BEHAVIOR OF LINEARLY POLARIZED (LP) MODES IN FIBERS CONTAINING BRAGG GRATINGS IN THE WIDE TEMPERATURE RANGE

A Thesis

Presented to

The Graduate Faculty of The University of Akron

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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August, 2011
BEHAVIOR OF LINEARLY POLARIZED (LP) MODES IN FIBERS CONTAINING BRAGG GRATINGS IN THE WIDE TEMPERATURE RANGE

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ABSTRACT

Understanding the physics of fiber Bragg gratings (FBGs) is very important in aerospace monitoring systems. This includes studies of non-linear temperature dependence, stability of chemical composition in a wide temperature range, quadratic behavior with temperature and long-term stability in harsh environment in silica based FBGs. It is important to study physical and chemical properties of FBGs in order to develop viable sensors. In this work we study, how light behaves in FBGs in a wide temperature range (77 K-1100 K). For a selected diameter of the fiber core (9.15 µm), a visible light (400-600 nm) transmitted through a fiber may form different modes at once competing one with another. Light inside the FBGs forms sets of different LP modes whose manifestation depends strongly on temperature and other parameters. The variations of LP modes with the temperature have been studied experimentally. Based on the experimental analysis of Bragg peak shift, it has been determined that the modes become unstable at the temperature around 700 K-710 K. A mathematical modeling of LP modes has been focused on the behavior of high order modes using analysis of Bessel equations. It has been observed that the order of LP modes increase when the temperature increases and at the high temperatures (1200 K), the mode structure is stable in FBGs compared to bare fibers.
ACKNOWLEDGEMENTS

I acknowledge the attention and valuable comments of Professor Robert R. Mallik and Professor Erol Sancaktar related to this project.

I would like to thank my co-workers that helped me during this project: Igor Fedin, Dr. Ivan Dolog (UA) and Jeff McCausland.

I am very thankful and grateful to my scientific advisor Dr. Sergei F. Lyuksyutov for his guidance during this project, help and support throughout two years of my studies and research. Without him this project would never be possible.
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CHAPTER I

INTRODUCTION

A fiber Bragg grating (FBG) is a small segment of an optical fiber which has a reflection grating along the fiber core. This was invented by Kenneth O. Hill et al. in 1978 [1]. The most common material used to make these optical fibers is silica (amorphous silicon dioxide (SiO$_2$)) because silica has some excellent properties such as high resistance for pulling and bending. This grating consists of a periodic or non periodic variation of the refractive index. That means in the grating region, the optical fiber has two different types of refractive indices. In most cases this variation of the refractive index is periodic for a particular length of the optical fiber. The length of the grating may vary from a few millimeters to centimeters. The distance between two consecutive lines inside the grating which is called the grating period (usually denoted by $\Lambda$), may have a length of the order of hundreds of nanometers.

Figure 1.1 shows a schematic diagram of a fiber Bragg grating inscribed in an optical fiber. Periodic pattern in the middle of the core represents the grating. Average diameter of the cladding for both single-and multimode fibers is approximately 125 $\mu$m. For the core, it is 8 to 10 $\mu$m and 50 or 62.5 $\mu$m for the single-and multimode fibers respectively [2]. The grating period may vary depending on the type of the grating. (from hundreds of nanometers to hundreds of micrometers).
Since FBGs are fabricated from optical fibers, it is important to discuss the theory of the optical fibers. Optical fibers are usually made of silica and they mainly consist of three parts which are the core, the cladding and the outer jacket. The core has a higher refractive index \( n_1 \) than the cladding \( n_2 \) for the light to be sustained in the core. Figure 1.2 (a) shows an illustration of the main three parts of a fiber and (b) shows how a light ray travels through the fiber (geometrical model).

\[
\theta_{NA} = \sin^{-1}\left(\frac{1}{n_0} \sqrt{n_1^2 - n_2^2}\right)
\]

Figure 1.2: (a) Illustration of an optical fiber. Main three areas are shown, the core, the cladding and the jacket. (b) Ray geometry of an optical fiber. \((n_1 > n_2)\).
When light coupled in, it travels through the optical fiber according to the total internal reflection. Since $n_1 > n_2$, the wave cannot leave from the core to the cladding (only within the geometrical model). The task of the cladding is to prevent the wave going out through the cladding.

1.1 Bragg Reflections

When the light is coupled in to the FBG, a portion of light is reflected by the grating. This reflected light has a maximum intensity in the neighborhood of the Bragg wavelength. Usually this Bragg wavelength is denoted as $\lambda_B$ and it is given by equation 1.1.

$$\lambda_B = 2N_{eff}\Lambda$$ (1.1)

$N_{eff}$ ($n_1 > N_{eff} > n_2$) is the effective refractive index of the fiber for a light propagating in a single mode and $\Lambda$ is the grating period. Normally the FBGs are made of silica which has a refractive index of 1.45 and the grating period is in between 450 nm and 500 nm. This distance is for the smallest Bragg reflection order which is in the range of 1300 nm to 1500 nm [3]. The reflected light is added and finally creates a strong beam of light. Waves that have the wave lengths larger or smaller than the Bragg wavelength propagate almost with no loss through the FBG. When the light is reflected by the FBG, a small fraction of the light is coupled in.
the cladding [4]. Figure 1.3\(^1\) shows a schematic diagram of an FBG (a), the variation of the refractive indices along the grating (b) and the spectral response of the input, output and transmitted waves (c). It can be noticed that the reflected wave gives a maximum when the wavelength is \(\lambda_B\) which is the Bragg wavelength. \(\Lambda\) is the grating period. \(n_0, n_1, n_2\) are the refractive indices of air, core and cladding respectively. \(n_3\) is the perturbed refractive index in the core after fabrication.

![Figure 1.3: (a) A schematic diagram of a FBG. (b) Variation of the refractive indices along the grating. (c) Variation of the intensity of the input, transmitted and the reflected waves with versus wavelength.](http://upload.wikimedia.org/wikipedia/en/d/d1/Fiber-Bragg-Grating-en.svg)

The reflectivity \((R)\) of the FBG depends on three main parameters [3].

1. Coupling coefficient, \(\kappa = \left(\frac{\pi}{\lambda}\right) \Delta n\) where \(\lambda\) is the operating wavelength and \(\Delta n\) is the amplitude of the index perturbation.

2. The mode propagation constant, \(\beta = \left(\frac{2\pi N_{eff}}{\lambda}\right)\).

3. Length of the grating, \(L\).

\(^1\)http://upload.wikimedia.org/wiki/pepa/en/d/d1/Fiber-Bragg-Grating-en.svg
When the acting wavelength is same as the Bragg wavelength, the reflectivity $R$ can be expressed only in terms of the coupling coefficient and the length of the fiber.

$$ R = (\tanh(\kappa L))^2, \quad (1.2) $$

where, $\kappa$ is the coupling coefficient at the Bragg wavelength [5]. It can be seen that the reflectivity depends on the product of $\kappa L$. This means that if the product $\kappa L$ increases, the reflectivity $R$ increases. Gratings can be divided into two categories according to the product $\kappa L$. If a grating has a large $\kappa L$ value, it can be categorized as a strong grating. On the other hand, when the product $\kappa L$ is small, it can be categorized as a weak grating.

Every grating has its own range of wavelengths which reflect light. This measurement is called the bandwidth of the particular grating. One way to calculate the bandwidth is to measure its full width at half maximum, $\Delta \lambda_{FWHM}$. Also the quantity $\Delta \lambda_0 = \lambda_0 - \lambda_B$ can be calculated where $\lambda_0$ is the wavelength of the first zero in the reflection. To calculate $\Delta \lambda_0$, one can calculate the difference between the propagation constants which can be expressed by $\beta_0 = \left(\frac{2\pi N_{eff}}{\lambda_0}\right)$ and $\beta_B = \left(\frac{2\pi N_{eff}}{\lambda_B}\right)$ [6].
1.2 Linearly Polarized Modes (LP Modes)

Since this project discusses the peculiarities of LP modes, it is important to give an introduction about LP modes. LP modes usually denote with two subscripts \( l \) and \( m \), \( \text{LP}_{lm} \) where \( l \) is the azimuthal mode number and \( m \) is the radial mode number. When the refractive index of the core \( (n_1) \) is slightly higher than the refractive index of the cladding \( (n_2) \) (weak-guidance approximation, \( n_1 \approx n_2 \)), a set of modes can be observed. These modes are usually known as linearly polarized or simply LP modes. The electric and the magnetic fields of these LP modes each occur in one direction in the propagating plane (linear polarization) [2]. \( \textbf{E} \) (electric field) and \( \textbf{H} \) (magnetic field) fields inside the fiber will be completely orthogonal to the direction of propagation. Linearly polarized modes are combinations of the general modes such as HE, EH, TE and TM [2].

Consider a light wave traveling along a fiber that has an electric field, \( \textbf{E} \) along the \( x \) direction and the magnetic field, \( \textbf{H} \) along the \( y \) direction. This means the \( \textbf{E} \) field and the \( \textbf{H} \) field are polarized to the \( x \) and \( y \) directions respectively. Following approximation are made in this case [2].

- Weak-guidance approximation, \( n_1 \approx n_2 \). (Light waves traveling through the fiber is almost a plane wave)

- \( z \) components of the fields are very small compared to \( x \) and \( y \) component of the wave.
1.2.1 Field Study of the Fiber (Weak-guidance Approximation)

The fields can be written as follows [2]:

\[
E = E_x(r, \phi, z) \hat{a}_x = E_{x0}(r, \phi) \exp(-i\beta z) \hat{a}_x
\] (1.3)

\[
H = H_y(r, \phi, z) \hat{a}_y = H_{y0}(r, \phi) \exp(-i\beta z) \hat{a}_y
\] (1.4)

Then the wave equation \( \nabla_i^2 E_0 + (k^2 - \beta^2) E_0 = 0 \) can be separated as;

\[
\nabla_i^2 E_{x1} + (n_1^2 k_0^2 - \beta^2) E_{x1} = 0, \ r \leq a \ (\text{core})
\] (1.5)

\[
\nabla_i^2 E_{x2} + (n_2^2 k_0^2 - \beta^2) E_{x2} = 0, \ r \geq a \ (\text{cladding})
\] (1.6)

where \( a \) is the radius of the fiber core, \( k_0 \) is the wavenumber in free space,

\[
\nabla_i^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2}, \beta \ is \ the \ wave \ propagation \ constant, \ (n_1^2 k_0^2 - \beta^2) = u^2 \ and \ (\beta^2 - n_2^2 k_0^2) = w^2.
\]

Wave equation can also be written in terms of \( r \) and \( \phi \) in either region,

\[
\frac{\partial^2 E_x}{\partial r^2} + \frac{1}{r} \frac{\partial E_x}{\partial r} + \frac{1}{r^2} \frac{\partial^2 E_x}{\partial \phi^2} + (k^2 - \beta^2) E_x = 0
\] (1.7)

It is assumed that the solution for the equation 1.7 \( (E_x) \) produces a discrete set of modes [2].

\[
E_x = \sum_i R_i(r) \Phi_i(\phi) \exp(-i\beta_i z)
\] (1.8)
For every $i=1,2,3,4,...,n$, there is a solution can be obtain from equation 1.7.

Substituting the equation $E_x = R\Phi \exp(-i\beta z)$ or $E_x = R(r)\exp(-il\phi)\exp(-i\beta z)$ (single mode) to the equation 1.7 one can get,

$$\frac{d^2R}{dr^2} + \frac{1}{r} \frac{dR}{dr} + \left(\left(n^2k_0^2 - \beta^2\right) - \frac{l^2}{r^2}\right) R = 0$$

(1.9)

Equation 1.9 only depends on $R$ which is only a function of $r$. For the case $k_1 \geq \beta$, equation 1.9 can be arranged to obtain the Bessel function.

$$\frac{\partial^2 R}{\partial \left(U_r^2\right)^2} + \frac{1}{\left(U_r^2\right)} \frac{\partial R}{\partial \left(U_r^2\right)} + \left[1 - \frac{l^2}{\left(U_r^2\right)^2}\right] = 0$$

(1.10)

where $U = ua = a\sqrt{n_1^2k_0^2 - \beta^2}$

Solutions for the equation 1.7 can be expressed using the solution of the equation 1.10 and equation 1.8 as follows,

$$E_x = \begin{cases} AJ_l(U_a^2) \cos(l\phi) \exp(-i\beta z), & r \leq a \\ CK_l(W_a^2) \cos(l\phi) \exp(-i\beta z), & r \geq a \end{cases}$$

(1.11)

where $A$ and $C$ are coefficients which can be evaluated using boundary conditions for $E$ and $H$, $J_l$ and $K_l$ are the ordinary Bessel function of the first kind and the modified Bessel function of the second kind respectively.

Equations 1.11 can be rearranged with the calculated coefficients,
\[ E_x = \begin{cases} 
E_0 J_l(U_r z) \cos(l \phi) \exp(-i \beta z), & r \leq a \\
E_0 \left[ \frac{J_l(U r z)}{K_l(W r a)} \right] K_l(W r a) \cos(l \phi) \exp(-i \beta z), & r \geq a 
\end{cases} \]

(1.12)

Same procedure can be followed for the magnetic field, \( H_y \).

1.2.2 Intensity Distribution of LP Modes

One part of this project is to model the LP mode intensity patterns. An expression for the intensity distribution can be obtained from the time-average Poynting vector \( S \) [2].

\[ |< S >| = \frac{1}{2} \text{Re} \left\{ E_x H_y^* \right\} = \frac{1}{2} \left\{ \frac{\varepsilon}{\mu} \right\} |E_x|^2 \]

(1.13)

where, \( \mu \) and \( \varepsilon \) are the magnetic permeability and the electric permitivity respectively.

Using equations 1.12 and 1.13, an expression for the intensity (for both the core and the cladding) can be obtained as follows.

\[ I_{lm} = \begin{cases} 
I_0 J_l^2 \left( U_r z a \right) \cos^2(l \phi), & r \leq a \\
I_0 \left[ \frac{J_l(U)}{K_l(W)} \right]^2 K_l^2 \left( W r a \right) \cos^2(l \phi), & r \geq a 
\end{cases} \]

(1.14)

where, \( I_0 \) is the maximum intensity given by \( I_0 = \frac{1}{2} \sqrt{\frac{\varepsilon}{\mu}} |E_0|^2 \), \( 2l \) is the number of the intensity maxima (or minima) along the \( \phi \) direction and \( m \) is the number of maxima along the \( z \) direction.
1.3 Variation of the Bragg Wavelength ($\lambda_B$) With the Temperature

As can be seen from the equation 1.1, the relation among the Bragg wavelength $\lambda_B$, the refractive index $n$ and the grating spacing $\Lambda$ can be expressed as follows.

$$\lambda_B = 2n\Lambda$$  \hspace{1cm} (1.15)

$n$ and $\Lambda$ can be also represented in terms of the temperature, $T$.

$$n = n_0 + \alpha T$$  \hspace{1cm} (1.16)

$$\Lambda = \Lambda_0(1 + \alpha_t T)$$  \hspace{1cm} (1.17)

where $\alpha, \alpha_t, n_0$ and $\Lambda_0$ are the thermo-optic coefficient, thermal expansion coefficient, refractive index of the material at 0 K and the grating spacing at 0 K respectively. By substituting the equations 1.16 and equation 1.17 in to the equation 1.15, an expression for $\lambda_B$ can be obtained as follows.

$$\lambda_B = 2(n_0 + \alpha T)(\Lambda_0(1 + \alpha_t T))$$

$$\lambda_B = 2n_0\Lambda_0(1 + \frac{\alpha}{n_0} T)(1 + \alpha_t T)$$

$$\lambda_B = 2n_0\Lambda_0 + 2\Lambda_0(\alpha + n_0\alpha_t)T$$  \hspace{1cm} (1.18)

From the equation 1.18 it can be seen that the relation between the Bragg wavelength, $\lambda_B$ and the temperature $T$ is linear if $\alpha$ and $\alpha_t$ are constants. According to the equation 1.18, for a graph of $\lambda_B$ Vs $T$, the intercept of the graph would be
\[2n_0 \Lambda_0 \text{ and the slope would be } 2\Lambda_0(\alpha + n_0 \kappa_t).\] If the thermal expansion coefficient, \(\kappa_t\) is known then the thermo-optic coefficient, \(\alpha\) can be calculated using the slope of the graph. However this is true only for certain regions of temperatures because \(\alpha\) and \(\kappa_t\) may vary with the temperature [7].

1.4 Statement of the Problem

There is a growing interest to use FBGs as sensors in aerospace applications and physical understanding of survivability of these sensors at temperatures of 1000 K and above. It is also important to understand how the FBG sensors perform at low temperatures when conditions are close to deep vacuum \((\approx 10^{-3} \text{ Torr})\). Sensors based on FBGs in standard telecommunications fiber (SM-28) has been used throughout this study. Our main goal is to investigate experimentally and theoretically, how light is transmitted through the FBG sensors at the wavelengths between 440 nm and 530 nm and temperature range between 70 K and 1100 K. For a selected diameter of the fiber core \((9.15 \ \mu\text{m})\), a visible light can form different TE and TM modes at once competing one with another. This light inside of the FBG sensors forms sets of LP modes of different orders whose manifestation depend strongly on temperature and other parameters. Specifically, the goals of this work included:

- An experimental study on how LP modes are to be sustained in silica-based fibers with and without FBG at different wavelengths and fixed temperature.
• An experimental investigation of LP modes sustainability at low (77 K) and high temperatures (above 700 K) and determination of critical conditions at which FBG sensors are destroyed.

• An assessment of the correlation between the formation and change of LP modes in FBG sensors and their Bragg reflectivity.

• Mathematical modeling of LP modes using analysis of Bessel functions in fiber with embedded FBGs.

1.5 Importance of the Study

Development of FBG sensors for use in aerospace health monitoring systems is a task of paramount importance. Extreme environmental conditions in space return vehicles and also in avionics require robust understanding of physical and chemical processes occurring in FBG sensors in a wide range of temperatures from deep vacuum to several thousands °C in propulsion systems. All sensors (based on commercially available telecommunications silica-based fibers (SM-28)) can be accommodated in almost any mechanical system ranging from automobile tires to space shuttles. The followings present importance of the study:

• Survivability of FBG sensors at different temperatures (critical conditions).

• Performance of the sensors in harsh environment.

• Understanding of physical and chemical processes inside the sensors.
CHAPTER II
BACKGROUND OF THE STUDY

2.1 Writing Fiber Bragg Gratings

Making FBGs is called writing fiber Bragg gratings or fabrication of fiber Bragg gratings. In order to write a fiber grating, the fiber core needs to be illuminated with a periodic interference pattern. Usually fiber core is irradiated with ultra violet (UV) laser light. This UV light can cause some permanent changes inside the fiber core. This UV light has shorter wavelengths which is less than 300 nm. The energy of these photones in the UV light can break the silicon-oxygen bonds and thus change the structure of the fiber core. This damage which is done by the UV light, makes the refractive index of the core to be slightly higher than the original refractive index of the fiber. It has been found that, when the a fiber is illuminated with UV light, the axial stress is increasing [8]. It has been also concluded that increase the tension is same as decrease the refractive index [9].

This ability of the light to make changes in refractive index inside the fiber core is called “Photosensitivity”. The above mentioned permanent periodic changes of the refractive index can act as a grating. There are several methods for writing fiber gratings (sections 2.2.1-2.2.4).
2.2 Photosensitivity

As mentioned in the section 2.1, refractive index of a fiber can be permanently changed by exposing to the ultraviolet light. Photosensitivity was discovered by Kenneth O. Hill et al. in 1978 [10]. This was done using germanium-doped silica fibers. Later it was found that the phenomenon of photosensitivity can be observed not only in germanium-doped silica fibers but also in a vast range of optical fibers. But germanium-doped silica fibers are commonly used. It has been found that this permanent change will last up to twenty five years if the fiber is heated and cooled gradually to prevent from internal stress [11]. If the perturbed refractive indices are $n_1$ and $n_3$ as can be seen in the figure 1.3, the change can be expressed as $\Delta n = (n_1 - n_3)$. This quantity $\Delta n$ depends on the following conditions [12]:

- Quantity, wavelength and intensity of the irradiated light.
- Ingredients of the material used for the fiber core.
- Some processing before irradiation.

To make this permanent change of the fiber core, various kinds of light sources can be used. Light can be varied from the visible range to ultraviolet range. KrF (248 nm) and ArF (193 nm) excimer lasers are used frequently. For a pulse rate between 50 to 100 pulses per second and the energy between 100 to 1000 mJ cm$^{-2}$ per pulse, germanium-doped monomode fiber gives a positive value for $\Delta n$ ($10^{-5}$ to $10^{-3}$) [12].
2.2.1 Internal Writing Technique

This method is the oldest method of fabricating FBGs. This was done by interfering two waves. One is the light wave that propagates to the positive $x$ direction and the other is the reflected light wave form the fiber end. The gratings made by this method are called “Hill gratings”. One main drawback of these gratings is that the grating period cannot be varied as desired because wavelength of the reflected wave is nearly equal to the wavelength of the UV light that is used for the fabrication. It can only produce a grating period which is equal to the wavelength used.

2.2.2 Transverse Holographic Technique

This method is more adaptable than the internal writing technique. As shown in the figure 2.1, two ultraviolet beams interfere on the fiber core and make an interference pattern which create the perturbation of the refractive index inside the core. The reason this technique named as “transverse holographic” because, the core is illuminated from the side [10]. The grating period $\Lambda$, depends on the intersecting angle between the two beams. The relation can be given by the equation 2.1.

$$\Lambda = \frac{\lambda_{uv}}{2 \sin \left(\frac{\theta}{2}\right)} \quad (2.1)$$

Where $\lambda_{uv}$ is the wavelength of the beam and $\theta$ is the intersecting angle between the two beams [13].
Figure 2.1: Shows a schematic diagram for the transverse holographic technique.

2.2.3 Phase Mask Technique

In this method, a plate which is made by a flat silica glass is used for the fabrication. On one side of this plate a periodic structure is imprinted using photolithographic techniques. As can be seen in the figure 2.2 [14], this structure can be modeled as a square wave. This flat silica sheet is called the phase mask. Phase mask is placed perpendicular to the fiber as can be seen in the figure 2.2. When the ultraviolet light goes through this phase mask, diffraction occurs. In most cases the diffracted light contains -1\textsuperscript{st}, 0\textsuperscript{th} and 1\textsuperscript{st} diffracted orders. The phase mask is designed such a way that the intensity of the 0\textsuperscript{th} order light can be reduced and -1\textsuperscript{st}, 1\textsuperscript{st} orders light can split in to two equal intense beams. Those two beams interfere and thus create the grating. The period of the phase mask is twice the period of the grating created.
Figure 2.2: Schematic diagram to illustrate how the phase mask technique works.

Phase mask technique has advantages when comparing with the other methods described earlier. The process of manufacturing is simple and gives better products. The apparatus used in the phase mask technique is steadier than the technique used in the holographic technique. Also this technique can be done by using a lower coherence ultraviolet laser. Hence cheaper ultraviolet lasers can be used for this technique. Another advantage of this phase mask technique is that several gratings can be created using a one illumination. One disadvantage of this technique is that for various Bragg wavelengths, different phase masks should be used. Phase mask technique is also used to make non periodic gratings. These gratings are used to make dispersion compensators [15].
2.2.4 Point by Point Technique

In this technique every change in the refractive indices inside the fiber core is created point by point. This is a very useful technique to create micro-Bragg gratings [16]. This method is not very good for the gratings which have so many variations in the refractive indices.

2.3 History Survey of Previous Work in the Area

As mentioned in section 1.4, FBGs are used as thermal sensors. These sensors can be used to monitor high temperatures (up to 1000\(^{\circ}\)C) which can be observed in places as aircraft engines. The problem is that at high temperatures the optical fibers are subjected to a devitrification. Also the capability of transmitting light is also reduced [17],[18],[19]. Normally the fiber core is doped with elements such as Silicon and Germanium. These dopants diffuse at high temperatures which disperses the FBG [20].

However many researches have been done to overcome this obstacle. It has been shown that these sensors based on FBGs can be used for high temperatures more than 1000\(^{\circ}\)C. FBGs have been subjected to a high temperature thermal cycling (more than 700 hours) [21] to check the long term performance of the sensors which is made from FBGs. For this particular experiment, FBGs are made to sustain up to 400\(^{\circ}\)C. Because of that around 1000\(^{\circ}\)C, one can expect the internal structure of the
FBG to be totally dispersed. But it has been shown [21] that the signal through the FBG comes to a steady level at the end although it drops at the beginning.

Development of the previous work has also been done [22]. High temperature FBG based sensors can be created in two steps. Since the optical fiber is fragile, the first step is to make a cover for the fiber. Those protecting covers can be made by ceramic [22]. Figure 2.3 [22] shows the set up for the protected fiber. FBG is placed inside of the ceramic tube (to the right side of the set up) and a fiber optic connector is fastened from the other side (to the left side of the figure).

As the second step, sensors are exposed to a high temperature around 1000°C and their performance is analyzed using an optical spectrum analyzer. Graphs in the figure 2.4 [22] show how the wavelength varies with the temperature. After completing the process the FBG sensor is exposed to a temperature of 1000°C for 500 hours.

At 1000°C, the wavelength reading is roughly 1311.8 nm [22]. According to this graph it can be seen that the wavelength is quite stable with the temperature although it fluctuates between 1311.95 nm and 1311.65 nm [22]. More tests have been
Figure 2.4: (a) Stability of the wavelength with time. (FBG is exposed to a temperature of 1000\degree C). (b) Variation of the wavelength of the FBG with the temperature.

done using another set of FBG sensors. Graph (b) shows how the wavelength changes when the the FBG is subjected to heating and cooling cycle from 400\degree C to 800\degree C. Upper and lower curves represent cooling and heating curves respectively. From both these tests, it can be concluded that FBG sensors can survive in hight temperatures.

2.3.1 Non-linear Temperature Dependence of FBG

It has been found that at vary low temperatures (from room temperature to 77 K [23],[24] and to 4.2 K [25]) the variation of the properties of the FBGs is non-linear with the temperature. This is because the thermo-optic and the thermal expansion behaviors of the FBG shows a non-linear relationship even though it is linear near the room temperature [7]. It has been also found that the non-linearity of the FBG can be seen the temperature range from -30\degree C to 80\degree C [26].
Shu et al. [27] have found the variation of the parameters of the fiber (thermo-optic and thermal expansion properties) with temperature for only one kind of fiber. This has been done for a wide range of temperatures. Later this has been done using two types of FBGs (type I and IIA)[7] for the temperature range from room temperature to 500°C.

Both the grating period (Λ) and the perturbation of the refractive indices (∆n) vary with the temperature because the thermal expansion and the thermo-optic coefficients are functions of the temperature. According to the work of Suchandan Pal et al. [7], the shift of the Bragg wave length ∆λ_B can be written as [7],

\[
\frac{\Delta \lambda_B}{\lambda_B} = (1 - p_e) \frac{\Delta L}{L} + \frac{\Delta n}{n} \tag{2.2}
\]

where \( \lambda_B \) is the Bragg wavelength, \( p_e \) is the photo-elastic coefficient of the fiber (≈0.22 for fused silica[23]), \( \frac{\Delta L}{L} \) is the strain of the fiber due to the thermal expansion coefficient, \( n \) is the effective refractive index of the fiber core and \( \frac{\Delta n}{n} \) is the fractional change of the refractive index due to the thermo-optic coefficient. These two coefficients are considered to be proportional with the temperature. Equation 2.2 can be expressed in terms of thermal expansion and thermo-optic coefficients.

\[
\frac{\Delta \lambda_B}{\lambda_B} = [(1 - p_e) \alpha_t + \alpha] \Delta T \tag{2.3}
\]

Where \( \alpha_t \) and \( \alpha \) are the thermal expansion and the thermo-optic coefficients respectively. \( \alpha_t \) and \( \alpha \) can be defined as follows.
\[
\alpha_t = \frac{1}{L} \frac{dL}{dT}
\]
\[
\alpha = \frac{1}{n} \frac{dn}{dT}
\]

Equation 2.3 [7] can be used only when the relation is linear. It means that it can be only used for a particular temperature range. For a wide temperature range equation 2.2 can be used [7]. Considering equations 2.2 and 2.3 an expression for the thermo-optic coefficient can be derived as,

\[
\alpha = \frac{1}{n} \frac{dN}{dT} = \frac{1}{\lambda_B} \frac{d\lambda_B}{dT} - (1 - p_e)\alpha_t
\]  

(2.4)

which is a function of the Bragg wavelength, \(\lambda_B\). Equation 2.4 can be used to calculate the thermo-optic coefficient, if the Bragg wavelength, thermal expansion coefficient and the photo-elastic coefficient are known.

The variation of the Bragg wavelength with the temperature has been observed in this particular work. For many number of cycles, a consistency can be seen in the Bragg wavelength. Variation of the Bragg wavelength with temperature has been graphed.

Figures 2.5 to 2.9 [7] show the variation of the Bragg wavelength with the temperature for various types of fibers. Type I grating in B-Ge co-doped, Type IIA grating in B-Ge co-doped, type I grating in GE-Er co-doped fiber, type IIA grating in Ge-Er co-doped fiber and type I grating in Ge-Sn-Er co-doped fiber are studied [7]. Two types of curves have been fit in the same graph.
Figure 2.5: Variation of the Bragg wavelength with respect to temperature for the type I grating in B-Ge co-doped fiber.

Figure 2.6: Variation of the Bragg wavelength with respect to temperature for the type IIA grating in B-Ge co-doped fiber.
Figure 2.7: Variation of the Bragg's wavelength with respect to temperature for the type I grating in Ge-Er co-doped fiber.

Figure 2.8: Variation of the Bragg's wavelength with respect to temperature for the type I grating in Ge-Er co-doped fiber.
Figure 2.9: Variation of the Bragg's wavelength with respect to temperature for the type I grating in Ge-Sn-Er co-doped fiber.
CHAPTER III
DESCRIPTION OF THE WORK

3.1 LP Mode Distribution Using Bessel Equation

Step-index fiber is a fiber that has a core with a uniform refractive index ($n_1$) and a cladding with a uniform refractive index ($n_2$). There is a sudden drop of the refractive indices at the core-cladding interface. If the wave vector denoted by $k$, the numerical aperture and the $V$ number can be expressed as $NA = \sqrt{n_1^2 - n_2^2}$ and $V = ka\sqrt{n_1^2 - n_2^2}$ respectively. Here $a$ is the radius of the fiber core. Linear polarized modes can be interpreted using the Bessel function $[2]$.

Cutoff frequencies for LP modes can be obtained from the solutions of the Bessel function of the first kind. Cutoff values for LP$_{lm}$ can be defined as follows.

- for $l \geq 1$, the $m^{th}$ root (exclude 0) of $J_{l-1}(x)$.
- for $l = 0$, the $(m - 1)^{th}$ root of $J_1(x)$.

Table 3.1 [28] shows the roots of the Bessel function of the first kind. Cutoff values of the LP modes can be determined using this table. Here, first six modes are considered. Table 3.2 shows the cutoff values for the first six modes. These modes are determined using the above two conditions. As an example, for the mode LP$_{21}$ the cutoff value is the first root of the Bessel function $J_1(x)$. From the table 3.1, the
Table 3.1: Roots of Bessel’s function of first kind

<table>
<thead>
<tr>
<th>m</th>
<th>( J_0(x) )</th>
<th>( J_1(x) )</th>
<th>( J_2(x) )</th>
<th>( J_3(x) )</th>
<th>( J_4(x) )</th>
<th>( J_5(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4048</td>
<td>3.8317</td>
<td>5.1356</td>
<td>6.3802</td>
<td>7.5883</td>
<td>8.7715</td>
</tr>
<tr>
<td>2</td>
<td>5.5201</td>
<td>7.0156</td>
<td>8.4172</td>
<td>9.7610</td>
<td>11.0647</td>
<td>12.3386</td>
</tr>
</tbody>
</table>

value for this mode can be obtained as 3.8317. This cutoff value is independent of the fiber parameters such as \( V \) number, numerical aperture because these are the roots of the Bessel function of first kind.

3.2 Construction of LP Modes (Computer Generated Modes)

To determine the allowed LP modes, consider the two eigenvalue equations,

\[
\frac{J_0(U)}{UJ_1(U)} - \frac{K_0(W)}{WK_1(W)} = 0 \quad (3.1)
\]

\[
\frac{J_l(U)}{UJ_{l-1}(U)} + \frac{K_l(W)}{WK_{l-1}(W)} = 0 \quad (3.2)
\]

Equations 3.1 and 3.2 are for the cases \( l = 0 \) and \( l \geq 1 \) respectively. In the above equations \( J \) and \( K \) are the Bessel functions of first kind and second kind (modified) respectively and \( U \) and \( W \) are called eigenvalues. These eigenvalues can
Table 3.2: First six LP modes and corresponding cutoff values

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cutoff value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP(_{01})</td>
<td>0</td>
</tr>
<tr>
<td>LP(_{11})</td>
<td>2.4048</td>
</tr>
<tr>
<td>LP(_{02})</td>
<td>3.8317</td>
</tr>
<tr>
<td>LP(_{21})</td>
<td>3.8317</td>
</tr>
<tr>
<td>LP(_{31})</td>
<td>5.1356</td>
</tr>
<tr>
<td>LP(_{12})</td>
<td>5.5201</td>
</tr>
</tbody>
</table>

also be expressed in terms of the \(V\) number of the fiber. Parameters \(V\), \(U\) and \(W\) can be defined as \(V^2 = U^2 + W^2\). These eigenvalues also can be defined in terms of the wave vector \(k\), propagation constant of electromagnetic waves in fiber \((\beta)\), radius of the fiber core \((a)\) and the refractive indices of the cladding \((n_2)\) and the core \((n_1)\). \(\beta\) values are restricted to the range \(n_2k \leq \beta \leq n_1k\) and also depend on the \(V\) number of the fiber. Intensity patterns of LP modes can be plotted using equation 1.14.

\[
U = ua = a\sqrt{n_1^2k^2 - \beta^2}
\]

\[
W = wa = a\sqrt{\beta^2 - n_2^2k^2}
\]

where \(u = \sqrt{n_1^2k^2 - \beta^2}\) and \(w = \sqrt{\beta^2 - n_2^2k^2}\).

Solutions to the equation 3.2 give phase constant values and field profiles, when it is used with the equation 1.12 for each mode under any condition [2].
Figure 3.1: Fundamental linearly polarized mode, LP$_{01}$

Figure 3.2: Linearly polarized mode, LP$_{11}$
Figure 3.3: Linearly polarized mode, \( \text{LP}_{02} \)

Figure 3.4: Linearly polarized mode, \( \text{LP}_{21} \)
Figure 3.5: Linearly polarized mode, LP\textsubscript{31}

Figure 3.6: Linearly polarized mode, LP\textsubscript{12}
3.3 Experimental Work of the LP Modes

An FBG is used for this part of the experiment. The purpose is to see how LP modes change with the temperature. The experiment is done in the temperature range 77 K-300 K. INNOVA 70-K, Argon-Ion laser is used. The fiber is well cleaved and laser light of 488 nm is coupled through it. The fiber is attached to a steel rod and it is placed inside a form box (figure 3.8). The purpose of the form box is to hold the liquid nitrogen which is used to cool down the fiber. A Silicon diode is used to track the temperature of the fiber. Forward voltage of a Si diode depends on temperature\(^1\). Hence, temperature can be determined by measuring voltage, with a calibrated sensor. The temperature and the modes are observed before adding liquid nitrogen. After adding liquid nitrogen, the voltage and the modes are monitored with a camera until it comes to the room temperature. A schematic diagram of the setup can be seen in figure 3.7. Temperature is recorded during the cooling. Finally snapshots were made to illustrate the main changes of the modes.

3.3.1 Variation of the Modes With the Temperature

The variation of the LP modes with the temperature can be seen in the figures 3.11 and 3.12. As can be seen in the figure 3.10, at the room temperature (300 K) the LP\(_{31}\) mode can be clearly observed. Then the liquid nitrogen is added to reduce the temperature. Just after adding liquid nitrogen, the mode suddenly changes to the LP\(_{21}\) mode.

\(^1\)http://en.wikipedia.org/wiki/Silicon-bandgap-temperature-sensor
Figure 3.7: Schematic diagram of the experimental setup for low temperature. (Not to scale)

Figure 3.8: Set up for the experiment. Grating area is inside the form box. A silicon diode is placed inside the box to track the temperature.
Figure 3.9: Inside the form box. The fiber is attached to a steel rod to make it straight. Silicon diode is also attached to the fiber.

Figure 3.10: Snapshot is taken in the room temperature (300 K), before adding liquid nitrogen. Starting mode is the LP$_{31}$, wavelength of the light is 488 nm.
Figure 3.11: Mode reduced to LP$_{21}$ from LP$_{31}$, just after adding liquid nitrogen. Voltage reading is 0.9846 V and the corresponding temperature is 95 K.

Figure 3.12: The LP$_{31}$ mode. The setup is coming back to the room temperature. Voltage reading is 0.5624 V and the corresponding temperature is 280 K.
3.3.2 Comparison of the LP Mode Structure with $\lambda_B$ in Various Temperature Ranges

As mentioned in the section 1.3, the relation between the Bragg wavelength and the temperature can be expressed by the equation 1.18.

$$\lambda_B = 2n_0\Lambda_0 + 2\Lambda_0(\alpha + n_0\alpha_t)T$$

Bragg wavelength was plotted for various temperature ranges as can be seen from the graphs 3.13, 3.14, 3.15, 3.16, 3.17. Graph 3.13 shows the variation of the Bragg wavelength with the whole temperature range which is 50°C-780°C. The graph was divided to 5 parts (50°C-200°C, 200°C-500°C, 500°C-660°C, 660°C-780°C). Those five parts were taken and plotted separately as can be seen in the graphs 3.14, 3.15, 3.16, 3.17.
Figure 3.14: Variation of the Bragg wavelength with the temperature (50°C-200°C).

Figure 3.15: Variation of the Bragg wavelength with the temperature (200°C-500°C).
Figure 3.16: Variation of the Bragg wavelength with the temperature (500°C-660°C).

Figure 3.17: Variation of the Bragg wavelength with the temperature (660°C-780°C).
Another set of FBGs were checked with the high temperature (up to 1200°C) and the mode structures are observed. The experimental setup (figure 3.18 [29]) contains two light sources. One light source is a 20 mW laser operating at a wavelength of 550 nm and the other one is a superluminescent laser diode (SLD) emitting 5 mW of infrared radiation with the central wavelength of about 1310 nm and a minimum bandwidth about 20 nm. Light from both sources is coupled into two identical pieces of a commercial optical fiber with core diameter of about 9.15 µm using an optical distribution board. One of the fibers has an FBG being written into it and the second one is a bare fiber. The peak wavelength of the FBG at 20°C is about 1300.135 nm and bandwidth is between 16.8 GHz and 25.7 GHz for 1 and 3 dB respectively. Both fibers are placed in ceramic capillary tubes and put inside a 24-inch long 1200°C split hinge tube furnace in such way that the FBG is approximately in the middle of the furnace heating tube. The temperature of the tube furnace is controlled in the range 20°C - 1200°C.

A portion of the infrared radiation from the semiconductor laser diode (SLD) is reflected from the FBG and detected by a photodetector incorporated an optical spectrum analyzer (OSA). As the temperature in the furnace changes, the wavelength of the radiation reflected by the FBG and detected by the OSA changes as well. Those changes are displayed on the screen of the OSA.

Radiation at the visible wavelength passes through both fibers and observed on a screen in the form of two patterns. One pattern is generated by a portion of
that radiation passed through a fiber with the FBG and the other one by radiation passed through the fiber without the grating. The transmitted visible light is also collected, analyzed and recorded with a CCD to monitor the distribution of the LP modes in the samples with and without FBG.

3.3.4 Mode Structure Results in High Temperature Range (Without and with FBG)


Figure 3.19 (a) shows the fiber modes without the FBG. It appears as a mixture of the LP_{21} and the LP_{02} modes and also it is more closer to the LP_{21} mode. The LP_{21} mode has a higher cutoff value than the LP_{02} mode (Table (3.2)). Figure (b) shows the mode observed with the FBG which is very closer to the LP_{02} mode.
Figure 3.19: Mode structures at 20\(^\circ\)C. (a) Without FBG. (b) With FBG

Figure 3.20: Mode structures at 50\(^\circ\)C.
Figure 3.21: Mode structures at $100^0$C.

Figure 3.22: Mode structures at $150^0$C.

Figure 3.23: Mode structures at $200^0$C.
Figure 3.24: Mode structures at $300^\circ$C.

Figure 3.25: Mode structures at $400^\circ$C.
Figure 3.26: Mode structures at 450°C.

Figure 3.27: Mode structures at 500°C.
Figure 3.28: Mode structures at 600°C.

Figure 3.29: Mode structures at 650°C.
Figure 3.30: Mode structures at 800° C.

Figure 3.31: Mode structures at 920° C.
Figure 3.32: Variation of the effective refractive index, $N_{eff}$ with the temperature
Figure 3.33: Variation of the thermo-optic coefficient with the temperature.
Two conclusions can be made by looking at these results. At room temperature (20°C), FBG gives a higher mode than the normal fiber. Also in the room temperature, the fiber with FBG gives a lower mode (LP_{02}) compared to other higher modes.

As the temperature increases, it can be seen that the mode structure of the bare fiber is changing. Around 100°C it has changes to the LP_{31} which is a higher mode than observed in 20°C. This trend can be seen up to 400°C and after that mode structure is completely changes. Around 450°C (figure 3.26), the mode is completely destroyed. But After 450°C, the distortion of the mode structure is stopped. At 500°C, the LP_{21} mode can be observed from the bare fiber. (figure 3.27). It is clear that when the temperature increases higher modes can be observed. This means higher the temperature makes the cutoff value to be also higher. Figure 3.28(a) shows the LP_{31} mode which has a higher cutoff value than LP_{21}. After 800°C distorted structures can be observed again. Figure 3.31 shows how the modes are distorted at 920°C. From the figures it can be concluded that the bare fiber has the modes LP_{02}, LP_{21} and LP_{31} within the temperature range from 20°C to 920°C.

The above description is for the bare fiber. Figures 3.19(b)-3.31(b) show the variation of the modes with the temperature (20°C-920°C) for the fiber with FBG. At room temperature(20°C) the LP_{02} mode can be observed. It can be observed that the mode structure of the FGB has not changed much during the heating process unlike the bare fiber. But Between 400°C and 500°C it can be seen that the mode structure is distorted for both bare fiber and the fiber with FBG. Then again after 900°C
the structures vanish for both the bare fiber and the fiber with FBG. The strange behavior of the modes around 450\(^{0}\)C can be related with the variation of the thermo-optic coefficient with the temperature (figure 3.33). The thermo-optic coefficient has a minimum at 436\(^{0}\)C, which lies in the above mentioned range (400\(^{0}\)C-500\(^{0}\)C).

3.3.5 Mode Structure Results for Various Wavelengths

Additional experiments were done to see how the mode structures change with the wavelength. The same Argon-Iorn laser (INNOVA 70-K) used for the low temperature experiments, was used. Laser light was coupled in to the FBG and wavelengths of the laser were changed from 470 nm and 515 nm (Bright green to dark purple). The setup was monitored with a digital camera to see how the LP modes changes with the wavelength. All these experiments were done at room temperature (20\(^{0}\)C). Experiments were started from a high wavelength (514.5 nm) and it was decreased to 472.7 nm. Table 3.3 shows the possible wavelengths for the laser and their maximum power.

Images were taken for each and every wavelength. Figure 3.34 shows the set up for the particular experiment. It can be seen that when the wavelength decreases the cutoff value of the mode increases. That means it gives high modes when the wavelength is decreasing. After a set of experiments the pictures of the modes were summarized as can be seen in figure 3.35.
Table 3.3: Wavelengths of the laser and their maximum power

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>514.5 (standard)</td>
<td>2.00</td>
</tr>
<tr>
<td>501.7</td>
<td>0.35</td>
</tr>
<tr>
<td>496.5</td>
<td>0.60</td>
</tr>
<tr>
<td>488.0 (standard)</td>
<td>1.50</td>
</tr>
<tr>
<td>476.5</td>
<td>0.60</td>
</tr>
<tr>
<td>472.2</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Figure 3.34: Experimental set up for the wavelength dependance
Figure 3.35: Variation of modes with the wavelength
CHAPTER IV

SUMMARY

Main goals of the project can be summarized as follows:

- Theoretical study of LP modes (computer modeling).

- Experimental study of LP modes change with the temperature with a fixed wavelength (770 K - 1100 K).

- Experimental study of LP modes change with the wavelength (472.7 nm - 514.5 nm) in a fixed temperature (300 K). (with and without FBG)

LP modes modeling was done by using MATLAB. For high temperatures (50 K - 780 K), the variation of the Bragg wavelength with the temperature does not show a continuous linear relationship when considering the whole range. However, it shows a linear relationship, when the range is split into several regions (figures 3.14-3.17). It seems that within these regions, the thermo-optic and the thermal expansion coefficients remain constants even though they are functions of the temperature (section 2.3.1).

For low temperatures, higher modes can be observed when temperature increases both for the bare fiber and for the FBG. That means cutoff values increase with the temperature. At high temperatures, mode structures of FBG does not show a
significant change when the temperature increases unlike the bare fiber, which means mode structure is stable at high temperatures. A possible reason for this observation is, in high temperatures (above 300 K), the thermal expansion coefficient dominates rather than the thermo-optic coefficient and vice versa for the low temperatures (below 300 K), when considering FBGs. According to the equations 1.16 and 1.17, both the grating spacing, $\Lambda$ and the refractive index, $n$ increase with the temperature. Cutoff values may depend on the properties of the fiber such as:

- Thermo-optic coefficient, $\alpha$
- Thermal expansion coefficient, $\alpha_t$
- Refractive index of the fiber core, $n_1$ and the cladding, $n_2$
- Grating spacing, $\Lambda$

The mode changing (cutoff values) can also be depend on the minor reasons such as bending of the fiber, small damages inside the fiber core (and the cladding), etc. For very high temperatures (900°C) the mode structure is completely get distorted since at high temperatures the grating does not exist.

For future work, changing the fiber modes (LP modes) with the strain, stress of the fiber can be carried out.


