photonic crystal fiber which guides light using the PBG mechanism has been reported. This fiber employed a two-dimensional periodic array of germanium-doped rods in the core region. It was therefore referred to as a nanostructure core fiber and exhibited a minimum attenuation of 2.6 dB km−1 at a wavelength of 1.59 µm. Furthermore, the fiber displayed greater bending sensitivity than conventional singlemode fiber as a result of the much smaller index difference between the core and the leaky modes which could provide for potential applications in the optical sensing of curvature and stress. In addition, it is indicated that the all-solid silica structure would facilitate fiber fabrication using existing technology, and birefringence of the order of 10−4 is easily achievable with a large mode field diameter up to 10 µm, thus enabling its use within fiber lasers and gyroscope applications.

7. (b) A multimode step index fiber has a relative refractive index difference of 1% and a core refractive index of 1.5. The number of modes propagating at a wavelength of 1.3 µm is 1100. Estimate the diameter of the fiber core.

$$\Delta = 1.0\% = 0.01$$

$$n_1 = 1.5$$

$$\lambda = 1.3 * 10^{-6}$$

$$M = 1100$$

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

$$NA = 1.5(2 * 0.01)^{1/2}$$

$$NA = 0.2121$$

$$M = \frac{1}{2}\left(\frac{\pi d}{\lambda} NA\right)^2$$

$$1100 = \frac{1}{2}\left(\frac{\pi d}{1.3 * 10^{-6}} * 0.2121\right)^2$$

$$d = 91.5\mu m$$