Microbending Effects in Singlemode Optical Fibers: Investigation and Novel Applications

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(ABSTRACT)

Microbends are axial distortions on the optical fiber that have a spatial wavelength small enough to effect coupling between guided and radiation or cladding modes. The magnitude of this wavelength-dependent coupling is a function of the nature and the number of microdeformations. Since these periodic perturbations lead to an attenuation in signal level, they are avoided in fiber-based communication systems. However, controlled induction and signal processing of microbending losses has led to the fabrication of novel optical fiber-based sensors, devices, and components.

A systematic study of microbending effects in singlemode optical fibers is presented in this thesis. The theoretical analysis is based on the coupling between the fundamental $LP_{01}$ mode to discrete cladding modes. An algorithm is developed to characterize optical attenuation as a function of the spatial period of the microbend deformation. Optical attenuation peaks are described in terms of central wavelength, amplitude and spectral width. An excellent correlation is shown between the experimental results and the theoretical predictions, with nominal errors less than 2.5%. The algorithm developed may be used with any commercially available singlemode fiber, and any kind of microbend deform fiber apparatus, provided the microbend deformation function $f(z)$ is known accurately.

Based on the above analysis, a wavelength-tunable fiber polarizer is proposed and demonstrated. The polarizer is fabricated by inducing a periodic perturbation on a high birefringence singlemode optical fiber. The fiber thus exhibits polarization-selective attenuation characteristics. The operating wavelength is shown to be tunable by changing the spatial period of the deformation. A polarization extinction ratio of 25 dB is obtained with an attenuation of 1.3 dB, at an operating wavelength of 1177 nm.

Abstract
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Chapter 1. Introduction

1.1 Optical fiber-based communication and sensing systems

Generation, transfer, and utilization of information using novel means has been the primary objective of technological advances in the latter half of the twenty-first century. Rapid advances in four areas: microelectronics, photonics, software and networking, have been the key factors contributing to this evolution. Perhaps the single most important factor responsible for the creation of this information age has been the advent of optical fiber-based transmission systems. Fiber optics has become a communication medium of necessity, rather than choice, in the design of any large scale information carrying system. Telecommunication channels carrying 10 Gb/s of digitized voice, video, and data information are being planned and implemented. This has made possible the concept of a global village.

Along with rapid advances in the state of the art in optical fibers, there has also been a quantum increase in research levels in semiconductor optical sources, photodetectors, passive optical components such as couplers, connectors, splices, etc. This has led to prolific use of fiber optic systems by the telephone and cable television industries, and in novel transportation systems. The distinct advantages that an optical fiber-based communication system possesses, as compared to a conventional copper system are listed below.

- Extremely high bandwidth enables very high data rate capability,
- All dielectric construction ensures immunity to electromagnetic interference,
- Low distortion due to extremely low signal attenuation and dispersion,
- Light weight, small size, and
- Cost-effective and efficient due to a very well developed technology base.

Another area in which the optical fiber has distinguished itself has been the field of sensor instrumentation systems. The advent of optical fiber-based sensing
instrumentation systems has revolutionized the way in which precision measurements are being made in the industrial and research environments. Since different physical perturbations affect light propagating in the fiber in different ways, unique signatures can be obtained which allow absolute or differential measurement of the incident disturbance. Optical fiber sensors have thus been configured to detect and measure different physical phenomena such as strain, pressure, temperature, acceleration, magnetic field, and electric field. Fiber-based sensors have found applications in industry for process control and, more recently, for monitoring the health of advanced civil structures.

Optical fiber-based sensors are classified as being extrinsic and intrinsic, referring to the sensing region of the fiber sensor being outside or inside the fiber, respectively. In intrinsic sensors the optical energy in the fiber is affected directly by the incident perturbation (the phenomena being measured), and changes in the output intensity give an indication of the magnitude of the disturbance. Such fiber sensors include the sapphire fiber-based intrinsic Fabry-Perot interferometric sensor (IFPI) [1,2], which has been successfully implemented for high temperature measurements. In extrinsic sensors the fiber only serves to carry optical power to, and sensing information from, an external region, usually air. Such sensors are often immune to vibration and temperature fluctuations. Extrinsic sensors based on the extrinsic Fabry-Perot interferometric (EFPI) scheme have been implemented using circular core singlemode [3] and elliptical core two-mode optical fibers for the measurement of strain, temperature [4], and vibrational mode analysis in smart structures [5].

Fiber sensors are also classified according to the transduction mechanism which brings about a change in some property of optical power propagating in the fiber, such as intensity, phase, polarization, modal content, etc. Hence the corresponding sensors are known as intensity-based, phase- or interferometric-based, polarimetric-type, and modal content-based. Intensity based fiber sensors offer the advantages of ease of fabrication, robustness, and simplicity of signal processing. The sensor consists of an optical power source, an optical fiber, and a photodetector or spectrum analyzer. The intensity modulation is effected through the use of periodic microbends [6,7], dielectric thin films offering differential spectral reflectivity [8], or Rayleigh scattering used in optical time-domain reflectometry (OTDR).

1. Introduction
Phase modulated or interferometric sensors offer extremely high levels of sensitivity as compared to the intensity based sensors. The sensor usually consists of a reference fiber which is isolated from the perturbation being measured, and a sensing fiber which is made extremely susceptible to the incident perturbation. The output from the two fibers interferes at the photodetector, and the magnitude of the interference is dependent on the incident perturbation. Since the light source and other external fluctuations affect both the sensing and reference fibers equally, the differential interference offers a self referencing mechanism. Interferometric sensors are hence more sensitive and accurate than intensity based sensors. However, they often involve complex output signal processing schemes. Interferometric sensors employ the fiber equivalent of classical interferometer schemes such as the Mach-Zehnder, Michelson, Fabry-Perot, and the Sagnac interferometers.
1.2 Microbending losses in optical fibers

Microbends are distortions to the fiber axis that have spatial wavelengths small enough to cause coupling between modal fields. These microdeformations typically occur when the fiber is sheathed within a protected cable. Since they lead to an attenuation in the signal level, they are avoided in communication systems. However, controlled induction and signal processing of microbending losses has led to the fabrication of novel optical fiber-based sensors, devices, and components.

To attain a preliminary understanding of microbending losses in an optical fiber, it is necessary to solve Maxwell's equations subject to the cylindrical boundary conditions of the fiber [9]. The appearance of modal fields in a planar dielectric slab waveguide are first examined for analyzing the propagating modes in a circular cross-section optical fiber. This waveguide is composed of a dielectric slab of refractive index \( n_1 \) sandwiched between dielectric material of refractive index \( n_2 (n_2 < n_1) \) called the cladding. If the electric field distributions for several of the lower order guided modes are considered, it can be seen that the fields are not completely confined to the central dielectric slab. Instead, the fields extend partially into the cladding. For lower-order modes the fields are strongly concentrated near the center, or axis, of the slab. However, for higher order modes, the fields are distributed more towards the edges of the guide and penetrate further into the cladding region.

In addition to supporting a finite number of guided modes, the optical fiber also supports an infinite continuum of radiation modes that are not trapped in the core, but are still solutions of the same boundary value problem. This field results from the optical power that lies outside the fiber's numerical aperture, and is hence refracted into the cladding. This leads to the induction of cladding modes which propagate along with the guided modes in the fiber. Whenever the fiber is distorted axially, it leads to power being coupled from the guided modes to the cladding modes, resulting in a loss of power from the waveguide. These distortion mechanism are of two types; macroscopic and microscopic [9]. Macroscopic distortion refers to large scale bending that can be caused by wrapping the fiber on a spool, or pulling the fiber around corners etc. These losses can be explained by the fact that whenever a wave moves around a bend, for the wave to be guided the light at the outermost layer (under tension) must move faster than the light.
in the innermost layer (compression). At this point the speed of the outer light wave may exceed the speed of light causing it to radiate out.

Microscopic losses in fibers, also known as microbends, cause coupling of lower-order modes to higher-order modes involving power transfer. Attenuation of the optical power takes place when light is coupled from a guided mode to a cladding or radiation mode. These micro-deformations can be induced on the fiber with microbend transducers which, with the correct spatial frequency, can cause selective coupling between guided and radiation modes. This selective coupling is wavelength dependent and has been extensively used for novel device applications.
1.3 Applications of microbending effects

Since the attenuation spectra obtained from inducing microbends on optical fibers is dependent on the spatial frequency and number of microbends, and the applied force on the microbend transducer, several interesting devices have been proposed and implemented. The key operating principle behind these devices is the selective coupling of guided and cladding or radiation modes, at wavelengths dictated by the application. These devices include modal couplers and converters, sensors, polarizers, filters, and other passive components. This section briefly reviews some of these devices and their applications.

1.3.1: Intermodal converters for all-fiber dispersion compensation

Novel dispersion compensating devices for long distance communication systems depend on the conversion of lower order guided modes to higher order modes which display a larger negative coefficient of chromatic dispersion near their cut-off wavelengths [10]. Figure 1 illustrates the functional schematic of a dispersion compensation scheme. The main feature of this schematic is the spatial mode converter which converts the $LP_{01}$ mode of the singlemode fiber into the higher order $LP_{11}$ mode of the compensating fiber. A similar modal converter converts the higher order mode back to the fundamental mode for the receiver.

The modal converters mentioned have been implemented efficiently by utilizing the mode coupling property of induced microbends in an optical fiber [11]. The spatial wavelength of the microbending transducer is matched to the beat length $L_b$ of the modes to be coupled. The magnitude of modal conversion can be varied by changing the amount of pressure exerted on the microbend transducers. Figure 2 illustrates the spatial orientation of the higher order $LP_{11}$ modes generated from the orthogonal polarizations of the fundamental $LP_{01}$ mode which is subjected to periodic microbending.

1.3.2: Acoustic wave detection for underwater applications

Microbend loss-based underwater acoustic wave amplitude and direction detection devices, called hydrophones, have been widely investigated [12]. These devices utilize cylindrical sensing elements instead of grooved deform plates. The advantages of the
cylindrical configuration include mechanical simplicity, acceleration insensitivity, and flexibility of shape.

Various hydrophone designs were proposed by Vengsarkar et al. based on slots cut around the circumference [12]. The fiber, wound around the cylindrical element is microbent at the positions of the axial slots, when an acoustic pressure wave is incident. The resulting change in optical intensity at the output is proportional to the magnitude of the incident acoustic pressure wave. Cylindrical sensing elements with varying spatial frequencies induce losses depending on the direction of the incident acoustic pressure wave. This information is then extracted from the output waveform.

1.3.3: Strain gages for material characterization
In this application [13], step-index plastic fibers with permanently induced microdeformations were used as strain gages. This gage, when unstrained, shows maximum losses since the microbend amplitude is at a maximum. When the sensor experiences strain, the spatial wavelength of the microdeformation increases, reducing the amplitude of the microbends. This results in an increase in the transmitted power through the fiber.

Regular silica fibers were found to be unsuitable for this application due to their low softening point which eliminated the use of high temperature for inducing the permanent microbends. Instead 240/250 micrometer, step-index, plastic fibers fabricated from pure and fluorinated PMMA (poly-methyl methacrylate) were used. The operating range of the strain gage was reported to be linear to at least 4 X 10^-3.
Figure 1: Schematic of an all-fiber dispersion compensation system [10].

Figure 2: Spatial orientation of the $LP_{11}$ modes generated from $LP_{01}$ modes by periodic microbending.
1.4 Outline

Modal analysis for optical fiber waveguides is reviewed in Chapter 2. The concept of eigenmodes in linear systems is discussed along with the conditions necessary for the existence of guided solutions. The range of propagation constants for non-guided modes in optical fibers such as radiation, cladding, and leaky modes is presented.

Chapter 3 presents a systematic study of microbending effects in singlemode optical fibers. The theoretical background responsible for losses due to these periodic perturbations is discussed. A numerical algorithm is developed for the analysis of mode coupling between the fundamental mode and discrete cladding modes. The theoretical predictions of the attenuation spectra are experimentally verified. Excellent correlation is achieved between theory and experiment, with nominal errors less than 2.5%.

Based on the analysis developed in Chapter 3, the principle of operation and experimental results are presented for a wavelength-tunable polarizer in Chapter 4. A high birefringence (High-Bi) fiber subjected to periodic perturbations shows polarization selective attenuation in the output spectra. The polarizer is specified to have an extinction ratio of 25 dB, with an attenuation of 1.3 dB, at an operating wavelength of 1177 nm.

Finally, recommendations for future work are presented in Chapter 5.

1.4.1: Significance of investigation

This thesis presents a numerical technique for very accurate prediction of microbend-based fiber device performance. The algorithm developed may be used with any commercially available singlemode fiber, and any kind of microbend deformer apparatus, provided the microbend deformation function \( f(z) \) is known accurately.
Chapter 2. Modal Analysis for Optical Fiber Waveguides

2.1 Modes in linear systems

Any continuous, linear system may be characterized by certain invariant inputs which are only altered by a multiplicative constant as they traverse the system [14]. These special inputs, known as modes or eigenfunctions (eigenvectors), and the multiplicative constants, called the eigenvalues, completely define the linear system. The eigenvalues may be considered to be the attenuation or amplification factors of the modes. The concept of modes is especially important since any arbitrary input to the system may be expressed as a summation of its weighted eigenvectors. The output of the system is then the product summation of the respective modes and their eigenvalues. It should be noted that for an ideal, undisturbed, linear system, there is no interaction between the modes.

Modal analysis is extremely useful in the analysis of optical power propagating in dielectric waveguides, such as optical fibers. The transverse electric field distributions (in the x-y plane) define the autonomous modes, which are altered only by multiplicative factors as they propagate along the z direction. These multiplicative constants, or eigenvalues, are the phase factor terms \( \exp(-j\beta_q z) \) where \( \beta_q \) is the propagation constant of mode \( q \). Every mode in the optical fiber is hence characterized by a distinct propagation constant \( \beta_q \), a distinct spatial electric field distribution \( (E_x, E_y; H_x, H_y) \), and two independent polarization states \( (E_x, E_y; H_x, H_y) \).

To summarize, any linear system operating on the function \( f(x, y) \) may be characterized by a number of orthogonal modes which satisfy the integral equation [14]

$$
\int_{-\infty}^{\infty} h(x, y; x', y') f_q(x', y') dx' dy' = \lambda_q f_q(x, y),
$$

(2.1.1)

where
$f_q(x,y)$ = eigenfunctions, eigenvectors, or modes,
$\lambda_q$ = eigenvalues and,
$\lambda_q f_q(x,y)$ = system outputs to input $f_q(x,y)$. 
2.2 Guided wave solutions in cylindrical coordinates

As illustrated in Figure 3, the monochromatic beam of light propagating through the optical fiber is composed of spatially varying electric and magnetic fields. Assuming the cladding radius to be infinite, the fields satisfy the scalar Helmholtz Equation. In cylindrical coordinates this equation may be written as [14]

\[
\frac{\partial^2 \Psi}{\partial r^2} + \frac{1}{r} \frac{\partial \Psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Psi}{\partial \phi^2} + \frac{\partial^2 \Psi}{\partial z^2} + n^2 k_o^2 \Psi = 0, \tag{2.2.1}
\]

where \( \Psi = \Psi(r,\phi,z) \) represents the complex amplitudes of the \( E \) and \( H \) field components, \( k_o = (2\pi/\lambda_o) \) is the free space wavenumber, and \( n \) is the propagation medium under consideration.

To describe the optical wave which travels in the \( z \) direction with a propagation constant \( \beta \), is a periodic function of the azimuthal component \( \phi \), and has only transverse spatial field distributions, \( \Psi \) may be expressed as

\[
\Psi(r,\phi,z) = \Psi(r) \exp(-j\phi) \exp(-j\beta z), \quad l = \ldots,-3,-2,-1,0,1,2,3\ldots \tag{2.2.2}
\]

Using Equation (2.2.1) to obtain an ordinary differential equation for \( \Psi(r) \) we get

\[
\frac{d^2 \Psi}{dr^2} + \frac{1}{r} \frac{d \Psi}{dr} + \left( n^2 k_o^2 - \beta^2 - \frac{l^2}{r^2} \right) \Psi = 0. \tag{2.2.3}
\]

The range of values that \( \beta \) may assume is limited by the total internal reflection condition, and also by the self consistency condition. The self consistency condition for the optical waveguide demands that for the optical wave to be guided, it must reproduce itself, i.e. constructive interference, after phase shifts accumulated in a round trip. Thus the propagation constant of any guided mode in the waveguide is limited to the interval

\[
n_2 k_o \leq \beta \leq n_1 k_o, \tag{2.2.4}
\]
where \( n_1, n_2 \) refer to the refractive indices of the core and cladding, respectively, and 
\( k_o = (2\pi / \lambda_o) \) is the free space wavenumber.

To conveniently describe the modal fields, we define the parameters [15]

\[
u = a(k_o^2 n_1^2 - \beta^2)^{1/2}, \tag{2.2.5}\]

and

\[
w = a(\beta^2 - k_o^2 n_2^2)^{1/2}, \tag{2.2.6}\]

where \( a \) is the radius of the core. Equation (2.2.3) may then be written as

\[
\frac{d^2 \Psi}{dr^2} + \frac{1}{r} \frac{d \Psi}{dr} + \left( \frac{\nu^2}{a^2} - \frac{l^2}{r^2} \right) \Psi = 0, \text{ for } (r < a, \text{ core}),
\tag{2.2.7}\]

and

\[
\frac{d^2 \Psi}{dr^2} + \frac{1}{r} \frac{d \Psi}{dr} - \left( \frac{\omega^2}{a^2} + \frac{l^2}{r^2} \right) \Psi = 0, \text{ for } (r > a, \text{ the cladding}).
\tag{2.2.8}\]

This allows a convenient representation of the modal fields in terms of the Bessel functions as

\[
\Psi(r, \phi, z) \propto J_i\left(\frac{\nu r}{a}\right) \exp(-jl\phi) \exp(-j\beta z) \ (r < a); \tag{2.2.9}
\]

\[
\propto K_i\left(\frac{\omega r}{a}\right) \exp(-jl\phi) \exp(-j\beta z) \ (r > a),
\]

where the temporal dependence is implicit. The first few Bessel function amplitudes are graphically illustrated in Figure 4. They represent the spatial variation of the modal fields as a function of radial distance in the waveguide, as given by Equation (2.2.9).

2.2.1: The 'V' Parameter

The \( u \) and \( w \) parameters, as defined by Equations (2.2.5) and (2.2.6) determine the rate of change of \( \Psi(r) \) in the core and the cladding, respectively. A larger \( u \) gives rise to faster
oscillations of the modal fields in the core; larger values of \( w \) imply a faster decay and reduced penetration into the cladding [14]. The sum of the squares of \( u \) and \( w \) at a given wavelength defines the characteristic 'V' number of the fiber, which is a constant for that given fiber.

\[
\begin{align*}
  u^2 + w^2 &= a^2 (n_1^2 - n_2^2)k_c^2, \\
  &= a^2 NA^2 k_c^2, \\
  &= V^2. 
\end{align*}
\] (2.2.10)

Equation (2.2.10) states that as \( u \) increases, \( w \) decreases and there is a greater penetration of the modal fields into the cladding. However, when \( u \) exceeds \( V \), \( w \) becomes imaginary and the field is no longer guided (bound to the core). The 'V' number thus determines the number of guided modes and their propagation constants.

2. Modal Analysis for Optical Fiber Waveguides

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Figure 3: Cylindrical coordinate system to analyze modal fields.

Figure 4: Amplitudes of the first few Bessel functions.
2.3 Non-guided modes in optical fibers

Considering only the radial part of Equation (2.2.3), we get [16]

\[ r^2 \frac{d^2 \Psi}{dr^2} + r \frac{d\Psi}{dr} + \left( \left\{ n^2(r)k_o^2 - \beta^2 \right\} r^2 - l^2 \right) \Psi = 0. \]  \tag{2.3.1}

Based on the behavior of the modal propagation constant \( \beta \), the solution for this equation can be divided into two parts,

a) \( k_o^2 n_1^2 > \beta^2 > k_o^2 n_2^2 \)

As was discussed in Section [2.2], for the values of \( \beta \) lying in this range, guided wave solutions are obtained. The fields \( \Psi(r) \) show oscillatory behavior in the core, and decay in the cladding. Since the guided modes represent solutions of the scalar wave equation (SWE), they may be considered to satisfy the orthonormality condition [16]

\[ \int_0^{2\pi} \int_0^\infty \psi^*_{lm}(r, \phi) \psi_{lm'}(r, \phi) r dr d\phi = \delta_{ll'} \delta_{mm'}. \]  \tag{2.3.2}

b) \( \beta^2 < k_o^2 n_2^2 \)

This expression represents a region where, according to Equation (2.2.6), the waveguide parameter \( \omega \) is imaginary, resulting in a complex value of the modal propagation constant \( \beta \), which indicates lossy guidance. This region physically represents fields that show oscillatory behavior even in the cladding region, and which allow the propagation constant to assume a continuum of values. Such solutions are known as radiation modes.

The concept of radiation modes allows the representation of any applied electromagnetic field to the fiber be represented as a summation of discrete guided modes, plus integrals over the continuum of radiation modes [17]. This may be mathematically stated as [16]

\[ \Psi(x, y, z) = \sum \limits_v a_v \psi_v(x, y) \exp(-j\beta_v z) \]

\[ + \int a(\beta) \psi(\beta, x, y) \exp(-j\beta z) d\beta, \]  \tag{2.3.3}
where $|a_v|^2$ is a factor proportional to the power carried by the $v^{th}$ mode; the constants $a_v$ being determined from the incident field at $z=0$, and by using the orthonormality condition.

It should be noted that the above analysis is based on applying the infinite-cladding assumption to the waveguide. In practice, the cladding extends only over a finite radial distance, surrounded by a lossy jacket. If the refractive index of the jacket is less than that of the cladding, the cladding-jacket interface forms a secondary waveguiding structure. This introduces solutions in the form of *cladding* modes. These modes can be considered to be discrete since they possess $u$ and $w$ parameters, unlike a continuum of propagation constants which characterize radiation modes.

In addition to supporting guided, radiation, and cladding modes, the optical fiber also supports certain solutions in the form of *leaky* modes. These modes are comparatively tedious to analyze, and are usually ignored while giving simple qualitative explanations for fiber-based devices and components. They will not be discussed in detail, and assumed to be included as part of radiation mode fields.

The understanding of cladding and radiation modes is extremely useful for the analysis of loss phenomena in singlemode optical fibers due to periodic, axial perturbations, such as microbends. In the analysis presented in Chapter 3, mode coupling is assumed to be between the fundamental mode and the discrete cladding modes.
2.4 Linearly polarized modes and the characteristic equation

Most singlemode optical fiber waveguides of interest permit only the propagation of the first few lower order guided modes which are spatially paraxial distributions (i.e. appx. parallel to the fiber axis). Hence the transverse electric and magnetic field components dominate over the longitudinal components, and the guided waves are approximately Transverse Electromagnetic (TEM). The wave is linearly polarized only in the x and the y directions. These types of modal distributions are called Linearly Polarized (LP) modes, and the fiber is said to be weakly guiding \((n_1 = n_2)\).

The modal field distributions in the fiber are subject to certain boundary conditions. Demanding the continuity of the \(E\) and \(H\) fields at the core-cladding interface \((r = a)\) turns out to be equivalent to the condition that \(\Psi\) for Equation (2.2.9) is continuous, and has a continuous derivative at \(r = a\) [14]. These conditions are satisfied if

\[
u |\frac{J_i'(u)}{J_i(u)}| = w |\frac{K_i'(w)}{K_i(w)}|,
\]

(2.4.1)

where the prime denotes the derivative. Using the recursive relation for the derivatives of the Bessel functions yields the characteristic equation [14]

\[
u |\frac{J_{i\pm 1}(u)}{J_i(u)}| = \pm w |\frac{K_{i\pm 1}(w)}{K_i(w)}|.
\]

(2.4.2)

This transcendental equation is solved graphically by plotting the LHS and the RHS, and finding the intersection points. This is illustrated in Figure 5 which is a computer simulation of the characteristic equation with \(\nu' = 9\). The Bessel functions in the graph are denoted as \(J_{\mu}(x)\) where \(\mu\) is the order, and \(x\) is the argument of the Bessel function, respectively. The vertical lines represent discontinuities, which correspond to the roots of the denominator \(J_0(x)\). The multiple intersection points correspond to different fiber modes. Each intersection is denoted by \(u_{im}, m = 1, 2... M_i\), where \(M_i\) is the mode number. Each \(u_{im}\) gives rise to a unique \(\beta_{im}\) which satisfies the cutoff conditions. Every mode (eigenfunction) is thus described by a propagation constant \(\beta_{im}\) (eigenvalue) which has the indices \(l\) and \(m\) characterizing its azimuthal and radial distribution, respectively.

2. Modal Analysis for Optical Fiber Waveguides
The first few modes of a circular core, step index waveguide are illustrated in Figure 6 [10]. The upper row shows the true eigenmodes that are obtained without using the weakly guiding approximations. It should be noted that the modal propagation constants are a function only of the intensity patterns, and are independent of the polarization. Hence the $LP_{11}$ mode has four degeneracies in the scalar approximation, corresponding to the four possible combinations of the $E$ and $H$ fields.
Figure 5: Computer simulation of the fiber characteristic equation with V=9.

Figure 6: First few modes of a circular core step-index optical fiber [10].
Chapter 3. Evaluation of Microbending Effects in Singlemode Optical Fibers

3.1 Introduction

Losses in optical fibers due to periodic, axial microdeformations have been used as the transduction mechanism in intensity modulated optical fiber sensors. Microbend sensors have been proposed for the measurement of various physical variables such as pressure, strain, temperature, acceleration, magnetic, and electric fields [13, 18-20]. These sensors are particularly attractive for the industrial sector because of their robust and simple construction. Moreover they do not require complex signal processing techniques, as needed for interferometric or phase modulated sensors.

The microbending mechanism in singlemode and multimode optical fibers has been studied by various researchers [20, 21-24]. When a fiber is subjected to axial deformations, mode coupling occurs between the guided modes and the cladding modes. The optical power coupled to the cladding modes is heavily attenuated due to the lossy plastic jacket surrounding the fiber. If these microdeformations, or periodic microbends, satisfy the phase matching condition \( L_n = 2\pi / \Delta \beta \), and the mode field overlap integral \( \int \int \psi_m^* \phi_{r,m} \cdot ds \) is nonzero, then strong wavelength dependent losses are observed in the output spectra of the fiber. These microbends can, for example, be induced on the fiber by placing it between two grooved deformer plates which have a periodic spatial structure. These plates act as a transducer to translate any incident perturbation into a longitudinal spatial deformation on the fiber. If a singlemode fiber is used, optical power from the guided \( LP_n \) mode is coupled to discrete cladding modes. This coupling is predominant at certain wavelengths, which is observed as distinct attenuation peaks in the output spectra. These wavelengths depend on a number of parameters including the amplitude, spatial period, number of microbends, and the fiber parameters. Hence a scheme which can be used to characterize such a fiber as a function of the given microbend deformer and fiber parameters.
parameters would be very useful in simulating the performance of microbend-based fiber devices and sensors.

In this chapter we describe a theoretical model which predicts losses in singlemode optical fibers as a function of microbend spatial deformation spatial period. Optical attenuation peaks are described in terms of central wavelength, amplitude, and spectral width. An excellent correlation is shown between the experimental results and the theoretical predictions, with nominal errors less than 2.5%.
3.2 Background

The theoretical analysis for singlemode fibers subjected to microbends begins by considering the refractive index distribution of a perfect fiber (without microbends) as given by \( n_0(r) \), where \( r \) is the radial coordinate of a cylindrical coordinate system. Since the microbend deformation function may also depend on the angular and axial coordinates, the index distribution of an imperfect fiber is given as \( n(r, \phi, z) \). Here \( n(r, \phi, z) \) may be given as a first order Taylor series expansion as [21]

\[
n(r, \phi, z) = n_0(r) + \frac{\partial n_0}{\partial r} E(z) \cos(\phi).
\] (3.2.1)

Here \( E(z) \) defines the microbend deformation function. The coupling strength between the guided mode and the discrete cladding modes due to the microbends is determined by the coupling coefficients \( C_\psi \). These coefficients may be expressed as integrals in the \( r, \phi \) plane over products of the kind \( (n(r, \phi, z) - n_0(r))E_{\psi}E_{\psi} \) [21]. Here \( E_{\psi} \) defines the guided mode field and \( E_{\psi} = E_{\psi} \cos(\psi \phi) \) is the field expression for the \( E_{\psi} \) cladding mode. Since the guided mode field is independent of \( \phi \), the coupling coefficients have non-zero values only for cladding modes \( LP_\psi \) which have the same \( \phi \) dependence as \( (n(r, \phi, z) - n_0(r)) \).

The microbend loss formula can thus be given from coupled mode theory as [17,25]

\[
2\alpha = \sum_{r=0}^{\infty} C_\psi^2 \Phi(\Delta \beta_\psi).
\] (3.2.2)

In this expression \( C_\psi \) is the \( z \) independent coupling coefficient given as [21]

\[
C_\psi^2(\lambda) = \frac{k^2}{2} \left( \int_0^\infty \frac{\partial n_0}{\partial r} E_{\psi} E_{\psi}' rdr \right)^2 \frac{\left( \int_0^\infty E_{\psi}' rdr \right)^2 rdr}{\int_0^\infty (E_{\psi}')^2 rdr},
\] (3.2.3)

where \( k = (2\pi/\lambda) \) is the free space wavelength. The spatial power spectrum is defined by [25]

3. Evaluation of Microbending Effects in Singlemode Optical Fibers
\[ \Phi(\Delta \beta_w) = \frac{1}{2L} \left| \int_L^L f(z) \exp(-j\Delta \beta z) dz \right|, \] (3.2.4)

where \(2L\) is the length of the microbend deformation region. From equations (3.2.3) and (3.2.4) it may be noted that both \(C_w\) and \(\Phi\) are functions of wavelength. Hence if the deformation spectrum \(\Phi(\Delta \beta_w)\) is made to peak at known spatial frequencies, high losses will occur at wavelengths where the peaks coincide with the positions of the coupling coefficients.
3.3 Theoretical analysis

To allow a graphical representation of the attenuation coefficients with wavelength, as described by Equation (3.2.2), expressions for both the coupling coefficients $C_\phi$ and the spatial spectrum $\Phi(\Delta \beta_\phi)$ as a function of wavelength and other known fiber and deformer plate parameters are calculated [6], as shown below. Now

$$\beta_{oi}(\lambda) = \sqrt{k_i^2 - (u/a)^2}, \quad (3.2.5)$$

where [15]

$$u = \frac{(1 + \sqrt{2})V}{1 + (4 + V^2)^{1/2}},$$

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2},$$

and

$$k_i(\lambda) = \frac{2\pi}{\lambda} n_i.$$

Here $a$ is the core radius, $n_i$ is the core refractive index, and $n_2$ is the cladding refractive index. Hence using Equation (3.2.5), $\beta_{oi}$ may be evaluated at any wavelength, if the fiber parameters are known. Similarly $\beta_m$, the propagation constant for the cladding modes may be approximated as [26],

$$\beta_m(\lambda) = \sqrt{k_z^2 - (j_m b)^2}, \quad (3.2.6)$$

where

$$k_z = \frac{2\pi}{\lambda} n_z.$$
and $j_m$ are the roots of the first order Bessel function for $m=0, 1, 2$ etc., and $b$ is the cladding radius. Only the first order Bessel functions are considered since the coupling coefficients, defined by Equation (3.2.3), vanish for the higher orders. $\beta_m$ can thus be evaluated as a function of wavelength only. Knowing both $\beta_{\sigma}(\lambda)$ and $\beta_{\rho}(\lambda)$, the variation of $\Delta \beta_{\sigma}$ with wavelength was then obtained.

The next objective is to find an expression for the variation in the spatial power spectrum $\Phi(\Delta \beta_{\sigma})$ with wavelength, in terms of the microbend deformer and fiber parameters. The deformer plates used in our experiments were circular in cross section with 'V' shaped grooves machined across the surface. When the fiber is sandwiched between a matched pair of these deformer plates, a sinusoidal perturbation is produced. The deformation function $f(z)$ can thus be expressed as

$$f(z) = Y_\sigma \cos(\Omega z), \quad (3.2.7)$$

where $Y_\sigma$ is the deformation amplitude and

$$\Omega = \frac{2\pi}{\Lambda}, \quad (3.2.8)$$

where $\Lambda$ is the microbend spatial period. Using Equation (3.2.7), Equation (3.2.4) was simplified to be of the form

$$\Phi(\Delta \beta_{\sigma}) = \frac{Y_\sigma^2 L^4}{2} \left[ \frac{\sin((\Omega + \Delta \beta_{\sigma})L)}{(\Omega + \Delta \beta_{\sigma})L} + \frac{\sin((\Omega - \Delta \beta_{\sigma})L)}{(\Omega - \Delta \beta_{\sigma})L} \right]^2. \quad (3.2.9)$$

Hence knowing the deformer and fiber parameters, the spatial power spectrum $\Phi(\Delta \beta_{\sigma})$ may be evaluated at any wavelength using the above expressions.

The final step in the calculation of the attenuation coefficients versus wavelength is deriving an expression for the coupling coefficients, as given by Equation (3.2.3), in terms of the fiber parameters. To simplify our calculation without losing accuracy, we assumed the guided mode electric field to be a Gaussian distribution in shape given by

3. Evaluation of Microbending Effects in Singlemode Optical Fibers
\[ E_e(\lambda) = E_0 \exp[-(r/w)^2], \quad (3.2.10) \]

where \( w \) is the mode field radius (MFR) given by [27]

\[ w(\lambda) = a(0.65 + \frac{1.619}{\nu^{1/2}} + \frac{2.879}{\nu^2}). \quad (3.2.11) \]

The cladding mode electric field was taken to be of the form [21]

\[ E_p = AJ_{\nu}(j_{\nu} \frac{r}{b})\cos(\phi)\exp(j(\omega t - \beta z)). \quad (3.2.12) \]

Due to the very small size of the core, we ignored the presence of the core in the above expression. Equations (11) and (12) were then substituted in Equation (3.2.4) to yield an expression for the coupling coefficients as a function of wavelength. Since the electric fields vanish at the cladding-jacket interface, the expression was integrated from \(+b\) to \(-b\), where \( b \) is the cladding radius.

Knowing the expressions for the coupling coefficients \( C_\nu \) and the spatial power spectrum \( \Phi(\Delta \beta) \), a program was written to numerically evaluate the attenuation coefficients. The fiber and deformer plate parameters used in this program were the same as those used for obtaining the experimental results. Figure 7 shows the attenuation coefficients as a function of wavelength. Four distinct peaks can be observed in the graph, which will be referred to as Peak 1 (maximum attenuation), Peak 2, Peak 3, and Peak 4 (minimum attenuation). The same program was modified slightly to obtain other characteristics. The shift in central wavelengths of the four peaks, with the change in microbend spatial period, is shown in Figure 8. The change in maximum attenuation and spectral width, with the change in number of microbends, is shown in Figure 9 and Figure 10, respectively.
Figure 7: Calculated variation of the attenuation coefficients with wavelength. These values were obtained using MATLAB.
Figure 8: Calculated shift in location of the central wavelength peak as a function of the deformation period.
Figure 9: Calculated amplitude of attenuation coefficient peaks as a function of the deformation period.
Figure 10: Calculated spectral width of the attenuation coefficient peaks as a function of the deformation period.
3.4 Experiments

The setup shown in Figure 11 was used for obtaining the experimental results. It consists of a SPEX white light source, a pair of microbend deformer plates, and the Optical Spectrum Analyzer. The microbend deformer plates used were made of aluminum with machined periodic V-shaped grooves to create a microbend inducing structure. The plates had a diameter of 12.69 cm, a V groove/deformation period of 0.72 mm, and were mounted on a stage which allowed plate rotation.

White light was injected into a singlemode fiber (Ensign-Bickford, cutoff wavelength 750 ± 50 nm, \(a=5\) μm, \(b=62.5\) μm, \(n_1=1.4574\), \(n_2=1.4529\)). The resultant spectra was monitored using the Optical Spectrum Analyzer which had a maximum resolution of 0.1 nm. Figure 12 shows the attenuation spectra of the fiber at a deformation period of 0.9399 mm. In order to subject the fiber to different microbend periods, the grooves on the plates were rotated at different angles, with respect to the fiber. To vary the number of microbends, the fiber was moved parallel to its original position, keeping the rotation angle constant. The experimental results are shown in Figures 13-15. Figure 13 shows the experimental results only for Peaks 2, 3, and 4, since the Optical Spectrum Analyzer (OSA) could not scan above 1.75 microns. Moreover Figure 15 shows the experimental results for only Peak 1 and Peak 2 since reliable measurements could not be done on the OSA for Peaks 3 and 4, due to its limited resolution.
Figure 11: Experimental setup used to measure microbending losses in singlemode optical fibers. The bottom figure shows a top view of the fiber placed between the deformer plate V-grooves.
Figure 12: Measured attenuation spectrum of the singlemode fiber when it was subjected to microbends.
Figure 13: Measured shift in location of central wavelength of the attenuation peaks with the change in deformation period. Results are shown only for peaks 2, 3, 4, since variation in peak 1 could not be measured by the OSA beyond 1.75 μm.

3. Evaluation of Microbending Effects in Singlemode Optical Fibers
Figure 14: Measured amplitude of the attenuation coefficient peaks as a function of deformation period.
Figure 15: Measured spectral width of the attenuation coefficient peaks as a function of the deformation period. Reliable measurements could be made only for peaks 1 and 2 due to the limited resolution of the OSA.
3.5 Results and discussion

From Figures 7 and 12 it may be observed that there is excellent correlation between theory and experiment for central wavelength prediction of the attenuation bands. Table (1) shows the error between the two results. For Peak 1, the error is only 0.76%. Results shown in Figures 8 and 13 are expected since the position of the attenuation peak wavelengths is dependent on the spatial power spectrum $\Phi(\Delta \beta_w)$. This factor, in turn, depends on $\Delta \beta_w$ which is a function of wavelength. The change in maximum attenuation and spectral width of the four attenuation peaks with change in number of microbends can be explained by the fact that with the increase in the number of microdeformations, the attenuation peaks elongate and move inwards. In other words, their maximum attenuation increases and their spectral width decreases. The reverse takes place when the number of microbends are decreased.

In conclusion, we have demonstrated a numerical technique for very accurate prediction of microbend-based fiber device performance. The theoretically obtained results correlate well with the experimentally obtained results, as shown in Table 1. The algorithm developed may be used with any commercially available singlemode fiber, and any kind of microbend deformer apparatus, provided the microbend deformation function $f(z)$ is known accurately.
<table>
<thead>
<tr>
<th>ATTENUATION PEAK</th>
<th>MEASURED WAVELENGTH</th>
<th>CALCULATED WAVELENGTH</th>
<th>ERROR %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak 1</td>
<td>1366.37 nm</td>
<td>1356.0 nm</td>
<td>0.76</td>
</tr>
<tr>
<td>Peak 2</td>
<td>1241.37 nm</td>
<td>1218.0 nm</td>
<td>1.88</td>
</tr>
<tr>
<td>Peak 3</td>
<td>1185.34 nm</td>
<td>1157.0 nm</td>
<td>2.39</td>
</tr>
<tr>
<td>Peak 4</td>
<td>1142.0 nm</td>
<td>1126.0 nm</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 1: Percentage error between the calculated and measured values of the location of central wavelengths of the attenuation bands.
Chapter 4. Wavelength-Tunable Polarizer based on Microbent High Birefringence Singlemode Optical Fiber

4.1 Polarizers in photonic systems

Polarizers constitute a class of photonic devices which allow preferential transmission of applied electric fields. A particular component of the applied E field parallel to the direction of the polarizer's transmission axis is transmitted, whereas the orthogonal component is blocked. This component selection is achieved in practice through the use of selective absorption, selective reflection from an isotropic medium, or selective reflection/refraction at the boundary of anisotropic systems [14]. The applied E field components referred to can be TE modes, as in unguided systems, or orthogonal spatial or polarization modes in guided media such as optical fibers.

Common types of polarizers used in optical systems include dichroic materials such as Polaroid 'H' sheets. These sheets are fabricated by impregnating polyvinyl alcohol with iodine atoms, after a period of heating and stretching in certain fixed directions. Since dichroic materials are anisotropic, their response is sensitive to the orientation or polarization of the applied electric field. Figure 16 illustrates the schematic of the polarization planes of a typical dichroic polarizer. The power transmittance curve [14] also illustrated in Figure 16, gives an idea of the spectral dependence of the isolation losses with the dichroic polarizer. Polarization with selective reflection of the TE or TM component is achieved by the reflection of light at the interface between materials of different refractive indices at the Brewster angle. Other types of commercial polarizers include anisotropic crystal-based Wollaston, Rochon, and Senarmont prisms.

Polarizers find extensive application in long-haul optical fiber communication systems as an integral part of optical isolators. As illustrated in Figure 17, the isolator comprises a non-reciprocal Faraday element between two polarizers. The objective of this device is to minimize back reflection from discontinuities in the fiber communication link, such as
those at connectors, splices etc. The back reflections from these junctions are a major cause of noise in the optical source, and are thus undesirable. High quality Faraday-rotator isolators fabricated with Yttrium-iron-garnet (YIG), or Terbium-gallium-garnet (TGG), can give up to 90 dB of back reflection losses [14]. A major concern however, is that such isolators are currently very expensive.
Figure 16: Polarization planes and power transmission function of a dichroic polarizer. The dual-headed arrows represent the oscillation of the E field vectors.

Figure 17: Schematic of an optical isolator for illustrating the role of polarizers. The dual-headed arrows represent the oscillation of the E field vectors.

4. Wavelength-Tunable Polarizer based on Microbent High-Bi Fiber
4.2 Optical-fiber based polarizers

Polarization control is necessary in many optical systems including coherent communication networks, fiber gyroscopes, and other fiber interferometers. Several polarizer techniques have been proposed for such systems. Bergh et al. proposed an in-line fiber polarizer [28], in which part of the cladding of a singlemode fiber was polished to access the core region, and a single crystal was then attached to the polished region. The attached crystal was aligned in such a way that the principal axes of the crystal birefringence were set to be perpendicular and parallel to the polished surface, respectively. The two orthogonal polarization modes experienced differential attenuation, since the coupling of the HE11 guided mode to the attached crystal layer was very sensitive to the refractive index of the crystal which was a function of polarization. With proper design of such a device, one polarization mode passes through the coupling region with very low loss while the other polarization mode is heavily attenuated. However, one of the problems associated with this device is the difficulty in exactly controlling the fiber polishing for a given operating wavelength.

The first commercially available polarizer was fabricated by 3M Specialty Optical Fiber, West Haven, CT [29]. It utilizes a W-type, or a depressed-well cladding, as shown in Figure18 taken from the 3M product catalog. The core is circular, surrounded by elliptical stress-inducing birefringence elements. The unique refractive index profile of the waveguide enables different polarization modes to 'see' different refractive indices as they propagate in the optical fiber. This allows preferential transmission (attenuation) of one of the polarizations. The advantages of this single polarization (polarizing) fiber include 40 dB extinction ratio, and microbend insensitivity which enables more flexible packaging without the introduction of excess losses. Moreover, as shown in Figure19, also taken from the 3M product catalog, the fiber has a wide polarizing band, approximately 12% of the operating wavelength.

Other techniques to fabricate optical fiber-based polarizers include the coupling of the evanescent field from a fiber to a surface-plasmon polariton supported by a metal-dielectric interface, investigated by Hasaka et al. [30]. Some recent progress in this area has also made been made by other researchers [31-33].

4. Wavelength-Tunable Polarizer based on Microbent High-Bi Fiber
Figure 18: Refractive index profile of the 3M Single Polarization fiber [29].

Figure 19: Spectral attenuation of the guided and unguided states in the 3M fiber [29].
4.2 Principle of operation

As discussed before, microbending or periodically deforming the fiber results in losses in the output spectra due to optical power radiating out of the waveguide. This loss phenomena is associated with coupling between guided and radiation modes propagating in the fiber. When a singlemode fiber is exposed to axial microbends, strong coupling from the guided mode to the cladding modes takes place, provided the spatial wavelength of the coupling transducer is phase matched to the beat length between the coupling modes. The microbending perturbation causes a periodic index change which can be written as

\[ n(r, \phi, z) = n_o + \Delta n \cos (\Omega z), \quad (4.2.1) \]

where \( \Delta n \) = fiber index without perturbation,
\( \Omega \) = spatial frequency of the perturbation and,
\( z \) = coordinate along the fiber axis.

Based on the coupled mode theory in optical waveguides, the attenuation coefficient between the \( HE_{11} \) mode and the discrete cladding modes may then be written as [17,25]

\[ 2\alpha_m = \sum_{p=1}^{\infty} C_{0p}^2 \Phi(\Delta \beta_{0p}), \quad (4.2.2) \]

where \( C_{0p} \) is the coupling coefficient given by [21]

\[ C_{0p}^2 = \frac{k^2}{2} \frac{\int_0^\infty E_{01} E_{0p}^{\text{clad}} r dr}{\int_0^\infty E_{01}^2 r dr \int_0^\infty (E_{0p}^{\text{clad}})^2 r dr}, \quad (4.2.3) \]

and \( \Phi(\Omega) \) is the Fourier spectrum, defined by [25]

\[ \Phi(\Omega) = \left. \frac{1}{2L} \int_{-L}^{L} \Delta n \cos(\Omega z) \exp(-j\Omega z) dz \right|_0^2. \quad (4.2.4) \]
As can be noticed from Equation (4.2.2), the loss coefficients are dependent on the difference in propagation constants. However, the propagation constants $\beta$ are a function of the normalized frequency, or 'V' number of the fiber, and are hence dependent on wavelength. Since $\Phi(\Delta \beta_p)$ shows peaks only at certain wavelengths, the attenuation coefficients also reach maxima at selected wavelengths.

Figure 20 illustrates the schematic of the operating principle of an in-line, wavelength tunable fiber polarizer based on high birefringence singlemode optical fiber [34]. The high birefringence (Hi-Bi) singlemode fiber experiencing a spatial periodic perturbation functions as the polarization selective element. This spatially periodic perturbation can be that produced by periodically microbending the fiber, by launching acoustic waves in the fiber, or by writing photorefractive index gratings in the fiber. The birefringence in the fiber is typically raised by the introduction of stress inducing elements. Due to the difference in the propagation constants of the two orthogonal guided polarization modes $HE_{II}'$ and $HE_{I}'$, two sets of attenuation peaks corresponding to the coupling between the $HE_{II}'$ mode to the cladding modes and $HE_{I}'$ mode to the discrete cladding modes, respectively, can be observed when the spatial period of the microbending transducer is properly selected for a given fiber.

Let us consider two adjacent absorption peaks, centered at $\lambda_1$ and $\lambda_2$, corresponding to coupling from the $HE_{II}'$ mode to cladding modes and $HE_{I}'$ mode to cladding modes, respectively. When the fiber is operated at $\lambda_1$, it will show very high attenuation for the $HE_{II}'$ mode, but almost no loss will be observed for the orthogonal polarization. Hence unpolarized light at $\lambda_1$ can be converted into high quality linearly polarized light after it is exposed to the periodic axial perturbations. Similarly when the fiber is operated at $\lambda_2$, only $HE_{I}'$ can pass through the fiber. Because of the strong polarization-selective attenuation property of the Hi-Bi singlemode optical fiber, which is periodically perturbed, a high quality in-line singlemode optical fiber polarizer may be fabricated. Since the attenuation spectra can be changed by changing the spatial frequency of the microbend deformers, a fairly broadband device operation can be expected.
Figure 20: Schematic of the operating principle of an in-line, wavelength-tunable fiber polarizer based on high-bi singlemode optical fiber. The bottom diagram illustrates the cross section of the fiber.
4.4 Experiments

The experimental set-up used to demonstrate the proposed polarizer approach is shown in Figure 21. A high birefringence singlemode optical fiber with a beat length of 1.3 mm and a cutoff wavelength about 850 nm for singlemode operation, manufactured by Corning, was used. A 150 mm long section of the fiber was sandwiched between two 'V' groove microbend plates with a spatial period of 1.1 mm. A white light lamp, serving as the optical source, allowed the measurement of the output attenuation spectrum of the fiber within a broadband wavelength range.

A linear polarizer was then placed at the output end of the fiber to evaluate the polarization dependence of the output spectrum, which indicates the polarizing performance of the fiber. The spectrum of the light after the polarizer was measured by an ANDO 6310 Optical Spectrum Analyzer which allows a measurement range of 0.4-1.7 μm, with the highest resolution of 0.1 nm. The polarizer was then rotated in steps of 5 degrees each. The output spectrum was recorded for each successive rotation of the polarizer. Three of these spectra are shown in Figures 22 through 24.

According to prior analysis, it is recognized that the orientations of the polarizer at 45° and 135° must correspond to the two principal axes of the fiber birefringence because only one strong and sharp attenuation peak is observed in Figures 22 and 24. It is important to notice that in Figures 22 and 24, the two strong peaks are located at different wavelengths; one is at 1177 nm and the other at 1195 nm. This means that when the fiber is operated at either of these two wavelengths, unpolarized input light will be converted into linearly polarized light whose polarization direction should be along one of the principal axes of the fiber birefringence. Hence the Hi-Bi fiber functions as a polarizer.

From Figures 22 and 24, it is seen that a polarization extinction ratio of 25 dB with an attenuation of 1.3 dB can be obtained when the fiber is operated at 1177 nm. The device performance, such as attenuation and isolation, can be further improved by optimizing the parameters of the fiber as well as the spatial periodic perturbation.

Experimental results presented in Chapter 3 have demonstrated that the major attenuation peak in the output spectrum of the singlemode fiber is a function of the spatial period of
the microbending transducer. The peak is shifted linearly towards the longer wavelengths with an increase on the microbending period with a measured coefficient of about 0.51 μm/mm. Moreover the spectral width of these peaks decreases with an increase in the number of perturbation periods. These features allow the tuning of the operating wavelength and bandwidth of the polarizer for a given application. Such tunable characteristics are extremely useful for Wavelength Division Multiplexing (WDM) based fiber communication systems.

In conclusion, a wavelength-tunable polarizer was proposed and experimentally demonstrated. This device is based on the coupling from guided polarization modes to cladding modes in highly birefringent (High-Bi) singlemode fibers. A polarization extinction ration of 25 dB was experimentally obtained with an attenuation of 1.3 dB. This device can be extremely useful for coherent fiber optic communications, fiber gyroscopes, fiber interferometer-based devices, and other active and passive components.
Figure 21: Experimental setup used to demonstrate the proposed polarizer approach.
Figure 22: Attenuation spectrum of the High-Bi fiber subjected to periodic microbends, with the polarization analyzer at 45°.
Figure 23: Attenuation spectrum of the High-Bi fiber subjected to periodic microbends, with the polarization analyzer at 90°.
Figure 24: Attenuation spectrum of the High-Bi fiber subjected to periodic microbends, with the polarization analyzer at 135°.
5. Future Work

5.1 Photoinduced effects in microbent germanno-silicate optical fibers

Photoexposure of germanno-silicate optical fibers with strong laser radiation has been widely investigated to be a useful mechanism for inducing photo-refractive non-linear changes. An alternate means of producing refractive index variations is through the induction of periodic axial perturbations in the fiber with the help of microbend transducers. Although the two mechanisms have been used to fabricate a variety of devices for optical instrumentation and communication, the response of the fiber to a combination of the two remains to be fully investigated. The aim of this investigation will be to investigate theoretically and experimentally the interplay of the two on optical fibers of varying geometries and core compositions.

The following procedure is proposed for the investigation:

a) Application of microbending transducers on fibers to optimize the microbend spatial period for maximum loss in output spectra.

b) Photoexposure of the fiber to intense laser radiation @488 nm, with the microbend plates at the optimized spatial period.

c) White light interrogation of the photo-bent fiber. Repetition of the above procedure for fibers of varying geometries and core compositions.

An experimental arrangement for the proposed investigation is illustrated in Figure 25. The fiber is dipped into index matching oil to prevent any back-reflections from the endface which may lead to grating formation. The main objective will be to correlate any attenuation in the output spectra, observed after the photoexposure, with the optimized spatial period of the microbends.
Figure 25: Experimental setup to investigate photoinduced effects in microbent germano-silicate optical fiber.
5.2 Refractive index grating formation using photomasking

Since the first demonstration of photosensitivity in germano-silicate fibers by Hill et al. [35], various devices and components have been fabricated by the induction of Bragg gratings in optical fibers. Various techniques used to fabricate in fiber Bragg gratings (IFBG) include the holographic side-writing technique, invented by Meltz et al. at United Technologies, CT [36]. Typically these gratings have a spatial wavelength on the order of microns, and require an extremely involved fabrication process.

In this section, we propose a simple and low cost technique to fabricate long period IFBG’s using amplitude photomasking. A schematic of the proposed technique is illustrated in Figure 26. Photosensitive fiber i.e. fiber with a high Ge concentration and which is hydrogen loaded to enhance photosensitivity, is placed on the photomask, after stripping the outer jacket. The amplitude photomask is fabricated by wrapping copper wire, with the same outer diameter as the period of the grating desired, around a glass slide. The fiber-photomask combination is then photoexposed with strong UV radiation at 244 nm. Due to the spatially selective absorbption of the UV radiation by the photosensitive fiber, refractive index variations follow the period of the photomask.

The main advantage of this technique is that on-line monitoring of grating formation can be implemented with a broadband source and a spectrum analyzer. This is also illustrated in the experimental schematic. The spectrum analyzer may be set on high resolution, low scan rate, and high sensitivity, to capture any wavelength attenuation. Spectrum attenuation, if any, can be theoretically correlated to the period of the amplitude photomask.
Figure 26: Experimental setup used for the fabrication and on-line monitoring of IFBG using amplitude photomasking.

5. Future Work
5.3 Acoustic wave detection using microbent-fibers

One of the main features of microbending optical fibers is that the spatial wavelength of the periodic deformations may be tuned depending on the application. This feature has made possible the fabrication of a number of devices in which selective coupling between modal fields can be effected by tuning the perturbation wavelength to the beat length between the coupling modes.

A possible application of the tunable characteristic of microbends can be to match the period of the axial perturbation to the wavelength of an acoustic/ultrasonic wavelength that may be generated using transducers. Then the resulting configuration may be optimized to function as an ultrasonic wave detector element. This method would have inherent advantages over using IFBGs for the same since the periodicity of microbends can be closely matched to the ultrasonic wavelengths. However, the main problems that can be foreseen will be the low amplitude of the acoustic signals that can be couple into the fiber. This would necessitate the use of complex signal detection and processing optics and electronics.
Conclusions

A detailed study of losses due to axial, periodic, microdeformations was presented in this thesis. A numerical algorithm was developed to analyze the attenuation spectra of a singlemode optical fiber when it was subjected to the microdeformations. Experimental verification of the theoretical predictions were performed which yielded excellent correlation, with nominal errors of about 2.5%.

Based on the developed theoretical analysis, a wavelength-tunable polarizer was proposed and demonstrated. The polarizer was constructed by applying periodic perturbations on a high-birefringence singlemode optical fiber. A polarization extinction ratio of 25 dB was obtained, with an attenuation of about 1.3 dB, at an operating wavelength of 1177 nm.

Finally recommendations for future research in this area were outlined.
References


References


Vita

Vivek Arya was born on September 29, 1971, in New Delhi, India. He graduated with a Bachelor of Engineering degree in Electronics and Communication Engineering from the Birla Institute of Technology, Ranchi in May 1993. He joined the Fiber & Electro-Optics Research Center at Virginia Tech. in August 1993, where he is currently working as a Graduate Project Assistant. Mr. Arya received his Master of Science degree from the Bradley Department of Electrical Engineering in December 1994.

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