Chapter 1

GENERAL INTRODUCTION
CHAPTER-1

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1.1 Brief History of Optical Waveguide

Optical waveguide consist of a high refractive index region surrounded by low refractive index regions. Typically fiber dimensions are 1000µm to 1500 µm diameter. Light guidance through such an optical waveguide, occurs through the phenomenon of total internal reflection. Optical waveguides are characterized by various discrete guided modes which propagate down the waveguide with most of most of their power confined to the high index region of the waveguide. Since the waveguide has a large index difference between the guide and air, the field decays very rapidly into the air region while it slowly decays in the substrate in case of planar waveguide.

The action of a waveguide can be partially understood by considering the rays down the fiber. A light-wave entering the fiber is either refracted into the cladding and attenuated, or is totally internally reflected at the core/cladding boundary. In this manner it travels along the length of the fiber. The maximum angle at which it may enter the guide and travel by total internal reflection is termed the acceptance angle. It is also possible for the wave to follow a helical path down the guide. These rays are called skew-rays.

It is not possible for the wave to take any ray down the guide. Only certain rays can be taken. These rays are called modes. The modal action of a waveguide
is a consequence of the wave nature of the radiation. A mon-mode fiber is a fiber that only has one acceptable ray-path per frequency. A multi mode fiber has a number of possible rays that light of a particular frequency may take.

Waveguides were first dealt with by Lord Rayleigh. Later the dielectric waveguide was investigated theoretically by Hendros and Debye in 1910 and experimentally by Schriever. The speculation of Kao and Hockham\cite{1} and Werts\cite{2} about the possibility of using optical fiber waveguides as transmission medium in the mid 1960's and subsequent fabrication of practical fibers by Kapron et al.\cite{3} in 1970 were the major breakthrough in this direction. Snitzer\cite{4} gave a general theory on the modes of a cylindrical dielectric waveguides. In 1967, Kapany\cite{5} published his work on dielectric waveguide for imaging applications at optical frequencies.

Study of optical waveguides using coupled mode theory was addressed by Marcuse\cite{6}, and by Yasumoto\cite{7}. A comparison of the coupled mode theory and the finite element method in the analysis of periodic waveguides was made by Ohkawa et al.\cite{8}.

Shenoy et al. studied optical fibers numerically using matrix approach. For large fibers, the ray theoretic approach was used for the study of optical fibers. Some work has already been done in this direction by many workers\cite{19-31}.

However, the failure of ray optics for the analysis of circular optical dielectric waveguides was pointed out by Snyder et al.
Although an exact analysis of optical fibers is somewhat complicated and the field solutions came out to be complex, an approximate analysis can be made for fibers which have small refractive index difference between the core and the cladding. Such fibers are generally called weakly guiding fibers Gloge\textsuperscript{[32]} gave, for the first time, an approximate analysis of such fibers in 1971. Dispersion characteristics of such fibers was reported by Gloge\textsuperscript{[33]}.

The technological developments in the areas of laser sources optical detectors and above all, optical fibers have revolutionized the area of telecommunication and networking. Earlier when it was known that light frequencies ($\sim 10^{14}$ Hz) have several orders of magnitude higher than the frequencies of radio waves ($\sim 10^6$ Hz) and microwaves ($\sim 10^{10}$ Hz), light beam was used as a carrier waves to carry far more information's in comparison to radio waves and microwaves. The idea of using light waves for communications was traced by Alexander Gram Bell, by inventing the photo phone. However, optical communication did not develop until around 1960 because of the absence of a suitable light source. Indeed it was the discovery of the laser in 1960, which triggered a serious interest in the development of practical optical communication systems. In the early sixties, preliminary experiments were carried out by propagating information carrying laser beams through the open atmosphere. It was soon realized that due to the vagaries of the atmosphere (like rain, fog etc.) it was necessary to have a guiding medium through which light waves could be reliably transmitted.
Thus following the development of laser and light-emitting diode (LED) sources in the early 1960's, Kao and Hockham (1966) recognized that glass waveguides could be a practical transmission medium if transmission losses could be reduced to 20 dB/km by elimination of metallic impurities. Naturally several researchers began to explore the potentiality of reducing the losses so that they might be comparable to 20 dB/km as speculated by Kao and Hockham.

1.2 Loss in Optical Fiber

Loss in optical fibers plays an important role in the efficiency of optical fibers as transmission media. Microbending loss is one of them. Loss due to microbending of optical fibers has been studied extensively by Gardner\textsuperscript{34} and Marcuse\textsuperscript{35}. Power attenuation due to bending was discussed by Love et al.\textsuperscript{36}. The beam propagation method in the analysis of loss due to bending was carried out by Miyagi\textsuperscript{37}.

However, the immediate problem at that time was that of optical attenuation of the fiber. The attenuation of light in the optical fiber has a number of sources. Absorption of light occurs in the glass and this decreases with frequency. Scattering of light from internal imperfections with the glass that is approximately constant with wavelength. Researchers are using techniques for evaluating the optical losses of a planar film by use of a quasi-waveguide configuration and a prism film coupler configuration. The technique can separate two contributions to optical loss; that form the surface scattering caused by the roughness of surface
and that from volume losses including volume scattering and volume absorption\textsuperscript{[37a]}. Bending the waveguide changes the local angle of total internal reflection and loss increases through the walls. A combination of these effects results in a minimum absorption of about 2 dB/km to 5dB/km in the 0.8 μm to 1.8μm wavelength region.

In addition to attenuation, optical waveguide also suffer from dispersion. It is now well known that a narrow light pulse injected into the fiber, usually gets broadened as they propagate along the fiber. One of the reasons for this broadening is the fact that different rays take different paths and hence, they reach the receiver end at different times. Therefore, in order to exploit the large repeater spacing offered by the presently available low-loss fibers, the minimization of pulse dispersion has become a subject of considerable interest\textsuperscript{[38-41]}. If a sufficiently sharp pulse is launched at one end of the fibre, the energy gets distributed into different modes. Thus there is a waveguide dispersion in addition to the material dispersion causing a pulse deterioration.

Thus within the space of 20 years, optical fiber losses were reduced to below 5 dB/km and suitable low loss joining techniques were perfected. However, even after this many researchers continuously tried to get still lower loss optical fibers. An intensive effort made at Corning glass works in the U.S.A. over a period of four years after the novel suggestions of Kao and Hockham and Werts, eventually succeeded in breaking the economic barrier target of 20dB/km set for
communication purpose, by producing a fiber that exhibited a loss of 17 dB/km at the 0.6328 μm wavelength of the He-Ne laser. This achievement immediately triggered a worldwide interest on optical fibers as the transmission line for optical telecommunication.

The design of the fiber can substantially reduce the dispersion caused by the waveguide propagation characteristics and the spectral width of the light source. Dispersion values of several tens of ns/km down to a few ps/km are possible. The equivalent information bandwidth is in tens of MHz – Km to tens of GHz /km, which is only a fraction of the bandwidths to be exploited in the optical frequency range. Hence, for optical fiber systems, there is a constant attenuation over any operating bandwidth; in contrast to copper cables, where the attenuation of the cable increases as the square-root of the bandwidth. This property simplifies the design of the optical system.

1.3 Advantages of Optical Fiber Communication

Since glass fibers were first proposed as transmission media for optical signals, the literature on them has virtually exploded. Review papers by Gloge [42], Miller et al. [43] and Clarriocoats [44] offer a much more detailed survey. As a result of intensive researches over the last decade, glass fibers have emerged as viable transmission media for communication at optical frequencies. The major advantage of optical fiber over conventional transmission media (e.g., coaxial cables, twisted wire-pair etc.) is due to their larger bandwidth. The optical carrier
frequency is in the range of $10^4$ GHz to $10^6$ GHz. Obviously, the information carrying capacity of optical fiber systems has proved far superior to the best copper cable systems and coaxial cable system. However, a large number of other side benefits, which are by no mean insignificant, are also available in optical fibers. For example:

The optical carrier dimension not greater than the size of human hair. Hence even when such fibers are covered with protective coatings they are far smaller and much lighter. This offers a reduction in the number of ducts for carrying cables in cities and because of light weight they are preferable to use within mobiles such as aircrafts, satellites etc. for signal transmission. As they are generally fabricated from glass, or sometimes a plastic polymer, they are electrical insulators. That is why they avoid many problems such as radiative interference, groundloop etc., and, when installed in a cable without metal, lightning- induced damage that exists in other transmission media. Therefore, they are suited for electrically hazardous environments.

Since glass is a dielectric material, fibers are free from electromagnetic interference, radio frequency disturbances, or switching transients giving electromagnetic pulses. Therefore, they are suitable for use in an electrically noisy environment without any shielding form electromagnetic interference (EMI). The fiber cable is also not susceptible to the effects of lightning even if we wish to use overhead cables. Since there is no optical interference between fibers unlike that in communication using electrical conductors, crosstalk is negligible, even when
many fibers are cabled together. Over the three decades of the evolution of optical fibers for transmission, the transmission loss in optical fibers has been tremendously reduced, almost to the theoretical limit. Now–a–days, fibers with a loss of less than 0.2 dB/km can be fabricated with little care. Thus, attenuation in fibers is no longer a real problem in optical fiber communication systems.

Another interesting feature of the optical fiber is that its performance is independent of the transmission rate below a certain optimum value, when used in a digital link. It can be used in a low- capacity (low bit rate) system and the same can be used in a high-capacity system (high bit rate) simply by changing terminal electronics.

Another advantage of the optical fiber communication system is that optical fibers provide very high degree of signal security, since the light from optical fibers does not radiate significantly. And signals from an optical fiber cannot be obtained in a non- invasive manner Therefore, theoretically any attempt to extract information from the signals transmitted in a fiber can be detected easily. This feature is very useful for those applications where secrecy is an important factor. In the last twenty years, the development of optical fibers has been tremendous and it has resulted in the production of very low loss optical fibers. This makes it possible to implement communication links with extremely wide repeater spacing, thus reducing system cost and complexity. And with a huge modulation bandwidth capacity, optical fiber links are very suitable for long haul telecommunication applications.
Lastly, glass being made from SiO₂ and silicates, is not a scarce resource. So in comparison with copper conductors, optical fibers, which are generally made of glass, offer a potential low-cost line communication. Today, a large number of research papers and some monographs such as those by Kapany and Burke⁴⁵, Marcuse⁴⁶ and Arnaud⁴⁷ provide a firm enough theoretical foundation to answer almost all questions that arise in communication application of fibers.

Much emphasis has been given in many research articles on single-clad optical fibers. For long-haul applications, minimization of dispersion is a prime problem, which can be met by either changing the refractive index profile of the core, or by a variations of propagation characteristics of the fiber. It may happen that a normally single-clad step-index monomode fiber presents index variation in the cladding also⁴⁸. Many investigators have in the recent past⁴⁹-⁵¹ paid attention to the subject of multi-clad optical fibers and their applicability.

In integrated optics, planar optical waveguides in the form of films and strips are used. The early efforts in the development of planar optical waveguides were made in the infrared range. Anderson⁵², Tien et al.⁵³, Miller⁵⁴, Barnosky⁵⁵ have advanced theories and methods not only to encompass all aspects in the analysis and design of guiding structures, but also to develop precise and reliable technologies for the fabrication of planar optical circuits. Wave propagation in dielectric slab waveguide of unlimited transverse extent was well understood, but its transversely limited form, the rectangular dielectric waveguide
was first studied theoretically by Schlosser et al.\textsuperscript{[56]}. More recently a number of investigators have extended the theoretical study for various characteristics\textsuperscript{[57, 58]}. However, in spite of that, an exact analytical study become forbiddingly difficult because of the presence of corners in the rectangular waveguides. In this thesis, we attempt a pragmatic exposition of the theory of wave propagation in multilayered planar optical waveguides. The absence of corners in the planar structures makes the study some what simpler. The study is of great importance in integrated optical devices.

An optical film waveguide consists of a thin dielectric film of low optical absorption on a substrate. A more important point, however, is that this dielectric film is actually used for guiding light. The different dielectric films find applications in the manufacturing of a number of optical components. The theory of dielectric waveguides in well known and several excellent text- books describe, in detail, the different approaches\textsuperscript{[59-62]}.

1.4 Optical Fiber Waveguides

In present day optical communication systems, optical fiber waveguides find their most important application as the transmission channels. An optical fiber may be defined as a waveguiding structure, which is cylindrical in shape and able to guide electromagnetic energy along its axis. An optical fiber transports energy in the visible and infrared spectrum because silica, which is the main constituent of the fiber material, has lowest attenuation at 1.3 \( \mu m \) and 1.55 \( \mu m \). These are known as the infrared windows.
Roughly, the mechanism of transmission of electromagnetic energy in an optical waveguide can be explained in terms of multiple total internal reflections at the core-cladding boundary, that is the core refracts the light and the cladding reflects the light. The core refracts the light and guides the light along its path. The cladding reflects any light back into the core and stop light form escaping through it. It bounds the medium. An optical fiber is a hair like structure made of dielectric material. The material is a kind of high silica glass. Optical fiber consists of inner cylinder of glass, which is guiding part of it and this forms the central region of the fiber called the core. The core is surrounded by another cylindrical shell of glass or plastic of lower reflective index, called cladding. The cladding supports the waveguide structure; and when it is sufficiently thick, it substantially reduces the radiation loss into the surrounding air. Also if the cladding is absent, there would be leakage of light energy from one fiber to another, when many fibers are cabled together, and it also protects the core from absorbing surface contaminants with which it may come in contact resulting in a change the behaviour of the guiding region. Actually the light energy travels both in the core and in the cladding, allowing the associated fields to decay to a negligible value at the cladding-air boundary. Thus the cladding, in reality, serves many purposes, although it is merely described as the non-guiding region. Optical fibers (light guides) may be classified in terms of the refractive index profile of the core, and the possibility of monomode or multimode transmission through the fiber.
If the core has a uniform refractive index, the fiber is called a step-index and if the core has a non-uniform refractive index that gradually changes (usually decreases from the axis towards the core cladding boundary), the fiber is called a graded index. Variations in index profile of the cladding are also considered for improving some propagation properties of the step-index fiber.

1.5 Step Index fiber

An optical fiber with a core of constant refractive index $n_1$ and a cladding of slightly lower refractive index $n_2$ is known as a step index fiber. It has abrupt change in the refractive index profile at the core cladding interface, as the name implies. This is the simplest type of fiber in use. Although an ideal step index optical fiber is impossible to manufacture, fibers with an approximate step index profile are quite common these days. The refractive index profile of such fibers may be defined mathematically as:

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

A step index fiber may be a multimode fiber, or a single mode (monomode) fiber according as the number of modes it can support. Generally, multimode fibers have large core diameters which are large enough to allow the propagation of many modes within the fiber core.

The transmission of light pulses in step-index optical fibers is greatly affected by an inherent property of the fiber called the intermodal dispersion;
different guided modes of a fiber have different velocities, thereby resulting in the broadening of pulses while traveling through a fiber. Intermodal dispersion which is of the order of a few ns/nm-km contributes the largest share in pulse broadening. However, if we consider a fiber which has only one propagating mode as a transmission channel, there is no question of intermodal dispersion. Such a fiber which allows to propagate only one guided mode is called a single mode fiber and dispersion in such a fiber is due to waveguide dispersion and material dispersion only, which collectively give a dispersion of the order of a few ps/nm-km only. In other words, the maximum attainable bandwidth for step-index single mode fibers in very large in comparison with those of multimode step-index fibers. However, multimode step-index fiber have some advantages over single mode step-index fiber which are-

(a) Low launching power

(b) Large numerical aperture and large core diameter giving easier coupling of power from optical sources.

(c) Easier splicing with high tolerance.

However, a monomode step-index fiber is generally preferred when the fiber is to be used for communication purposes where we need minimum distortion of the signal after traveling a long distance.

1.6 Multimode Step-Index Fibers

A multimode step-index fiber, generally, has a finite number of allowed guided modes, which propagate along the fiber. The number of guided modes
allowed in a multimode step-index fiber is fixed for a particular fiber for a particular operating wavelength. It is determined by the physical parameters (i.e. the relative refractive index difference of the core and cladding and the core radius) of the fiber and the wavelengths of the transmitted light. These parameters can be expressed as a single combined parameter called the $V$-parameter or the normalized frequency parameter, $V$. Below the lowest cutoff value of $V$ for guided modes, no modes can be sustained in the fiber and only leaky modes whose amplitudes decrease gradually, propagate along the fiber and these modes can travel considerable distances. Also, choosing a proper value of $V$, we can restrict the number of guided modes in the fiber for a particular operating wavelength. It is the guided modes which are of great importance in optical fiber communications as these are confined to the fiber over its full length. Gloge$^{[63]}$ showed that the total number of guided modes or mode volume $M_v$, for a step-index fiber is related to the $V$ value for the fiber by an approximate relation.

$$M_v \equiv \frac{V^2}{2}$$

in which $V = (2\pi \alpha / \lambda_0)(n_1^2 - n_2^2)^{1/2}$ and this gives the estimate of the number of guided modes propagating in a particular multimode step-index fiber.

Multimode fibers (both step-index and graded-index) have several advantages compared to single mode fibers. The larger core radii of multimode fibers makes it easier to launch optical power into a fiber and it is easier to connect two such similar fibers together. Another advantage is that light can be launched
into multimode fiber using a light-emitting diode (LED) source, whereas for a single mode fiber, lasers diodes are to be used. LED's are easier to make are less expensive and need less complex circuitry. Also, they have longer lifetimes than laser diodes, thus making them more desirable in many applications.

Intermodal dispersion is the main disadvantage of multimode fibers. Graded index multimode fibers can reduce intermodal dispersion greatly. Consequently, they have much larger bandwidths than those of step-index multimode fibers. Intermodal dispersion effects are absent in single mode (step-index or graded-index) fibers.

Since multimode fibers are easier to fabricate, and splicing and connection are easier, the study of multimode fibers was given due attention by many researchers. In 1971, Personick[64] observed that pulse dispersion can be reduced by the coupling the coupling effects among guided modes of a multimode waveguides. Marcuse[10, 65, 66] studied pulse propagation power distribution and radiation losses in multimode dielectric waveguides in great detail. Transmission distortion in multimode random waveguides has been studied by Rowe and Young[65]. The far field output distribution as a function of fiber length was calculated by Gloge[67] and he made a comparison of this result with the experimental results for low-loss multimode fibers. It was found that average coupling of the neighbouring modes is about 1.6 percent per millimeter and coupling among other modes other than the neighbouring ones seems to be of an order of magnitude less. He suggested that random bends in the fibers would be
the prime cause among the possible sources of mode coupling. Pulse dispersion in multimode fibers with alternate thin and thick layers was studied theoretically by Chakravarty et al.\textsuperscript{[68]} Power attenuation in multimode fibers was calculated by Love and Pask\textsuperscript{[69]} Kaminow et al.\textsuperscript{[70]} gave a general theory on multimode fiber bandwidth and Cibotto and Someday published a paper on the calculation of bandwidths of multimode fibers\textsuperscript{[71]}.

1.7 Single Mode Fibers

In order to minimise signal distortion theoretically, a multimode fiber, having a perfect cylindrical boundary throughout the length of the fiber, can be operated in single mode condition. But the propagation of a single mode in a multimode step index fiber cannot be maintained within the fiber because coupling between the guided modes takes place due to input mismatches and fiber imperfections. Thus arises the need for a fiber which allows only one guided mode to propagate along it and such a fiber is called a single mode fiber. With only one possible propagating mode, a single mode fiber has the advantage that the signal dispersion caused by the delay differences between different modes is absent. Hence a single mode fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by absorption or leakage. For the design of a single mode fiber, the normalized frequency parameter, $V$ for the fiber is very important. A proper choice of this parameter determines whether a fiber will be a single mode or a multimode fiber. The larger the $V$ parameter, the larger is the number of guided modes allowed in a fiber. The lowest mode, i.e., the
fundamental mode, has no cutoff. The next higher mode just above the fundamental LP$_{11}$ mode is the LP$_{01}$ mode, it has a cutoff normalized frequency $V_c = 2.405$ for a step-index fiber. Thus, a single mode propagation of the fundamental mode in step-index fibers is possible over the range $0 \leq V \leq 2.405$ for the normalized frequency parameter, as there is no cutoff for the fundamental mode. In other words the fundamental mode has a cutoff at $V=0$, which is possible only when the operating wavelength is infinite or the core radius is zero. Both the conditions are physically unacceptable. Another condition for $V$ being zero is that there is no difference in the index of refraction between the core and the cladding. In this case, there is no guidance. It is seen from the expression for $V$ that single mode fibers may be designed by adjusting "a", the core diameter and "$\Delta$", the difference of refractive indices between the core and the cladding for a particular operating wavelength. These two quantities may be called controlling parameters in the design of a step-index fiber. It be seen that single mode operation within a fiber can be achieved by reducing the two controlling parameters. However, these reductions create problems in the fabrication and performance of the fiber. Because when the core diameter is small, a difficulty in launching light energy into the fiber arises. Again, a small relative refractive index difference creates a severe difficulty at the time of fabrication and it is very difficult to maintain a uniform and small $\Delta$ value throughout the length of the fiber. Thus we have to optimize these parameters in the design of a fiber. There is another problem related to single
mode fibers. Because of the small refractive index difference and low V-value, there is a large part of the electromagnetic power spreading into the cladding for the fundamental mode since the fundamental mode carries maximum amount of power. It was shown that for step index fibers with a V-value less than 1.4, over half of the core power goes into the cladding. Gloge\textsuperscript{[72]} should that to avoid losses in the cladding of single mode fibers, a cladding of thickness 50 \textmu m is needed. Commercially available single mode step-index fibers have cladding thicknesses more than this minimum limit.

Because of its enormous bandwidth, single mode fibers have been studied extensively both theoretically and experimentally\textsuperscript{[73-82,5,83-86]}. Studies of propagation characteristics, modal characteristics, cutoff characteristics, attenuation properties, dispersion and other related properties of a single mode fiber have been studied by many investigators, sometimes with the help of approximation techniques\textsuperscript{[87-99]} . Design of single mode fibers and devices based on single mode fibers have been discussed by some researchers\textsuperscript{[100-104]}.

Losses in fibers is one of the main problems in fiber-optic communication. Due to excessive loss in early fibers, fiber-optic communication was not considered to be feasible and economical three decades ago. Many researchers gave attention to the study of reducing loss and attempted to understand loss mechanisms in fibers. One of the major factors contributing to fiber loss is the bending loss in optical fibers. Studies on bending losses and their measurements
and mode filed diameters of single mode fibers were also made\textsuperscript{[103-114]}. From the scattering studies of single mode silica-based fibers it was found that even larger bandwidths can be achieved if dispersion can be made zero at or around 1.3 \( \mu \text{m} \) and 1.5 \( \mu \text{m} \) wavelength windows of silica fibers.

Single mode fibers in fact, support two polarization states of the fundamental mode. This creates another problem in pulse transmission known as polarization mode dispersion\textsuperscript{[115-117]}. Studies of polarization in optical fibers were carried out by Kaminow\textsuperscript{[118,119]} and Ramaswamy et al.\textsuperscript{[120]}.

Another development in single mode fiber optics is the observation of nonlinear optical phenomena in optical fibers\textsuperscript{[121-126]}. It has many promising application such as controlled phase modulation\textsuperscript{[124]} pulse narrowing by soliton effects\textsuperscript{[125]} etc. Bordon and Anderson\textsuperscript{[126]} reported propagation of nonlinear pulse in dispersion adapted monomode fibers.

1.8 Slab waveguides:

Film and planar waveguides differ greatly from glass fibers. Film and strip-guides as well as other planer waveguide structure serve as optical components and as connecting lines in Integrated Optics. In these applications, the length of a planar waveguide ranges from a fraction of a mm up to a few mm only. Guided mode attenuation for a waveguide of such a short length need not be much lower than a few dB. cm\textsuperscript{-1}. Because of the small length, their transmission dispersion is very low and will not cause any noticeably signal distortion. An optical film waveguide consists of a thin dielectric film of low optical absorption, deposited
and a transparent substrate, preferably of likewise low absorption and a refractive index lower than that of the guiding region. The symmetrical dielectric slab or film represents the simplest form of optical waveguide and serves as a model to gain an understanding of wave propagation in optical waveguide of rectangular symmetry. The asymmetric dielectric film on a substrate, although rather more general types of optical waveguides. A cross-sectional view and the manner of ray propagation through a slab waveguide are depicted in Fig. 1-1.

1.9 Optical Waveguide Theory:

In a waveguide, the propagating light rays, or electromagnetic fields assume certain patterns whose theoretical analysis is important in order to obtained the various experimental observables. In optical waveguide theory generally three different approaches are used namely ray theory, wave theory and electromagnetic theory. We shall now briefly review these approaches one by one. But before that we mention the parameter and notation used in the present thesis.

Parameters and Notions

Given a step-index waveguide, we define the following parameters: angular frequency of the light signal $\omega$; the free-space wavenumber $k_0 = \omega / c$; core refractive index $n_1$; the cladding refractive index $n_2$; the profile height parameter $\Delta = (n_1^2 - n_2^2) / 2 n_2^2$.

Further $r_0$ = radius of the core and $\beta$ (= $k_0 n_e$) is an unknown propagation constant i.e, the longitudinal component of the wave vector and $n_e$ is the effective refractive index.
Fig. 1-1: (a) Cross-sectional view of a dielectric slab waveguide. (b) Zig-zag path of meridional rays in a step-index slab waveguide. (c) Helical path of a skew ray in a parabolic-index circular guide.
Also we have the core parameter as \( u = \gamma_1 \tau_0 \), with \( \gamma_1 = (n_1^2 k_0^2 - \beta^2)^{1/2} \) and the cladding parameter \( w = \gamma_2 \tau_0 \), with \( \gamma_2 = (\beta^2 - n_2^2 k_0^2)^{1/2} \). The normalized frequency parameter \( V \) is defined such that \( V^2 = u^2 + w^2 \).

We shall now briefly review the three viewpoints referred to above.

1. Ray analysis: When the wavelength of the radiation is small compared with the transverse dimension of the guide or, equivalently, when the waveguide parameter is large compared with unity (\( V \gg 1 \)), geometrical optics can provide an approximate description of light propagation through an optical waveguide (see Fig 1-1). In this approximation, the waves can be represented by rays, which are normal to the wavefronts. In general, a ray incident on the core-cladding interface at a glancing angle \( \theta \) will be partly reflected and partly refracted. Condition for guidance through total internal reflection is \( \theta < \theta_c \), with \( \theta_c = \cos^{-1}(n_2/n_1) \), is the critical angle. In optical fibers, where the cross-section is circular, two types of rays exist. In one of these, the incident ray, the reflected ray, and the fiber axis lie in the same plane and in this case, we have meridional rays. The other type of ray propagation, which is more complicated, is when the rays move in a zig-zag way, giving rise to a helical path. This kind of propagation is through skew-rays.

Although the ray analysis is discussed thoroughly in the literature\(^{127-130}\) and is useful in calculating the dispersion\(^{131,132}\) as well as giving a pictorial view...
of the system, yet it becomes rather laborious even for multi-layered structures. This exercise would be useful if the method is accurate, but as said earlier, the description is only an approximate one. For multilayered guides with three or more parallel boundaries instead of the two boundaries of the usual films, it would be impractical to trace rays of uniform plane waves, to calculate their reflection and to determine the phase conditions for self-consistent solutions. Here it is much easier to solve the more accurate Maxwell's equations directly subject to the boundary conditions of the particular planar structures. Further, the ray approach becomes invalid for single-mode waveguides which have very small core dimension and thereby a small value of the V-parameter.

(2) Wave analysis: This treats light as a wave disturbance described by the Scalar Helmholtz wave equation:

\[(v_i^2 + n^2 k_z^2 - \beta^2) \psi(\vec{r}) = 0 \quad (1-1)\]

where \(\beta\) is the longitudinal component of the wave vector, \(n\) equals \(n_1\) (or \(n_2\)) in the core (or cladding). The quantity \(\psi\) is a scalar which may represent either the transverse component of the electric field or the magnetic filed. Here the \(z-t\) dependence of the function \(\psi\) through the phase factor \(\exp\{i(\beta z - \omega t)\}\) has been suppressed. It must be emphasized at the very outset that eqn. (1-1) is incapable of accounting for polarization phenomenon directly. The more general vector wave equation (to be discussed later) can deal with polarization completely. In this case,
one uses the so called weak-guidance approximation where $\Delta \ll 1$. Nevertheless, this is of very great importance in dealing with both complicated structures and different refractive index profiles. This solution for simple geometries is relatively easy, particularly when there is some symmetry in the waveguide which dictates the choice of the appropriate coordinate system. Thus it leads to several important physical concepts mentioned below pointwise.

**Modes** - Modes are permitted field patterns within the medium, satisfying the wave equation and all the boundary conditions of the problem. This implies that the field and their derivatives are both continuous across the core-cladding interface, together with the physical requirements that $\psi$ is everywhere finite and decays naturally at large distances form the waveguide axis.

**Propagation constant** - The imposition of boundary conditions on $\psi$ give rise to a consistent condition in $\beta$ called the eigen value (or characteristic equation), whose solutions supply the unknown propagation constant $\beta$ of the waveguide structure. The constant $\beta$ is related to the free-space wave number ($k_o$) and the effective refractive index

\[(n_e) \text{ as: } \beta = k_on_e \tag{1-2}\]

Sometimes it is more convenient to work with the normalized propagation constant $b$, defined as
\[ b = \frac{\beta^2 - n_2^2 k_o^2}{(n_1^2 - n_2^2) k_o^2} \times \frac{(n_2^2 - n_1^2)}{(n_1^2 - n_2^2)}; \quad 0 < b < 1 \quad (1-3) \]

Plots of \( b \) versus \( V \) (for specified fiber geometry and index profile) are called dispersion curves, which contain much information about the transmission properties of the guide. The mode having largest value of \( b \) at any \( V \) is called the fundamental mode.

**Guided and unguided modes**

The solution of the wave equation, in general, provides two types of modes, viz., guided (bound) and unguided (radiation) modes. For a guided mode, \( \beta \) is discrete, real and confined in the range

\[ n_2 k_o < \beta < n_1 k_o \quad (1-4) \]

Corresponding to the fact that the phase velocity of the mode lies between the phase velocities of the signal in the core and that in the cladding region. Also the power of the guided mode does not attenuate in a non-absorbing medium. On the other hand, the unguided modes have a continuous spectrum of \( \beta \) in the range

\[ -\infty < \beta < n_2 k_o \quad (1-5) \]

corresponding to an attenuation of the optical power. Further, the waveguide here acts more like a radiating antenna. The present thesis will be concerned solely with the guided modes. A special situation which is interesting and gives some insight
into propagation through waveguide is the one when a particular mode is near the
cutoff, which means that it ceases to behave as a mode. This situation is described
below for the scalar wave propagation.

Regions near-and-far from cutoff

The near cutoff situation arises when the phase velocity of the mode tends
to become equal to the propagation velocity of light in the bulk material of the
cladding i.e.,

\[
\frac{\omega}{\beta} \rightarrow \frac{c}{n_2}; \beta \rightarrow n_2 k_0, \gamma_2 \rightarrow 0, \nu \rightarrow 0; u \rightarrow V = V_c
\]  

(1-6)

The eigen value equation can now be used to determine the discrete modal
cutoff values \(V_c\) of the waveguide parameters. As a mode gradually approaches the
cutoff, more and more power gets into the cladding. In geometrical optics
(Fig.1-1), the situation corresponds to the critical angle \(\theta_c\) of total internal
reflection. Similarly, the far from cutoff situation arises when the phase velocity of
the mode tends to the propagation velocity of light in the bulk material of the core
i.e.,

\[
\beta \rightarrow n_1 k_0, \nu \rightarrow 0
\]  

(1-7)

The fundamental mode in the waveguide has a zero cutoff value while for
single - mode operation, the waveguide parameter must be kept below the cutoff
frequency of the first- higher mode.
At this point, we may introduce more significant parameters in propagation through waveguides. These are (1) time delay and (2) dispersion. We shall now discuss these two parameters.

Consider a source and a receiver placed at the ends of a wavaguide of length 1 and use the geometrical optics picture (Fig.1-1). Rays of a given wavelength λ inclined at different angles with respect to the axis have to traverse, in general different optical path lengths. Also, if the source is non-monochromatic in nature, then rays at a given inclination θ, having different wavelengths will have varying speeds of propagation. Consequently, the received signal will show a pulse-spreading in time, whose origin is partly of intermodal and partly of intramodal nature. In the wave picture, the phase \( (β1-ωτ) \) becomes stationary in the \( k_o \) variable at \( 1\partial β/ \partial k_o - cτ = 0 \), yielding for the group delay

\[
τ = \frac{1}{(c)} \frac{(∂β/∂k_o)}{c}
\]  \hspace{1cm} (1-8)

If the source emits light with wavelengths lying between \( λ \) and \( λ+δλ \), then the net dispersion produced at the receiver is \( (1\partial β/ c) (\partial^2 β/∂λ^2) \). In order to minimize the waveguide dispersion, one uses single-mode system with suitably graded-index profile\(^{[133]}\).

(3) Electromagnetic wave analysis: The rigorous viewpoint is to regard light as a disturbance involving the electric field \( \vec{E} \) and magnetic field \( \vec{H} \) described by the Maxwell's equations
\[(\nabla + i\beta \hat{z}) \times \vec{E} = i k_0 \vec{H}\]

\[(\nabla + i\beta \hat{z}) \times \vec{H} = -i k_0 n^2 \vec{E}\]  \hspace{1cm} (1-9)

where $\nabla$ is the 3-dimensional gradient operator and $\hat{z}$ is a unit vector along the waveguide axis. Eqn. (1-9) produce a coupling between $\vec{E}$ and $\vec{H}$ in such a way that form a knowledge of the longitudinal components $E_z, H_z$, the remaining components can be constructed. The allowed solutions must satisfy the requirements that the tangential components of field vectors are continuous across the core-cladding interface, the fields are bounded everywhere and vanish asymptotically in the transverse plane.

On taking the curl of the quantities on both sides of the above equations, we get the vector wave equations:

\[\left(\nabla^2 + n^2 k_0^2 - \beta^2\right) \vec{E} = -\nabla (\vec{E}, \nabla, 1 n n^2)\]

\[\left(\nabla^2 + n^2 k_0^2 - \beta^2\right) \vec{H} = (\nabla \times \vec{H}) \times (\nabla, 1 n n^2)\]  \hspace{1cm} (1-10)

The following inferences may be draw from the above equations.

(i) **Coupling of field components**

The equations for $\vec{E}$ and $\vec{H}$ in (1-10) have become formally decoupled. In the equation for the transverse electric vector $\vec{E}_t$, the components $(E_x, E_y)$ get coupled together due to the $\nabla_i \ln n^2$ term. Also, in the equation for the longitudinal component $E_z$ there appears a contribution from $E_t$. The $\nabla_i \ln n^2$ term is responsible for the hybrid nature of the modal fields and for the polarization
phenomenon in dielectric waveguides. One may comment here that for homogeneous media, the $\bar{\nu}_1 \ln n^2$ is zero. This term, therefore becomes important for graded index waveguides.

(ii) TE, TM and hybrid modes

Electric and magnetic fields in a homogeneous unbound medium are TEM waves, i.e., they do not have any longitudinal component $E_z$ or $H_z$. However, a guided wave always possesses either one or both of them because of restrictions imposed in the transverse plane. Modes can be of the TE (i.e., $E_z=0$), TM (i.e., $H_z=0$) or hybrid (i.e., $E_z\neq 0$, $H_z\neq 0$) varieties. In planar waveguides, the modes are pure TE or pure TM as they can preserve their character upon multiple reflections. In circular waveguides, i.e., optical fibers, azimuthally invariant modes are either TE or TM (corresponding to the meridional rays (Fig.1-1) while azimuth dependent modes are hybrid (corresponding to the skew rays). In dielectric guides of other geometries, the modes generally hybrid. The hybrid modes can be further classified\textsuperscript{[134]} into HE or EH variety according to the relative magnitudes of the contribution of $H_z$ or $E_z$ in construction of transverse components of the fields.

Polarization

If a non-circular waveguide possesses a pair of mutually orthogonal preferred symmetry axis, then the guide can support modes whose electric vector is oriented predominantly along either axis i.e., the guide acts like a polarizer.
Furthermore, these two types of modes have, in general, different $\beta$ values giving rise to what is known as birefringence. Of course, apart from this type of geometrical anisotropy, one can achieve more prominent birefringence with the help of stress, twist or material-induced anisotropies. It has been shown that the modes of a weakly guiding fibers are almost linearly polarized$^{[46,135]}$.

(4) Solution techniques: A vast literature is available$^{[136-144]}$ on the actual methods for solving the scalar/vector wave equation in step/graded-index dielectric waveguides of circular/arbitrary cross-sectional shapes. Most of these approaches are generalizations of those used in metallic waveguides. In the present thesis, multilayered planar structures have been investigated regarding the field behaviour in these structures. The emphasis has been to use the structure either as mono-mode information carrier or find the possibility of making a mono-mode operation of the device. For the first purpose, doubly-clad optical waveguides with circular cross-section have been investigated, and for the other purpose multilayered planar structures have been considered. These multilayered structures have been investigated$^{[145-147]}$ regarding the wave propagation characterization. However in order to have a deeper insight into the physical and analytical properties of propagating EM waves through multilayered structures beyond three layers, we use a perturbation approach, which a fairly simple and derive information about complicated structures step-by-step starting from a simpler structure.
(5) **Perturbation technique:** The perturbation method is a recognized technique for dealing with complicated problems by making use if an approximation. The essential idea is simple and can be explained as follows. Suppose we have an analytical or sufficiently accurate numerical solution to the problem of determining the behaviour of some system. If now the system is made a little more complex by the addition of some new structural or physical feature, it may be assumed that the behaviour of the system is modified slightly. One then goes on to find out the disturbance or perturbation in the behaviour due to the introduction of an additional feature in the problem. Perturbation techniques have found diverse uses in Classical Physics and Quantum Physics. In multilayered structures where it becomes rather difficult to deal with the problem even with the approximate scalar wave technique, the perturbation method is of great relevance\(^{[148-150]}\). Let us begin with a waveguide having \(N\) boundaries between the media, and have a solution to its complex propagation and attenuation behaviour. We can now introduce an additional layer, thus, increasing the number of boundary surfaces to \((N+1)\), and use the perturbation technique to find out the modifications introduced due to the presence of the additional layer, Through approximate in nature, the perurbative approach is very useful for a physical as well as mathematical understanding of the problem, because it goes step-by-step from a simpler to a more complicated system. Here we give a very brief account of the technique. Suppose that the behaviour of the unperturbed system is described in the form of some physical measurable quantity, say \(G\) as \(f_a(G_a) = 0\). For example the quantity \(G_a\) may be
related to the energy of a system or the propagation constant of a waveguide. Then, when the system is modified, there is a perturbed behaviour which can be expressed as

\[ f(G) = f_u(G) + f_p(G) = 0 \] (1-11)

where \( f_p(G) \) is the perturbation term introduced in the system.

The behaviour of the unperturbed part is assumed to be known. Further, the measurable quantity itself undergoes a change and can be written as

\[ G = G_u + \delta G \] (1-12)

where \( G_u \) is the measurable quantity of the unperturbed structure and \( \delta G \) is the change in the value of \( G_u \) caused by perturbation. We can expand the L.H.S. of eqn. (1-11) using Taylor expansion in view of eqn. (1-12) to obtain the change in measurement due to the perturbation. Thus, up to the first order approximation, we have

\[ \delta G = - \left. \frac{f(G)}{f_u'(G)} \right|_{G = G_u} \] (1-13)

The above-mentioned procedure describes the essence of the perturbation technique; particular problems, however, may require further sophistication.

Having described the outline of the theoretical techniques used for the investigation of the electromagnetic waves through dielectric waveguides, we now focus our attention on various types of multilayered waveguides, the study of which is the main object of this thesis.
1.10 Problems of Multilayered Waveguides

Multilayered fibre

The analysis of the step-profile fiber is readily extended to multilayered fibers with a uniform refractive index in each layer. Consideration of attenuation and dispersion have led to different types of fibers which can be broadly classified as zero dispersion fiber\[^{151,152}\] and dispersion flattened fibers\[^{153,154}\]. In dispersion flattened fibers, the refractive index profile of a single mode fibre is suitably tailored to obtain extremely small dispersion over a wide wavelength range viz., (1.30-1.60) \(\mu\)m. This may be achieved by having several cladding layers. Thus either for the technological manufacturing reasons\[^{155,156}\] or for enhancing some propagation characteristics\[^{48}\], it may happen that a nominally step-index singlemode fiber presents index variations in the cladding. Multi-clad fibers allow a scope for enhancing the core dimension of the monomode fiber also, which makes such fibers easier to fabricate than the usual single-clad monomode fibers with extremely small dimensions. Considerable work has been done on these types of multilayered fibers in the recent past\[^{143,157,158}\].

Multilayer structure waveguides have been widely used recently in many optical devices, such as modulators, switches, directional couplers, Bragg deflectors, spectrum analyzers, and semiconductor lasers. A three-layer slab waveguide is the simplest optical waveguide that has been well studied documented\[^{159-163}\]. Waveguides with more than three layers have been studied by
many authors[164-177]. The eigen value equations for the four layer structure have been derived by the wave theory and the ray theory[165-169]. The five layer symmetrical guide with anisotropic dielectric permittivity has been considered by Nelson and Mc Kenna[170]. A special structure of a five-layer waveguide, the so-called W waveguide, has interesting properties with respect to mode cutoffs and confinement factors[171]. Ruschin and Marom[172] have obtained the explicit eigenvalue equations of the symmetrical seven-layer waveguide for both even and odd modes by using matrix treatment. Multilayer waveguides with periodic index distribution have been studied[173-175]. A explicit eigenvalue equation of a periodic stratified waveguide has been obtained by Yeh et al.[175]. By using the matrix method, Walpita and Revelli have studied the general N-layer waveguide, but their results involved complex matrices[176-177].

Multilayered slab waveguide

Integrated optics came into being in early 1970's. At that time, low-loss optical communication system had already got itself established and there was a surge of interest in the study of compact optical systems. The use of thin dielectric films for the guidance of optical energy began to be explored. Such waveguides could be used in fabricating distributed components in integrated optical devices including lasers, modulators, detectors, polarisers, couplers and also to interconnect them. Thus the use of guided light waves through thin films has placed integrated optics closer to microwave technology than to geometrical
optics. In forming a complete integrated optical circuit, one has to deposit many thin dielectric films on a common substrate. Thus multilayered structures have become a focal point of interest. Further, in electrooptic devices\cite{178-179} metal-clad optical guides are of significance, because the metal cladding can be used as a part of electrical circuits. This guide is also suitable for the mode filter and other applications\cite{180-181}. Thus multilayered planar waveguides have been investigated in view of their properties such as mode discriminator, device connector (reducing the attenuation) and field and power distribution in different layers of the multilayered structures with various types of refractive index profiles in the guiding region.

1.11 Scope of the Present Thesis

The central aim of this thesis is to gain further insight into the above mentioned multilayered structures going beyond the existing treatment.

In chapter two, the propagation of electromagnetic waves through various types of four-layer metal-clad slab waveguide is studied. A general and unified characteristic equation, valid both for the TE and the TM mode, is reported for such a waveguide, with the guiding layer having a truncated semi parabolic refractive index. Using the perturbation technique, the attenuation behaviour of the waveguide structure is studied.

In chapter three, the propagation constants of various types of four-layer waveguides without any metal cover are estimated and also a comparative study
for the two special types of waveguides i.e., the semi-parabolic graded-slab waveguide (SPSW) and the step-index slab waveguide (SSW), has been made. Further a characteristic equation for a five-layer slab waveguide is developed and hence the effect of an additional layer on a four-layer (SSW) structure is estimated through the simple analytical expressions obtained by a perturbation approximation.

When one studies a waveguide, the propagation constant and the attenuation parameter, although important, are not the only features to be emphasized. The field intensity pattern and the confinement of power in different regions must also be examined. For this reason in chapter five, we find out the field intensity distribution and develop the analytical formulae for the confinement factors in the different layers of three types of four-layer slab waveguides, viz., the SSW, the SPSW and the parabolic-graded slab waveguide (PSW). We also briefly consider the possible application of this study in distributed feedback lasers.

Finally, chapter four gives the general conclusions of the thesis along with the scope for further research in the same field.