CHAPTER (I)

GENERAL INTRODUCTION
1.1 **Introduction:**

In this thesis, a theoretical study of the modal characteristics of some optical waveguides with unconventional geometrical shapes of the core-cladding boundary cross-section has been presented. Before going into the subject matters of the thesis, it is necessary to indicate the context by outlining the development of the fields of optical communication and integrated optics. Some concepts, definitions and standard theoretical techniques associated with the analysis of waveguide characteristics should also be explained before a detailed account of the work reported here becomes intelligible and relevant to the already rich field of optical waveguides. A brief survey of the extensive literature in the field is also a prerequisite for the presentation of the investigation undertaken here. This chapter briefly provides the necessary background material.

The last few decades have seen a tremendous advance in lightwave communication systems, integrated optical communication technology, and general data processing application [1-4]. The advent of the semiconductor lasers and the recent advances in opto-electronics have resulted in the use of the infrared and visible parts of the electromagnetic spectrum for optical communication purposes. This revolutionary new technology is transforming the communication networks of the world. Huge quantities of information in the form of voice signals, video and digital data can be rapidly and efficiently transmitted from one place to another by using an ever-expanding grid of optical waveguides. In this way this new technology has shrunk the physical size of the world. Some basic concepts on general and optical communication theory and practice, general waveguide theory, integrated optical devices,
optical sources, and primary definitions and formulae are to be discussed in the following sections.

1.2 Historical background for the development of the optical communication system:

Since the dawn of civilization, man has felt the necessity of communicating with each other. Early attempts for long distance communication included various means like smoke signals, carrier pigeons, light beams and letters transported by a variety of ways. An early solution to long distance communication was provided by using electrical signals over a pair of wires or coaxial cables. During and after World War II, there was a vast growth in the field of electrical communication through radar, microwave systems, transistors, integrated circuits and communicating satellites etc. Today electrical communication systems span the entire world carrying voice, data, text, pictures and a variety of other messages and news.

Communication means the transfer of news or messages from one place to another. There are different ways of communication depending on the nature of the information to be sent. Speech and music are transmitted directly from their source to the listeners across short distances by means of sound or acoustic waves. A picture is similarly transmitted directly by light or optical waves across a short distance. When the information is to be sent over longer distances, a proper communication system is needed. Any information can be transmitted by superimposing (or modulating) the information on an electromagnetic wave called the carrier wave. The modulated wave is transmitted to its destination where it is demodulated and the original information is restored. There are various types of communication channels depending upon the frequency range of the carrier waves, [Figure
(1.2.1)], the distance between the transmitter and receiver and different applications. Of these, there are some channels (media) where the waves are unguided and others where the waves are guided.

A medium or channel of transmission where the waves are unguided is the atmosphere itself which is widely used in commercial radio broadcasting, television, microwave relay links in television, etc. However, for communication from one place to another, the guided waves are much more advantageous than the unguided ones. The guided waves offer confidentiality, remain unaffected by atmospheric turbulence and can carry much more information without a significant loss of power.

Low frequency radio waves can be transmitted through guided channels like a pair of copper wires. However, for high frequency radio waves, coaxial cables are used as the guiding channels. At microwave frequencies, hollow metal pipes called waveguides are used for guiding. The carrier waves can be transmitted over a long distance through all these channels but their massage carrying capacity is very small and limited. The information carrying capacity is indirectly related to the bandwidth or frequency extent of the modulated carrier, which is generally limited to a fixed fraction of the carrier frequency. Thus, the greater the carrier frequency, the larger is the available bandwidth. Due to this reason, radio communication was extended to high frequencies (V.H.F and U.H.F), leading to the introduction of microwaves with still higher frequencies and also to the millimeter wave transmission. Such communication systems are called electrical communication systems. A communication system using electromagnetic waves of wavelength \( \lambda = 10^{-6}\text{m} \) to \( 10^{-9}\text{m} \) is called an optical communication system. In the case of optical frequency electromagnetic wave
Fig. 12.1 The electromagnetic spectrum showing the region used for optical fiber communications.

- Frequency (Hz)
- 10, 100, 10^3, 10^4, 10^5, 10^7 km
- 3000, 30 km, 3 m, 3 cm, 3 mm, 3 pm, 0.3 pm, 0.3 mm, 0.3 nm, 0.3 m, 0.3 km

- Long wave
- Standard wave
- Short wave
- Ultraviolet
- X-rays
- Gamma rays
- Cosmic rays
- Infrared
- Microwave
- Millimeter wave
- VHF
- UHF
- Radio frequencies
- Shortwave
- Ultraviolet
- Visible spectrum
- Red
- Near infrared
- Microwave
- Millimeter wave
- VHF
- UHF
- Radio frequencies
- Shortwave
- Ultraviolet
- Visible spectrum
- Red
- Near infrared
transmission, the available bandwidth is $10^4$ times greater than that of in the case of microwave transmission. Therefore, using optical frequency transmission, much more information can be sent with low loss of power. Light has a frequency in the range of $10^{14}$ to $10^{15}$ Hz, compared to radio frequencies of about $10^9$ Hz and microwave frequencies of $10^8$ to $10^{16}$ Hz. Therefore, a transmission system that operates at the frequency of light can theoretically transmit information at a higher rate than systems that operate at radio or microwave frequencies. Thus, it seemed worthwhile to develop an optical wave technology in which optical waves could act as carrier waves and optical waveguides as guiding channels.

Although hand signals, fires etc., could be taken as examples of light wave communication in its earliest form, the first lightwave communication device was the photophone, invented by Sir Alexander Graham Bell [5] in 1880. Although this device worked well up to a distance of 200m, it remained discarded in favour of electrical telephony due to the lack of suitable optical sources. Investigators in this field were also looking for a suitable guiding system through which information could be transmitted by guiding the lightwaves. The transmission of light in a dielectric waveguide structure was first proposed and investigated at the beginning of twentieth century. In 1910, Hondros and Debye [6] conducted a theoretical study and experimental work was reported by Selhriever in 1920 [7]. However, a transparent dielectric rod made of silica glass with a refractive index around 1.5, surrounded by air, proved to be an impractical waveguide due to its unsupported structure and heavy loss. The invention of the laser in 1960, [8] instigated a tremendous research effort into the study of optical waveguides for the transportation and distribution of information at a high rate with
Fig. 1.2.2 A Cylindrical silica pipe as an Optical waveguide (fiber)
<table>
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<tr>
<th>Application</th>
<th>Source</th>
<th>Detector</th>
<th>Specimen</th>
<th>Repetitor</th>
<th>Loss</th>
<th>Type of Fiber</th>
<th>Operating Wavelength (nm)</th>
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considerably low loss. The optical lasers are analogous to radio frequency (RF) oscillators and can serve as information carriers. Because of their high frequency ($10^{14}$Hz), they can theoretically accommodate many orders of magnitude more bandwidth of information than can an RF information carrier. During this early period a new structure was proposed for guiding light and this was called an optical waveguide (fiber). This structure is shown in Figure (1.2.2) having a core of refractive index $n_1$, slightly greater than the refractive index $n_2$ of the cladding. The first serious proposals were made by Kao and Hockhan [9] and Werts [10] in 1966 to utilize such a structure as a communication channel even though it had losses in excess of $10^3$dB/Km. They proposed that these high losses were due to the impurities of the fiber material. These proposals stimulated efforts to reduce the losses by the purification of the constituting materials. Further studies in this resulted in the first practical realization of an optical fiber with low loss ($<20$dB/Km) in 1970. The fibers made of the fluoride based glasses shows the lowest loss ($10^{-12} \rightarrow 10^{-13}$dB/Km) at the wavelength region 4-6μm; whereas the silica fibers show the lowest loss at $λ=1.55$μm. Intensive effort in this direction for the search of extremely low loss fibers in the far infrared region is evident from a number of research papers available in the literature [11-19]. These recent developments in the field of optical waveguide are here presented in the chronological order in Table (1.2.1).

1.3 The basic components of an optical communication systems:

Communication technology got a boost after the invention of the first laser in 1960. Laser radiation is coherent, very intense and highly monochromatic in nature. The problem of the non-availability of enormous bandwidth for communication purposes was solved by using the He-Ne laser system. In
1966, Kao and Hockham pointed out that for low loss of power, a cylindrical silica pipe must be used as an optical fiber. This foresight of Charles K. Kao and Hockham [9] on the use of glass optical waveguides for long distance optical information transmission has proved to be one of the most remarkable events in the history of modern communication technology.

The lightwave communication system is similar in the basic outline to any other communication system [20-26]. A communication system may be defined as a system to transmit massage carrying signals from a source situated at one point in space to a user destination located at another point. A block diagram of a basic communication system is shown in Figure (1.3.1). The main components are:

a) the optical source;
b) a means of modulating the optical output from; the source with the signal to be transmitted;
c) the transmission medium;
d) the photo-detector which converts the received optical power back into an electrical waveform;
e) electronic amplification and signal processing required to recover the signal and present it in a form suitable for use.

The block diagram Figure (1.3.1) may also be used to represent analog or digital, guided or unguided systems. Thus we learn that the optical light source generates the optical energy which serves as the information carrier, just as a radio wave source supplies electromagnetic energy at radiowave wavelength serving as the information carrier. The optical photodetector detects the optical energy and converts it in to an electrical form. The optical
Fig. 1.3.1 A block diagram of a basic Communication system.
(a) General Communication system.
(b) Optical fiber Communication system.
fiber transmission line is equivalent to a pair of copper wires and functions as the conductor of optical energy.

When optical waveguides are used as transmission channels, semiconductor light-emitting diode (LED) and laser sources and semiconductor junction photodiode detectors are sensibly compatible. A great merit of the semiconductor sources is that their optical output power can be modulated directly and very easily by controlling the flow of electric current. But the choice of detectors depends upon the physical size of the system.

The optical carrier waves can be modulated in two ways: (1) by using an analog information signal (2) by using a digital information signal. In the case of analog modulation the light emitted from the optical source varies continuously, whereas in the case of digital modulation, light intensity changes discretely (i.e., on-off pulses). In the case of an optical fiber communication system, analog modulation is less efficient than digital modulation. Therefore, analog optical communication links are generally limited to shorter distances and lower bandwidths than digital links. The most modern communication systems are “digital” because of the excellent transmission quality that can be achieved. In a simple digital communication system (Figure 1.3.2) all information is encoded into binary digits consisting of zeroes or ones and combined through a multiplexer. The signal from the multiplexer is used to turn a laser or light emitting diode (LED) on and off at a given transmission rate. The light generated in this manner is transmitted through an optical fiber, and then the output signal falls on a photodetector. The electric signal generated at the photodetector is fed into a demultiplexer, which separates the various signals and routes them to their final destination.
Fig. 1.3.2 A Simple Digital Optical Communication System.
In digital optical communication, the efficiency of the system is measured mainly by the efficiency of the medium used for the transmission of light wave signals. In the coming years, these fiber-based lightwave communication systems will increasingly be used to carry voice, video and computer data across the country and across the world.

1.4 **Superiority of optical communications over electrical communication:**

Light wave communication through a dielectric channel is much superior to the conventional electrical communication through copper wires or coaxial cables. Some special characteristics of optical fiber communication are given below.

(1) **Potential larger bandwidth:**

Light wave has a frequency in the range of $10^{14}$-$10^{15}$Hz, compared to radio frequencies of about $10^9$Hz and microwave frequencies of $10^8$-$10^{10}$Hz. Since the carrier frequency is directly proportional to the available bandwidth, for optical frequency electromagnetic wave transmission, the available bandwidth is $10^4$ times greater than that in microwave transmission. Hence using optical frequency transmission, much more information can be sent over longer distances, with a very small loss of power. This superior information carrying capacity makes them an attractive alternative to copper wires and coaxial cables. Thus a major attraction of fiber optics is its capacity to send high-speed signals over a long distance with low attenuation.

(2) **Potential low transmission loss:**

Optical fiber attenuation depends on the wavelength of the light of optical sources as shown in Figure (1.4.1). Early fiber links exclusively used the 800-900nm range, where there was a local attenuation minimization called the
Fig. 1.4.1 Optical fiber attenuation as a function of wavelength.
first-window [25]. Achievement of lower attenuations created an interest in longer wavelengths around 1300nm called the second-window, and there is a third-window around 1550nm operation. The recent development of optical fibers has resulted in the fabrication of optical fiber cables which show very low transmission loss in comparison with the best copper wires. By reducing the concentration of OH ions and metallic ion impurities in the fiber material, recently fibers have been fabricated with losses as low as 0.2dB/Km. This low loss property of the optical fiber cables reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Therefore, optical fibers are able to send the message over a very long distance with very small loss.

(3) *Hair-sized dimension and light weight* :
Optical fibers are as thin as human hair having very small weight compared with that of the conventional copper cables. This is a great boon and makes it possible to reduce duct congestion in cities and also permits an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

(4) *Electrical isolation or insulation* :
Since optical fibers are made up of dielectric materials (glass or plastic polymers), they act as good insulators. They are ideally suited for communication in electrically hazardous environment as they create no arcing or sparking in short circuits. Further there is no cross talk of the nature known in conventional cables.

(5) *Immunity to interference and crosstalk* :
The dielectric medium of a fiber is immune to electromagnetic interference and thus enjoys noise immunity. It is fairly easy to ensure that there is no optical interference between fibers and crosstalk is negligible, even when
many fibers are cabled together. This is a great advantage over copper cable communication systems where crosstalk cannot be eliminated.

(6) *Signal security* :

By using an optical fiber, a high degree of data security is obtained, since the optical signal is well confined within the core of the optical waveguide covered by the cladding and jacket. This makes them attractive in military banking and computer network applications where security is on top priority.

(7) *Flexibility and roughness* :

Optical fibers are fabricated with very light tensile strengths, so that they can be bent to quite small radii or twisted without break. These fibers are externally rough, flexible and compact. Therefore, the optical fiber cables are far superior in terms of the storage, transmission, handling and installation to corresponding copper cables.

(8) *Potential low cost* :

Generally glass is used as a transmission channel (medium) in optical fibers and this glass is made up of sand which is very cheap, though the cost increases when the glass is purified. The cost of lasers, detector photodiodes etc. are relatively high. The overall cost, however, remains reasonably low.

(9) *Wide temperature working ability* :

The optical fibers are made of inorganic glasses. The melting point of high-silica-glass is at least 600°C. The refractive-index change with temperature is about 0.0001°C [26]. This shows that optical fibers can work at high temperature without damage and with negligible change in the refractive index of the core of the fiber.
1.5 **Disadvantages of optical fibers**:
The use of fibers for optical communication does have some drawbacks in practice. Hence to provide a balanced picture, these disadvantages must be considered. They are:
(I) the fragility of the bare fiber;
(II) the small size of the fibers and cables which creates some difficulties with splicing and forming connectors;
(III) some problems concerning the forming of low-loss T-Couplers;
(IV) the presence of moisture may affect the long-term reliability of optical fibers;
(V) independent electrical power feeds are required for electronic repeaters.
But some disadvantages are there not only in optical fiber systems, but are always present whenever a new technology is introduced. But by both continuing development and increased experience with optical fiber systems, these problems are being gradually tackled.

1.6 **Fiber optic applications**:
Bundles of fibers used for transmitting light in one direction, either independently or connected to a fiber-optic viewing instruments, are termed lightguides. In the opto-electronic context, where scanning and process control fiber-optic instruments are used, the word probe is used. Probes transmit light by a coaxial arrangement of optical fibers in both directions. This ability to transmit light in either direction along straight or curved paths is the foundation of fiber-optic technology and a useful component for other technologies. There are three types of optical fiber systems.
(a) Transmission systems
(b) Distribution systems
(c) Sensor systems.

(a) Transmission systems are point to point links. Because of the low loss and high band-width transmission characteristics such optical fiber systems operate with advantage for many different applications. The more important uses are:

1) for the public telephone/data trunk network,
2) for cable T.V. network and cable T.V. trunking,
3) for improved privacy and tamperproof link,
4) for military applications:
    interbase link, entrance link, mobile link, weapon guidance etc.

(b) Distribution systems are multiuser-multiservice systems aimed at singly and multiply interconnected modes of usages. The more important uses are:

1) for the integrated multiservice network:
   wired office, wired city and computer network.
2) for the cable T.V. network and distribution

(c) Sensor systems employ a fiber not as a transmission medium, but as a sensor. The ability of single mode fibers to transmit coherent radiation and retain the phase information enables fibers to be used in sensor systems. Thus one may use a fiber as a gyroscope, an acoustic sensor or a temperature sensor. Optical sensors are used to measure pressure, rotation, soundwaves, magnetic fields and many other quantities. Also fiber optic bundles are used for illumination and imaging, such as endoscopes to view the inside of the body and treat diseases with light (lasers) and without surgery.

Fiber optics technology holds promise of providing a telecommunication network that will bring the entire world to an individual's
living room. Optoelectronics in telecommunications has two main areas of thrust:

(a) Optical memories for stored programme control (SPC) switching and
(b) fiber optics for telecommunications.

Fiber optics can be broadly classified into the present generation technology-based silica fibers operated in the 800-1600 nm wavelength, and the future generation of fibers in the infrared range over the 2-30 μm region.

Developments in the areas of fibers and equipment are intended to produce high performance and low cost fiber optic elements providing future safe implementation of the technology.

1.7 Integrated optics:

In 1966, Anderson [27] suggested that a microfabrication technology could be developed for single-mode optical devices with semiconductor and dielectric materials in a similar way as in electronic circuits. The term “integrated optics” was first introduced by Miller in 1966 [28]. Integrated optics is the technology of the constructing optical devices and network on suitable substrates [29-32]. It is similar to the construction of integrated electronic circuits.

Thus integrated optics is the optical counterpart of integrated electronics, and is primarily based on the fact that lightwaves can be guided and confined in very thin films (with dimensions ~ wavelength of light) of transparent materials on suitable substrates. By a proper choice of substrates and films and a proper configuration of the waveguides, one can perform a wide range of operations such as modulation, switching, filtering, multiplexing or generation of optical waves. Such circuits are expected to be
compact, lightweight, of faster response and larger bandwidth and compatible with a single mode fiber optic system.

Integrated optics is expected to play an important role in the field of optical fiber communication. The most promising application of integrated optics is expected to be in optical signal processing at the transmitting and receiving ends and in the course of regeneration at the repeaters. The very high concentration of energy in very small region in the light waveguide leads to enormous intensities leading to the realization of nonlinear devices employing second harmonic generation. This confinement of light energy in small region of space also leads to an efficient interaction of the optical energy with an applied electric field or an acoustic wave, thus leading to much more efficient electro-optic and acoustooptic modulators and deflectors requiring very low drive powers. The most important thing is that the integrated optical concept may result in devices which are not normally feasible in bulk form. Using semiconducting materials as substrates, optoelectronic integration is possible which may lead to optoelectronic circuits with great potential applications. In addition to this, integrated optics can also be employed in optical sensor signal processing, real time spectrum annuluses, optical signal processing and computing. Integrated optical circuits and devices coupled with integrated electronics will form the basic integrated photonic circuits, in which various functions of the circuits such as generation, modulation and detection can be realized.

In integrated optics two main kinds of waveguides are used. These are:

(a) planar integrated optical waveguide;
(b) strip integrated optical waveguide.
(a) *Planar integrated optical waveguide*:
This waveguide is concerned with the manipulation of sheet beams. In this waveguide the confinement of the light energy is only along one transverse dimension and the light energy can diffract in the other transverse dimension. Figure (1.7.1) shows a three-layer planar guide formed by depositing a thin layer of material of high refractive index on a thicker, low index substrate. The third layer in the system can often be air itself, or an additional low index cover layer can be used. Again, guidance is provided by total internal reflection at the layer interfaces. Because sheet beams allow many operations that are possible using free space optics, planar integrated optic chips often contain circuits that are effectively miniaturized and ruggedized versions of the bulk optic systems.

(b) *Strip integrated optical waveguide*:
This waveguide shown in figure (1.7.2) confines the light energy in both transverse dimensions. This confinement is a desirable feature for the fabrication of devices such as amplitude or intensity modulators, directional couplers, optical switches etc.

Optical waveguides have various discrete guided modes which propagate down the waveguide with most of their power confined in the high refractive index region. Since the waveguide has a large index difference between the guide and air, the field decays slowly in the substrate but it decays very rapidly in the air region. Most of the integrated optic devices are based on single mode waveguides wherein there is only one propagating guided mode. Various devices are based on adjusting the phase polarization, amplitude or frequency of the propagating mode using several physical phenomena (effects).
Fig. 1.7.1 A planar integrated optical waveguide.

Fig. 1.7.2 A strip integrated optical waveguide.
There are three most important effects which are used in integrated optical devices. These are:

1. electro-optic effect;
2. acoustic-optic effect;
3. non-linear optical effect;

1. **Electro-optic effect**:

When an external electric field is applied on an optical medium, the distribution of electrons within it is distorted in such a way that the refractive index of medium changes anisotropically.

This change can be written as:

\[
\Delta n = -\frac{n^3 r E}{2} = -\frac{n^3 r V}{2d}
\]

where

- \( n \) = the refractive index of the medium,
- \( E \) = the applied electric field,
- \( V \) = the applied voltage between the electrodes,
- \( d \) = the distance between the electrodes,

and \( r \) is the effective electrooptotic coefficient depending on the material, the direction of the applied electric field and the polarization state of the light beam.

2. **Acousto-optic effect**:

This effect refers to a periodic change in the refractive index of the medium due to the propagation of periodic acoustic waves in the medium. This periodic change in the refractive index corresponds to a volume phase grating which can diffract an incident lightwave. This diffraction is given by the Bragg condition.
\[ \beta_1 - \beta_2 = \frac{2\pi}{\lambda} \]

where \( \beta_1 \) and \( \beta_2 \) are the propagation constants of the incident and diffracted modes respectively and \( \lambda \) is the wavelength of the acoustic wave.

(3) **Non-linear optical effect**

This effect refers to the change in the refractive index of the medium due to incident light of enormous intensities. At such high intensities the medium behaves in a non-linear way. Such effects are studied for optical switches. The lightwave coupling between parallel waveguides has a fundamental importance in optical communication systems. Most useful waveguide devices, such as modulators, switches directional couplers, isolators, polarizers etc. are based on the abovementioned effects. The electro-optic effect is one of the major effects used in fabricating active devices in integrated optics.

1.8 **Optical sources for lightwave communication**

The optical source is often considered to be the active component in an optical fiber communication system. Its fundamental function is to convert electrical energy in the form of a current into optical energy (light) in an efficient manner which allows the light output to be effectively launched or coupled into the optical fiber. Three main types of optical sources are available. These are:

(a) wideband continuous spectra sources (incandescent lamps);
(b) monochromatic incoherent sources (light emitting diodes LEDs);
(c) monochromatic coherent sources (injected lasers diodes, ILDs);

In the early stages of optical fiber communication the most powerful narrowband coherent light sources were necessary due to severe attenuation
and dispersion in the fibers. Therefore, gas lasers (helium-neon) were utilised initially [33]. However, the development of the semiconductor injection laser and the LED, together with the substantial improvement in the properties of optical fibers, has given prominence to these two specific sources [34-35]. To a large extent these two semiconductor light sources fulfill the major requirements for an optical fiber emitter.

1.8.1 **Light emitting diode (LED) sources**: LEDs that emit invisible near-infrared light are common light sources for short fiber systems. In its simplest form, a light emitting diode (LED) consists of a p-type doped semiconductor and an n-type doped semiconductor forming a p-n junction shown in Figure 1.8.1(a). When the LED is forward biased, charge carriers flow across the junction and it is the recombination of the positive (holes) and negative (electron) charge carriers that results in the emission of light from the vicinity of the p-n junction. As long as the voltage is applied, electrons keep flowing through the diode and recombination continues at the junction.

In many semiconductors, notably silicon and germanium, the released energy is dissipated as heat. However, in other materials, usable in LEDs, the recombination energy is released as photons of light, which can emerge from the semiconductor material. The most important of these semiconductors, gallium arsenide and related materials, are made up of elements of IIIa and Va columns of the periodic table. The usual LEDs used in fiber optic systems are made of gallium aluminum arsenide or gallium arsenide. Gallium arsenide LEDs emits near 930nm. Adding aluminum decreases the threshold current to improve the lifetime and can also increase the energy gap and shift emission to shorter wavelengths of 750 to 900nm. The usual wavelengths for
Fig. 1.8.1 (a) Basic idea for LED operation. (b) LED as packaged (surface-emitting)
fiber-optic applications are 820 or 850nm. The most important compound for higher-performance fiber optics is InGaAsP, made of four elements, indium, gallium, arsenic and phosphorous. But such compounds are harder to make than the three-element compounds such as GaAlAs, but are needed to produce output at 1300 and 1550 nm. In practice, LEDs are often used for short systems at 1300nm, where conventional fibers have low chromatic dispersion but are rarely used at 1550nm, where dispersion is much higher.

The simple LEDs emit light in all directions, as shown in Figure 1.8.1(b) and are packaged, so most emission comes from their surfaces. The light is emitted in broad cone, with intensity falling off, following the lambertian distribution. In the case of the edge-emitting diode shown in Figure 1.8.1(c), electrical contacts cover the top and bottom of an edge emitter, so light can not emerge there. The LED confines light in a thin narrow strip in the plane of the p/n junction. This is done by surrounding that strip with regions of lower refractive index, creating a waveguide that functions like an optical fiber, and channeling light out both ends where it can be coupled into a fiber. One disadvantage is that this increases the amount of heat the LED must dissipate.

One of the major application of LEDs is in electronic displays. LEDs form a very useful source in fiber optic communications, particularly for short range applications. LEDs used in optical communication usually radiate in the near infrared region of electromagnetic spectrum, and it is in this wavelength range that the transmission properties of optical fibers are best utilized.

Before using an LED as an optical source in a fiber communication system, it is important to know the basic optical and electrical characteristics.
Fig. 8.1(c) An edge-emitting LED.

Fig. 8.2 Semi Conductor energy level diagrams (a) and (b).
of the LED, such as; V-I characteristics, maximum forward current, I-P characteristic, radiant power, peak emission wavelength, spectral bandwidth, frequency response or modulation efficiency etc. [36].

1.8.2 **Semiconductor lasers or injection laser diode (ILD):**

The semiconductor laser (junction laser or diode laser) is today one of the most important types of laser with its very important application in fiber optic communication. These lasers use semiconductors as the lasing medium and are characterized by specific advantages such as the capability of direct modulation in the gigahertz region, small size and low cost, the capability of monolithic integration with electronic circuitry, direct pumping with conventional electronic circuitry, and compatibility with optical fibers.

The basic mechanism responsible for light emission from a semiconductor is the recombination of electrons and holes at a p-n junction when a forward bias is applied across the diode. As in other laser systems, there can be three interaction processes:

a) an electron in the valance band can absorb the incident radiation and be excited to the conduction band leading to the generation of electron hole pair;

b) an electron can make a spontaneous transition in which it combines with a hole, i.e., it makes a transition from the conduction to the valance band and in the process it emits radiation;

c) a stimulated emission may occur in which the incident radiation stimulates an electron in the conduction band to make a transition to the valance band and in the process emit radiation.
If now by some mechanism a large density of electrons is created in the bottom of the conduction band and simultaneously in the same region of space a large density of holes is created at the top of valance band as in Figure 1.8.2 (a), then an optical beam with a frequency slightly greater than \( \frac{E_g}{h} \) will cause a larger number of stimulated emissions as compared to absorptions and thus can be amplified. Here \( E_g \) is the band gap energy. In order to convert the amplifying medium into a laser, one must provide optical feedback which is usually done by cleaving or polishing the ends of the p-n junction diode at right angles to the junction.

Thus, when a current is passed through a p-n junction under forward bias, the injected electrons and holes will increase the density of electron in the conduction band and holes in the valance band and at some value of current, the stimulated emission rate will exceed the absorption rate and amplification will begin. As the current is further increased, at some threshold value of the current, the amplification will overcome the losses in the cavity and the laser will begin to emit coherent radiation.

The early semiconductor lasers were based on p-n junctions formed on the same material by proper doping and these are referred to as homojunction lasers. Due to the absence of any potential barriers for the confinement of carriers or abrupt refractive index discontinuities for the confinement of optical radiation, these laser structures required large threshold current densities (50000A/cm²). The absence of carrier confinement resulted in a diffusion of the carriers near the p-n junction plane due to which a significant optical gain was available only over a very small region around the junction.
The absence of any strong optical confinement resulted in the optical energy penetrating beyond the gain region where it was absorbed. Thus larger current densities were required for laser operation.

A significant reduction in threshold current densities was achieved by forming a new junction called heterojunction. A heterojunction is a junction formed between two dissimilar semiconductors. The present day lasers are based on the double heterojunction (D H) in which a thin active layer of a semiconductor with a narrow bandgap is sandwiched between two larger bandgap semiconductors as shown in Figure 1.8.2(b). It is clear from this figure that the regions in which the electron and holes recombine is bound on either side by potential barriers and thus they are confined to the thin active region. Luckily the refractive index of the semiconductor decreases with an increase in the bandgap. Thus the refractive index of the central active layer is higher than the two surrounding regions (~ 5 to 10% higher). Such a refractive index profile can confine the emitted optical radiation to the active region by the mechanism of waveguidance which occurs due to total internal reflection taking place at the boundaries. In addition, since the layer surrounding the active central region has larger bandgaps, the optical field which penetrates into the surrounding region is also not absorbed. Use of such double heterojunctions results in a reduction of the threshold current densities to ~2000 to 4000A/cm².

In (D H) laser, the carriers and the optical waves are confined only along one direction. One can provide in addition a confinement in the lateral direction also. In such a laser, the active region will have an approximately rectangular cross-section and will be surrounded by higher bandgap materials.
Fig. 1.8.2 (b) A double heterojunction (D-H) injection laser.
on all sides. Such a laser is called a buried heterostructure laser shown in Figure 1.8.2 (c). This type of laser can operate with threshold currents which are much smaller. Thus if the current is restricted to flow across a lateral dimension of \( \sim 5 \mu m \), then the threshold current for a threshold current density of 4000 A/cm\(^2\) will be

\[
I_{th} \approx 5 \times 300 \times 10^{-8} \times 4000 = 60 mA,
\]

which is a significant reduction in the threshold current [37].

Lasers operating in the 0.8-0.9 \( \mu m \) spectral region are based on gallium arsenide. By replacing a fraction of gallium atoms by aluminium, the bandgap can be increased. Thus one can form heterojunctions by proper combinations of GaAlAs and GaAs which can provide both carrier confinement and optical waveguidance. For example, the bandgap of GaAs is 1.424 ev and that of Ga\(_{0.7}\)Al\(_{0.3}\) As is \( \approx 1.798 \) ev, the corresponding refractive index difference is \( \Delta n \approx 0.19 \). Thus, surrounding the GaAs layer on either side with Ga\(_{0.7}\)Al\(_{0.3}\) As, one can achieve confinement of both carriers and light waves. For lasers operating in the range 1.0 to 1.7 \( \mu m \), the semiconductor material is In P with Ga and As used to replace fractions of In and P respectively. The above wavelength region is extremely important in connection with fiber optic communication since silica based optical fibers exhibit both low loss and very high bandwidth around 1.55\( \mu m \).
Fig. 1.8.2 (C) Bureid heterojunction (B. H.).
laser structures (a) and (b).
### 1.8.3 Semiconductor optical source characteristics:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>ILDs</th>
<th>LEDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power; mw</td>
<td>1 to 10</td>
<td>1 to 10</td>
</tr>
<tr>
<td>Power launched into fiber; mw</td>
<td>0.5 to 5</td>
<td>0.03 to 0.3</td>
</tr>
<tr>
<td>Spectral width; nm</td>
<td>2 to 4</td>
<td>15 to 60</td>
</tr>
<tr>
<td>Brightness, W/cm²/Sr</td>
<td>~10⁵</td>
<td>10 to 10³</td>
</tr>
<tr>
<td>Rise time; ns</td>
<td>≤ 1</td>
<td>2 to 20</td>
</tr>
<tr>
<td>Frequency response; MHz</td>
<td>&gt; 500</td>
<td>&lt; 200</td>
</tr>
<tr>
<td>Forward current; mA</td>
<td>10 to 300</td>
<td>50 to 300</td>
</tr>
<tr>
<td>Threshold current; mA</td>
<td>5 to 250</td>
<td>NA</td>
</tr>
<tr>
<td>Cost</td>
<td>expensive</td>
<td>cheap</td>
</tr>
<tr>
<td>Linearity</td>
<td>No linear out put</td>
<td>Linear output against current characteristics.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Less reliable</td>
<td>More reliable</td>
</tr>
<tr>
<td>Temperature dependence</td>
<td>More temperature dependent</td>
<td>Less temperature dependent</td>
</tr>
</tbody>
</table>
1.9 **Waveguides in the microwave range**: 

There has always been a demand for increased capacity for transmission of information; and scientists and engineers continually pursue technological routes for achieving this goal. The low frequency radio waves can be transmitted through guided channels like copper wires. However, for higher frequency radiowaves, coaxial cables are needed as the guiding channel. These carrier waves can be transmitted over long distances through these conventional channels but their message carrying capacity is very small and limited. To increase the capacity of conventional guiding channels for transmission of information, scientists and technologists invented a new channel called a waveguide which in the beginning operated at microwave frequencies [38-41]. A waveguide is a simple hollow metallic tube which transports energy at microwave frequencies [Figure (1.9)]. Indeed, waveguides are superior to the conventional channels (copper wires and cables) in terms of loss of power per unit length experienced by the wave propagating through them.

1.9.1 **Principle of waveguidance**: 

Let us consider two parallel and perfectly conducting planes of infinite extent in the y and z-directions, through which an electromagnetic wave is propagating in z-direction as shown in Figure 1.9.1 (a). In order to find out the electromagnetic field configuration in the space between the parallel planes, we have to solve Maxwell’s equations using suitable boundary conditions at the parallel conducting planes. Since the region between the parallel planes is infinite in the y-direction, there are no boundary conditions to be met in this direction and it can be assumed that the field is uniform or
Fig. 1.9 A Simple hollow metallic tube as a microwave guide

Fig. 1.9-1 (a) Two parallel conducting planes

Fig. 1.9-1(b) Attenuation versus frequency characteristics waves guided between parallel conducting planes.
constant in the y-direction. We see that there are three types of the waves propagating through the parallel planes. These are:

(a) *Transverse electric wave: (TE wave)*

In this wave, a component M of the magnetic field in the direction of propagation is present but the electric field component E is absent in the z-direction.

(b) *Transverse magnetic wave: (TM wave)*

In this wave, a component E of the electric field in the direction of propagation is present but the magnetic field component M is absent in the z-direction.

(c) *Transverse electromagnetic wave: (TEM waves)*

In this case, both the components E and M are absent in the z-direction. Thus the electromagnetic field is totally transverse in nature. This is a special case of guided wave propagation through two conductor transmission lines at low frequencies. This wave is called the principal wave.

The most important quantity in waveguide transmission theory is the propagation constant, which is written as: \( \gamma = \alpha + i\beta \), where \( \alpha \) is called attenuation constant and \( \beta \) is called the phase shift constant. In the range of frequencies where \( \gamma \) is real, \( \alpha \) has some non-zero value but \( \beta \) is zero. This shows that there is only attenuation without phase shift. Thus there is no wave motion in this case. In the other case where \( \gamma \) is imaginary, \( \alpha \) is zero but \( \beta \) has non-zero value. Thus, there is propagation of waves without attenuation. This is the most important case for the transmission of microwaves through waveguides without loss of power.

The other important factor in waveguide theory is the cutoff frequency below which wave propagation cannot take place. Actually, the conductivity
of the walls of the waveguides is very large but not infinite, and there is usually some attenuation also. The attenuation versus-frequency characteristics of guided waves between parallel conducting plates is shown in Figure 1.9.1 (b) for different modes.

In wave propagation between parallel conducting plates, when a system of conductors guides the low frequency TEM wave, it is called a transmission line. But in the case of microwaves TE or TM waves can be sustained and then it is called a microwave waveguide. Practical microwave waveguides usually take the system of rectangular or circular cylinders. Other cross sectional shapes are also possible. But in general these other shapes offer no general electrical advantages over the simpler form in use and are more expensive to fabricate.

1.10 **Waveguides in optical range:**

Any system of conductors, insulators or any other material in cylindrical form used for guiding electromagnetic waves can be called a waveguide. It is customary to take a specially constructed cylinder for a waveguide. If these cylinders are filled with optically transparent materials and the transverse dimensions are comparable to the wavelength of light, these are called optical waveguides. The optical waveguide is the building block of optical fiber communication.

1.10.1(a) **Classification of optical waveguides:**

There are three types of optical waveguides:

(i) Slab optical waveguide

(ii) Rectangular optical waveguide

(iii) Cylindrical optical waveguide or (optical fiber),
(i) *Slab optical waveguide*:

The slab optical waveguides in the form of thin films and strips are very useful in integrated optical circuits. A dielectric slab waveguide is shown in Figure 1.10.1(a) and 1.10.1(b). It consists of a core of high refractive index. This core region is deposited on a substrate having a slightly smaller refractive index than that of the core. The region above the core, called the superstrate, may be air or some other material with refractive index lower than that of the core.

There are two types of slab waveguides. If the refractive index $n_0$ of the substrate is equal to the refractive index $n_z$ of superstrate, as shown in Figure 1.10.1(a) the waveguide is called a symmetric slab waveguide. On the other hand, if $n_0 \neq n_z$, it is called an asymmetric slab waveguide. The modes in asymmetric waveguides are somewhat more complicated than those of symmetric slab waveguide [42]. The lowest order modes in the symmetric waveguide have no cutoff at low frequencies. Therefore, these modes can propagate at low frequencies. In the case of asymmetric waveguide, all modes have cutoff, if the operating frequency is sufficiently low. Thus for the asymmetric waveguide, operating frequencies are higher than those of the symmetric waveguides.

Optical slab waveguides with three layers in symmetric or asymmetric form are the most fundamental guiding structures in integrated optical circuits. However, slab waveguides with more than three layers (i.e. multilayered guides) are also useful in optical waveguide technology, the multilayered guides, like four layered or five layered guides, are nothing but extended forms of three-layered guides. These multilayered waveguides
Fig 1.10.1 (a) The Cross section of a thin film slab waveguide.
(b) Geometry of symmetric dielectric slab waveguide.
(c) A rectangular Optical waveguide.
(four layered ones) are very useful in large optical cavity laser [43-44]; as waveguide lenses used to transfer guiding radiation from one layer to another [45-46], as thin film taper couplers [47-48] and thin film waveguide TE-TM mode converters [49].

The use of the metals in optical waveguides is of great interest, because metal clad optical waveguides show large differential attenuation between the TE and TM modes [50-57]. These are much useful as polarizers and can serve as electrodes [58-59]. The metallic cover of the waveguides is also useful in the protection of the optical devices and also for connections with other circuits [60]. The characteristics of waveguides are strongly influenced by the properties of the metals. This was demonstrated experimentally by Wilmot et. al. [61] and Thyagarajan et. al. [57]. Many investigators [62-65] have studied metal clad waveguides extensively because they show distinct properties which are very useful in integrated optics. The propagation characteristics of a multilayered waveguides were firstly studied by Shubert and Harris [66], Chilwell et. al. [67] and Walpita [68]. Chaubey et. al. [69] have calculated the attenuations of lower order TE and TM modes in four-layer metal clad planar waveguides with a semi-parabolically graded guiding layer and they found that the attenuation is not considerably sensitive to the changes of the guiding layer thickness.

Recently Offersgaard [70] analyzed multilayered waveguides using complex variable theory with the help of a matrix formulation. Yi-Fan Li et al. [71] derives a formula which describes generalized dispersion properties of the TE and TM modes in a multilayered waveguides. Ulrich and Martin [72] used geometrical optics to analyze thin film light waveguides.
(2) **Rectangular Optical waveguide:**

After the introduction of optical transmission through waveguides, the rectangular waveguide has established itself as one of the primary waveguides in integrated optical circuits and optical waveguide technology. The rectangular waveguide shown in Figure 1.10.1(c) is the transversally limited form of the slab waveguide. The confinement of light in the planar slab waveguides is in only one direction i.e., the light waves are confined in the guiding region near the surface of the substrate and covers, but diffract in the plane parallel to these surfaces. In many integrated optical circuits, modulators, directional couplers etc., it is useful to confine the light so that there is lateral confinement also. Thus in the case of a rectangular waveguide, a confinement of light is introduced in the lateral direction also. Rib waveguides or channel waveguides having rectangular cross-sections are very useful in integrated optics [73-74]. Therefore, a number of researchers have studied the rectangular waveguides in order to understand their modal characteristics by using different methods. Direct numerical integration of the field equations [75-76], finite element method [77-78], finite different analysis [79-80], beam propagation method [81], circular harmonic analysis [82] are some of the numerical methods used. For better understanding of the modal behaviour of the rectangular waveguide, some approximation methods such as the effective index method [83-84], the modified effective index method [85], the weighted index method [86], perturbation method [87] and variational method [88-89] have been used. Since the characteristics of optical waveguides are strongly affected by the properties of metals, the
metal-clad rectangular optical waveguides is of great interest. It can be used in polarizers.

(3) Cylindrical Optical waveguide (Optical fiber):

An optical fiber basically is a dielectric waveguide which confines and guides the visible and infrared light beam by the process of total internal reflection. This fiber waveguide is generally in the cylindrical form with the standard circular cross-section. Actually it is a thread-like long cylinder having human hair sized dimension.

Configuration:

In the most simplest form, an optical fiber consists of a solid dielectric cylinder of radius \( a \) and index of refraction \( n_1 \), as shown in Figure 1.10.1 (d). This cylinder is known as the core of the fiber. It is also called the guiding region of the fiber because the light is guided through the core region only. The core is surrounded by a solid dielectric cladding having a refractive index \( n_2 \), slightly less than \( n_1 \). This cladding is also called the non-guiding region. The whole structure is enveloped by a suitable jacket [90-91] to prevent it from external hazards. The core diameter can vary from about 5\( \mu \)m to about 100\( \mu \)m and the cladding diameter is usually 125\( \mu \)m. For greater strength and protection of the fiber, there is usually a soft plastic coating whose diameter is about 250\( \mu \)m which is often followed by another layer of coating shown in Figure 1.10.1 (d). The operating wavelength is usually between 0.5\( \mu \)m and 1.6\( \mu \)m of the electromagnetic spectrum.

Although a cladding is not absolutely necessary for light to propagate along the fiber, it reduces the scattering loss due to dielectric discontinuities at the core surface and also adds mechanical strength to the fiber. Further it protects the core from absorbing surface contaminant with which it could
Fig. 1.10.1(d) Geometry of an Optical fiber.
(e) Principle of an Optical fiber.
come in contact. The buffer coating or protective coating adds further strength to the fiber and mechanically isolates the fiber from small geometrical irregularities or roughness of adjacent surfaces. That is, it cushions the fiber from mechanical forces.

1.10.1(b) **Principle of optical wave guidance**:

Propagation of optical waves through the fiber is shown in Figure 1.10.1(e). For a ray entering the fiber, if the angle of incident $\phi$ (at the core cladding interface) is greater than the critical angle $\phi_c = \sin^{-1} \frac{n_2}{n_1}$, then the ray will undergo total internal reflection at the interface. Further, because of the cylindrical symmetry in the fiber structure, this ray will suffer further total internal reflection all around and, therefore, get guided through the guiding region (core) by repeated total internal reflection. Thus an optical fiber acts as a “light guide” and it is therefore called an optical waveguide.

The transmission properties of an optical fiber are dictated by its structural characteristics, which have a major effect in determining how an optical signal is affected as it propagates along the fiber. The structure basically establishes the information carrying capacity of the fiber. Almost all present day communication grade fibers are silica ($\text{SiO}_2$) based fibers. In low and medium loss fibers the core material is generally glass (silica) and is surrounded by either a glass or plastic cladding. Higher loss plastic core fibers with plastic cladding are also widely used. Since glass is a strong and durable material, fibers of glass materials are very strong and durable. These glasses can negotiate very small bends and are also highly flexible.
1.10.2 **Classification of optical fibers**:  
Optical fibers are classified on the basis of the nature of refractive index distribution in the core. Mainly there are two types of optical fibers: These are:
(i) the step index fiber;
(ii) the graded index fiber;
(i) **Step index fiber**:  
A fiber consisting of a core of constant and uniform refractive index \( n_1 \), and a cladding of a slightly lower refractive index \( n_2 \), as shown in Figure 1.10.2(a), is called the step index fiber. In this fiber, the refractive index \( n_1 \) of the core remains uniform and homogeneous and there is an abrupt change at the core-cladding interface. Mathematically, the refractive index profile of the step index fiber may be written as:
\[
\begin{align*}
n(r) &= n_1, & r \leq a & \quad \text{(core)} \\
n(r) &= n_2, & r \geq a & \quad \text{(cladding)}
\end{align*}
\]
where \( n_2 = n_1 (1 - \Delta) \) and \( \Delta = (n_1^2 - n_2^2) / 2n_1^2 \) = relative core-cladding index difference.

It is clear from the figure that for all the rays incident at an angle greater than critical angle, total internal reflection takes place and since such reflection takes place throughout the fiber length, the rays are confined to the core.

Practically the abrupt change of the refractive index at the core-cladding interface is somewhat complicated because some index transmission always occurs from the core to the cladding. In a solid fiber, generally there is a fluctuating transition of index from the end of the core to the cladding. Therefore this type of fiber is not suitable for optical signal transmission.
Fig. 1-10-2(a) The refractive index profile and ray transmission in step index fibres: (i) Multimode step index fibre and (ii) Singlemode step index fibre.
(ii) *Graded-index fiber:*

Such fibers do not have a constant refractive index in the core, but a decreasing core-index \( n(r) \) with radial distance from a maximum value of \( n_1 \) at the axis to a constant value \( n_2 \) beyond the core radius \( a \) in the cladding as shown in Figure 1.10.2(b). Here the distribution of \( n_1 \) is not uniform and homogeneous. Therefore, sometimes this fiber is also called the inhomogeneous core fiber. Mathematically, the index variation is written as:

\[
    n(r) = n_i \left[ 1 - 2\Delta \left( \frac{r}{a} \right)^2 \right]^{1/2}, \quad r < a \quad \text{(core)}
\]

\[
    = n_i \left[ 1 - 2\Delta \right]^{1/2} = n_2, \quad r \geq a \quad \text{(cladding)}
\]

Where \( \alpha \) is the profile parameter, and \( 1 \leq \alpha < \infty \).

If \( \alpha = \infty \), the above equation represents a step index profile. If \( \alpha = 1 \), it gives a triangular profile, and if \( \alpha = 2 \) [92-93], it gives the parabolic refractive index profile. The different refractive index profiles are shown in Figure 1.10.2(c).

The continuous change in the refractive index can be thought of as a series of very small step changes. Any ray crossing the fiber axis strikes a series of boundaries, each time traveling into a region of lower refractive index and thus bending towards the fiber axis. As the ray angle exceeds the critical angle, it is totally reflected back towards the fiber axis. Now the ray travels from low to high index media, thus bending towards the normal until it crosses the fiber axis. At this point, the procedure will repeat itself and the ray will be confined in the core as shown in figure.

In the case of step index fiber shown in Figure 1.10.2 (a)] when rays make larger angles to the axis, they have to travel larger optical paths to reach the receiving end than those rays which travel as lesser angles. This results in a substantial amount of pulse broadening in a fiber [94-96]. In
Fig 1.10.2 (b) The refractive index profile and ray transmission in a multimode graded index fibre

Fig 1.10.2 (c) Possible fibre refractive index profiles for different values of α.
contrast to this, in graded index fibers, smaller values of pulse dispersion have been observed as compared to that in the step index fiber [97-100].

1.10.3 Subdivision of optical fiber:

Both the step index and graded index fibers can be further divided into two subclasses as given below:

(a) Monomode fiber:

(b) Multimode fiber:

(a) Monomode fiber:

Monomode fibers can have the step index profile or a graded index profile. These fibers have very small core radii (2μm-5μm) and the thickness of the cladding should be 50μm so that only the lowest order modes are allowed. As there is only a single mode, the effect of intermodal dispersion is not to be considered. This is one of the most important advantages of the single mode fiber. But these fibers suffer some difficulties in splicing and coupling due to their small size.

Monomode fibers are the most important channels for modern telecommunication systems. These offer extremely low loss of power (0.2dB/km, at 1.55μm wavelength) and high bandwidth. This characteristic of a single mode fiber is utilized for sending information over very long distances with no significant loss and no confusion. Therefore for reliability and reduced distortion, the single mode fiber is preferred.

For the design of a single mode fiber, the normalized frequency parameter called the \(V\)-parameter is very essential. This parameter is defined as:

\[
V = a(2\pi/\lambda_0) \left( n_1^2 - n_l^2 \right)^{1/2}
\]

where \(a\) is the core radius and \(\lambda_0\) is the free space wavelength.
A proper choice of the V-parameter determines whether a fiber will be a single mode fiber or a multimode fiber. For large V-values, more guided modes are allowed in a fiber. The smaller the value of V, the fewer the guided modes. This is due to the fact that each mode has a minimum V-value below which it cannot propagate. This V-value is called cutoff V-value, $V_c$, of the mode. As the V-value decreases, an increasing number of modes get cut off. Actually, it is possible to have just one guided mode if the V-value is very small. In the case of a step index fiber, only one mode is possible, if $V<2.405$. This mode is termed as the HE_{11} or the LP_{01} mode.

Graded index fibers may also be designed for single mode operation. It may be shown that [101] the cutoff value of normalized frequency $V_c$ to support a single mode in graded index fiber is given by

$$V_c = 2.405(1+2/\alpha)^{1/2},$$

where $\alpha$ is the profile parameter. For single mode operation $V<V_{cutoff}$.

(b) **Multimode fiber:**

As the name suggests, such types of fibers can sustain more than one mode, and only a finite number of guided modes are allowed. The number of allowed modes is fixed for a particular fiber. The core radius of the multimode fiber lies between 12$\mu$m and 100$\mu$m. Also it has large difference in refractive index between the core and cladding. So these fibers generally have high V-values. One can restrict the guided modes in the fiber by selecting a proper V-parameter. The total number of guided modes propagating in a particular multimode step-index fiber is related to the V-number, according to the formula [102]

$$M_0 \approx V^2/2$$

$M_0$ being the total number of modes or mode volume and
Fig 1.10.3 Single mode and multimode fibers.
V = a(2π/λ₀) (n₁² - n₂²)¹/².

This formula shows that if V-number is high, M₀ is high and many modes can be sustained.

**Comparision between multimode and single mode fibers:**

<table>
<thead>
<tr>
<th>Multimode fiber</th>
<th>Single mode fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) The core radius is not very small compared to the wavelength of the light (0.8-1.6µm) propagating in the fiber. Here the radius of the core lies between 12µm to 100µm.</td>
<td>(1) The core radius is very small compared to λ of the light propagating through it. The radius of the core lies between 2µm to 5µm.</td>
</tr>
<tr>
<td>(2) It can sustain hundreds of modes.</td>
<td>(2) It sustains only a single propagating mode.</td>
</tr>
<tr>
<td>(3) Δ = ( \frac{n₁² - n₂²}{2n₁²} ) = 0.1 to 0.03</td>
<td>(3) Δ = ( \frac{n₁² - n₂²}{2n₁²} ) = 0.1 to 0.003</td>
</tr>
<tr>
<td>(4) It suffers from intermodal dispersion.</td>
<td>(4) There is no such dispersion.</td>
</tr>
<tr>
<td>(5) Due to the rather large core, optical power is launched into it easily.</td>
<td>(5) Optical power is not launched easily.</td>
</tr>
<tr>
<td>(6) Light can be launched into it using light emitting diode (LED) source. This light source has less output power but it is less expensive with less complex circuitry.</td>
<td>(6) It is excited with injected laser diode (ILD) source. This light source has greater output power but is much expensive.</td>
</tr>
<tr>
<td>(7) Fiber splicing is very easy.</td>
<td>(7) Splicing is not so easy.</td>
</tr>
</tbody>
</table>
1.11 **Some optical waveguide parameters and concepts:**

Some fundamental parameters and concepts concerning optical waveguides are presented here.

(A) *Waveguide parameters:*

**V-parameter:**

This is a very important parameter in which all the structural and material characteristics of a fiber are put together. This parameter includes the refractive indices \( n_1 \) and \( n_2 \), the core radius \( a \) and the operating wavelength \( \lambda_0 \). It is also called the V-number. Mathematically, it is written as:

\[
V = \left( \frac{2\pi a}{\lambda_0} \right) \left( \frac{n_1^2 - n_2^2}{\lambda_0^2} \right)^\frac{1}{2}.
\]

It is a dimensionless parameter and only positive V-numbers are taken. This parameter decides the number of modes which are supported by the fiber. On the basis of this parameter, we can distinguish between multimode mode and single mode fibers. If the value \( V \) is sufficiently high, the fiber is called multimode and if the V-number is less than the critical value, the fiber is called a single mode fiber.

**Normalized propagation constant \( (b') \):**

The number of modes that can exist in a waveguide as a function of the V-parameter may be expressed in terms of a normalized propagation constant \( b' \) [103]. Mathematically, it is written as:

\[
b' = \left( \frac{\beta / k_0}{n_1^2 - n_2^2} \right)^{2} - \frac{n_2^2}{n_1^2 - n_2^2}
\]

where \( k_0 = \frac{2\pi}{\lambda_0} \) and \( \beta \) is the longitudinal component of the propagation vector \( \vec{k} \). Here \( n_1 > k_0 > n_2 k_0 \).
1 > b' > 0

Since b' changes from 0 to 1, it is called the normalized propagation constant.

A plot of b' (in terms of β/k) as a function of V is called a dispersion curve. This curve is very important for the understanding of the dispersion characteristics and modal cutoff conditions of the various modes. In this plot, it is clear that when V increases, the number of modes increases. If V decreases, the number of modes decreases. At a particular value of V, the number of modes becomes zero. This is called the cutoff V-value.

(B) **Modal Parameters**

The two dimensionless parameter U and W for the core and the cladding respectively are given by

\[ U = a(k_1^2 - \beta^2)^{\frac{1}{2}} \quad ; \quad W = a(\beta^2 - k_2^2)^{\frac{1}{2}}. \]

These parameters are real for bound modes in non-absorbing fibers. There is a relationship among V, U and W; which is written as:

\[ V^2 = a^2[U^2 + W^2] \]

For a given value of V, the condition for a guided mode is

0 ≤ U < V

0 < W ≤ V

when \( \lambda_0 \rightarrow \infty, \) V \( \rightarrow 0. \)

**Modal Cutoff**

A mode is said to be cutoff when it is no longer bound to the guiding region of the waveguide and it does not decay in the cladding. The parameter \( W = (\beta^2 - k_1^2)^{\frac{1}{2}} \) determines the rate at which cladding fields decay. If value of W is large, the field is tightly confined into the core. If the value of W is
small, the fields come into the cladding. Finally if \( W = 0 \), the field detaches itself from the core and the entire field goes into the cladding. When this condition is satisfied, the frequency is called the cutoff frequency of the mode and propagation constant \( \beta \) is given by
\[
\beta^2 = k_0^2 n_i^2.
\]
At modal cutoff, we have \( W = 0 \) or \( V = U_a \).

c) Maxwell’s Equations:
All the electromagnetic phenomena can be said to follow from Maxwell’s equations. These equations are based on experimental laws and are written as:
\[
\begin{align*}
\vec{\nabla} \cdot \vec{D} &= \rho \\
\vec{\nabla} \cdot \vec{B} &= 0 \\
\vec{\nabla} \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\vec{\nabla} \times \vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t}
\end{align*}
\]
where \( \vec{E} \) and \( \vec{H} \) are the electric and magnetic fields, \( \vec{D} \) is the electric displacement, \( \vec{B} \) the magnetic induction and \( \rho \) and \( \vec{J} \) the charge and the current densities respectively. We can have the solution of above equations in a linear, isotropic and homogeneous medium where the following constitutive equations are satisfied:
\[
\begin{align*}
\vec{D} &= \varepsilon \vec{E}, \quad \vec{B} &= \mu \vec{H}, \quad \vec{J} &= \sigma \vec{E}.
\end{align*}
\]
where \( \varepsilon \) = the dielectric permittivity
\[\mu \] = magnetic permittivity (or permeability)
\( \sigma \) = the conductivity of the medium.
For a charge free, lossless and linear isotropic medium, the above equations can be written as:
\[
\vec{\nabla} \cdot \vec{E} = 0 \\
\vec{\nabla} \cdot \vec{H} = 0 \\
\vec{\nabla} \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \\
\vec{\nabla} \times \vec{H} = \sigma \vec{E} + \epsilon \frac{\partial \vec{E}}{\partial t}
\]

From these coupled equations, decoupled second order vector wave equations are derived and this procedure is very useful in solving boundary value problem.
\[
\vec{\nabla}^2 \vec{\psi} - \mu_0 \epsilon \frac{\partial^2 \vec{\psi}}{\partial t^2} = 0
\]

where $\vec{\nabla}^2$ is the vector Laplacian operator and $\vec{\psi}$ can be $\vec{E}$ or $\vec{H}$. But in the case of the scalar wave equation instead of $\vec{\psi}$, we have $\psi$ and $\nabla^2$ is the scalar Laplacian operator. Here $\psi$ may represent the z-component of $\vec{E}$ or $\vec{H}$ (or any of the cartesian components).

Also $\mu_0 =$ permeability of free space.
$\epsilon =$ permittivity of the medium.

(D) Propagation of EM waves in terms of modes:
Electromagnetic light fields in the waveguide can be expressed as the superposition of simpler field configurations called the modes of the fiber. Mathematically, the modes of a waveguide are the allowed solutions of Maxwell's equations under the boundary value problem of propagation in the waveguide [104-107]. Since light is an electromagnetic wave, the solutions are nothing but the various possible electric and magnetic field distributions. Thus a mode is a particular pattern of electric and magnetic
fields that is repeated along the fiber axis at intervals of a full wavelength. Only a certain number of discrete modes can propagate along the fiber because of lateral confinement.

The concept of "modes" of an optical waveguide can be best understood by considering a planar waveguide as described in section (1.9). For giving a designation to the modes we can use the terminology of metallic microwave waveguides. That is, (i) Transverse Electric (TE) modes ($E_z = 0$), (ii) Transverse Magnetic (TM) mode ($H_z = 0$), and (iii) Hybrid modes TEM ($E_z$ and $H_z \neq 0$). In the case of hybrid modes, if the component of $H$ makes the larger contribution to the transverse field, the mode is HE and if the $E$ contribution is large; the mode is EH. Generally, the waveguide is bounded in two dimensions, therefore, two integers $l$ and $m$ are necessary in order to specify the modes. Thus we have modes designated as $TM_{lm}$, $TE_{lm}$, $EH_{lm}$ and $HE_{lm}$ etc.

It is known that the electric fields of the guided modes are not well confined to the middle of the waveguide. They do not become zero at the core-cladding boundary but they extend partially into cladding. The field in guiding region varies harmonically and decays exponentially outside this region. In the case of lower order modes, the fields are tightly bound near the axis of the fiber with little penetration into the nonguiding region. But for higher order modes, the fields are distributed more towards the edge of the guide and extend further into the nonguiding region. Electric field distributions of some lower order modes in symmetric slab waveguide are shown in Figure 1.11(a). For guided modes, the propagation constant $\beta$, has an upper and lower limit [104]. Thus we have

$$n_1k_0 > \beta > n_2k_0$$
Fig 1.11(a) Electric field distributions for some guided modes.
where \( k_0 \) is the propagation constant of plane wave in free space.

In addition to the guided modes, there is an other class of modes called radiation modes or leaky modes. These modes exist when the propagation constant \( \beta \) satisfies the condition [104]
\[
\beta < n_2 k_0.
\]

In the case of weakly guiding fibers (\( \Delta \ll 1 \)) the propagation constant of a guiding mode satisfies the condition [108]
\[
\beta \approx n_2 k_0.
\]

Under this weak guidance approximation, the fields of the guiding modes are linearly polarized (LP) and can be designated as LP modes.

(E) Dispersion in optical fibers:

The temporal broadening of an optical pulse is a topic of tremendous interest in fiber optics as it plays a major role in determining the information carrying capacity of an optical communication system. The pulse broadening mechanism can be broadly classified under three categories:

(i) intermodal dispersion, (ii) intramodal or waveguide dispersion, (iii) material dispersion.

(i) Intemodal dispersion:

This dispersion is due to the fact that different modes take different times in propagating through a certain length of the fiber. In the case of a multimode step index fiber, the temporal broadening is given by the expression [36]
\[
\delta \tau = \frac{n_1 \Delta L}{c}
\]
and for a multimode parabolic index fiber,
\[
\delta \tau = \frac{n_1 L}{2c} \Delta^2 \quad \text{where} \quad \Delta = \frac{n_1 - n_2}{n_2}, \quad c= \text{velocity of light in freespace and } L= \text{length of fiber. If } n_1=1.5 \text{ and } \Delta \approx 0.01
\[ \delta \tau \approx 50 \text{ns/Km for a step index fiber} \]

\[ \approx 1/4 \text{ ns/Km for a parabolic index fiber} \]

In the case of a parabolic index fiber \( \delta \tau \) is small, because the optical path length covered by all the rays along fiber are nearly the same and hence they are characterized by the same transit time. On the other hand, in a step-index fiber, rays traveling at different angles are characterized by different transit times, leading to a higher value of \( \delta \tau \).

(ii) *Intramodal dispersion*:

This waveguide dispersion is due to the intrinsic characteristics of the waveguide and will occur even when the refractive indices of the core and cladding are strictly independent of the wavelength. Even in a single mode fiber, there is a temporal broadening of a pulse which is due to the explicit dependence of the normalized propagation constant \( b' \) on \( V \)-parameter. This temporal broadening is given by

\[ \delta \tau_w = -L \frac{n_2}{c} \frac{\Delta \lambda}{\lambda} \left( V \frac{d^2}{dV^2} (b') \right) \]

where \( \Delta \lambda \) = spectral width of the source and the suffix \( w \) refers to the waveguide dispersion. For a laser diode having a spectral width \( \Delta \lambda \approx 2 \text{nm} \), we get [109],

\[ \delta \tau_w = -8.68 \text{ ps/Km} \]

(iii) *Material dispersion*:

This dispersion is due to the fact that any light source has a certain spectral width \( \Delta \lambda \) and different wavelength components travel with different group velocities. For a source of given \( \Delta \lambda \), we have

\[ \delta \tau_m = -\frac{L}{c\lambda_0} \left( n_0^2 \frac{d^2n}{d\lambda^2} \right) \Delta \lambda \]
where $\lambda_0$ = free space wavelength, and the suffix m refers to the material
dispersion. Since the dispersion is usually measured in picoseconds per
kilometer length of the fiber per nanometer spectral width of the source, we
take
$L=1$Km$=10^3$m,
$\Delta \lambda=1$nm$=10^{-9}$m,
c$=3\times10^8$m/sec, and get

$$\delta \tau = -\frac{1}{0.0003 \lambda} \left( \lambda^2 \frac{d^2 n}{d \lambda^2} \right) ps / Km - nm$$

where $\lambda$ in the denominator is in meters and the quantity inside the parenthesis is a dimensionless quantity. At

$\lambda=1.55 \mu m$ , $\lambda^2 \frac{d^2 n}{d \lambda^2} \approx -0.01 \quad \Rightarrow \delta \tau \approx 22 ps / Km - nm$ (neglecting negative sign)

For a laser diode with $\Delta \lambda=2$nm ,
we have $\delta T_m = 44$ps/Km-nm.
Notice that the waveguide and material dispersions are of opposite signs and
one can design the fiber in such a way that the two cancel each other to have
a negligible total dispersion [109].

(F) **Attenuation of light signals**

As described in section (1.4) , attenuation is one of the principal
characteristics of an optical fiber. The variation of attenuation as a function
of the wavelength is shown in Figure (1.4.1) Attenuation means the
transmission loss of the optical power signal. It plays a major role in
measuring the transmission distance between a transmitter and a receiver.
The basic attenuation mechanism [110-112] in an optical fiber consists of
absorption, scattering and radiative losses of the optical energy. Absorption
is related to the fiber material and with structural imperfections in the optical
waveguide. Attenuation due to radiative effects originates from perturbations of the fiber geometry. Whenever an optical fiber undergoes a bend with a finite radius of curvature [113-114], radiative losses occur. The amount of optical radiation from a bent fiber depends on the field strength at the critical distance from the center of the fiber and on the radius of curvature. Scattering losses in glass arise from the microscopic variations in material density, from compositional fluctuations and from structural defects occurring during the manufacturing processes. In the case of multimode fibers scattering losses are generally greater than those of single mode fibers. This is due to higher dopant concentrations and the greater compositional fluctuations in multimode fibers.

Signal attenuation within optical fiber is usually expressed in the logarithmic unit of decibel (dB). For a particular optical wavelength, the attenuation in decibel is related to the ratio of input power $P_i$ to the output power $P_o$. Mathematically it is written as

\[
\text{Loss of power in dB} = 10 \log_{10} \left( \frac{P_i}{P_o} \right) \text{ for a particular length } L \text{ of a fiber.}
\]

where $P_i = \text{transmitted input optical power}$

$P_o = \text{received output optical power}.$

For the configuration shown in Figure 1.11(b), the input power $P_i = 100\mu\text{w}$ and output power $P_o = 15\mu\text{w}$

$\Rightarrow \text{Total attenuation in traversing 5Km length of fiber } = 10 \log_{10} \frac{100}{15} \approx 8.24\text{dB.}$

or loss in the fiber $\approx 1.65\text{dB/Km}$. 
Fig. 1.11(b) A fiber loop of length 5 km carrying optical power.

Fig. 1.11(c) The acceptance angle $\theta_a$ for launching light into an optical fiber.

Fig. 1.11(d) Condition for total internal reflection in a fiber.
(G) **Numerical aperture (NA)**:

It is defined as the light acceptance cone of the fiber and is related to the maximum acceptance angle $\theta_a$ (conical half angle) as shown in Figure 1.11(c) and Figure 1.11(d). For total internal reflection within the core, it is necessary that the incident ray at the core must be within $\theta_a$. Therefore, $\theta_a$ is the maximum angle of acceptance for total internal reflection. If any incident ray is out of $\theta_a$ at point A in Figure [1.11(d)] then this ray will not be totally reflected.

Let $\theta_1 < \theta_a$

Therefore, at point B, we have $n_0 \sin \theta_1 = n_1 \sin \theta_2$ .................(1)

But $\phi = \pi/2 - \theta_2$ or $\theta_2 = \pi/2 - \phi$ .........................(2)

From (1) and (2), $n_0 \sin \theta_1 = n_1 \cos \phi = n_1 (1 - \sin^2 \phi)^{1/2}$ .................(3)

For total internal reflection at B,

$\phi = \phi_c$ and $\sin \theta_c = n_2/n_1$ ............................................(4)

In this limiting case, $\theta_1 = \theta_a$ .............................................(5)

From (3), (4) and (5) $n_0 \sin \theta_a = n_1 \left(1 - \frac{n_2^2}{n_1^2}\right)^{1/2}$ or $n_0 \sin \theta_a = \left(n_1^2 - n_2^2\right)^{1/2}$.

For air, $n_0 = 1$, $\therefore \sin \theta_a = \left(n_1^2 - n_2^2\right)^{1/2} = N.A.$ where $0 \leq \theta_1 \leq \theta_a$

This is called numerical aperture of an optical fiber.

Numerical aperture is commonly used to describe the light gathering capacity of an optical fiber. It is used to calculate optical power coupling efficiencies from the source to the fiber. It is a dimensionless quantity and is always less than unity. For telecommunication purposes its value lies between 0.1 to 0.2; therefore $\theta_a = 5.7^0 - 11.5^0$. But for non-telecommunication purposes N.A. = 0.5 and $\theta_a \approx 30^0$. 
1.12 Some important methods for solving the problems of determining the modal behaviour of waveguides:

Any given problem can be understood, simplified and solved in three different ways: first, by the analytical method, second, by a numerical method and finally, by the experimental method. An accurate logical and legitimate approach to the first two methods make the things better for an experiment. Therefore, it is necessary to solve the problem analytically or (numerically as the case may be) because theoretical analysis gives a sort of direction to experimental studies. In the present thesis all given problems have been treated either by the analytical methods or by some numerical method. The present work, therefore, provides a stepping stone towards the fabrication of a practical optical waveguides of different types.

1.12.1 Analytical Method:

Several extensive researches have been done on EM wave propagation through different types of standard optical waveguides using different methods. The exact solution of conventional optical waveguides i.e., slab waveguides [115-116] and circular fibers [117-129] are easily available in the literature. The conventional coordinates systems (like rectangular and cylindrical polar coordinate systems) can be used conveniently for the study of standard waveguides. But in the case of unconventional waveguides having unconventional geometrical structures, materials and refractive index profiles, the conventional methods and the conventional coordinates cannot be used due to the complicated boundary conditions.

For obtaining the modal characteristic of an optical waveguide analytically, first of all we have to solve the Maxwell’s equations under a given set of boundary conditions and a given set of constitutive equations.
Depending upon the dimension of the waveguide, the guidance problem can be solved in two ways. If the dimension of the optical waveguide is large enough compared to the wavelength of light, we can use the ray theoretical treatment for the analysis of the waveguide. On the other hand, we can solve the wave equation directly using the boundary conditions and the associated constitutive equations. This approach is called the boundary matching approach. The wave equations which can be derived from the Maxwell equations with the associated constitutive equations and the boundary conditions, are generally vector wave equations. Unfortunately, the vector wave equation is hardly solvable for most of the waveguide structures which have non-circular or non-rectangular cross-sections. Therefore, the vector wave equations can be solved only by numerical methods or by some approximate methods. The usual method is, therefore, to assume weak guidance in which case we get the scalar wave equation. This is not a great handicap because when we want to reduce the number of modes, the weak guidance condition actually must hold good. However, even the scalar wave equation is exactly solvable only in some special cases (for the circular waveguide and for TE and TM modes in planar waveguides). Other than these simple structures, one has to take some approximations for solving the scalar wave equation also. For some symmetrical and non-symmetrical non-circular cross-sections, the standard coordinate systems are not suitable and some new coordinates are chosen depending on the nature of the geometry of the cross-section. Due to the non-circular cross-section of the guiding region, the scalar wave equation becomes complicated and the separation of variables technique cannot be applied. Even if the variables are at last separated, the resulting differential equation may not be solvable in a closed form because
of the presence of singularities. In the case of chiral waveguides, it is impossible to reduce the vector wave equation to a scalar wave equation due to coupling of field components with associated constitutive equations.

In the present thesis some of the problems have been tackled analytically under weak guidance. In this analytical method, firstly we choose the cross-section of the waveguide in a loop (closed) of any form. Then we write down the equation of the chosen curve in cartesian coordinates. If the equation of the curve is in polar coordinates, we transform it into the cartesian coordinates. Thus, when the equation of chosen curve is known, we try to find its normal curve using the method of calculus. Now taking these two equations and choosing an appropriate new coordinate system, we try to find out the scale factors. When the scalar factors are known, we can write down the scalar wave equation, remembering that the z-coordinate is unaltered and \( \frac{n_1 - n_2}{n_1} \ll 1 \).

where \( n_1 = \) refractive index of core,
\( n_2 = \) refractive index of cladding.

1.12.2 **Numerical Methods**:  
In most of the engineering applications today, we find it necessary to obtain approximate numerical solutions to the problems rather than exact closed form solutions. Engineers and physical scientists have in recent years become very conversant with numerical analysis. Several approximate numerical analysis methods have evolved over the years and the techniques are based on approximate solutions of an equation or a set of equations describing the physical problem. One of the most widely known approximate methods as the finite differences scheme which gives a pointwise approximation to the
governing equation [130-133]. This method becomes hard to use, when irregular geometries or unusual specification of boundary conditions are encountered and also one has to work with a greater number of points to get better results. In addition to the finite difference method, another numerical method known as the Finite Element Method has evolved. This FEM method discretizes the domain of the problem under consideration into a number of elements or cells and gives a piecewise approximation to the governing equations. FEM method is widely used in many fields like fluid and structural problems [130,132,134]. Although the FEM method can easily handle inhomogeneities and complex geometries, it has always proved perplexing, when solving problems with infinite domains, due to the difficulty of representing boundary conditions properly. Moreover, it requires large computer storage and long computing time to solve the matrix equations [135-136].

Another important development in approximate analysis is the Boundary Element Method which is an elegant and economic alternative to the domain method. It is delineated as a combination technique of conventional boundary integral equation method and a discretization technique, such as the finite element method. The BEM involves a much smaller system of equations with considerable reduction in data and is useful in solving a complex problem. Another advantage of the BEM is that it becomes possible to represent the region of stress concentration in a better manner than the Finite Element Method. In addition, the numerical accuracy of the BEM is generally greater than that of FEM. It is a prudent method for solving unbounded problems. Hence it is suitable for electromagnetic field analysis which often include unbounded regions. This method uses nodes on
its boundary for calculation, and hence it requires less storage and computation time [137-140].

1.12.3 The Point Matching Technique:

In the present thesis, however, it has been found convenient to use another numerical method, known as Goell’s point matching method, which is particularly suitable for tackling waveguide problems. We discuss this method briefly [141].

This point matching method is based on the expansion of the EM field expressions as a series in terms of a set of orthogonal functions. In cylindrical polar coordinates the solutions of Maxwell’s equations can be expressed in the form of a series having Bessel functions, modified Bessel functions and their derivatives multiplied by trigonometric functions. The field solutions must involve the Bessel functions of the first kind in the core, because the Bessel function of the first kind have no singularity at the origin. In the cladding region the field solutions involve modified Bessel functions of the second kind because these modified functions have a decaying behavior as the argument increases. In other words, the field in the core is expressed as the sum of a series of the Bessel functions of the first kind multiplied by trigonometric functions because it shows the field’s oscillating nature inside the core. Similarly, the field in the cladding is expressed as the sum of a series of the modified Bessel functions of second kind multiplied by trigonometric functions because it shows the field’s decaying nature as distance increases from the core-cladding interface. The electric and magnetic fields inside the core and cladding are matched at some selected and appropriate points on the boundary. The points are so chosen that they represent the geometry of the waveguide under consideration. The field derivatives are also matched at
these selected points. A number of equations are thus obtained and their consistency depends on the vanishing of a complicated determinant, the size of which depends on the number of matching points. This determinantal equation involves the propagation constant $\beta$, the possible values of which can be obtained by solving the equation graphically or numerically. This equation, known also as the characteristic equation contains all information regarding the modal properties.

1.12.4 **The weakly guiding approximation:**

The problems in the present thesis have been treated using the weak guidance approximation. This approximation makes the calculation simpler because the vector wave equations are no more required; only the scalar wave equation is needed to be solved. To get an exact characteristic equation, one needs the six field components obtained from Maxwell’s equations and then the appropriate boundary conditions are to be applied. This is mathematically, a very difficult task. A simplified characteristic equation may be obtained by assuming that the refractive index of the guiding region and that of the non-guiding region differ slightly. That is, $\frac{n_1 - n_2}{n_1} \ll 1$. Fibers satisfying this condition are called "weakly guiding fibers" [142]. This approximation enables to ignore the coupling terms in the vector wave equations and a simple scalar wave equation which is satisfied by the electric and magnetic field components along the axis of the fiber. The transverse components of the fields can then be obtained via Maxwell’s equations. The field description is further simplified by the use of rectangular Cartesian coordinates instead of cylindrical polar coordinates. Using this approximation, the characteristic equation of an optical fiber appears in a
much simpler form than the characteristic equation of the exact-mode fields. With the help of this simplified characteristic equation, simple approximate solutions for situations near the cutoff and also those far from cutoff are obtained. The simplified modes can be obtained by the superposition of two nearly degenerate modes. The convenience of this approximation has encouraged a number of researchers to make their analysis of electromagnetic waves through optical fibers by using this simple approximation [143-151].

1.12.5 **Strong guidance condition:**

We know that in the case of weak guidance approximation, the refractive index $n_1$ of the core is nearly equal to the refractive index $n_2$ of the cladding such that $\frac{n_1 - n_2}{n_1} \ll 1$. Also, in this case fields and power are loosely bound to the core. The fields components $E_z$ or $H_z$ and the derivatives are continuous at the boundary.

But in the case of strong guidance $n_1 - n_2$ is large. Here the fields and powers are more tightly packed in the core and the boundary conditions are according to the conditions of the electromagnetic theory. The results are more accurate if one uses the electromagnetic boundary conditions. The weak guidance approximation is applicable in the case when one wants only a few modes to be sustained.

The exact strong guidance analysis involving the vector wave equation is very difficult, but it is possible to deal with strong guidance via the scalar field approximation and the Maxwell equations. Some authors have used this procedure to compare the strong guidance results with the weak guidance results.
The characteristic equations for a dielectric hypycloidal waveguide have been obtained by Rao et. al. [152-153] using the weak as well as the strong guidance approximation. A comparative study has been made for the modal behavior and dispersion curves for such a waveguide under these different conditions. It is seen that there is no trivial cutoff \( V=0 \) in the case of weak guidance whereas it appears in the case of strong guidance. Another remarkable point is that the dispersion curves show under strong guidance that two modes emerge from every cutoff point. No such separation of modes occurs under weak guidance.

1.13 Unconventional optical waveguides:

The conventional waveguide structure is a planar /rectangular waveguide or a circular step index fiber with dielectric core and dielectric cladding. Thus a conventional waveguide has three characteristics:

(a) the shape of the core should be either circular or planar /rectangular,
(b) the refractive index profile should be the step-index profile;
(c) the core and the cladding should be of same dielectric material.

Any deviation from the abovementioned characteristics gives rise to an unconventional waveguides. These are :

1.13.1(a) Unconventional waveguides with respect to different cross sectional shapes:

Such type of waveguides can be obtained by altering the cross sectional geometry of the core (the guiding region ) of the waveguide. This type of change may occur during the manufacturing processes or it may be a deliberate choice. The most popular waveguide for optical communication is the optical fiber having a standard circular cross section. This fiber is also called the standard optical waveguide. The other standard waveguides are the
slab (planar) and the rectangular waveguide. As far as planar or circular fibers are concerned, extensive theoretical and experimental work has been done successfully by various workers and result for these problems are available in the literature [154-170].

Interesting changes in modal characteristics occur when the circular symmetry is broken deliberately or during the manufacturing processes. Therefore, in recent years, light wave propagation through the various types of symmetrical and non-symmetrical, non-circular cross-sections of the waveguide constituted an important specialized area of research in optical wave technology. Initially, only two types of non-circular cross-section, namely the planar and the elliptical, were studied widely [171-175]. These waveguides are very useful in the field of integrated optics. But currently various non-circular waveguides having unconventional shapes such as rectangular, triangular, pentagonal, annular, Piet-Hein, cardiodic, hypocycloid and others have been studied by many researchers [176-184] and several significant results have been obtained. We call them unusual in the sense that such waveguides having typical cross sectional shapes are not commonly used in optical fiber telecommunication systems. These unconventional non-circular waveguides may prove very useful in multifarious integrated optic circuits.

1.13.2(b) **Unconventional waveguides with respect to different refractive index profiles**:

Such types of waveguides can be obtained by changing the refractive index profile. The study of different refractive index profile started very early with the heading “graded- index fibers” [185-190] as described in the previous section. Parabolic and triangular profiles are common. Recently non linearity
induced refractive index change [191] received great attention from many researchers because such waveguides have potential applications in optical switching, and compression [192-195]. A graded index fiber with double cladding was first proposed by Kawakami [196] and further analysis is going on [197-198] as it has large spicing tolerance and is very suitable for high data transmission as compared to the conventional single mode fiber.

1.13.3(c) **Unconventional waveguides with respect to different core-cladding materials**:

Conventional waveguides consist of dielectric materials in the guiding region and the non-guiding region both. The modal propagation properties of the optical waveguide change considerably as the dielectric material of the core and cladding are replaced by other materials. In the beginning metallic covers over the dielectric core and cladding were used to protect them and to facilitate their connection with other circuits [199] as described in the previous section. Such waveguides became of considerable interest because of their large differential attenuation between TE and TM mode polarization. Many metal loaded optical waveguides have been studied using different methods [200-202] and it is found that the characteristics of waveguides are strongly influenced by the properties of the metals.

In recent years, the increased demands in communication networks have stimulated the use of new materials called "smart materials" to provide needed properties of optical systems. These new materials may be liquid crystals, polymers, bianisotropic materials, chiral materials etc. [203-204]. Chiral materials show the property of handedness or mirror asymmetry. They are also optically active. Liquid crystals in fiber core [205-208] and in fiber cladding [209-211] have been studied experimentally and theoretically by
many researchers. Chirowaveguides having chiral media in the core have been studied by Pelet and Engheta [212]. and many others [213-216]. The essential feature of these waveguides is that the propagation modes are always hybrid. Polymer optical fibers and electro-optically active polymer films have received much interest as they are most suitable in integrated optical switching and frequency doubling devices. More recently, fibers with semiconductor materials [217] are suggested to have application as light amplifiers, light filters, and as non-linear devices.

The present thesis is concerned with the investigation of the propagation characteristics of EM waves in some waveguides with guiding regions having unconventional cross sectional shapes. The structures taken are:

(i) A waveguide with a cross sectional shape resembling a lune. And in another problem a waveguide having a cross sectional shape resembling a lune with various types of metal loading on the core boundaries.

(ii) A waveguide with a core cross-section having a sinusoidally varying closed loop boundary.

(iii) A waveguide with a cross sectional shape resembling an ellipse compressed along the minor axis.

(iv) A waveguide with a core cross section bounded by two spirals.

For all these structures, the modal characteristics, dispersion characteristics and modal cutoff conditions of the guided modes have been investigated in detail by using Goell’s point matching method in some cases and an analytical approach in other cases.
1.14 **Arrangement of the thesis:**

The thesis is arranged to give a clear and logical sequence of the findings of some investigations on an optical waveguide of various symmetrical and non-symmetrical core cross-sectional shapes. Here we present a chapter by chapter summary of the investigations carried out. The introductory chapter (called chapter I) gives a brief historical background of communication system developments and shows how the operating region of optical fibers fits into the EM spectrum. It also includes an account of the basic components of an optical communication systems, the superiority of optical communication over electrical communication, the development in the field of integrated optics, semiconductor optical sources, waveguides in microwave as well as in optical ranges, classification of optical waveguides and their modal characteristics investigations, some basic optical waveguide concepts, optical and modal parameters. In addition, chapter I notes the different analytical and numerical methods to study the modal characteristics of unconventional non-circular optical waveguides having different structures. Our primary aim in this chapter is to build up the necessary background of the thesis.

Apart from the introductory chapter, there are five additional chapters among which chapter II, chapter III, chapter IV and chapter V consist of the description of the particular problems taken up by the author and chapter VI describes the summary and conclusions drawn from all the chapters of the thesis.

In chapter II, a waveguide with a cross-section having the shape of a lune has been chosen. Using Goell's point matching method under the weak guidance condition, the dispersion characteristic equation has been derived
and some low order dispersion curves are obtained both in the optical frequency range and also in the microwave range. In this Chapter the abovementioned waveguide with various types of metal loading on the core boundaries has been studied. Using the abovementioned point matching method again, we have derived the modal characteristic equations in two cases. In one case, the lune has on its convex side a dielectric material and the other side is bounded by a conducting material. In the other case, both the boundaries are conducting. Dispersion curves are obtained for both the cases by using the characteristic equations.

In chapter III, we have taken a waveguide having a core with a sinusoidally varying closed shape cross-sectional boundary. Here we have again utilized the Goell’s point matching technique under the weak guidance to study the modal properties of the waveguide. The modal dispersion equation and cutoff condition have been derived. The modal dispersion curves for some lower order modes have been obtained and interpreted.

Chapter IV is devoted to the analytical study of the cutoff conditions and the dispersion curves of a waveguide with a cross-sectional shape resembling an ellipse compressed along the minor axis. A new coordinate system is introduced and using the boundary conditions for the proposed waveguide under weak guidance, the cutoff condition and modal characteristic equation have been obtained. From the cutoff equation we find the number of modes propagated through the guiding region. Also from the modal characteristic equation the dispersion curves for some lower order modes are obtained and interpreted.

In Chapter V of this thesis, an analytical study of the modal characteristics cutoff condition and dispersion characteristics of an optical
waveguide with a core cross-section bounded by two spirals has been taken up. A segment of the core cross-section can be considered as a distorted planar waveguide in which a curvature and a flare have been introduced. Here again a mathematical analysis under the weak guidance condition has been made for the modal characteristics of the proposed waveguide. Choosing an appropriate coordinate system, (which is here introduced for the first time), we find out the scale factors and then write down the scalar wave equation, remembering that coordinate $z$ remains unaltered and $\frac{n_1 - n_2}{n_1} \leq 1$. The characteristic and cutoff equations are subsequently obtained and interpreted.

Finally, the concluding chapter VI gives the summary of important findings and results and indicates some possible practical application and extension of the work presented in this thesis.
SECTION A

OPTICAL WAVEGUIDE ANALYSIS BASED ON NUMERICAL METHOD

(CHAPTEII & III)