CHAPTER (VI)

SUMMARY, CONCLUSIONS, GENERAL REMARKS
AND SCOPE FOR FURTHER RESEARCH WORK
6.1 **Summary and conclusions**:  
In the present thesis, the findings of some investigations on optical waveguides of various unconventional symmetrical and non-symmetrical core cross-sectional shapes have been presented. The present author has considered, as far as is known to him, for the first time four new cross-sectional shapes. These are:

1. optical waveguides with lens (lune) shaped cross-sections bounded by different media.
2. an optical waveguide with a guiding cross-section bounded by a sinusoidally varying closed curve.
3. an optical waveguide with cross-sectional shape resembling an ellipse compressed along the minor axis.
4. an optical waveguide with a core cross-section bounded by two spirals.

The findings of the investigations of above mentioned waveguides have been divided into two sections. In one section (chapter II and chapter III) the widely used numerical method known as Goell’s point matching method has been applied to investigate and determine the modal properties and dispersion characteristics of two optical waveguides. In one case we have considered waveguides with lune shaped cross-sections bounded by different media and in the other case we have taken a waveguide with sinusoidally varying closed shape cross-section. In the next section (chapter IV and V), the analytical method has been utilized to study the modal behaviour, cutoff conditions and dispersion characteristics of two unconventional waveguides. In one case we have chosen a waveguide with cross-sectional shape resembling an ellipse compressed along the minor axis, and in other case we have considered another waveguide with a core cross-section bounded by two
spirals. Thus chapter II-V constitute the main body of the thesis, where the
description of the problems undertaken, methods of analysis and theoretical
and computational details have been presented.

In chapter I, the necessary background of the development of optical
fiber communication and integrated optics has been presented. Basic concepts
of optical and microwaveguides, notations and definitions of various
parameters used in this thesis have also been described. A summary of the
research work done by various researchers in this field and a survey of the
literature related to the present study can also be found in this chapter.

In chapter II, four cases of the lunar shaped waveguide have been
considered. The dielectric lunar shaped (DLS) waveguide has been treated in
the first case. Next, the problem of dielectric lunar shaped waveguide is
considered when both the boundaries are conducting. We call this the metal-
dielectric-metal (MDM) waveguide. In the third case, we consider a guiding
cross-section whose concave boundary is metallic and the convex boundary is
adjacent to a dielectric material. We designate this structure as the concave
metallic (CNM) waveguide. Finally, we have a guiding cross-section whose
convex boundary is metallic and the concave boundary is adjacent to a
dielectric material. We describe this as the convex metallic (CVM)
waveguide. Using Goell's point matching method under the weak guidance
the modal characteristic equations have been derived in all the four cases
remembering that the fields on the cladding side must tend to vanish due to
the large conductivity of the metallic cladding/claddings. It is seen that the
modal characteristic equations in all the four cases are nearly similar. In the
case of DLS waveguide, the modal characteristic equation has been solved
numerically for the optical frequency range and also in the microwave range.
The $b' - V$ (dispersion curve) curves show that a large number of modes can be sustained for a low value of $V$-parameter. Here $b'$ is the normalised propagation parameter and $V$ is the dimensionless parameter defined in chapter I. Here two interesting features have been noticed. First of all, we infer that a dielectric lunar shaped waveguide can sustain numerous modes even for a small size. Secondly, as the size parameter increases, the number of sustained modes remain almost unaffected. That is the number of modes sustained is independent of the operating wavelength/frequency. One may thus say that the lunar cross-section shows a more or less broad performance in respect of the $\beta$ values. This is however, not true for a planar waveguide. The cross-section of a planar waveguide has to be bent and contracted at both the ends to be distorted into the shape of a lune and consequently the modal properties are greatly changed.

The problem of the DLS waveguide has been considered next with metal claddings in three different cases: 1) metal claddings on both sides MDM, 2) metal cladding on the concave side CNM and 3) metal cladding on the convex side CVM waveguides. The modal characteristic equations for all three cases have been analyzed and solved. We have plotted the $(b' - V)$ dispersion curves for each case. These curves have the expected standard shapes. Comparing the dispersion curves of the CNM with those of the MDM waveguide, two interesting features can be noted. In both the cases the cutoff $V$-values of different modes are crowded together which means that a number of modes are introduced in quick succession as one increases the value of $V$. The other important feature is that the curves corresponding to the MDM waveguide tend to reach saturation at smaller values of $V$ than those for the CNM waveguide.
In the case of CNM and CVM waveguides, it is seen that the two sets of dispersion curves are similar in nature. But on closer inspection we find some significant differences. Both the CNM and the CVM waveguide show a mode-bunching property near the cutoff $V$-values at $V \approx 0.3$. However, the dispersion curves for the modes of CVM guide are more separated than those of CNM guide near cutoff. Beyond $V \approx 0.8$, the curves corresponding to the CNM guide slowly converge; whereas for $V > 0.8$, the CVM curves become more or less parallel. This shows that the CNM structure discriminates the modes better for intermediate $V$-values than the CVM structure.

In general, we conclude that waveguides with lune shaped cross-sections have a bunching of the cutoff $V$-values. This means that the optical power transmitted by such waveguides will increase considerably as a certain $V$-value is increased, which may be interpreted as a kind of switching property. This is not the situation in most other fibers where the cutoff $V$-values are widely separated.

Chapter III is devoted to the study of the modal properties of a waveguide the cross-section of whose core-region is separated from that of the cladding region by a closed loop that can be described as a sinusoidal distortion of a circle. If the radius of the core is $a$, and the size of maximum distortion, $b$, we define the distortion ratio as $\frac{b}{a}$. Using Goell’s point matching method, dispersion curves of low order modes have been drawn for $\frac{b}{a} = 0.1$ and $\frac{b}{a} = 0.2$. It has been found that the general effect of a small distortion is to shift the first cutoff $V$ value for $V = 3.8$ (standard fiber) to $V = 7.6$ for $\frac{b}{a} = 0.1$. The next cutoff values however, occur in quick
succession, while in the case of the standard circular fiber, they are considerably separated. For $\frac{b}{a} = 0.2$, the dispersion curves are similar to those for $\frac{b}{a} = 0.1$. However, the whole set of curves is shifted towards the higher $V$-values; for example, the first cutoff $V$-value is shifted from $V \approx 7.6$ to $V \approx 8.6$ as we go from $\frac{b}{a} = 0.1$ to $\frac{b}{a} = 0.2$.

In chapter IV an analytical study of a dielectric waveguide with a cross-sectional shape resembling an ellipse compressed along the minor axis (ECMI) has been made under the weak guidance approximation. This approximation is taken to simplify the mathematical details and yet obtain some insight into the modal characteristics of such a waveguide. The characteristic equation and cutoff equation have been derived using the relevant boundary conditions. From the cutoff equation we find the number of modes propagated in the guiding region. Also from the modal characteristic equation we obtain the dispersion curves (the $b' - V$ curve) for some low order modes. The dispersion curves have the usual shape, although the curves for the lowest mode attains a saturation rather quickly. The other two curves do not show a saturation in the range $0 < V < 25$. An interesting feature is that, even for as large a value of $V$ as twelve, the waveguide behaves as single mode guide and even for $V = 25$, there are only three modes.

The consistency of the cutoff equation with the characteristic equation has also been verified by consulting Fig (5.2) and (5.3). For this one refers to Fig (5.2) where the L.H.S of characteristic equation is plotted against $U_a$. There are three zero crossing at $U_a = 4.47$, $U_a = 12.49$ and $U_a = 19.73$. Now we consult Fig (5.3) to determine the cutoff values, which must
correspond to the values of $V$ for $b'=0$. These values are 4.3, 12.45 and 20.24, showing that Fig (5.2) and Fig (5.3) are consistent.

In chapter V, we have presented an analytical study of an optical waveguide with a core cross-section bounded by two spirals. The present study incorporates a detailed analysis of the modal dispersion characteristic and modal cutoff condition for the proposed waveguide. Using boundary conditions for the said waveguide under the weak guidance approximation, the characteristic equation has been derived. Next, from this equation, the cutoff condition is also obtained. The characteristic equation has been solved numerically and the dispersion curves (the $b'-V$ curve) are obtained. These characteristic curves show the standard behaviour, showing that the cutoff values of successive modes are at $V=4.4$, $V=12.0$, $V=19.2$ and $V=26.8$. We find that these values are regularly spaced. For $V<14$, there is only a single mode sustained. It can thus be said that a single mode performance can be obtained for the relatively large value of the $V$-parameter. The $b'$ value of the first mode attains a saturation value at $V\approx20$. The cutoff values can also be obtained by plotting the L.H.S. of the cutoff equation against $U(b-a)$. The zero crossing of Fig (5.3) gives the successive cutoff values namely $U(b-a) = 4.8$, $U(b-a) = 12.4$, $U(b-a) = 19.2$ and $U(b-a) = 25.9$. We find that the cutoff values determined from the characteristic equation agree well with cutoff values obtained directly. It is known that a planar waveguide can sustain several modes for moderately large value of $V$. The present analysis shows that if the cross-section of the planar guide is bent along a spiral such that one side is wider than other, this results in a reduction of the number of modes sustained.
6.2 General remarks and scope for future research work:

The author is keenly aware of many approximations and limitations of the theoretical work presented in this thesis. We have utilized Geoll's point matching method under the weak guidance approximation.

This point matching method is fairly reliable for smooth structures but presents difficulties when any discontinuity or sharp corner points are present. So the matching points are to be crowded near the corners. Also, in the investigation of the MDM, CNM and CVM waveguides, no account has been taken of the absorption losses which are expected to occur in the presence of metallic regions in the non-guiding regions. Naturally, the result obtained in this analysis are not exact because of the approximations which have been used in the calculation; yet they have some reliability. For an exact analysis of any non-circular structured core, the vector wave equation must be solved for the given boundary conditions. But this exact analysis has not been tried here. Though the scalar wave approximation and solving its equation cannot give a very accurate modal behaviour, its usefulness lies in the fact that it still gives some insight into the modal characteristic of the waveguides.

It is hoped that other researchers will be prompted and encouraged to use more rigorous analytical approaches for the analysis of the problems taken in the present thesis. They may try to deduce the characteristic and cutoff equations under the strong guidance condition. This will involve the solving of vector wave equation which is going to prove very difficult. However, a non-circular geometry demands a vector wave treatment.

One may also investigate the modal behaviour of waveguides taken in this thesis by choosing new materials (chiral, liquid crystal, polymers, etc.)
as core-material or cladding material. Another way for exploration lies in choosing conducting helical outer boundary for all problems taken here.

Tapered waveguides with new cross-sectional shapes of the guiding region may also be tried. Various refractive index profiles other than the step-index profile, both on the transverse plane and the longitudinal direction may be incorporated. All this will need further painstaking work.

Finally, the experimental workers may be prompted to study the actual behaviour of these waveguides presented in this thesis in the laboratory so that the theoretical results may be compared with experimental findings. From the technical point of view, such a study, it is hoped, will be useful in integrated optical devices.