CHAPTER 1. INTRODUCTION

Optical fiber is the backbone component in long-distance and high bit-rate optical communication and networking systems. The choice of fiber depends on where and how it is applied and what one kind of fiber can offer over the other. Optical fibers find important applications in a variety of sensors, communications systems, and telecommunications networks. In particular, Polarization-Maintaining (PM) fibers are desirable for use in optical fiber sensing and coherent long-distance optical communication systems [1].

Optical fibers are making ever increasing demand into areas traditionally satisfied by older, more established technologies [2]. Interest in the utilization of polarization effects in fibers is continuing to grow. In ordinary single-mode fibers, widely used in present optical communication systems, the polarization states of the input and the output light beams do not match, since the polarization of the output light beam is unstable [3]. By contrast, PM fibers maintain the state of polarization of a light beam passing through them. PM fibers are imperative for obtaining a stable output in interferometric fiber optical sensors. In optical communication devices the use of PM fiber becomes mandatory when performing any polarized waves operations; e.g., for polarization combining [3]. There are many applications where the polarization of the light is required to be stable and well defined; such as coupling to the integrated optical circuits, interferometric sensors, coherent optical communication systems, and certain in-line fiber optic components [4].

Nowadays, one of the issues of concern is the kind of fiber to use in all optical networks and the advantages they can offer regarding polarization-mode dispersion, chromatic dispersion, and optical fiber nonlinearities.

1.1 PRESENTATION OF THE PROBLEMS AND SOLUTIONS

In ordinary circularly cylindrical fibers, there are two types of hybrid modes, $HE_{\nu\mu}$ and $EH_{\nu\mu}$ modes. The label ν refers to the azimuthal variation of the field while the label μ accounts for modes of different radial variation. The dominant mode of an ordinary optical fiber is designated as the HE_{11} mode. However, under weakly guiding condition, an approximate modal field description can be obtained by solving the scalar wave equation instead of the full set of Maxwell's equations. This dominant mode solution is designated as LP_{01} mode for which the electric field is linearly polarized [5]. In the framework of Cartesian coordinates, the electric field of the dominant mode has three components, Ex, Ey and Ez. One of the two transverse components, Ex or Ey predominates, while the Ez component, considered in the direction of the fiber axis, is much smaller than the transverse. If Ex is the dominant field component in an isotropic circularly symmetric fiber, the LP_{01} mode is said to be polarized in the x-direction, while for if Ey is the dominant component, the mode is y-polarized. Thus, single-mode fibers can, in fact, simultaneously support two identical modes which are mutually orthogonally polarized. In an ideal dielectric waveguide of circular cross section, these two modes are degenerate; that is, there is no difference between their propagation constants, and thus propagate with same phase-velocity. In practical situations, an actual optical fiber is not absolutely perfect. It is neither completely axially-symmetric nor perfectly straight. In addition, the fiber material is often assumed to be nominally isotropic, in which the refractive index is the same regardless of the direction of the polarization of the electric field. This is also not strictly true in practical fibers. Small departures from perfect circularity and fluctuations of the anisotropy of the fiber material, couple the x-polarized mode to the y-polarized mode since both modes are very nearly degenerate. These conditions lead to a complete mixing of the two polarization states so that the initially linearly polarized light field quickly reaches a state of arbitrary polarization [6].

Furthermore, environmental factors such as twists, bends, anisotropic stress and ambient conditions also cause unstable fluctuations in the polarization state of the propagating light. In multimode fibers, such instability usually causes little trouble except for its possible effect on modal noise [7].

The following problems arise in a single-mode fiber due to the factors mentioned previously:

1- The two polarization states travel at different phase velocities, which causes the state of polarization of the output light to change randomly with time. Fluctuations in the received signal level are not desirable when the receiver is sensitive to polarization. In many applications, the output state of polarization should be strictly maintained, such as interferometric sensors, coherent transmission systems and for coupling to integrated optical circuits, i.e., when the heterodyne-type or homodyne-type optical polarization state is required between the received signal and the local oscillator [8].

2- The polarization instability deteriorates measurements accuracy in magnetooptic current sensors and in laser gyroscope [7], and [9]. In coherent systems, polarization instability adversely affects the bit-error rate.

3- A slight geometrical deformation exists in single-mode circular fibers. This residual deformation breaks the degeneracy of the two orthogonal dominant modes. These modes propagate with different group velocities, causing polarization-mode dispersion which can limit the ultimate bandwidth of a single-mode optical communication system.

Thus, there are good reasons why it is often desirable to use fibers that will permit light to pass through without changing its state of polarization; i.e., polarization-maintaining fibers. Various polarization-maintaining fibers are discussed in Chapter 2. The most successful structures in preserving the polarization state are the PANDA fiber and modulated refractive index fiber. The analysis and design of single-polarization single-mode fibers are discussed and carried out in Chapter 3.

As important as this issue is, a fiber with zero polarization-mode dispersion is in great need in today's expanding and vastly growing telecommunications applications. The design of a single-mode optical fiber should consider the following conditions:

1- Small transmission loss
2- Large modal birefringence for high-birefringence fibers
3- Wide single-polarization and/or single-mode bandwidth
4- Zero or small total dispersion with large effective area.

New fiber designs, optical components and devices are emerging to meet the 1550 nm network design requirements that use high output power Erbium-Doped Fiber Amplifiers (EDFAs) and multi-channel Dense Wavelength Division Multiplexing (DWDM) technology. A range of optoelectronic devices have been developed for high-speed, long-haul transmission and CATV applications including 10 Gbits/s lasers, uncooled lasers, and analog CATV modulator. The fiber's role as a medium for information transport is to carry multiple high-bit-rate channels in the 1550 nm window over long lengths. Other uses include medium-to-long distance single-channel 1550 nm systems for interoffice and long-distance applications.

The push to expand network capacity with the latest Time Division Multiplexing (TDM) and DWDM technologies continues to persist. The migration to all optical networks has started in recent years, where some components necessary in the all optical network are being deployed in today's network. Some of these components are laser transmitters used at the 1550 nanometer band, EDFA's, Ultra (U)DWDM and TDM technology platforms, and single mode fibers.

Prior to the invention of the optical amplifier, the primary optical fiber parameters of importance were optical attenuation and chromatic dispersion. Installed fibers were optimized for use at 1.3 μm and 1.55 μm (dispersion-shifted fiber) with low dispersion and losses approaching theoretical limits set by Rayleigh scattering. The widespread introduction of erbium-doped fiber amplifiers and the large transmission distance attainable before regeneration have shifted the focus on the fiber properties to optical nonlinearity and polarization-mode dispersion. Multiple wavelength channels propagating with the same velocity in zero-dispersion fiber are seriously degraded by four-wave mixing of nearby channels. New fiber designs which incorporate a small amount of dispersion at the signal wavelength eliminate this problem, allowing long-haul transmission of multiple wavelength channels. At high frequencies, OC-192 (optical carrier at 10 Gbit/s) and above, and long distances, dispersion compensation is necessary. For longer distances or high bit rates, dispersion compensation can be accomplished by appropriate cable design (dispersion managed cables) or by dispersion compensation in amplifier modules. Dispersion shifted fibers support high-bit-rate transmission but are not suitable for DWDM. Polarization-mode dispersion in early installed fibers may hinder upgrading to OC 192. Conventional unshifted fiber which can be used for DWDM requires too much dispersion compensation at 1.55 μm.

The limitations and requirements for high-bit-rate transmission and the implementation of all optical networks brings the question of what kind of fiber is best for use in future long haul and high capacity systems. This question will be addressed in Chapter 4 and a solution is proposed by introducing a fiber that provides zero polarization-mode dispersion, small chromatic dispersion, and large effective area.

Another structure investigated in this dissertation is a dielectric waveguide with conducting boundaries. They may be used as elements of integrated circuit devices, polarizers, mode analyzers, and mode filters. An important class of these waveguides with planar geometry, such as microstrip lines, H-guides, image lines, and fin lines, have been studied exhaustively for microwave and millimeter wave applications [10]-[11]. At optical frequencies, both planar and cylindrical geometries are of interest for integrated-optic devices and in-line all-fiber components, respectively. Propagation characteristics of planar optical waveguides with metal boundaries have been studied by many researchers

[12]-[15]. The investigation of waveguides involving both planar and curved boundaries is more complicated and has been carried out using experimental and numerical techniques. However, investigation of a wedge-shape waveguide consisting of two conducting plane boundaries with the interior of the wedge partially filled with a dielectric material for use as polarization and mode filtering, and elements of integrated circuits, has not been done before. This structure is thoroughly studied in Chapter 5. A special case of this waveguide corresponding to a wedge angle of 180^o, that is a semi-circular rod backed by a conducting plane, has been examined before [16]. Optical fiber polarizers are examples of such mixed boundary waveguides which find applications in fiber optic communication systems and sensors [17]-[18].

1.2 SCOPE OF INVESTIGATION

In this dissertation, optical polarization-maintaining fiber designs are proposed and their transmission properties are investigated. Design and optimization of anisotropic fibers for use as : a) high-birefringence polarization-maintaining fibers, (b) single-polarization single-mode fibers are discussed in Chapter 3.

Next, attention is focused on polarization-mode dispersion due to core ellipticity. A comprehensive investigation of this effect is carried out in Chapter 4. Fiber design with zero polarization-mode dispersion, small dispersion, and large effective area are introduced.

Finally, a wedge-shape dielectric waveguide bounded by conducting planes for applications as polarizers, and mode filters is studied in Chapter 5.

An overview of these three investigations is presented below.

1.2.1 Design of Polarization-Maintaining Fibers With Zero Dispersion at 1.3 μm and 1.55 μm

Single-polarization single-mode fiber designs can be achieved in several ways. In this dissertation two schemes are used to design fibers with such characteristics. The first scheme is to incorporate an anisotropic internal stress inside the fiber. This can be achieved by means of heavily doped rods located outside the core creating stress-induced anisotropy. The presence of anisotropy in a fiber results in two different refractive-index profiles along the x and y axes, and thus different propagation constants for x- and y-polarized fundamental modes. The larger the anisotropy, the larger is the difference between the propagation constants and hence the smaller the coupling between the two polarizations. The design considered is a circular fiber consisting of a central core region and several claddings. The design of high-birefringence fibers with zero dispersion starts by simulating the effects of stress-induced anisotropy on the refractive indices of the fiber layers and then calculating the propagation constants for each polarization of the fundamental LP_{01} mode. In order to achieve zero dispersion at the operating wavelength, the fiber parameters such as refractive index profile, material compositions, the number of cladding layers, and layers' radii are all investigated. These parameters have been determined for several refractive index profiles.

Increasing the fiber length in communication applications could cause crosstalk degradation due to random coupling between the two polarizations of the fundamental mode along the fiber length. Therefore, a second scheme is used to design polarization-maintaining fibers that can offer a better solution. The principal design criterion is to have the cutoff of one polarization of the fundamental mode above and the cutoff of the other polarization below the wavelength of operation, so that only one polarization exists in an operating wavelength region.. The design of such single-polarization single-mode fiber will also accomplish zero or low dispersion at the operating wavelength.

In both techniques, the field solutions and the characteristic equation for guided modes are found by employing the scalar-wave analysis, assuming weakly guiding conditions. The propagation constants and the cutoff wavelengths are calculated. The variation of the propagation constants and the chromatic dispersion as a function of wavelength are examined.

1.2.2 Analysis and Design of Fiber With Zero Polarization-Mode Dispersion And Large Effective Area

The previous discussion indicated the importance of achieving zero polarization-mode dispersion, small chromatic dispersion, and reducing the effects of nonlinearities in optical fibers. The goal to be pursued in Chapter 4 is to design a fiber having the aforementioned characteristics. A complete analysis of circular fiber with small core ellipticity is carried out to find the modal birefringence due to small elliptical deformation. The analysis of effective area and mode-field diameter are based on investigation in a companion work [19]. The design process begins with choosing a refractive-index profile and performing a systematic search for determining the proper fiber's dimensions and material compositions such that design requirements are met. In addition, tolerance analysis on the polarization-mode dispersion, chromatic dispersion, effective area, and mode-field diameter due to $\pm 1\%$ and $\pm 2\%$ of radii variations are performed to assess the sensitivity of the design to small parameter variations.

1.2.3 Wedge-Shape Dielectric Waveguide With Metal-Coated Boundaries

The proposed waveguide consists of two conducting plane boundaries with the interior of the wedge partially filled with a dielectric material and the remaining portion of the wedge interior is free space or is occupied by another dielectric material of lower dielectric constant. The dielectric-free space boundary is assumed to be circularly cylindrical. The existence of the metal in the immediate vicinity of the guided wave discriminates against TM modes and attenuates TE modes less than TM modes at optical frequencies [15], [17], and [20]-[22], which makes this type of waveguide very useful for mode and polarization filtering applications.

A comprehensive analysis of wedge-shape dielectric waveguides bounded by conducting planes and with arbitrary wedge angles is presented. Propagation properties of guided modes are studied. Field solutions, dispersion relations, cutoff conditions, and conductor and dielectric losses are examined.