CHAPTER 2. LITERATURE SURVEY

2.1 POLARIZATION IN SINGLE-MODE FIBERS

Shortly after the introduction of single-mode fiber, it became evident that linear polarization states were not preserved in long fiber lengths. This was recognized as being due to perturbing birefringences resulting from either internal defects such as the nonideal geometry of the core and cladding or externally applied bends, twists, squeeze, clamps, etc. to the fiber. This effect causes difficulties in fiber pigtailing of integrated optic devices and to polarization fading in interferometers [23]. These problems motivated the development of fibers that maintained linear polarization states by building in the fiber a high uniform birefringence, to exceed by far the random birefringences in ordinary single-mode fibers.

Active research toward such fibers, started in late 1970s after some of the optical fiber specialists who originally came from microwave research area believed that axially nonsymmetrical single-mode fibers would become common in the future, as early as the mid 1980s. In the following, the polarization of wave is briefly reviewed, then various polarization-maintaining schemes, as classified in [4], and [8], and shown in Table 2.1, will be reviewed and discussed.

The polarization of wave describes the time-varying direction of the electric field vector at a fixed point in space. Polarization is observed along the direction of propagation by tracing out the tip of the instantaneous electric field. There are three types of wave polarization: linear, circular, and elliptical. In general, the tip of the electric field vector traces out an ellipse and the wave is said to be elliptically polarized. The other two types of polarization, linear and circular, are special cases of elliptical polarization. The linearly polarized wave is characterized by the property that the orientation of the electric field vector is the same everywhere in space and is independent of time. In linear polarization,

Table 2.1 Classification of Polarization-Maintaining Fibers

	Gepmetry Type	Stress Type
Circularly Birefringent Fibers	-Helical Core -Spun	-Twisted Round-Fiber
Linear Single Polarization (Differential Attenuation Fibers)	-Side Pit -Side Tunnel	-Bow Tie -Flatenned Depressed Cladding -Stress Guiding
Linearly Birefringent Fibers	-Elliptical Core -Dumbell Core -Side Pit -Side Tunnel	-Elliptical Cladding -Elliptical Jacket -PANDA -Four-Sector Core -Bow Tie

the field vector is directed along a line. The circularly polarized wave is characterized by a constant amplitude field vector, and the field vector orientation in space changes continuously with time so that the tip of the field vector traces out a circular locus in a plane transverse to the direction of propagation.

The polarization of light propagating in a single-mode fiber is initially determined by the polarization of the output light from the laser source. Often the polarization of light generated by a laser diode is linear and so is the polarization of light in the excited mode. However, at some distance away from the light source, the polarization of light in regular non-polarization-preserving fibers becomes random due to various perturbing effects. Using appropriate techniques, it is possible to generate and maintain any of the three types of polarization in a fiber.

2.2 POLARIZATION-MAINTAINING FIBERS

2.2.1 Circular Polarization-Maintaining Fibers

It is possible to introduce circular-birefringence in a fiber so that the two orthogonally polarized modes of the fiber are clockwise and counter-clockwise circularly polarized. The most common way to achieve circular birefringence in a round (axially symmetrical) fiber is to twist it [24]-[25] to produce a difference between the propagation constants of the clockwise and counterclockwise circularly polarized fundamental modes. Thus, these two circular polarization modes, i.e., HE^{+}_{11} and HE^{-}_{11} are decoupled. Also, it is possible to conceive externally applied stress whose direction varies azimuthally along the fiber length causing circular birefringence in the fiber [26]. If a fiber is twisted, a torsional stress is introduced and leads to optical-activity in proportion to the twist [26]. It is shown theoretically that if ϕ represents the twist rate per unit length then the plane of polarization of a linearly polarized light is rotated in the same direction with a rate of $g\phi$ where $g \approx 0.07$ for silica [25]. The birefringence of such a fiber is very small (as g is small) and it is difficult to obtain beat lengths less than 10 cm, because fiber breaks at high twist rates and such fiber is difficult to handle. It is shown that the twist rate required to provide immunity from external effects such as pressure and bends is excessively large.

Circular birefringence can also be obtained by making the core of a fiber follows a helical path inside the cladding as shown in Figure 2.1. This makes the propagating light, constrained to move along a helical path, experience an optical rotation [27]-[28]. The birefringence achieved is only due to geometrical effects and a large birefringence value B $= 2\times10^{-4}$ has been reported [29]. Such fibers can operate as a single mode up to a very large value of the normalized frequency ($V \approx 25$), and suffer high losses at high order modes. One practical fiber design has been reported in which beat lengths as short as 8 mm have been obtained [2]. This type of fiber finds applications in sensing electric current through Faraday effect. Helical-core fibers have been fabricated from composite rod and tube preforms, where the helix is formed by spinning the preform during the fiber drawing process.

2.2.2 Linear Polarization-Maintaining Fibers

As seen in Table 2.1, the linear polarization-maintaining fibers are of two types. The linear single polarization type is characterized by a large transmission loss difference between the two polarizations of the fundamental mode. The linearly birefringent fiber type is such that the propagation constants between the two polarizations of the fundamental mode are significantly different [8]. Linear polarization may be maintained using various fiber designs which are reviewed next.

2.2.2.1 Polarization-Maintaining Fibers With Side Pits and Side Tunnels

Side-pit fibers, as shown in Figure 2.2, incorporate two pits of refractive index n_p less than the cladding index , on each side of the central core. This type of single-polarization fiber was first proposed by Okoshi and Oyamada [30]. This type of fiber has a W-type index profile along the x-axis and a step-index profile along the y-axis. A side-tunnel fiber is

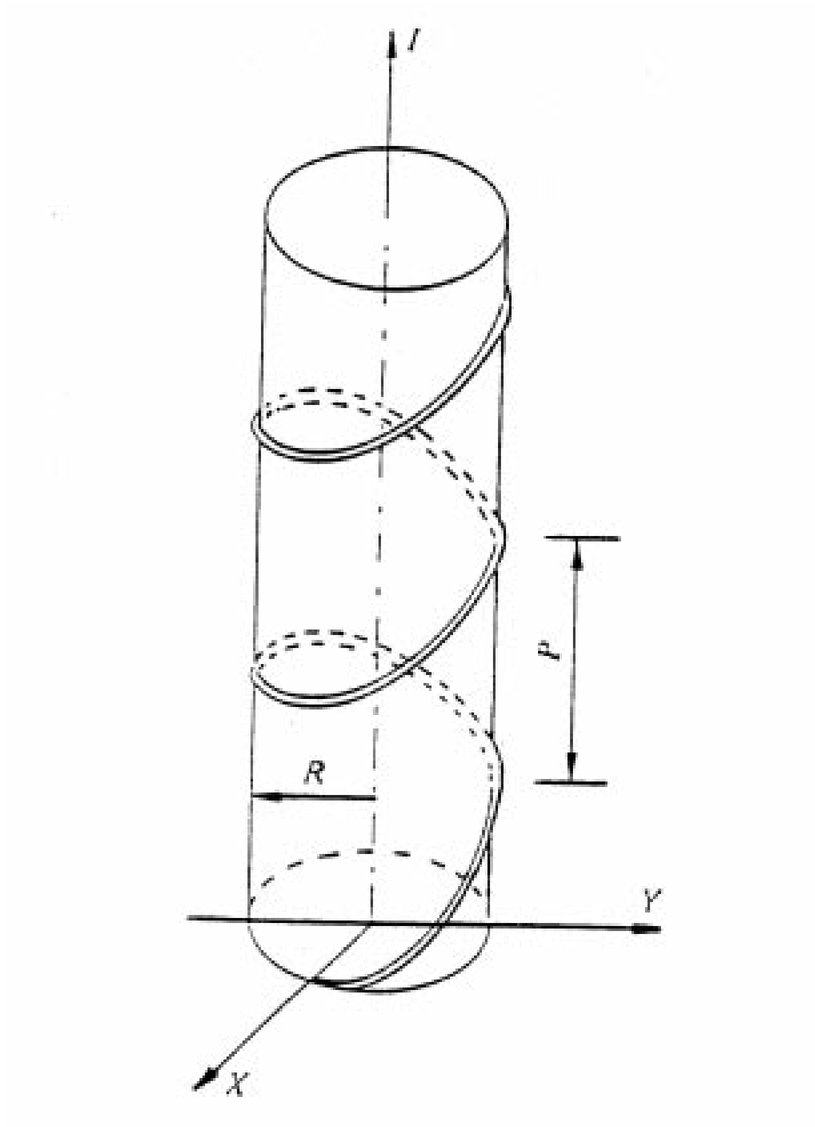

Figure 2.1 The structure of a helical or spiral fiber [23].

a special case of side-pit structure when the two pits are hollow with $n_p = 1$. In these fibers, a geometrical anisotropy is introduced in the core to obtain a birefringent fibers. Different methods have been used to analyze these fibers. The finite element method was used by Okoshi et. al. [31]-[32] an H-field finite-element method was used by Hayata and co-workers [33] and the effective-index method was used in [34]. A relatively simple and approximate method for the side-tunnel fibers is presented in [35], where a rectangular-core waveguide model is used as an approximation for side-tunnel structure to obtain the polarization characteristics.

A single-mode fiber with asymmetrical refractive index pits on both sides of the core was fabricated by the Modified Chemical Vapor Deposition (MCVD) method [36]. The fiber consists of a SiO_2 cladding, B_2O_3-doped asymmetrical side pits and a P_2O_5-doped core. From the measurement, the beat length was found to be about 23 mm and a birefringence $B = 5x10^{-5}$ was obtained. Stress analysis of a fiber by the finite element method [37] shows that the contribution of the stress-induced birefringence to modal birefringence is much larger than that of the geometrical anisotropy [30]. The strain birefringence is caused by the presence of the asymmetrical refractive index pits consisting of B_2O_3 and SiO_2 [38]. A fiber consisting of GeO_2-doped core and two layers separated from the core and placed in the pure SiO_2 cladding has also been fabricated [38]. The magnitude of strain birefringence is proportional to the molar concentration of B_2O_3 and is inversely proportional to the distance between the side pits and the core. Minimum losses of 0.62 dB/Km at 1.5 μm wavelength and 1 dB/Km at 1.3 μm wavelength have been reported for manufactured side pit fibers. At wavelength of 1.15 μm, the modal birefringence is 8.5×10^{-5} and the beat length is 13.5 mm.

2.2.2.2 Polarization-Maintaining Fibers With Stress Induced Parts

An effective method of introducing high birefringence in optical fibers is through introducing an asymmetric stress, with two-fold geometrical symmetry, in the core of

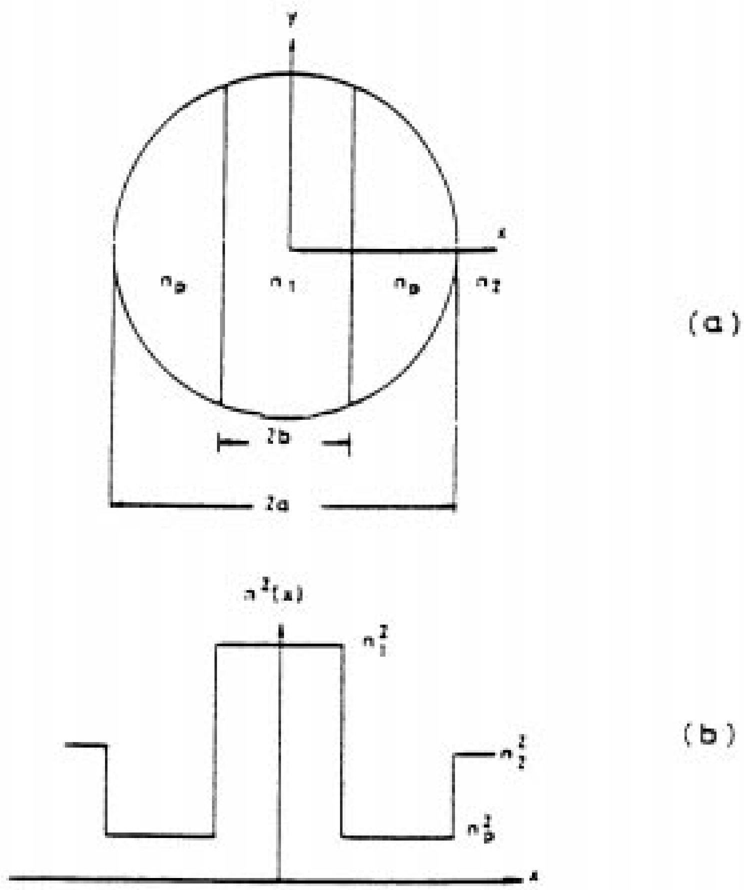

Figure 2.2 Side-pit fiber (a) cross section, (b) refractive index distribution versus x-axis [4].

the fiber. The stress changes the refractive index of the core due to photoelastic effect, seen by the modes polarized along the principal axes of the fiber, and results in birefringence. The required stress is obtained by introducing two identical and isolated stress-applying parts, SAPs, positioned in the cladding region on opposite sides of the core. Therefore, no spurious mode is propagated through the SAPs, as long as the refractive index of the SAPs is less than or equal to that of the cladding. The SAPs have different thermal expansion coefficient than that of the cladding material due to which an asymmetrical stress is applied on the fiber core after it is drawn from the preform and cooled down. The most common shapes used for the SAPs are: bow-tie shape [39], and circular shape [38], and [40]-[41]. These fibers are referred to as Bow-tie [39], and PANDA fibers [41], respectively. The cross sections of these two types of fibers are shown in Figure 2.3. The modal birefringence introduced by these fibers represents both geometrical and stress-induced birefringences. In the case of a circular-core fiber, the geometrical birefringence is negligibly small. Two methods have been used to calculate the stress distribution due to SAPs in these fibers, a finite element method [37], and an analytical method [42], and [43]. It has been shown that placing the SAPs close to the core improves the birefringence of these fibers, but they must be placed sufficiently close to the core so that the fiber loss is not increased especially that SAPs are doped with materials other than silica. The PANDA fiber has been improved further to achieve high modal birefringence, very low-loss and low cross-talk. PANDA fiber with optimum design parameters have been fabricated and measured. The measured results indicate 0.22 dB/Km loss with birefringence $B = 3.2\times10^{-4}$ and cross talk of -27dB in 5 Km length at a wavelength of 1.56 μm [44]. Sasaki has also reported a low-loss dispersion shifted PANDA fiber [45]. A minimum loss of 0.27 dB/Km, zero dispersion at wavelength of 1.56 μm, a modal birefringence $B = 4.0\times10^{-4}$, and a crosstalk of -22 dB over 4.1 Km have been achieved.

With the purpose of designing an optimum waveguide structure to provide maximum modal birefringence, theoretical and experimental investigations on polarization

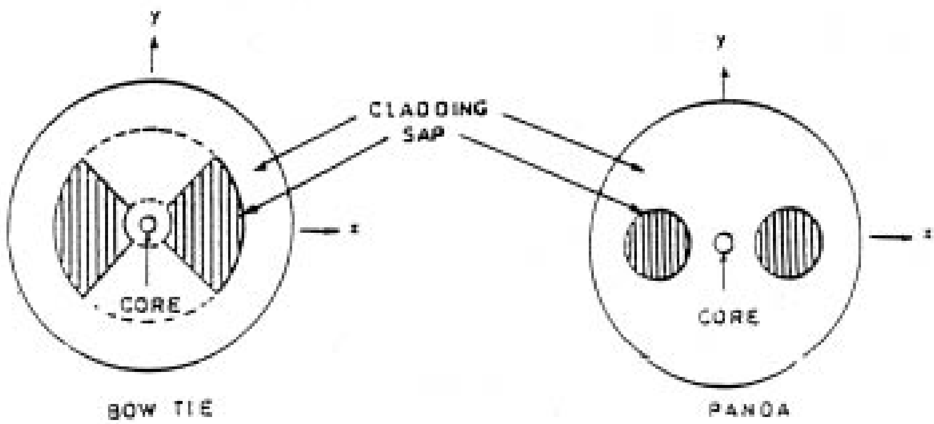

Figure 2.3 Cross sections of Bow-tie and PANDA fibers [4].

characteristics of PANDA fiber with flat cladding were presented [46]. The dependence of birefringence on the thickness of the flat cladding was calculated using the finite element method [37]. Stress analysis demonstrated that when the radius of the stress-applying part is smaller than 0.6 times the cladding thickness, the modal birefringence in flat-clad PANDA fiber is larger than that of a circular-clad PANDA fiber. The model birefringence measured at 1.15 μm was $B = 5.9\times10^{-4}$.

Based on research and development work performed on side pit and PANDA fibers, a new single-polarization optical fiber was proposed and investigated in [1]. Two structures were investigated, one with one hollow circular pit across the core-clad interface, and another with two hollow circular pits across the core-clad interface. Only the geometrical birefringence resulting from noncircular core or angularly nonuniform refractive-index distributions was considered. The modal birefringence was computed using the improved point matching method [1]. It was realized that the largest modal birefringence is obtained when two hollow circular pits are used, with $B_{max} = 4.49\times10^{-4}$ for core-clad refractive index difference of 0.5 %.

Further investigations were carried out on fibers with the two hollow pits to achieve small transmission loss, large modal birefringence, wide single-polarization bandwidth, and small total dispersion [47]. Numerical results for a pure silica core with fluorine doped cladding and hollow pits showed that modal birefringence and single-polarization bandwidth assume their maximum values of 1.133×10^{-3} and 100.6 nm, respectively, for core-clad refractive index difference of 1.6 % at the operating wavelength of 1.55 μm [48]. In another work, a similar structure was used with two isolated stress-applying parts [49], instead of the hollow pits mentioned before. This fiber consists of inner and outer claddings, and the SAPs are located between the inner and outer cladding. This fiber features a depressed cladding structure formed by the core, the inner cladding, and the

SAPs. The refractive index for the SAPs is chosen between that of the core and the outer cladding. The measured modal birefringence for this fiber is 6×10^{-4} [45].

2.2.2.3 Polarization-Maintaining Fibers With Geometrical Asymmetry

Prior to 1977, the modal birefringence caused by an unintentional elliptical deformation of the core was the principal topic of research related to polarization-effects in fibers. After 1978, various kinds of linear polarization-maintaining fibers, such as elliptical core fibers, dumbbell core fibers, stress-induced (elliptical cladding) fibers were proposed and investigated. The early research on elliptical-core fibers dealt with the computation of the polarization birefringence. In the first stage [50], propagation characteristics of rectangular dielectric waveguides calculated by Marcatili [51], were used to estimate birefringence of elliptical-core fibers. Computations based upon a rigorous analysis by Yeh [52], were performed by Adams et. al. [53], and Love et al. [54], and showed a better accuracy than various approximate analysis performed previously [55]-[57]. The first experiment with polarization-maintaining fiber was reported by Ramaswamy et. al. [50], in 1978, in which a fiber having a dumbbell- shaped core was fabricated. The beat length L_b was about 55 mm [7], whereas it was believed that L_b should be less than 1mm to make it well below the typical perturbation periods that can exist in actual fibers. The beat length can be reduced by increasing the core-cladding refractive index difference. It was shown by Dyott et al. [58], that by increasing the core-clad refractive index difference to 4.3 %, L_b could be reduced to as low as 0.75 mm. However, the index difference cannot be increased too much due to practical limitations. Increasing the index difference increases the transmission loss, and splicing would become difficult because the core radius must be reduced [59].

The first proposal on practical low-loss single-polarization fiber was experimentally studied for three fiber structures: elliptical core, elliptical clad, and elliptical jacket fibers [59]. The elliptical core and the elliptical clad fibers were fabricated using the MCVD method. To make elliptical clad fibers, borosilicate clad and pure silica core layers were deposited in a tube. Then the tube was collapsed while the inner pressure (vacuuming) of the tube was monitored. The core circularity and the clad ellipticity were controlled by the careful selection of the softening points of the core/clad materials and the inner pressure. Then, the preforms were drawn into fibers to give HE_{11} mode propagation. However, the elliptical jacket fiber is formed by a circular GeO_2-P_2O_5 doped core and silica clad for constructing the low-loss waveguide, and the B_2O_3 doped elliptical-jacket and the silica outer support for introducing the large nonsymmetric stress in the core. GeO_2 was also doped in the jacket to give the same index as SiO_2. These fibers were fabricated by the same method mentioned above. The jacket ellipticity was mainly controlled by monitoring the pressure during the collapsing stage [60]. The results showed that typical values of birefringence for the elliptical core fiber are higher than elliptical clad fiber. However, losses were higher in the elliptical core than losses in the elliptical clad fibers. For instance, transmission losses in the elliptical core and elliptical clad fibers with GeO_2 dopant are typically 30dB/Km at 1.5 μm and 5dB/Km at 1.1 μm, respectively [61]. Detailed studies were carried out for various dopants effects on the coupling length L_c of the two orthogonal fundamental modes to preserve linear polarization over long lengths. Experimental results showed that anisotropic stress increases nonlinearly with molar concentrations of dopants and the B_2O_3 dopant yields larger birefringence than GeO_2 and P_2O_5. The coupling length was found to be inversely proportional to the core ellipticity for the GeO_2- or P_2O_5 doped elliptical core fibers and decreases considerably with the clad ellipticity for the B_2O_3-doped elliptical clad fibers. Minimum value of L_c for the elliptical core fibers lies in the wavelength window 1.1-1.5 μm, while it is constant for elliptical clad fibers in the single-mode regime. The experimental and the theoretical study on the low-loss elliptical jacket fiber was carried out in [62]. It was reported that the ratio of core to clad radius must be below 0.5 to allow a transmission loss of less than 1 dB/Km at 1.55 μm wavelength.

Research effort devoted to the design and fabrication of birefringent fibers that propagate one and only one polarization state of the fundamental mode has continued. Various fiber structures have been proposed and experimented with. A flat elliptical side-pit fiber having two pits on both sides of the core was proposed and analyzed [63]. This analytical study gave a guideline to achieve an optimum structure by adjusting values of the optical fiber parameters. This type of fiber was proposed to obtain better birefringent characteristics than those of a flat elliptical core fiber treated by the same authors before. The AT&T rectangular polarization-maintaining fiber [64], was considered for a study on its polarization properties and experimental results were presented [65]-[66]. It was demonstrated that the extinction ratio of a PM fiber obeys random coupling theory due to its rectangular geometry which facilitates winding and packaging of fiber with minimum external perturbations. The data obtained from the measurement showed an extinction ratio of -27dB/Km and a mode coupling parameter $h \approx 2.08\times10^{-6}$/m. At a wavelength of 1320 mm, a beat length of 6.78 mm was measured.

2.2.2.4 Polarization-Maintaining Fibers With Refractive Index Modulation

One way to increase the bandwidth of single-polarization fiber, which separates the cutoff wavelength of the two orthogonal fundamental modes, is by selecting a refractive-index profile which allows only one polarization state to be in cutoff [67]. A case study was performed on a fiber having a circular core and inner cladding, surrounded by an elliptical stress applying region. The index profile of the fiber considered was the W-profile with all portions of the profile interior to the stress layer being identical except for the splitting caused by the birefringence between the minor and major axes of the elliptical stress layer. It was found that both polarization states of LP_{11} mode had cutoff wavelength with a broad single-polarization band of about 110 nm centered at 840 nm. The bandwidth for the single polarization is defined as the wavelength range over which the fundamental mode of one polarization state is attenuated by at least 25dB. At 840 nm, the attenuation of the guided state is 5.5 dB/Km, and at 633 nm the birefringence was measured to be 6.9×10^{-4}.

A class of polarization-maintaining fiber having an azimuthally inhomogeneous index profile with a circular core and cladding has also been proposed [68]. Numerical results showed that the modal birefringence induced by the geometry is much larger when perturbation is in the cladding region than when perturbation is in the core region. The propagation constants of the two orthogonal fundamental modes were calculated using a variational formula for propagation constants and treating the azimuthal variations of the refractive index as perturbations [69].

In another design, high birefringence was achieved by introducing, in a three-layer elliptical fiber, an azimuthal modulation of the refractive index of the inner cladding [70]. A perturbation approach was employed to analyze the three-layer elliptical fiber, assuming a rectangular-core waveguide as the reference structure [71]. The method adopted is described in [72], which takes into consideration the presence of corners in a rectangular structure. Examination of birefringence in three-layer elliptical fibers demonstrated that a proper azimuthal modulation of the inner cladding index can increase the birefringence and extend the wavelength range for single-polarization operation [73].

A refractive index profile, called Butterfly profile, was reported in [74]. The refractive index profile is an asymmetric W profile, consisting of a uniform core, surrounded by a cladding in which the profile has a maximum value of n_{cl} and varies both radially and azimuthally, with maximum depression along the x-axis. This profile has two attributes to realize a single-mode single-polarization operation. First, the profile is not symmetric, which makes the propagation constants of the two orthogonal fundamental modes dissimilar, and secondly, the depression within the cladding ensures that each mode has a cutoff wavelength. The butterfly fiber is weakly guiding, thus modal fields and propagation constants can be determined from solutions of the scalar wave equation. The solutions involve trigonometric and Mathieu functions describing the transverse coordinates dependence in the core and cladding of the fiber. These functions are not orthogonal to one another which requires an infinite set of each to describe the modal fields in the different regions and satisfy the boundary conditions. The geometrical birefringence plots generated vs. the normalized frequency V showed that increasing the asymmetry through the depth of the refractive index depression along the x-axis increases the maximum value of the birefringence and the value of V at which this occurs. The peak value of birefringence is a characteristic of noncircular fibers. The modal birefringence can be increased by introducing anisotropy in the fiber which can be described by attributing different refractive-index profiles to the two polarizations of a mode. The analysis of the anisotropic fiber showed that the geometric birefringence is smaller than the anisptropic birefringence. However, the depression in the cladding of the butterfly profile gives the two polarizations of fundamental mode cutoff wavelengths, which are separated by a wavelength window in which single-polarization single-mode operation is possible.

2.3 FIBERS / WAVEGUIDES WITH METAL BOUNDARIES

Another method of controlling polarizations is by means of metal-clad optical waveguides which are of interest in integrated optics and optical fiber devices. Interest in metal-clad planar optical waveguides is mainly due to their large TM-to-TE mode loss ratio which can be used to produce a polarizer or mode analyzer for integrated optics circuits [75]-[77]. A metal-clad waveguide is also attractive in providing electrodes for electrooptical devices.

2.3.1 Planar Waveguide Polarizers

In 1969, Marcatilli [51], and Goel [78], analyzed planar metal-dielectric waveguides by combining dielectric slab waveguide solutions in two transversal directions. Marcatilli suggested that the degeneracy of two modes of different polarizations could be split by using a lossy metal sheet at the interfaces between the core and cladding. The analysis methods for metal-clad optical waveguides have been summarized by Reisinger [79]. In [79], boundary conditions for dielectric thin film waveguides with metal boundaries have been treated in general. Losses in the conducting regions are accounted for by letting the corresponding refractive indices become complex. In general, the transverse propagation vector of guided modes in the guiding region, the decay constants of evanescent fields in the cladding regions, and the propagation constant are all complex. In the microwave frequency range, an approximation for losses due to conducting boundaries can be obtained using the well known perturbation analysis. This perturbation approach is based on the assumption that the field distribution is the same as that which would exist if metal boundaries were perfect conductor. An implicit assumption of this approach is that the displacement current is negligible compared to the counduction current in the metal region. This condition is usually well satisfied at frequencies in the microwave range. However, at optical frequencies, metals do not behave as nearly perfect conductors and do not satisfy this condition. Conducting boundaries at optical frequencies have also been treated. Although, exact solutions of the fields are available, a set of approximate field distributions are obtained by neglecting the imaginary part in the decay constant of evanescent field in the cladding region, and the imaginary part of the propagation constant to simplify the problem. As a result, only the decay constant in the conductor region remains complex, giving rise to a complex evanescent field in the conductor, which in turn leads to complex wavefunctions in the dielectric regions.

Metal-clad optical waveguides can also be treated using the concept of equivalent-current and the theory of coupled waveguides [12], and [80]. Considering a system of two coupled waveguides, the electromagnetic fields can be regarded as the combination of the field of waveguide 1 (in the absence of waveguide 2), the field of waveguide 2 (in the absence of waveguide 1), and the field excited by the equivalent currents. According to the theory stated here, the electromagnetic field of the metal-clad waveguide is equal to the total field excited by the equivalent current and the guided wave of the dielectric slab waveguide. The attenuation coefficient of the guided wave is obtained when the effect of the metal on the guided wave is weak. Since it is difficult to get the normal-mode solution of the metal-clad waveguide, it is assumed that the field inside the metal is the transmitted wave when the field is incident upon the metal boundary. At the same time, a reflected wave is introduced for the purpose of field matching at the metal boundary. But, this reflected wave is much smaller than the incident wave between the guiding layer and cladding , so it can be neglected. Thus, the field solution satisfies both the metal boundary condition and the dielectric boundary condition between core and cladding. The equivalent current theory showed, in comparison with the exact solution, that the theory is valid for the TE and TM mode except for the small core layer because the assumption that the field in the metal is that which exists in the absence of the metal multiplied by the transmission coefficient is no longer appropriate. The behaviour of propagating modes of a symmetrical metal-clad dielectric slab waveguide at optical wavelengths has been predicted from a simplified analysis of a lossless dielectric-slab waveguide with a cladding of negative permittivity. The solution of dispersion equations for the lossless waveguide is analyzed analytically, assuming that the penetration depth of the fields into the metal clads are very small [13]. The analysis made based on the simplified model reveals two kinds of cutoff phenomena; those similar to parallel-plate waveguide, and those due to negative permittivity of the cladding. The propagating modes have the attributes of the modes of a conventional dielectric-slab waveguide as well as those of a parallel-plate waveguide. One feature of the lower order TM modes is a slowly propagating surface wave on the interfaces.

The attenuation properties of planar optical waveguides with metal boundaries of both symmetric and asymmetric structures have been studied analytically and experimentally [14]. It has been demonstrated that the attenuation of the waveguide modes depends on the waveguide thickness, choice of metal, and the type of mode, and increases with the mode order [15], and [20].

The analysis of guided modes for various index profiles in a slab waveguide with metal cladding has been made. The dependence of the attenuation constant of guided modes on the mode order and the width of the guiding layer, core, has been investigated. Several authors have studied such loss for waveguides with linearly [81], exponentially [82], and arbitrary graded index profiles [83] . The analytical and numerical results show that the dependence of modal attenuation on mode order is related to the index profile. The mode attenuation increases with mode order in metal-clad waveguides with exponential [82]-[83], Gaussion [83], and parabolic profiles [83], and [21].
Since attenuation is partly caused by ohmic losses at the interfaces, graded-index slab waveguides are expected to have lower losses than step-index slab waveguides. The dependence of the modal attenuation on the guiding-layer width a has been determined to vary as a^{-1} for a linear-index profile [81], as $a^{-3/2}$ for a parabolic index profile [21], and as a^{-3} for a step index profile [20]. Contrary to the case of uniform metal-clad dielectric slab waveguides, the attenuation of metal-clad diffused waveguides decreases with increasing the mode order [82], due to the fact that in graded index waveguides higher order modes have deeper penetration into the substrate, and thus thicker effective guiding layers, and thereby, lower losses. Electrooptic crystals, such as $LiNbO_3$ and $LiTaO_3$, are of particular interest for use as the substrate for integrated optical circuits due to the excellent electrooptic and acoustooptic properties inherent in these materials. Various techniques can be used to form a waveguiding layer of graded index profile on $LiNbO_3$ or $LiTaO_3$. The two main techniques that have been employed are the in-diffusion [84]-[85], and out-diffusion techniques [82], and [86].

Research on propagation characteristics of metal-clad planar waveguides has been extended to multilayer geometries with a lossy layer or an active layer with negative loss [87]-[89], and [22]. The analysis of metal-clad multilayer dielectric waveguide has been carried out using perturbation techniques. The dependences of the attenuation constant on core thickness, buffer layer thickness, mode number, and refractive index difference between core and buffer layers have been examined [89]. The results show that the attenuation constants of the well-guided TE and TM modes in waveguides with large buffer layer thickness increases with mode order and buffer layer thickness, and varies as 2 a^{-3} where 2a is the core thickness.

An analytical treatment of metal layer in optical waveguides has been performed for planar heterostructures [90], and cylindrical fibers [91]. The study of modes involves one or two media with negative dielectric constant, where the metal medium is considered to have no losses with pure real and negative dielectric constant. A classification of possible optical guided modes that are able to propagate in such structures are determined and discussed.

2.3.2 Fiber Polarizers

Fiber-optic polarizers can be constructed by removing a portion of the fiber cladding and replacing it either with a birefringent crystal or metal. A fiber polarizer with partial metal-cladding is preferred for its stable polarization, but it has been reported in [76] that it has a high insertion loss for a given extinction ratio.

Improving in the performance of fiber-optic polarizer is possible by placing a buffer layer between the fiber surface and the metal layer as shown in Figure 2.4. The refractive index of the buffer layer may be chosen so that the TM-plasmon wave at the metal-buffer layer interface has the same propagation constant as the fundamental mode of the fiber [76]. Experimental results show that introducing a buffer layer, separating the dielectric core from the metal layer, increases the attenuation ratio of TM/TE and decreases the TE-insertion loss in comparison with designs without buffer layers.

The equivalent current theory has also been applied to a fiber polarizer which is formed by partially polishing out the cladding on one side of a single-mode fiber and evaporating a metal on the polished surface, as shown in Figure 2.5 [12]. The extinction ratio of the single-mode fiber polarizer is calculated using the attenuation coefficient expressions in [80] for x- and y-polarized HE_{11} modes. The calculated extinction ratio is in agreement

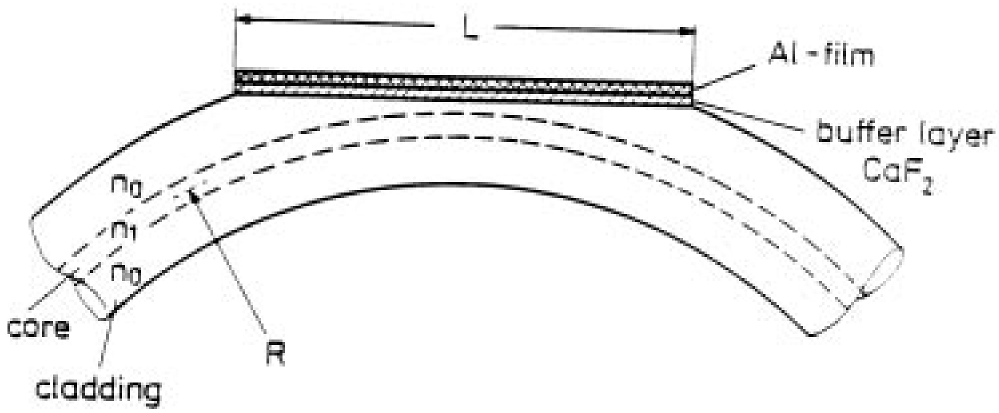

Figure 2.4 Side view of a fiber optic polarizer with buffer layer [76].

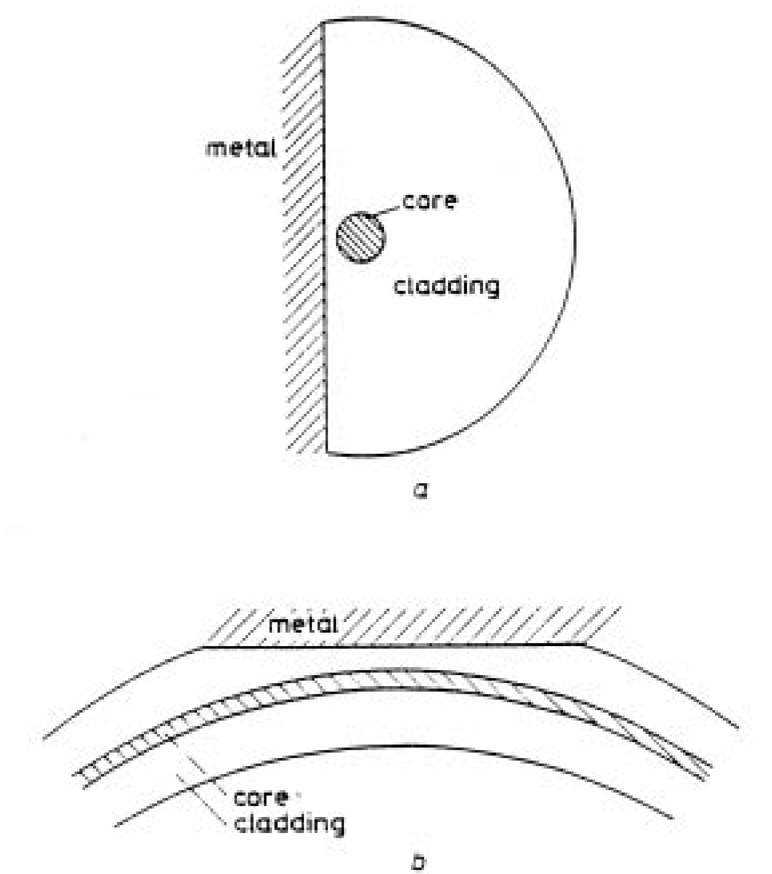

Figure 2.5 A partial metal-clad fiber (a) cross section view of fiber optic polarizer, (b) side view of in-line fiber optic polarizer [17].

with experimental results. But, for small buffer layer thickness, the differences between them are rather large, for the same reason stated previously in the case of planar waveguide polarizers.

To solve the problem of polarizing light within a fiber, a novel approach was presented in [92]. The polarizer is formed by partially removing the cladding from one side of a single mode circular fiber and replacing it by a birefringence crystal with lower refractive index than the core. The result is a structure combining a single mode fiber and a planar birefringent layer. This layer is separated from the fiber core by the remaining part of the fiber cladding serving as a buffer layer. It was shown experimentally that attenuation in a single mode fiber can be achieved by coupling the core-guided mode to an external medium and that high quality polarizers with extinction ratios in excess of 60 dB can be obtained for the best orientation of the crystal axes.

To achieve a better polarizer performance, an indium-coated D-shaped fiber with elliptical core and elliptical inner cladding, as shown in Figure 2.6, was proposed and fabricated [18]. The principle behind this D-shaped fiber is to use the evanescent fields in the fiber cladding to couple out the unwanted polarization from the guide. The fiber provides a birefringence of 5×10^{-4} by an elliptical core with a high core-cladding index difference of 0.04. The best results reported was -39 dB of polarization suppression ratio and an insertion loss of 0.2 dB on a polarizer length of about 70 mm, where the suppressed mode is the even HE_{11} mode with the electric field along the minor axis of the elliptical guide and normal to the flat of the D-fiber. The analysis showed that a saturated extinction ratio is observed beyond a critical polarizer length. Variations of the propagation constant and birefringence as a function of the depth of polishing for circular and elliptical core fibers were obtained using a rectangular-core waveguide model analysis [93]. It was found that in the case of circular core fibers or elliptical core fibers polished parallel to the major axis the effect of polishing increases the geometrical birefringence. However, if the fiber is polished perpendicular to the major axis, the birefringence first decreases to zero and then

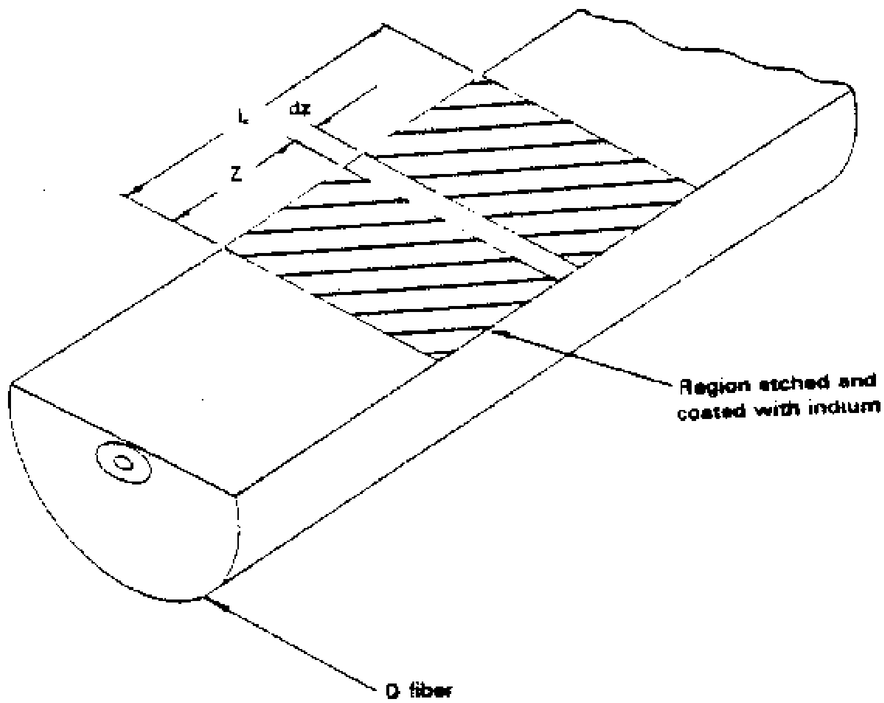

Figure 2.6 D-shaped fiber polarizer with elliptical core [18].

increases sharply in the reverse direction. A novel technique to improve the design and implementation of a highly elliptical core fiber for use in integrated optical components has been reported in [94]. A mathematical model is presented to predict birefringence in a highly elliptical core fiber as the cladding is removed, where the elliptical core is approximated by a rectangular dielectric waveguide. This model helps in controlling the amount of cladding removed for a D-fiber to within ~ 0.05 μm for use in the production of passive and active fiber components.

2.4 POLARIZATION-MODE DISPERSION (PMD) IN OPTICAL FIBERS

The issues of polarization-mode dispersion in optical fibers has attreacted considerable attention over the past few years [95]-[100]. Different techniques for PMD measurements and characterization have been reported [101]-[105].

Two main factors contribute to PMD in circular fibers: the deformation of the circular geometry of the fiber, and the internal stresses which leads to stress anisotropy, both of which could happen during manufacturing. Other factors that could contribute to PMD in fibers are bends, twists, and cabling process.

A circular fiber with small core elliptical deformation causes a difference between the group velocities in the two orthogonal polarizations of the fundamental LP_{01} mode. This difference contributes to the overall dispersion and the effect is referred to as polarization-mode dispersion. The magnitude of PMD in fibers depends on this difference in propagation constants. In ordinary step-index single-mode fibers, PMD vanishes outside the single-mode wavelength region [106]. To improve fiber performance in long-haul high bit rate systems, a zero PMD must be within the single-mode wavelength region. A method for lowering intrinsic polarization-mode dispersion has been proposed and verified experimentally [107], that low intrinsic PMD due to form-induced and stress-induced factors can be achieved for short-length PMD (measured in ps/km) by partial cancellation of the two induced factors. An extensive literature search did not uncover a fiber design with zero PMD in the single-mode wavelength range.

2.5 SUMMARY

Review of polarization-maintaining/eliminating waveguide structures and their designs have been presented. Limiting the propagation to one polarization state can be achieved by either breaking the degeneracy between the mutually orthogonal polarization states through deforming the circular geometry of a fiber and/or introducing shape, stress regions, certain refractive index profiles, or by incorporating metal boundaries into the structure of waveguides.

Side-pit and side-tunnel PM fibers offer low birefringence except one structure reported in [47] which can provide a high birefringence if the index difference between core and cladding is taken to be 1.6 %. A successful structure to maintain polarization as suggested by many authors is the PANDA fiber. With this structure, a high birefringence can be achieved along with a low loss and low cross-talk [46].

In elliptical fibers, the birefringence is not as high as in PANDA fibers, and the required core size becomes impractical (extremely small) for the fiber to operate as a single mode waveguide. This problem can be solved by introducing stress regions in the fiber or azimuthal variations of the refractive index.

Another technique that breaks the degeneracy of the fundamental mode with two polarizations is based on using metal as an interface layer in dielectric waveguides. This metal-dielectric waveguide can be used as a polarizer and as mode filter for integrated circuits operating in the microwave and optical frequencies.

Several metal-dielectric waveguide structures have been suggested and analyzed for use in the optical frequency range. The methods used to analyze such waveguides are: the perturbation technique, the equivalent current theory, and treating metal as a lossless medium with negative permittivity. The first method involves approximations to simplify the analysis and provides special features that distinguish between the TM and TE modes for a planar structure. The last two methods provide accurate results except for certain conditions that makes them inapplicable when the core thickness becomes small.

Planar metal-clad waveguide and metal fiber polarizers produce high attenuation difference between the TE and TM modes, while the elliptical core D-shaped fiber generates a high attenuation between the even and odd polarizations of the fundamental HE_{11} mode.

Finally, the causes of PMD in optical fibers and its effects have been addressed. PMD is considered as a residual dispersion due to stress anisotropies, geometrical noncircularities, and external effects. Polarization-mode dispersion affects the bandwidth of digital and the linearity of analog optical communication systems. Some of the accomplishments and suggestions on lowering PMD in optical fibers have also been discussed.