2004-11-23

Polarimetric Temperature Sensor Using Core-replaced Fiber

Benjamin L. Ipson
Brigham Young University - Provo

POLARIMETRIC TEMPERATURE SENSOR USING CORE-REPLACED FIBER

by

Benjamin L. Ipson

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Electrical and Computer Engineering

Brigham Young University

December 2004

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Benjamin L. Ipson

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Stephen M. Schultz, Chair
Date	Richard H. Selfridge
Date	Karl F. Warnick

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Benjamin L. Ipson in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date

Stephen M. Schultz
Chair, Graduate Committee

Accepted for the Department

Michael A. Jensen
Graduate Coordinator

Accepted for the College

Douglas M. Chabries
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

POLARIMETRIC TEMPERATURE SENSOR USING

CORE-REPLACED FIBER

Benjamin L. Ipson

Department of Electrical and Computer Engineering

Master of Science

Optical fibers are increasingly being used to create sensing devices. The D-fiber has an elliptical core and exhibits birefringence. This birefringence can be used to create a polarimetric sensor. The elliptical core supports two orthogonal modes that have separate effective indices of refraction. The indices of refraction change with a change in temperature. Since the effective indices of refraction change differently for the two modes, the birefringence also changes. This change in birefringence can be seen as a change in detected power through the fiber through the use of polarizers. The fiber then becomes a temperature sensor.

The sensitivity of the fiber can be enhanced by replacing a section of the core of the fiber with a sensing material. With the sensing material in the core of the fiber, it has direct interaction with the light and strongly affects it. A polarimetric temperature sensor is created by replacing a section of the core with a polymer, which is sensitive to temperature. The core-replaced fiber in a polarimetric sensing configuration is compared to a a unetched fiber set up in the same way. The core-replaced fiber sensor is five times as sensitive to temperature as an unetched fiber.

ACKNOWLEDGMENTS

I would like to express my thanks to all those that have supported me in this research. First of all I would like to thank Dr. Richard Selfridge and Dr. Stephen Schultz for the opportunity to work in the Optics Lab and for their guidance in the research. I would also like to thank all those that I have worked with in the lab, especially Doug Markos for helping me get started in the research, Kevin Smith for directly working with me on it, and John Barber for discussion of ideas and theories.

I would also like to thank my family for their support in my schooling and research. I would especially like to thank my parents. They have helped me in many ways and given me full support. Most of all I would like to thank my future wife (wherever she is) for all the time she has given me to finish this work.

Contents

List of Figures

Chapter 1

Introduction

Optical fiber sensors are playing an increasingly important role in many applications. They are used to monitor environmental conditions such as temperature, strain, pressure, and the presence or absence of chemicals [1]. They are having a tremendous impact on civil structures such as roads and buildings, on the aviation and navigation industries, and are beginning to play a more prominent role in national security.

There are many benefits of using fiber sensors as opposed to other types of sensors. First, the fiber sensors are immune to electro-magnetic interference that other electronic devices often experience. This is because they use light instead of electrical signals. Additionally, the glass fibers are lightweight, inert, noncorrosive, and will not spark. This means that they can be used around flammable materials and in other situations that might be hazardous with other types of sensors. They can provide for a variety of measurements with just one fiber sensor. They can also have several sensing points along a single fiber. Also, the fibers could be embedded directly into the materials used in building a structure.

The optical characteristics of fiber sensors change in response to changes in the environmental variables to be measured. Changes in the optical response of the fibers are then correlated to changes in the environmental variables. This is illustrated in Fig. 1.1. Light travels down the fiber until it reaches a section that responds to environmental stimuli. The light is modified and then continues down the fiber to be detected. The modification may be a change in reflection/transmission spectrum, amplitude, phase, frequency or polarization. The majority of fiber sensors currently

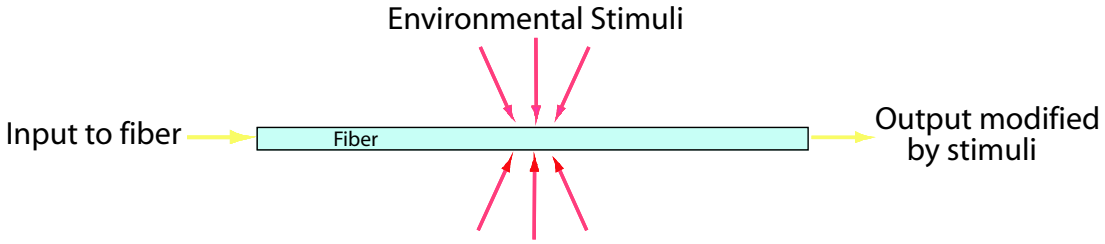


Figure 1.1: Fiber sensor schematic.

in use rely on the response of the intrinsic characteristics of the optical fiber.

Fiber Bragg gratings (FBGs) [2] are the most prevalent example of intrinsic fiber sensors, wherein the period of the grating and/or the effective indices of fiber modes are a function of environmental variables. Figure 1.2 shows a fiber with a Bragg grating in it. The index of refraction of the core has been modified in a periodic manner to create the grating. In FBGs the light is modified in its reflection/transmission spectrum. Because of the Bragg grating, a certain wavelength of light, the Bragg wavelength, is reflected back down the fiber. The Bragg wavelength changes as a function of the environmental variable.

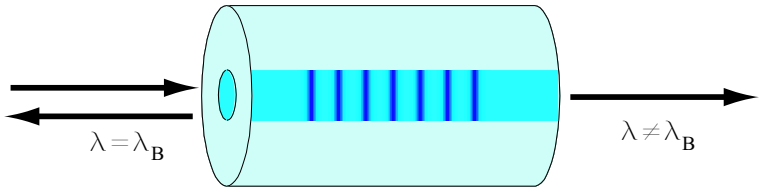


Figure 1.2: Fiber Bragg grating.

Alternative methods of sensing involve coating a fiber with a sensing material and using evanescent field interaction [3] or long period gratings (LPGs) [4] to couple light from the fiber core to the coated cladding. This extrinsic method allows the detection of changes in index of refraction, the presence of chemicals, etc. which cannot be detected with FBGs.

1.1 D-fiber as Sensor Platform

In this thesis I present a novel and more direct method for creating sensors in optical fiber by replacing a section of the core of a D-shaped fiber with a sensing material. This places the sensing material directly in the path of the beam propagating in the fiber, thus increasing the strength of the interaction between the light and the sensing material.

Figure 1.3 illustrates the need for placing the sensing material into the core of the fiber. In the first image, a fiber has been coated with a sensing material. This sensor will be mechanically strong. However, there is only a weak interaction between the light in the fiber and the sensing material, since it depends on interaction with evanescent fields.

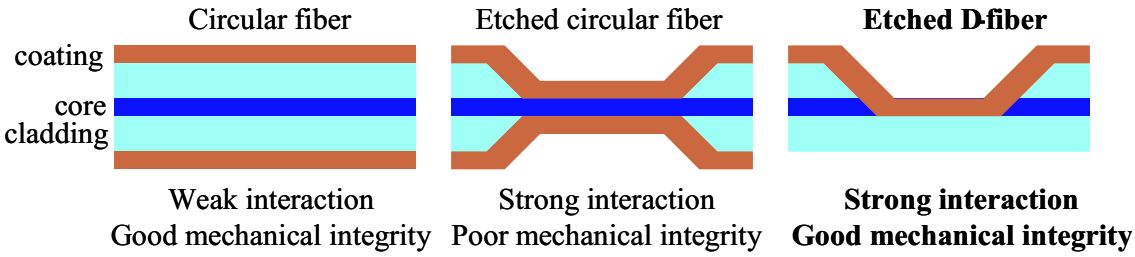


Figure 1.3: Fiber sensor interaction.

The second image in Fig. 1.3 shows a fiber that has been etched to the core in order to get the coating of sensing material closer to the core. This sensing device would have a much stronger interaction between the light in the fiber and the sensing material. The drawback of this method is poor mechanical integrity.

The third image in Fig. 1.3 demonstrates the D-fiber with the core-replacement technology as a sensing device. Part of the core is removed and replaced with the sensing material. This means that the light actually guides in the sensing material, providing a strong interaction between the light and the material. Since the core is near the flat side of the fiber, it can be replaced while maintaining the structural integrity of the fiber. This method should provide a good platform for a fiber sensor.

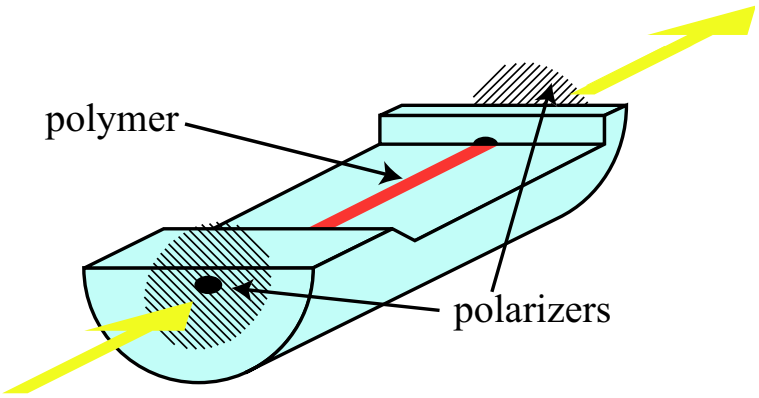


Figure 1.4: Polarimetric sensor.

Figure 1.4 shows a diagram of a D-fiber with a sensing material replacing a section of the core to form an in-fiber sensor. This type of sensor allows a wide variety of sensing materials to be incorporated into the fiber without changing the characteristics of the entire fiber. The D-fiber then, along with our core-replacement technology, provides a good platform to build a sensing device.

There are many advantages to creating an in-fiber device rather than an external one that the fiber connects to. In-fiber devices eliminate interface problems since the device is contained within the fiber. There is no need for costly fiber pigtailing, and there is good mechanical integrity within the device. Also, insertion loss can be kept quite low since the light is kept within the fiber, which can be fusion spliced into systems with low loss.

In this thesis I first examine the D-shaped optical fiber, which is the basis for core-replaced in-fiber devices. I then describe our method for partially removing a section of the core of the fiber. Once the core has been removed, it can be replaced with any number of different sensing materials depending on the specific environmental variable to be measured. I present the theory behind the polarimetric sensing configuration. To demonstrate the validity of this approach to in-fiber sensing I replaced the core of the fiber with a polymer and measured the temperature response of this sensor in a polarimetric configuration. I then describe the setup used to test the sensor, followed by the results of the core-replaced fiber compared to an unetched

fiber. The core-replaced fiber sensor demonstrates a fivefold increase in sensitivity over an unetched D-fiber sensor.

Chapter 2

Background

2.1 D-Fiber

Figure 2.1 shows a D-shaped fiber. This fiber, provided to us by KVH Industries, is composed of an elliptical germania-doped core surrounded by a fluorine-doped cladding and an undoped supercladding and is coated with a polyurethane jacket. The fabrication process results in an undoped region in the center of the core. The fiber has a cross-sectional view that is like a circle cut in half. This half-circle shape gives the fiber the name D-fiber. The diameter of the circle is 125 μm.

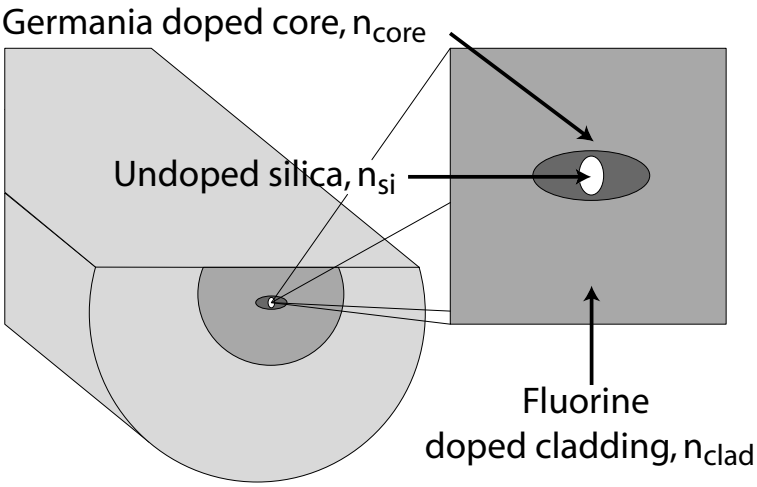


Figure 2.1: D-fiber structure.

Figure 2.2 shows a scanning electron microscope (SEM) image of a zoom in of the core in a cross-sectional view of the fiber. The elliptical shape of the core can be

seen. The core is about 13 μm from the flat side of the fiber. Since the core is close to the flat side of the fiber, the core can be accessed through a chemical etch of the fiber while maintaining the structural integrity of the fiber. Access to the core of the fiber allows access to the light traveling through the fiber and provides for a strong interaction with this light when constructing fiber devices.

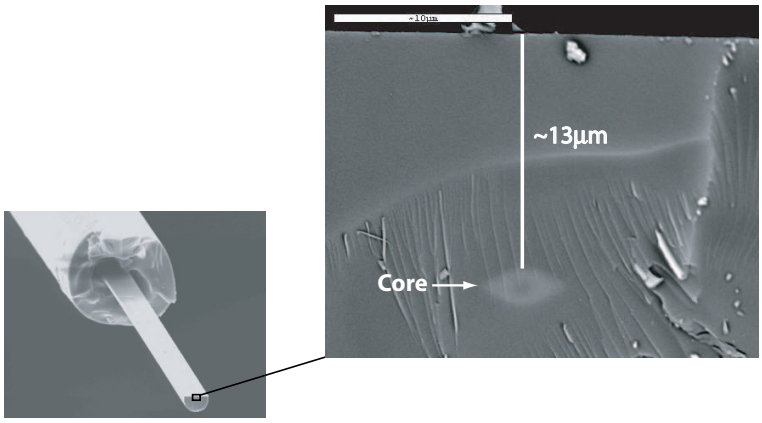


Figure 2.2: D-fiber core.

This fiber is a polarization-maintaining fiber designed to be used at 1550 nm. The core is elliptical in shape with dimensions of about 4 μm and 2 μm. There are two varieties of this fiber. The first is standard or horizontal core fiber, with the major axis of the core parallel to the flat side of the fiber. This is the type shown in Fig. 2.2. The second type is rotated or vertical core fiber, with the major axis of the core perpendicular to the flat side of the fiber.

2.2 Selective Etch

When constructing in-fiber devices it may be desirable to etch to the core without etching into the core or to etch to the core and into it without removing too much cladding. It is possible to etch the fiber in these ways through selective chemical etching. Since the core and cladding are doped differently, they have different etch rates in hydrofluoric acid. It is possible to remove the core without removing much

cladding using this etch. The fiber also undergoes a selective etch in buffered oxide etch. The selectivity of the etch allows the core to be exposed without etching into it.

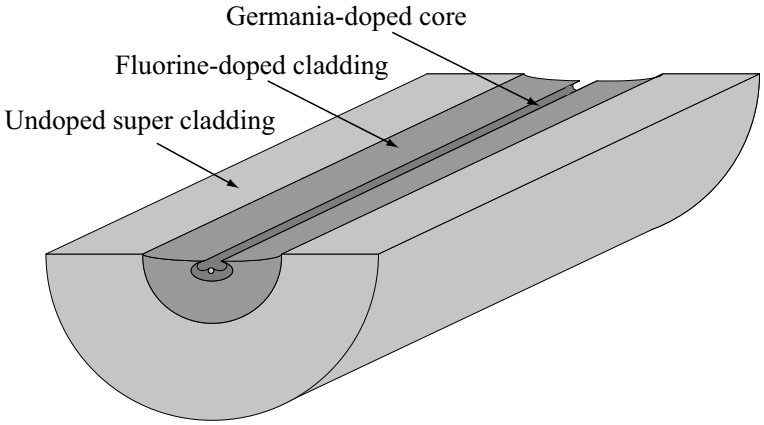
2.2.1 Hydrofluoric Acid

The different doping levels of the D-shaped fiber allow selective etching of the fiber in hydrofluoric (HF) acid. The HF acid etches the germania-doped core region about 8 times faster than the fluorine-doped cladding region and about 11.5 times faster than the undoped supercladding region [5]. Since the core is relatively close to the flat side of the fiber, the fiber can be etched until the core region is exposed while maintaining the structural integrity of the fiber. The core region can then be removed or partially removed through the selective etch with minimal removal of the cladding [6]. Figure 2.3 shows how this selectivity affects the fiber. The core has been reached and partially etched away through the selective etch. This process leaves a groove along the core of the fiber that can be used for creating in-fiber devices.

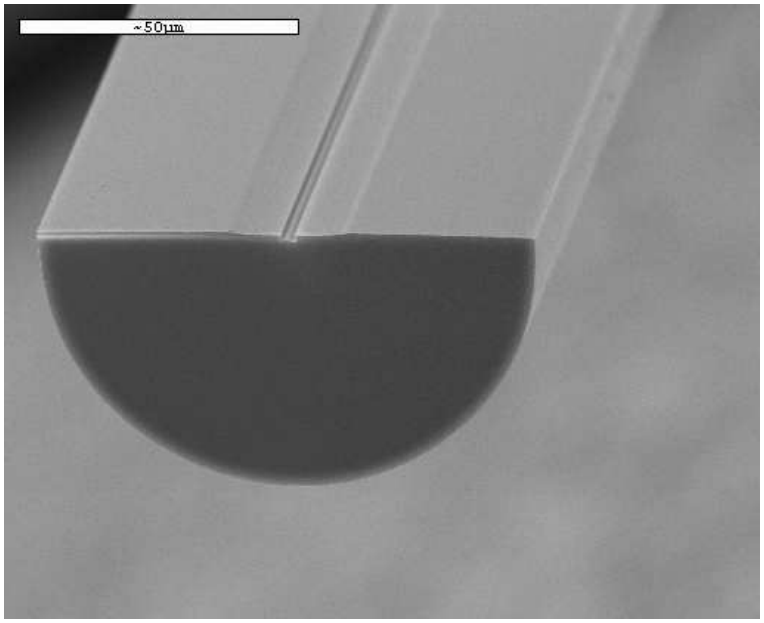
The selective chemical etch removes the core without the need for photolithographic patterning. This eliminates the need to align a mask to the optical fiber. The partially removed core is exactly aligned with the optical fiber. In addition to the reduction in production time and the increase in yield, the self-alignment also decreases the insertion loss.

2.2.2 BOE

The fiber also experiences a selective etch in buffered oxide etch (BOE). BOE is a buffered HF acid solution that contains NH_4F. The selectivity of this etch is different. Figure 2.4 shows that the germania-doped core region etches much more slowly than the cladding regions. Also, the fluorine-doped region etches faster than the undoped region. Because of this selectivity, this etch can be used to expose the core rather than to remove the core. The exposed core appears as a ridge on the fiber, seen in Fig. 2.4, instead of a groove, seen in Fig. 2.3.



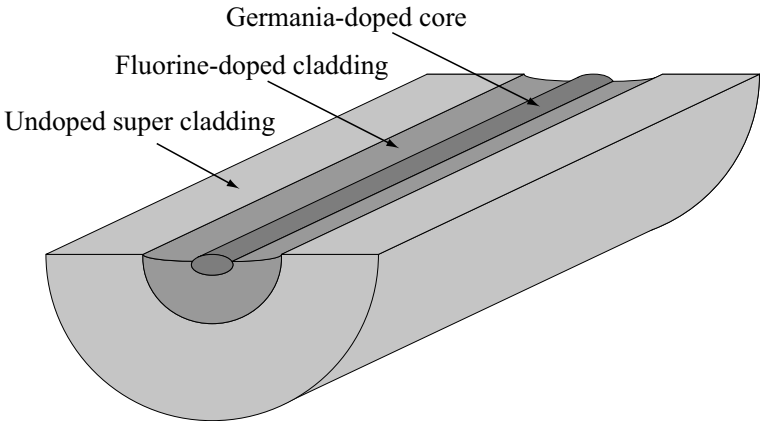
(a) Diagram



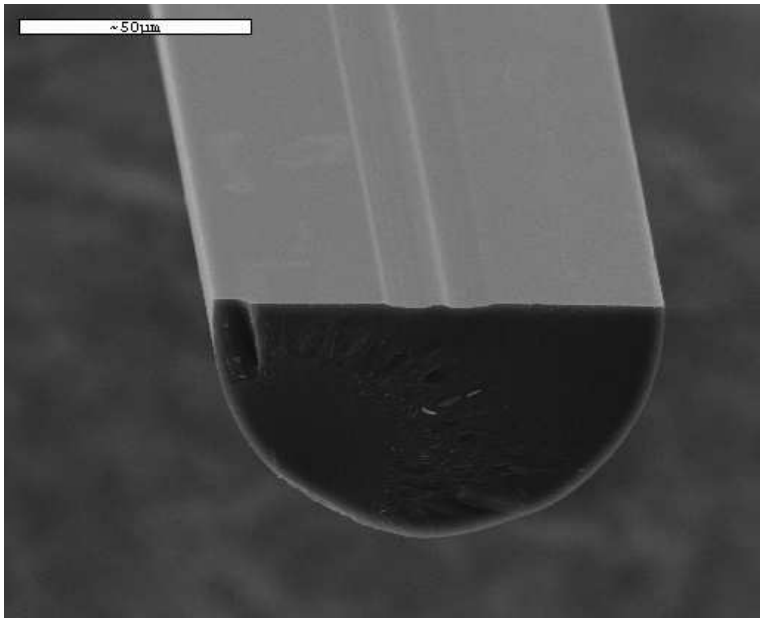
(b) SEM image

Figure 2.3: D-fiber after selective etch from HF acid.

Exposing the core is more desirable than etching into the core for creating some devices. Since we want the core removed in this project, the HF acid is used instead of BOE.



(a) Diagram



(b) SEM image

Figure 2.4: D-fiber after selective etch from BOE.

2.3 Core Removal Process

A controlled etch process allows the core to be etched to a certain depth [6]. We use a dip-etch process because it creates gradual transition regions between the etched and unetched regions. The gradual transition regions are needed for creating low-loss waveguides in etched fibers [7]. Figure 2.5 illustrates how the fiber is etched in a dip etch configuration. The jacket is stripped over a section of the optical fiber and a 2 cm section is placed in HF acid. Laser light is transmitted through the fiber and monitored during the etch for control purposes. Figure 2.6 shows a picture of the actual setup used. A two-step etch process is used. The first step uses a 25% HF solution to quickly etch to the core. The majority of the cladding above the core is removed in this step. The fiber is left in the 25% solution until the core has been reached. This usually occurs in about 35-40 minutes for a horizontal-core fiber and about 25-30 minutes for a vertical-core fiber.

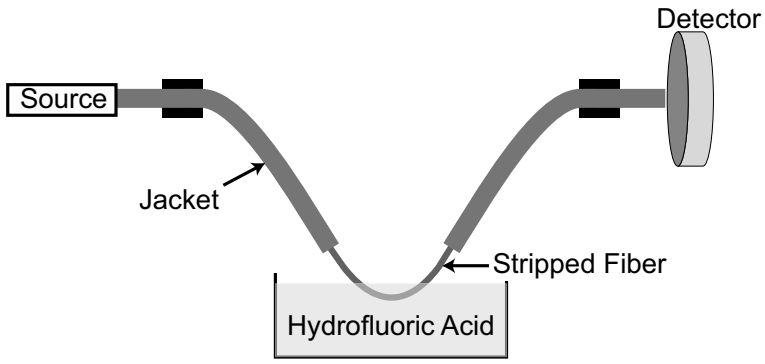


Figure 2.5: Diagram of dip-etch setup.

In the second step, the fiber is etched in a less concentrated solution of acid for a slower, more controlled etch of the core. We have found that a 5% solution of HF acid works well for the core etch. Figure 2.7 shows the progression of the selective etch with a series of SEM images and drawings. Figure 2.7(a) shows that the fluorine-doped cladding region etches slightly faster than the undoped super-cladding resulting in a slight depression. However, before the core is reached the surface is fairly uniform.

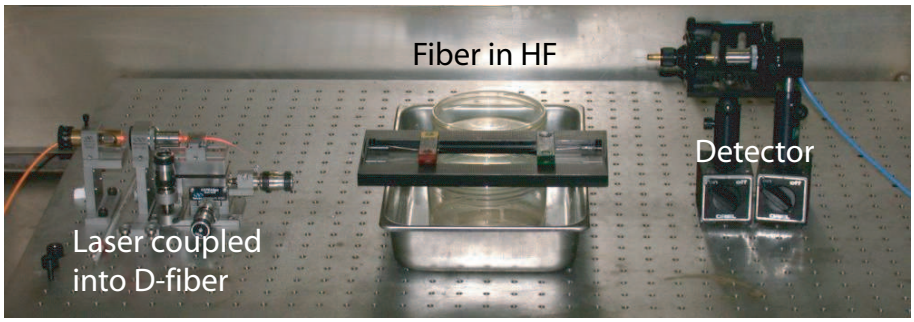


Figure 2.6: Diagram of dip-etch setup.

Figures 2.7(b)-2.7(d) show that when the core is breached the germania-doped core etches substantially faster than the other materials, resulting in core removal with very little cladding removal. Figures 2.7(e) shows that when the acid reaches the undoped region there is a reduction in the etch rate near the center. This reduced etch rate results in a hump near the center of the core.

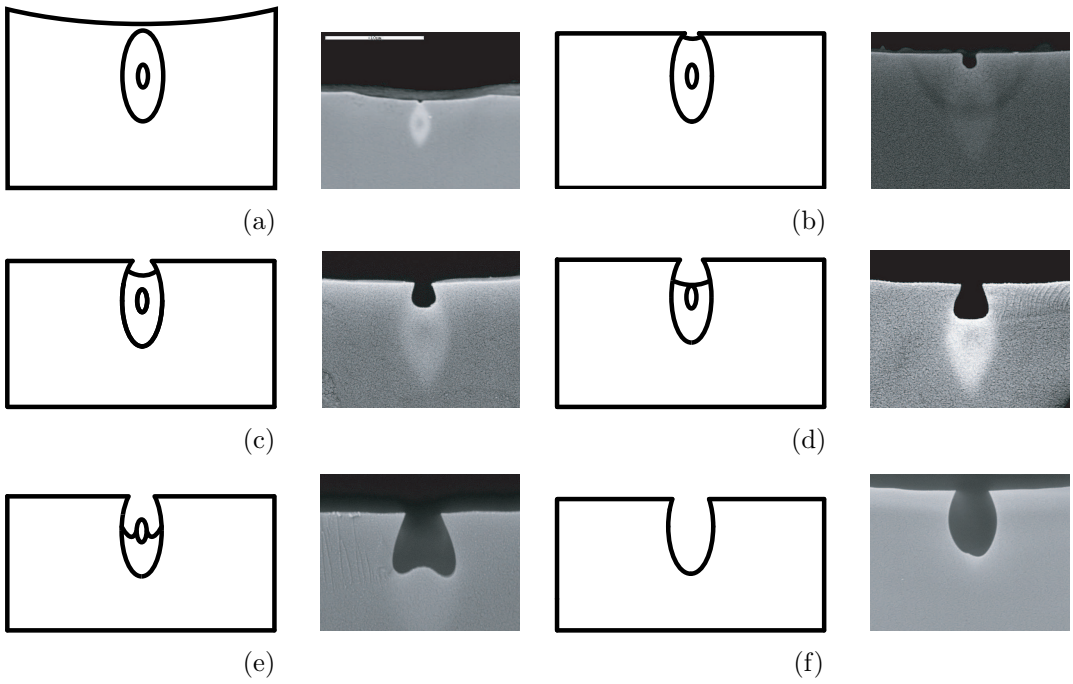


Figure 2.7: Progression of selective etch in core of fiber.

Even with a reasonably slow etch rate, it is not possible to know the exact time required to produce a particular partially etched core profile. Many factors contribute to the variability in the etch time such as variability in the fibers themselves, acid concentration, temperature, humidity, glass doping, etc. Therefore, the etch termination is determined by using an in-situ monitoring technique. The in-situ monitoring is accomplished by monitoring the power transmitted through the etched fiber section. During the etch process, red laser light is transmitted through the fiber. The power of this laser light is monitored at the output of the fiber. The power reading corresponds to the depth of the etch in the core. When the power first starts to drop significantly, it means that the core has been reached. That is when it is removed from the 25% HF acid solution and put into the 5% solution. The power continues to drop as the core is etched deeper. The red light (670 nm) is used instead of 1550 nm light because it does not drop off as quickly as the core is etched away. This is because the fiber is multimode at the red wavelength. The modes gradually drop out as the core is etched.

Figure 2.8 shows a plot of the power detected through the fiber during the 5% HF acid etch. Several SEM images of the core region of the fiber show how the etch progress corresponds to the power plot. The fiber is removed from the 5% solution and placed in the water bath when the loss in transmitted power through the fiber reaches the amount associated with the desired etch profile. The fiber is then left with a groove in the core region that can be used for the creation of in-fiber devices.

Figure 2.7(f) shows that etching eventually undercuts the undoped region and progresses to complete core removal. If the optical fiber remains in the HF acid beyond this point the cladding will continue to etch in an isotropic manner.

It is possible to create a waveguide in the groove by depositing a material into it. This is described in more detail in the next section. In order to keep the insertion loss of the waveguide to a minimum, the core is only etched about halfway. This corresponds to an etch loss of 6.8 dB. The process is similar for both the vertical-core and horizontal-core fibers. Figure 2.9 shows an SEM image of a horizontal-core fiber that has been etched to the -6.8 dB point.

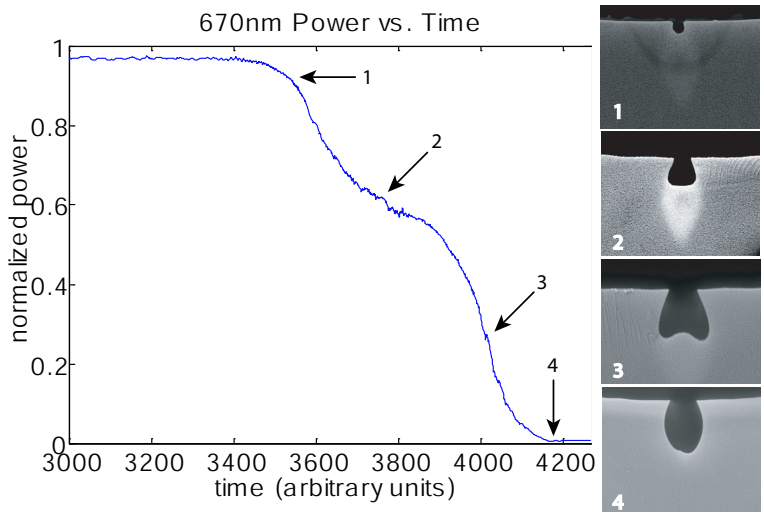


Figure 2.8: Power plot of power through fiber during etch with corresponding SEM images of core.

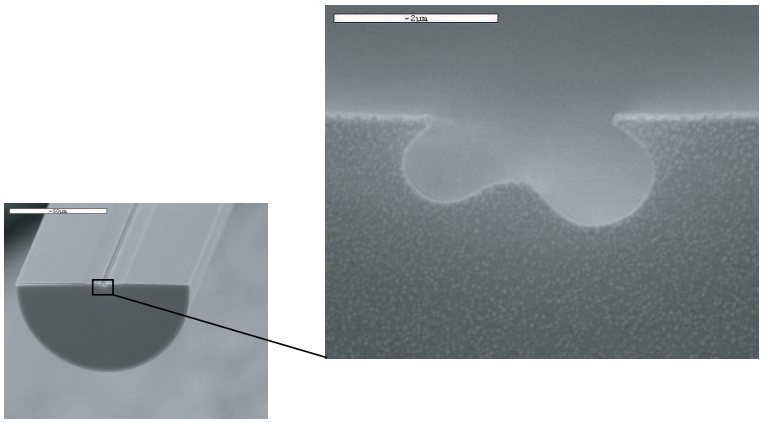


Figure 2.9: SEM image of horizontal-core fiber etched to -6.8 dB point.

2.4 Polymer Waveguide

A waveguide can be created inside the groove of a fiber with the core partially removed. This can be done by depositing a material into the groove created by removing part of the core. To do this, the fiber is taped to a silicon wafer with the flat side of the fiber facing up. The material is then deposited on the fiber in solution form, using a pipette. The wafer with the fiber is then spun. The spinning process coupled with surface forces spreads a uniform layer of the material onto the flat surface of the fiber and forces a thicker layer into the fiber groove. The material in the groove acts as a waveguide.

One material that has been successfully used to create a low-loss waveguide is a polymer made from polymethyl methacrylate (PMMA) doped with DR1-azo dye [8]. The basic polymer solution consists of PMMA and DR1 azo dye dissolved in a solvent consisting of methyl ethyl ketone (MEK) and chlorobenzene. The solution is mixed and then stirred for 24 hours to produce a uniform mixture. It is then filtered with a 0.2-μm filter. After material deposition, it is cured by baking the fiber in a vacuum oven for an hour at 90° to remove any excess solvent.

Optical polymers tend to have a higher index of refraction than the existing optical fiber core, so the polymer waveguide must have a smaller size to maintain single mode operation. It is therefore advantageous to remove only a portion of the fiber core along the region of interest. The smaller size also results in a mode field diameter that is different than that of the fiber mode. The mode-field mismatch results in additional loss unless the transition between the two modes is gradual. Figure 2.10 illustrates these points. It shows a fiber with part of the core replaced. The cutout views show the thicker polymer in the core area and the thinner polymer above. They also show how the light guides through the fiber. As it reaches the polymer region, the power transfers into the polymer. At the end of that region it transfers back to the core, resulting in low loss.

It is important that the polymer above be kept thin. If the polymer above is too thick, it behaves as a a slab waveguide, carrying light away from the region directly over the core. The light coupled into the slab waveguide does not couple back

into the core of the fiber. The layer of polymer on the flat of the fiber needs to be kept thin enough that it does not support any modes, and the light stays in the core region.

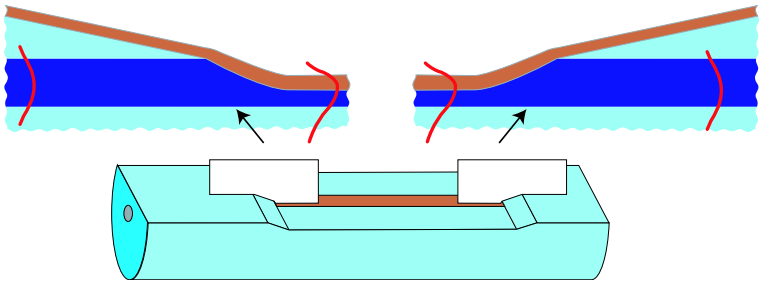


Figure 2.10: Fiber with gradual transitions into and out of polymer.

The dimensions of the waveguide depend on many factors such as viscosity of the material, spin speed, spin ramp time, and the profile of the removed core. The viscosity of the polymer solution is controlled by changing the ratio between the solvent's volume and the mass of the solids. It has been determined that in order to obtain a low-loss waveguide, we should use a polymer solution consisting of 8 g PMMA, 0.6 g DR1 azo dye, 30 mL MEK, and 90 mL chlorobenzene. The spin speed is 2000 rpm, and the ramp time is a few seconds. Spinning the solution in this way results in a layer of polymer about 700 nm thick in the core and about 200 nm thick on the flat of the fiber. Figure 2.11 shows an SEM image of a cross section of a low-loss fiber waveguide made in a vertical-core fiber. The white line shows the boundary between the glass fiber and the polymer. It has minimal polymer on the flat part of the fiber but a substantial amount in the core region. This waveguide has a measured loss of 1.6 dB [8].

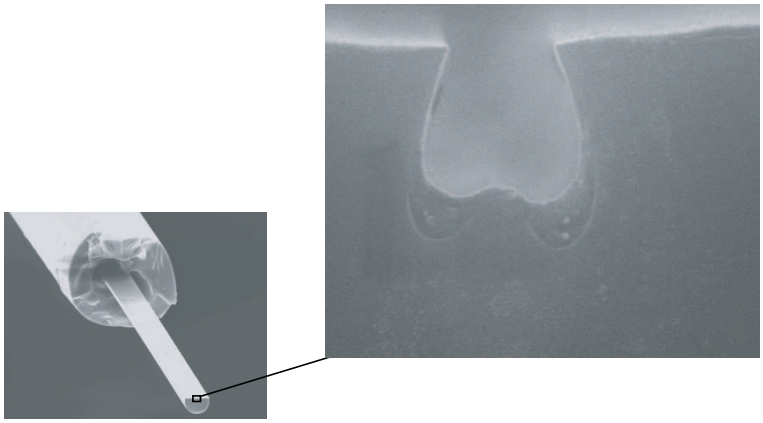


Figure 2.11: SEM image of cross section of fiber with low-loss waveguide.

Chapter 3

Temperature-Sensitive Device

The goal of this project is to demonstrate the viability of sensing environmental change with a core-replaced D-fiber. Temperature is used as the environmental parameter because of its ease of control.

3.1 Sensing Configurations

There are different configurations that could be used to make a D-fiber temperature sensor. Probably the simplest configuration has to do with absorption of light in the fiber. This configuration is shown in Fig. 3.1. The core is partially removed and replaced with a material that absorbs the light differently according to the environmental variable. This may be a material that becomes more lossy with increased temperature.

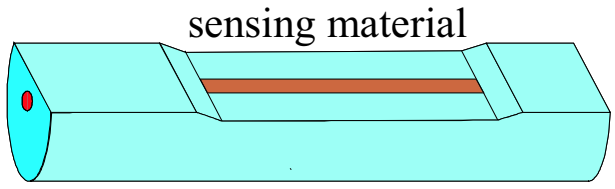


Figure 3.1: Absorption sensing configuration.

Figure 3.2 shows that the second sensing configuration is the polarimetric configuration. This configuration depends on the polarization of light in the fiber.

The core is replaced with a material in which the index of refraction changes with the environment. This causes a change in polarization of the light as it travels through the material. A polarizer at the input and an analyzer at the output allow this change to be detected as a change in intensity of the light through the fiber.

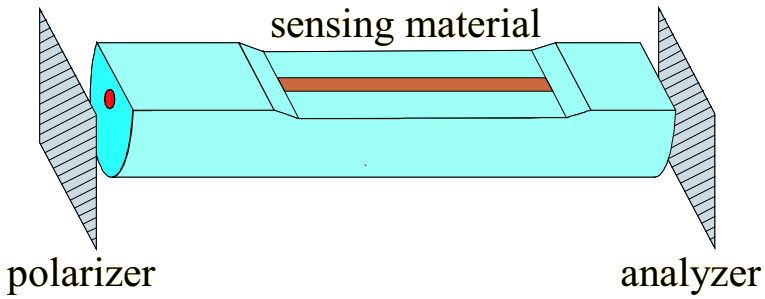


Figure 3.2: Polarimetric sensing configuration.

Another configuration also uses a material with a change in index of refraction. As shown in Fig. 3.3, this sensor uses a grating in the fiber. The grating is placed at both ends of the core-replaced section to create a Fabry-Perot cavity. The change in index of refraction is then seen as a change in the transmission spectrum of the fiber. Other possible configurations are a grating fabricated into the polymer, a Mach-Zehnder configuration, sensing involving fluorescence, etc.

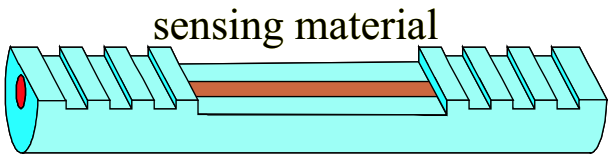


Figure 3.3: Fabry-Perot sensing configuration.

3.2 Polarimetric Sensor

Out of these different sensing configurations, I chose to use the polarimetric sensing configuration. It is a simple and easy method to implement, while providing substantially more sensitivity than an absorption based method. However, it is not the ideal method for absolute temperature sensing. In this method the change in temperature is seen as a change in intensity, which does not have a one-to-one correspondence. The intensity changes in a periodic manner as the temperature increases, so more than one temperature would have the same intensity. This method can be used to gauge the performance of a core-replaced fiber against that of an unetched fiber. A more sensitive device will have more periods in the intensity for a given temperature range.

3.2.1 Polarized Light in the Fiber

Since the D-shaped fiber has an elliptical core, it actually supports two orthogonal modes that are aligned with the axes of the ellipse. We can therefore look at the light as a sum of two orthogonally polarized electric fields. Figure 3.4 shows a diagram of the input end of a fiber with a linearly polarized electric field at an angle θ_p with respect to the major axis of the core. The fields at the input of the fiber are expressed as:

$$E_{xi} = E_0 \cos\theta_p \cos(\omega t - \phi_0) \tag{3.1}$$

$$E_{yi} = E_0 \sin\theta_p \cos(\omega t - \phi_0), \tag{3.2}$$

where ϕ_0 is the arbitrary phase of the light entering the fiber.

As the light travels through the fiber, the two orthogonal modes experience different phase shifts due to the birefringence of the fiber. At the output of the fiber the fields become

$$E_{xo} = E_0 \cos\theta_p \cos(\omega t - \phi_0 + \beta_z^x L), \tag{3.3}$$

$$E_{yo} = E_0 \sin\theta_p \cos(\omega t - \phi_0 + \beta_z^y L), \tag{3.4}$$

where

$$\beta_z^x = k_0 n_x, \tag{3.5}$$

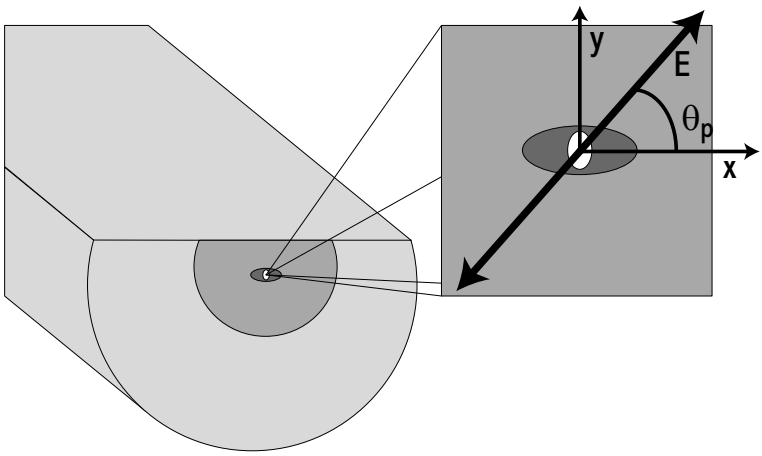


Figure 3.4: Input field at angle θ_p to major axis of core.

$$\beta_z^y = k_0 n_y, \tag{3.6}$$

$k_0 = \frac{2\pi}{\lambda}$ is the free space wave number of the light propagating in the fiber, λ is the wavelength of the light, L is the length of the fiber, and n_x and n_y are the effective indices of refraction of the two modes.

With a polarizer placed at the output at an angle θ_a with respect to the major axis of the core of the fiber, the field becomes

$$\begin{aligned} E &= E_{xo}\cos\theta_a\hat{x} + E_{yo}\sin\theta_a\hat{y} \\ &= E_0\cos\theta_p\cos\theta_a\cos(\omega t - \phi_0 + \beta_z^x L)\hat{x} + E_0\sin\theta_p\sin\theta_a\cos(\omega t - \phi_0 + \beta_z^y L)\hat{y}. \end{aligned} \tag{3.7}$$

The intensity of the light detected through the analyzer is the time-averaged square [9] of the fields

$$I = \frac{1}{T}\int_0^T \|E\|^2 \mathrm{d}t. \tag{3.8}$$

Substituting in the field from Eq. 3.7, the intensity becomes

$$I = \frac{1}{2}{E_0}^2\Big[\big(\cos^2\theta_p\cos^2\theta_a + \sin^2\theta_p\sin^2\theta_a\big) + \frac{1}{2}\sin(2\theta_p)\sin(2\theta_a)\cos\big[(\beta_z^x - \beta_z^y)L\big]\Big]. \tag{3.9}$$

If both the polarizer and the analyzer are oriented at 45° to the major axis of the core ($\theta_p = \theta_a = 45°$), then the intensity becomes

$$I = \frac{1}{2}{E_0}^2 \cos^2\left[\frac{(\beta_z^x - \beta_z^y)L}{2}\right]. \tag{3.10}$$

If one is at 45° to the major axis and the other one is at −45° to the major axis ($\theta_p = -45°, \theta_a = 45°$ or $\theta_p = 45°, \theta_a = -45°$), then the intensity is

$$I = \frac{1}{2}{E_0}^2 \sin^2\left[\frac{(\beta_z^x - \beta_z^y)L}{2}\right]. \tag{3.11}$$

This is the case I will use. In terms of the phase difference between the two modes this is

$$I = \frac{1}{2}{E_0}^2 \sin^2\left[\frac{\Phi}{2}\right], \tag{3.12}$$

where

$$\Phi = \phi_x - \phi_y = (\beta_z^x - \beta_z^y)L, \tag{3.13}$$

is the phase difference.

3.2.2 Birefringence

The two orthogonal modes travel with different phase velocities, which results in birefringence in the fiber. The birefringence is defined mathematically as

$$B = \frac{\beta_z^x - \beta_z^y}{k_0}, \tag{3.14}$$

where β_z^x and β_z^y are the two phase constants for the the two modes.

A change in certain environmental variables such as temperature can cause the bulk index of refraction to change. Changes in the bulk index of refraction causes a change in the propagation constant of each of the two modes traveling through the fiber [10]. If the propagation constants of the two modes change at different rates, then the birefringence also changes. This change is given by

$$\Delta B = (n_{x,T} - n_{y,T}) - (n_{x,0} - n_{y,0}), \tag{3.15}$$

where $n_{x,t}$ and $n_{y,T}$ are the effective indices of the modes at temperature T and $n_{x,0}$ and $n_{y,0}$ are the effective indices of the modes at room temperature. The change

in the phase difference between the two polarizations of light in the fiber is directly proportional to the change in the birefringence and is given by

$$\Delta\Phi = k_0 \Delta B L, \tag{3.16}$$

where L is the length of the fiber being affected.

3.2.3 Detection of Change in Birefringence

Since the intensity depends on the phase difference between the two modes, it also changes with temperature. Looking at the intensity in terms of birefringence or the phase difference, we have

$$I = \frac{1}{2}{E_0}^2 \sin^2\left[\frac{k_0}{2} B L\right] = \frac{1}{2}{E_0}^2 \sin^2\left[\frac{\Phi}{2}\right]. \tag{3.17}$$

The intensity at the output due to a change in birefringence is then

$$\begin{aligned} I &= \frac{1}{2}{E_0}^2 \sin^2\left[\frac{k_0}{2}\Delta B L + \Phi_0\right] \\ &= \frac{1}{2}{E_0}^2 \sin^2\left[\frac{\Delta\Phi}{2} + \Phi_0\right], \end{aligned} \tag{3.18}$$

where Φ_0 is the phase at a reference point.

Another way to look at this is in terms of the polarization state of the light. As the birefringence of the fiber changes, it causes a change in the polarization of the light traveling through the fiber. Figure 3.5 illustrates this change. The light starts out linearly polarized at a $-45°$ angle. As it travels down the length of the fiber, it changes as a function of the birefringence times the length. It passes into elliptical then circular polarizations. When the phase difference becomes π, the polarization is again linear but at a $45°$ orientation. At 2π, the light is back to its original polarization. At the analyzer this is translated into an intensity change. The figure indicates the fraction of the light that makes it through the analyzer for the given polarization.

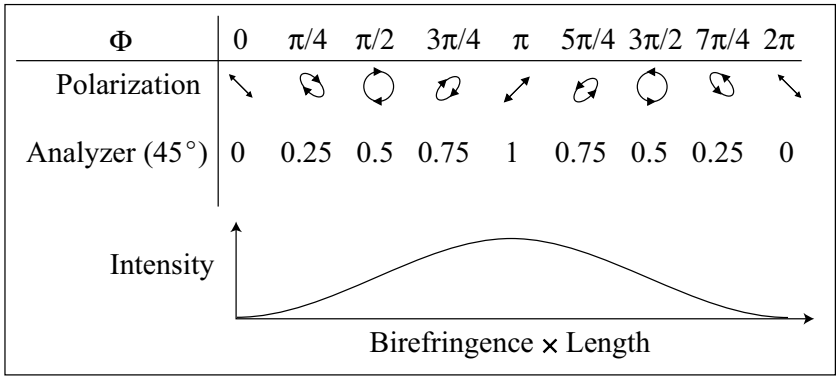


Figure 3.5: Polarization change from change in birefringence.

3.3 Temperature Sensitivity of D-fiber

Temperature change causes a change in sensor length, waveguide cross-section dimensions, and bulk index of refraction. As the fiber is heated, it undergoes thermal expansion. The fiber dimensions increase according to the coefficient of thermal expansion. The index of refraction changes because of the displacement of the absorption edge in the UV towards longer wavelengths and the lowering in density from the expansion [11]. As the bulk index of refraction changes, the effective indices of the two modes also change. The two effective indices change by different amounts because of the elliptical shape of the core. This means that the birefringence of the fiber depends on the temperature.

Since the birefringence and length of the fiber change with temperature, the phase difference also changes. From Eq. 3.16 the change in phase with respect to change in temperature becomes

$$\frac{\mathrm{d}\Phi}{\mathrm{d}T} = k_0\left(\frac{\mathrm{d}B}{\mathrm{d}T}L + \frac{\mathrm{d}L}{\mathrm{d}T}B\right). \tag{3.19}$$

Since we will have a set length of fiber, the change in fiber length is only due to thermal expansion and $\frac{\mathrm{d}L}{\mathrm{d}T}$ depends on the coefficient of thermal expansion. In silica this value is $5 \times 10^{-7}{}^{\circ}\mathrm{C}^{-1}$. For a 100° temperature change, the length changes by about 5 nm. B is about 0.2×10^{-3} and $\frac{\mathrm{d}B}{\mathrm{d}T}$ is about 1.5×10^{-7} [11]. This means that for a 2 cm length $\frac{\mathrm{d}B}{\mathrm{d}T}L = 3 \times 10^{-9}$ and $\frac{\mathrm{d}L}{\mathrm{d}T}B = 1 \times 10^{-12}$. The second term is several orders of magnitude smaller than the first term and can be ignored. The change in

phase difference is then proportional to the change in birefringence, or the change in effective indices with temperature:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}T} \approx k_0\Big(\frac{\mathrm{d}B}{\mathrm{d}T}L\Big) = k_0\left[\left(\frac{\mathrm{d}n_x}{\mathrm{d}T} - \frac{\mathrm{d}n_y}{\mathrm{d}T}\right)L\right]. \tag{3.20}$$

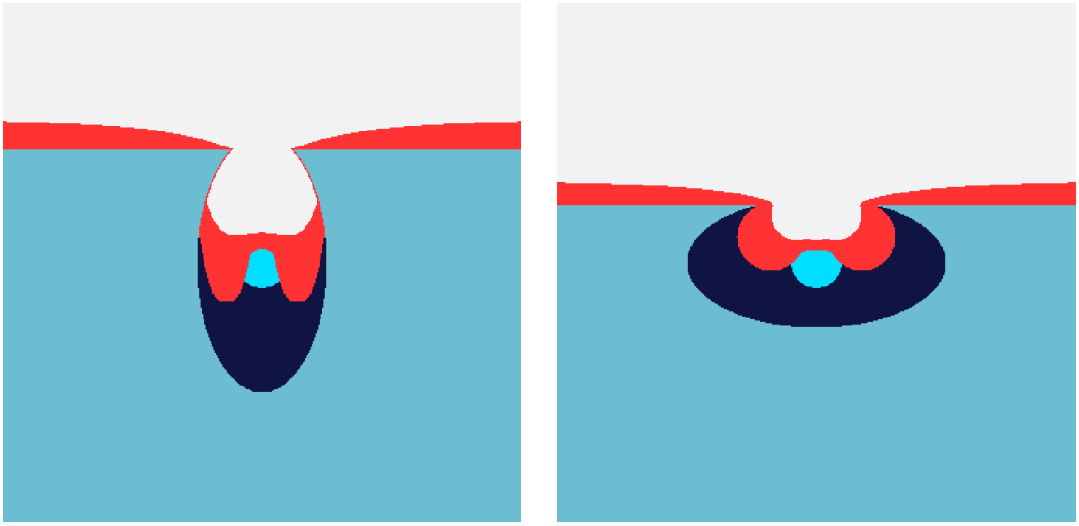
3.4 Enhanced Sensitivity of Polymer Waveguide

The sensitivity of the fiber can be enhanced by replacing a section of the core with a material more sensitive to temperature. PMMA has much greater sensitivity to temperature than the fiber core. Typical values of $\frac{dn}{dT}$ are $-2.6 \times 10^{-6}(^{\circ}\mathrm{C})^{-1}$ for the germania-doped core and $-1.2 \times 10^{-4}(^{\circ}\mathrm{C})^{-1}$ for PMMA. In order to see how this affects the sensitivity, there needs to be a link between the change in bulk index and the the change in birefringence. This is done through numerical simulations.

3.5 Numerical Simulations

In order to simulate the performance of a polarimetric temperature sensor relative to an unetched fiber the mode solver in the software package BeamPROP$^{\mathrm{TM}}$was used to compute the propagation constants of each of the two modes at different temperatures. Figure 3.6 shows the cross-section profiles used in the simulation. In order to match the experiments I performed, outlined in the next chapter, these simulations modeled sensors which were 12 cm long. Figure 3.7 shows a diagram of the fiber heated. For the core-replaced sensor, 2 cm of this length had the core replaced with PMMA. The full 12 cm section of fiber was affected by the temperature changes. The simulations were performed for both horizontal-core and vertical-core fibers.

Figure 3.8 shows a plot change in birefringence as a function of temperature for unetched and core-replaced vertical-core and horizontal-core fibers. This plot shows that the core-replaced fibers experience a greater change in birefringence than the unetched fibers. It can also be seen that the change is negative for the unetched vertical-core fiber and positive for the unetched horizontal-core fiber. The horizontal-core fiber will have a better result than the vertical-core fiber because the unetched section adds to the birefringence from polymer section. With the vertical-core fiber,



(a) (b)

Figure 3.6: Cross-section profiles used in simulation for (a) vertical core and (b) horizontal core.

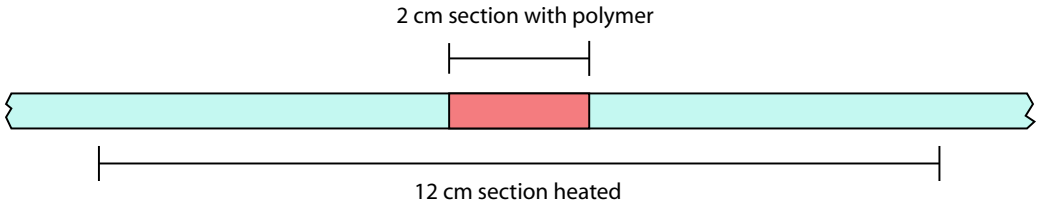


Figure 3.7: Diagram of fiber heated in experiment.

the unetched section subtracts from the birefringence of the polymer section. This happens because of the geometry of the waveguides. In vertical-core fiber, the long axis of the high-index material (the germania-doped region) is oriented in the vertical direction. However, when the core is removed and replaced with a polymer waveguide, the long axis of the polymer waveguide is in the horizontal direction. The simulations show that in unetched vertical-core fibers the change in birefringence with increasing temperature is negative. In the polymer waveguides in the vertical-core fiber, the change is positive. Since some of the unetched fiber is also heated, the change in birefringence from the one section is partially offset by the opposite change in the other section. In the horizontal-core fiber, the long axis of the polymer waveguide is in the same direction as the core of the unetched fiber. This means that the overall change in birefringence is additive between the two sections.

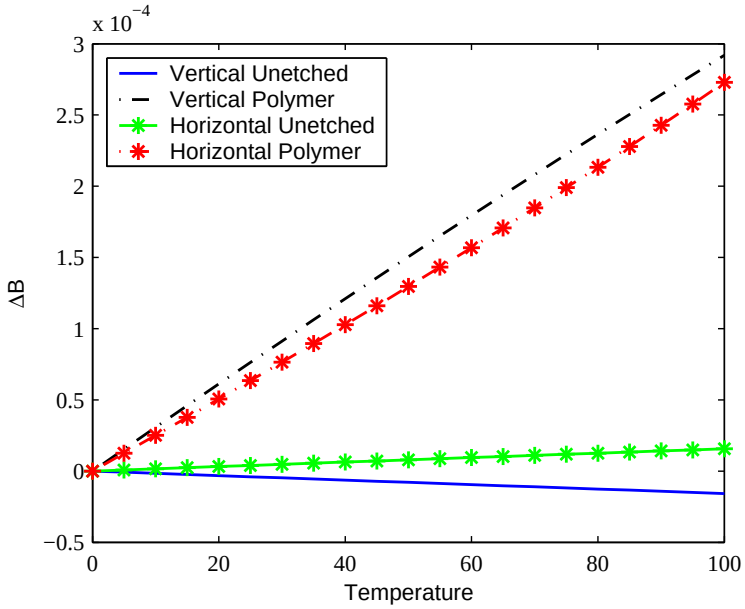
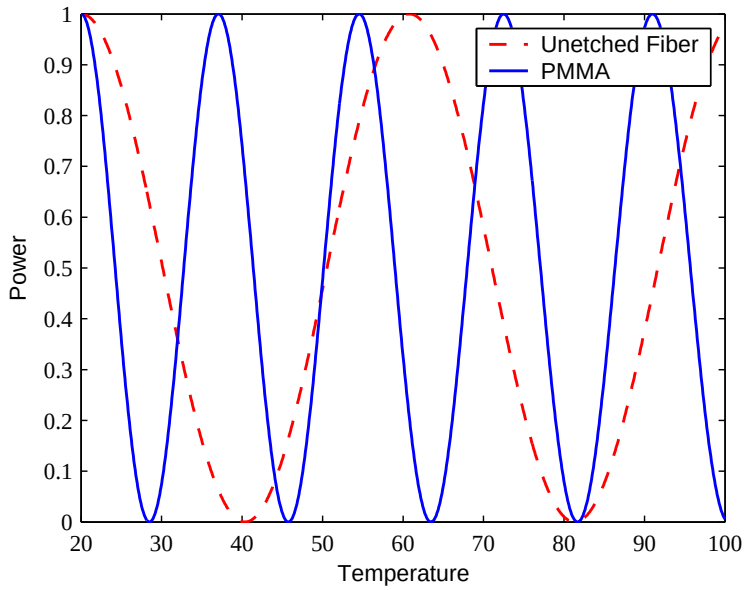


Figure 3.8: Plot of ΔB as a function of temperature.

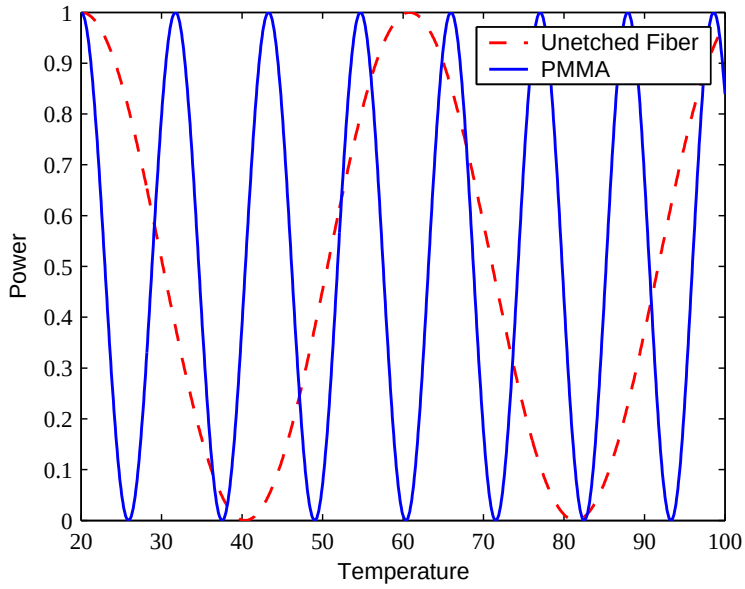
Figure 3.9 shows plots of the throughput power versus temperature from the simulations. In these plots, the greater change in birefringence can be seen as a greater number of oscillations. They show that for both core orientations, the core-replaced

fibers are more sensitive (more oscillations for a given temperature range). They also show that the horizontal-core fiber has higher sensitivity than the vertical-core fiber.

For my experiments, I decided to use horizontal-core fiber. The simulations showed that horizontal core-replaced sensors were about $3\frac{1}{2}$ times more sensitive than unetched D-fiber sensors. Simulations of a core-replaced sensor having the entire 12 cm length filled with polymer showed an improvement in sensitivity by a factor of 21 over a completely unetched 12 cm sensor.



(a)



(b)

Figure 3.9: Simulation of power vs temperature in simulations for (a) vertical-core fibers and (b) horizontal-core fibers.

Chapter 4

Experimental Results

In order to experimentally verify the results of the previous chapters, I created a fiber temperature sensor using the core-replacement technology and a polarimetric sensing configuration [12][13]. This fiber was compared to an unetched D-fiber also put into a polarimetric sensing setup. In this chapter I describe the setup used and present the results of the experiments.

4.1 Fiber Preparation

4.1.1 Core-replaced Fiber

Based on the numerical simulations shown in section 3.5, horizontal-core D-fiber was used as the platform to produce a core-replaced fiber. It is important that the fiber be low loss in order to get a good power measurement and a good response. The basic process is described in sections 2.3 and 2.4. A detailed list of the entire process is in Appendix A. About 2.5 cm of jacket was stripped off from the middle of the fiber, and about 2 cm of that region was etched in HF acid. It was removed at the -6.8 dB point to remove about half of the core. Figure 4.1 shows an SEM image of a fiber removed at this point.

A polymer made of PMMA and red dye was spun onto the fiber. Figure 4.2 shows an SEM image of a cross-sectional view of the fiber. There is a good amount of polymer in the core, and a minimal amount on the flat of the fiber. This fiber had about 2.3 dB of insertion loss.

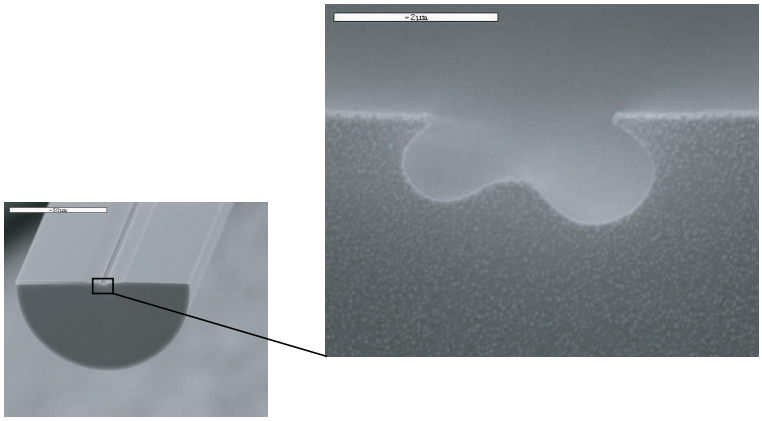


Figure 4.1: SEM image of horizontal-core fiber etched to -6.8 dB point.

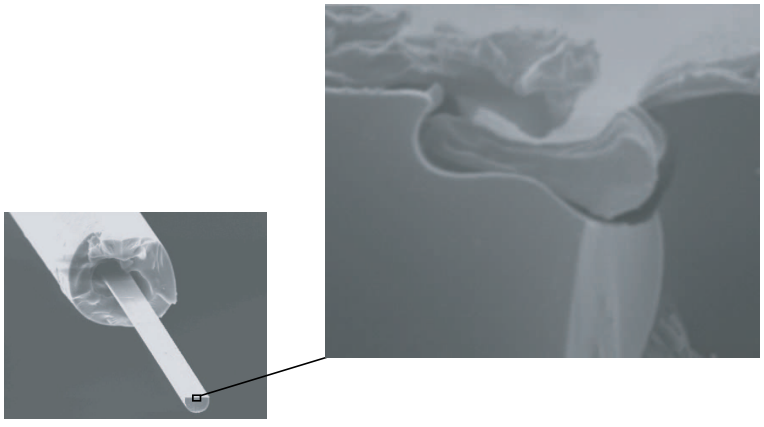


Figure 4.2: SEM image of fiber with polymer in etched core.

4.1.2 Unetched Fiber

I also performed the experiment on an unetched D-fiber to compare with the core-replaced fiber. I tried to give it similar conditions to the core-replaced fiber. First I took a length of fiber that was similar and stripped off the jacket along a 2.5 cm region in the middle. I taped the fiber onto the same wafer as the core-replaced fiber, so they would be next to each other on the same wafer. This should ensure similar conditions. I could only look at the power throughput of each fiber separately, so I heated them up multiple times, sometimes monitoring one, and sometimes monitoring the other.

4.2 Polarimetric Setup

In order to create a polarimetric setup with a fiber, light needs to be focused into the fiber and the transmitted light needs to be detected. Polarizers also need to be inserted at the input and output of the fiber. Also, the fiber needs to be able to be heated up, with a way to detect the temperature. Figure 4.3 shows a simplified diagram of the setup that was used. The source, detector, polarizer, and analyzer are shown. The temperature was varied in a controlled manner using a hot plate.

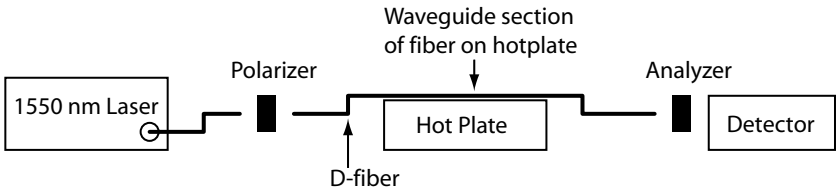


Figure 4.3: Simplified diagram of polarimetric sensor setup.

Figure 4.4 shows a more detailed diagram of the experiment setup. The laser used for these experiments is a 1550 nm wavelength lightwave transmitter. A standard commercial fiber is used to take the light from the transmitter to the system. This fiber is not polarization-maintaining fiber, and if it is moved, the polarization of the the light in the fiber will change. The fiber is taped down to keep the source

polarization constant during the experiment. The output end of the fiber is placed into a holder so that the light exits the fiber and travels openly in air. Since the beam exiting the fiber end diverges quickly, the beam is collimated using a lens. After some space I put an x,y,z stage with an objective lens to focus the light into the D-fiber. A polarizer is placed in the space between the collimating lens and the objective lens. It is oriented at a 45° angle from horizontal.

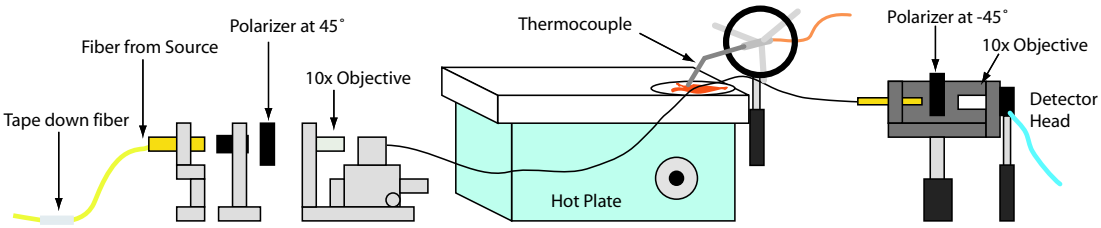


Figure 4.4: More detailed diagram of polarimetric sensor setup.

The x,y,z stage has a holder for the fiber. The fiber was placed in the holder such that the flat side is up. This means that the light entering the fiber should be polarized at a 45° angle with respect to the major axis of the core of the fiber. Equal amounts of power should go into each orthogonal mode. The fiber was focused until maximum throughput was measured.

The output end of the fiber was placed in a chuck and put in a holder with another objective lens. The light goes through the objective lens and then goes to a detector head, as shown in Fig. 4.4. This end of the fiber was also adjusted in the x, y, and z directions to obtain maximum power throughput. At this position, there is room between the fiber end and the objective lens to place a polarizer to use as an analyzer. I placed a polarizer at a -45° angle to use for the analyzer. I also had to make sure this end of the fiber was flat side up.

Enough space was left between the input focusing optics and the output focusing optics for a hot plate to use to heat the fiber. During processing steps, the fiber is usually mounted on a silicon wafer. The wafer provides an easy way of handling the fiber for the experiment. The wafer containing the fiber was placed on the corner of

the hot plate, as shown in Fig. 4.4. This was done to keep the heated portion of the fiber to a minimum. With this setup, about 12 cm of fiber is heated. A thermocouple was placed against the wafer right next to the fiber to obtain the temperature of the fiber.

Both the detector and the thermocouple were interfaced to a computer running LabVIEW. The LabVIEW program continuously recorded the detected power and temperature at regular intervals. The hot plate was heated up and then left to cool while the program recorded. The data from the cool down period is more accurate because it happens much more slowly.

4.3 Experimental Results

4.3.1 Unetched Fiber

Figure 4.6 shows a plot of the detected power as a function of temperature for the unetched fiber. For the given temperature range, the output power does not even go through one full period. For the temperature range used, the change in the phase difference is linear [14], which means that the measured optical power varies periodically with temperature.

4.3.2 Core-replaced Fiber

The core-replaced fiber was placed in the setup described above and heated from about 20°C to about 95°C, similar to the process used with the unetched fiber. Again the data was taken while the fiber was cooling down rather than when it was heating up.

Figure 4.6 shows a plot of the detected power as a function of temperature for the core-replaced fiber. For this temperature range, the power curve goes through about three and a half cycles. This is about five times greater than in the unetched fiber, showing a large increase in temperature sensitivity due to the core-replacement technique. The numerical simulations presented in Section 3.5 showed a $3\frac{1}{2}$ times improvement. This may mean that the effective index or another parameter used was a little off. The oscillations become more frequent at higher temperatures. This

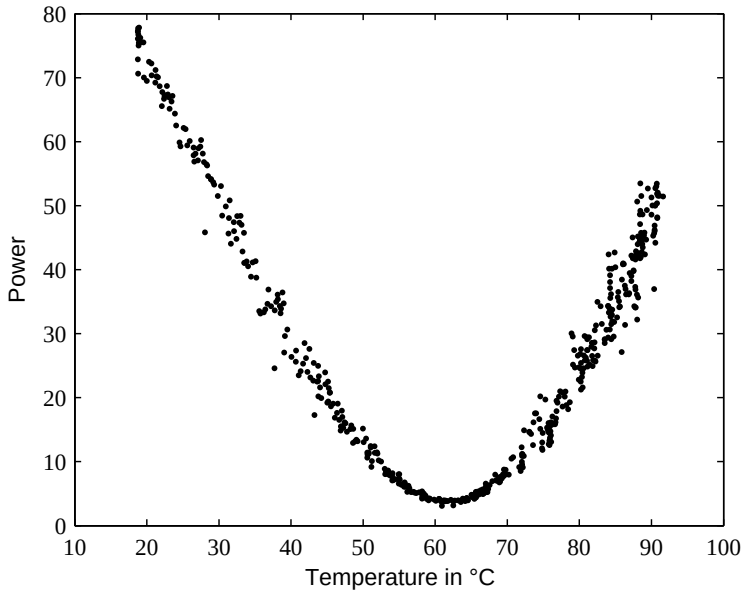


Figure 4.5: Plot of power vs. temperature for an unetched fiber.

indicates that the change in birefringence in the polymer waveguide does not remain linear with temperature.

The polarimetric sensor can be used for detecting relative changes in temperature. Since there are more oscillations in the power curve for the core-replaced fiber, it is more sensitive to temperature. This means that it could be used to detect a smaller change in temperature than the plain fiber could. For example, if our setup could detect a change in power of 1 μW, then the unetched fiber could only detect a minimum change of 0.43°C. The core-replaced fiber, would be able to detect a change of 0.08°C. So the core-replaced fiber is five times more sensitive to small changes in the temperature.

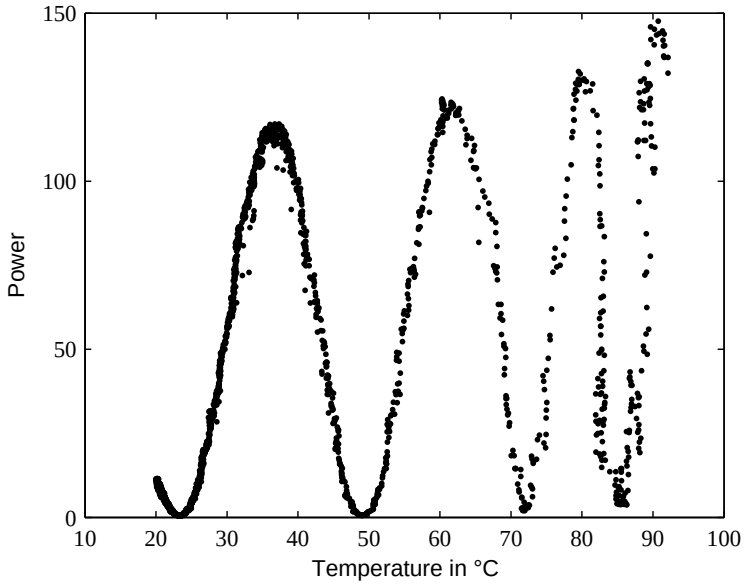


Figure 4.6: Plot of power vs. temperature for a core-replaced fiber.

Chapter 5

Conclusions

5.1 Contributions

Selective chemical etching with HF acid enables the core to be removed out of the cladding. This core removal process produces a platform which can be used to replace the core with another material. The new core material can be used to sense various parameters.

The goal of the work was to demonstrate enhanced sensing by replacing the core of a D-shaped optical fiber with polymer. My contribution can be summarized by the following list:

- Demonstration of sensing using a core-replaced D-fiber.
- Demonstration of a fiber polarimetric temperature sensor.
- Demonstration of enhanced sensing using core-replacement technology in the polarimetric fiber sensor.

5.1.1 Demonstration of Sensing Using a Core-replaced D-fiber

First of all, I demonstrated that the core-replaced D-fiber can be used for sensing. As an example of this, I replaced a section of the core of the fiber with a polymer made from PMMA and DR1 azo dye, which is more sensitive to temperature than the core. In order to do this we had to develop methods for etching out the core of the fiber and forming a low-loss polymer waveguide in it.

5.1.2 Demonstration of Fiber Polarimetric Temperature Sensor

Using these methods I created a core-replaced D-fiber sensor and tested it over a range of temperatures from 20°C to 95°C. I created the fiber temperature sensor using a polarimetric sensing configuration. This was done by sending polarized light into the fiber at a 45° angle to the major axis of the core and using a polarizer oriented at −45° to the major axis of the core at the output of the fiber as an analyzer. A laser at 1550 nm was sent through a polarizer and then focused into one end of the fiber. The polarizer was oriented at a 45° angle to the major axis of the core. A second polarizer was placed at the output to act as an analyzer. It was oriented at −45° to the major axis of the core. A detector was placed after the polarizer to monitor the intensity as temperature was varied.

This configuration uses the birefringence of the fiber to detect changes in the fiber's temperature. The light travels in two orthogonal modes in the fiber. As the temperature of the fiber changes, the effective indices of refraction of the modes change. This change results in a change in the polarization of the light. This change in polarization is then detected as a change in intensity through the use of the polarizers.

5.1.3 Demonstration of Enhanced Core-replaced Sensor

The sensitivity of the polarimetric fiber sensor created can be enhanced by replacing the core of the fiber with a material more sensitive to the environmental variable. A polymer waveguide in the core of the fiber has an increased $\frac{\mathrm{d}n}{\mathrm{d}T}$ over the glass fiber. Because of this, there is more change in polarization of the light in the core-replaced fiber for a given length of fiber and temperature range than there is in an unetched fiber. The increased change in polarization means an increased change in sensitivity. The core-replaced sensor showed a sensitivity of about five times that of an unetched fiber sensor.

5.2 Future Work

5.2.1 Different Sensing Configurations

The polarimetric temperature sensor created for this thesis shows that a core-replaced fiber can be used for creating sensors. However, this type of sensor may not be the ideal type to use for sensing temperature because of the periodic change in intensity with temperature. The idea can be expanded to other types of sensing configurations. Future work involves figuring out how to use this core-replacement technology in other configurations that may work better for different applications. One possibility is the use of gratings at both ends of the section of replaced core to set up a Fabry-Perot type device. Other sensing configurations could also be explored.

5.2.2 Different Sensing Materials

Another avenue of exploration in this work is in the use of other sensing materials. The polymer used is sensitive to temperature. Other materials could be used that are sensitive to other environmental variables such as pressure, humidity, or the absence or presence of chemicals or biological substances. Through the development of these other materials as waveguides in the fiber, sensors for these different areas can be created and used.

Appendix A

Detailed Processes

A.1 Fiber Preparation

A.1.1 Stripping

1. Cut a length of fiber from the spool. It should be long enough to easily use for the etch setup and the experiment setup. It should be long enough to allow maneuverability of the fiber holder in the setup without putting tension on the fiber.

2. Put on appropriate gloves for handling Dichloromethane.

3. Strip a section of the middle of the fiber:

   (a) Locate the middle of the fiber and hold it in a loop. As long as the jacket is still on the fiber, it can go into a fairly tight loop. If a section without jacket is bent into a loop tight enough to go into the vial, it will most likely break.

   (b) Lower the loop into the vial of dichloromethane and let sit for a few seconds.

   (c) Pull the fiber out of the vial and pull your fingers along the fiber where it was in the dichloromethane. The jacket should crumble off in your fingers. Stop pulling when the stripped section is long enough. Two centimeters is usually a good length for an etch.

   (d) If the jacket did not come off, try the process again.

4. Strip the ends:

   (a) Dip the ends of the fiber into the dichloromethane for several seconds.

   (b) Take each fiber end out of the dichoromethane separately.

   (c) Grab the end with your fingers and pull the jacket off. It should easily slide off. If this does not happen, put it back into the dichloromethane for several more seconds.

   (d) The stripped part should be about $1\frac{1}{2}$ to 2 centimeters long.

A.1.2 Cleaving

1. Cleave the ends of the fiber using the Fujikura cleaver:

   (a) Make sure the blade is in the forward position.

   (b) Place the fiber in the holder on the cleaver with the stripped part over the blade area and close the first part of the holder.

   (c) Turn the fiber so that the flat side is up.

   (d) Close the top (1).

   (e) Slide blade in the direction of the arrow (2).

   (f) Tap lever down (3).

   (g) Remove the fiber and check the cleave using a 40× objective.
   NOTE: the only way to get valid max throughput measurements is to have "perfect cleaves."

A.2 Fiber Holder

1. Place the fiber in the fiber holder. Make sure that when the magnet holders slide toward each other the fiber does not bend to one side. This is often a tedious job.

   (a) Remove the top magnets.

   (b) Place the fiber over the holder so that the etched region is in the center.

(c) Replace one of the top magnets.

(d) Let the other end of the fiber hang down in a natural way. It likes to curve so that the flat side is up.

(e) Pull the fiber tight and replace the other magnet.

(f) Remove the first magnet and repeat for that side. It might take a couple of times for each side to get it straight. Test by sliding the magnets together. The fiber should bend in a curve that goes straight down.

2. For an etch, the fiber must be able to make a loop deep enough to allow the 2 cm of stripped region to be submersed in the HF.

A.3 Dip Etch

1. Place the metal pan on the optical breadboard in the fume hood (Doug's little etch hood).

2. Fill the water container(labeled H_2O) with DI water and place it in the metal pan. The DI water is in a five-gallon container under the sink. It can be refilled from behind the clean room.

3. Place the fiber holder with the fiber on the water container.

4. Use the 670 nm red laser for the etch. Focus the light into the fiber and record the max value in the correct cell of the Excel program. This will tell the loss at which the fiber should be removed from the 5% etch. There should be an excel sheet kept for every etch performed.

5. Suit up in the acid gear: apron, splash goggles, face shield, nitrile gloves.

6. Start the LabVIEW program "red.vi."

7. Place the container of 25% HF acid into the pan and remove the lid.

8. Clean off the fiber by spraying methanol down the stripped region of the fiber.

9. Place the fiber holder on the HF container and move the magnets until 2cm of fiber are under the acid. Start a timer to time the process. You probably don't want to inhale deeply unless you like the smell of HF. (Do not breath fumes.)

10. Monitor the etch using the LabVIEW program and/or a timer.

11. Remove the fiber and place it in the DI water container after the core has been penetrated. This occurs when the power starts to drop quickly. At 20°C it will take ∼40 minutes.
    NOTE: Make sure the section of the fiber that was being etched is under the water or the etch will not be entirely neutralized.

12. Remove the container of 25% HF acid and place the container of 5% HF acid in the pan.

13. Place the fiber in the 5% HF acid. Make sure the entire region that was etched in the 25% HF acid is completely submerged in the 5% HF acid. Since this one etches so much slower, it is okay to put it in as far as it will go. For example it would be fine if the jacket section is under the HF acid.

14. Remove the fiber from the 5% HF acid at the desired power loss and place it in the DI water. We aim for a loss of -6.8 dB. Focus the fiber. Usually it has fallen out of alignment. If the power yields less than -6.8 dB dip it back in the acid. Continue to dip and focus until the desired power is achieved.
    NOTE: Do not dip the fiber in too long or it may easily etch past the point of interest. We usually dip it in and remove it immediately.

15. Record the power in the appropriate cell of the Excel spreadsheet.

16. Clean off the fiber with methanol and place in the clean room. Do this quickly to avoid getting any contaminants in the etched out core.

17. Stop LabVIEW by pressing the "Stop and Save" button.

18. Put the lid back on the acid and put it away.

19. Rinse out water container and metal pan.

A.4 Polymer Application

These steps take place in the clean room.

A.4.1 Apply Polymer

1. Set the spinner to spin at the desired spin speed when a 4-inch wafer is placed on it. This can be done when cleaning the wafer off with acetone, methanol, and isopropyl alcohol. When it is at the desired speed, just flip the switch to shut off the motor. Leave the speed set. The control box above the spinner can be used to determine the speed. Multiply the number displayed by five to obtain the correct rpm.

2. Remove the fiber from the holder and clean the etched region using methanol followed by isopropyl alcohol. These solvents should be squirted down the length of the fiber.

3. Blow the fiber dry using the nitrogen gun.

4. Tape the fiber securely to the back of a 4-inch wafer. (It is a lot easier to see the etched out groove when the fiber is taped to the back of the wafer.) The flat of the fiber must be up. This should be obvious under the microscope. The microscope can also be used to check for junk and "hills."

5. Place the end of four 2-inch pieces of tape on the back of a clean wafer. Wrap the excess fiber around the wafer sticking it to these pieces of tape. When the fiber has been wrapped, stick the tape down on the front of the wafer.
   NOTE: do not squeeze the tape loop together.

6. Place the wafer with the fiber on the spinner. Be careful not to pinch the fiber.

7. Apply the polymer using a plastic pipette. Avoid getting bubbles on the fiber. Immediately turn on the motor for the spinner and time it for one minute.

8. Turn off the spinner and remove the wafer.

A.4.2 Bake

1. Turn on the LFE vacuum pump behind the clean room before entering the clean room.

2. Make sure that the vacuum oven is set to 90°C (This is so when the knob is set to the little scratch.), but be sure to start with it cooler than 50°C with the door shut.

3. Turn on the oven and let it heat to 50°C.

4. When the oven has reached 50°C, open it and place the wafer with the fiber inside.

5. Close the door and open the vacuum valve. Let it pump down until the pressure gauge has the needle pointing straight up, then close the valve.

6. Let it bake for at least one hour. It should heat up to 90°C during this time.

7. After an hour turn off the oven and purge the chamber.

8. Remove the fiber.

A.5 Polymer Mixing

1. Clean a glass jar using acetone and isopropanol. Dry it with the nitrogen gun.

2. Measure 8 g of PMMA into the jar.

3. Measure 0.6 g of DR1 into the jar.

4. Measure 30 mL of MEK into the jar.

5. Measure 90 mL of Chlorobenzene into the jar.

6. Place a clean stir bar into the jar.
7. Put the lid on the jar.
8. Place the jar on the stirrer set at 6-7.
9. Let stir for 24 hours.
10. Put a .2μm filter on a 60 mL syringe.
11. Draw the polymer through the filter into the syringe.
12. Remove the filter and squirt polymer into clean container.

Bibliography

[1] J. M. López-Higuera, Ed., *Handbook of Optical Fibre Sensing Technology*, Wiley, Chichester, UK, 2002.

[2] E. Udd, "An overview of fiber-optic sensors," *Rev. Sci. Instr.*, vol. 66, pp. 4015–4030, 1995.

[3] A. Messica, A. Greenstein, A. Katzir, U. Schiessl, and M. Tacke, "Fiber-optic evanescent wave sensor for gas detection," *Opt. Lett.*, vol. 19, pp. 1167–1169, 1994.

[4] V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors," *Opt. Lett.*, vol. 21, pp. 692–694, 1996.

[5] S. Mononobe and M. Ohtsu, "Fabrication of a pencil-shaped fiber probe for near-field optics by selective chemical etching," *Journal of Lightwave Technology*, vol. 14, pp. 2231–2235, 1996.

[6] D. J. Markos, B. L. Ipson, K. H. Smith, S. M. Schultz, R. H. Selfridge, T. D. Monte, R. B. Dyott, and G. Miller, "Controlled core removal from a d-shaped optical fiber," *Applied Optics*, vol. 42, no. 36, pp. 7121–7125, Dec 2003.

[7] K. H. Smith, R. H. Selfridge, S. M. Schultz, D. J. Markos, and B. L. Ipson, "Analysis of replacing an optical fiber core with polymer," *Optics Express*, vol. 12, no. 3, pp. 354–360, Feb 2004.

[8] K. H. Smith, D. J. Markos, B. L. Ipson, S. M. Schultz, R. H. Selfridge, J. P. Barber, K. J. Campbell, and T. D. Monte, "Fabrication and analysis of a low-loss in-fiber active polymer waveguide," *Applied Optics*, vol. 43, no. 4, pp. 933–939, Feb 2004.

[9] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, John Wiley & Sons, Inc., New York/ Chichester / Brisbane / Toronto / Singapore, 1991.

[10] W. J. Bock, T. R. Wolinski, and A. Barwicz, "Development of a polarimetric optical fiber sensor for electronic measurement of high pressure," *IEEE Transactions on Instrumentation and Measurement*, vol. 39, no. 5, pp. 715–721, Oct 1990.

[11] R. B. Dyott, *Elliptical Fiber Waveguides*, Artech House, 1995.

[12] B. Ipson, R. Selfridge, K. Smith, and S. Schultz, "Enhanced temperature sensing with in-fiber polymer waveguides," *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 5391, pp. 286–292, Jul 2004.

[13] K. Smith, B. Ipson, R. Selfridge, and S. Schultz, "Versatile in-fiber sensing using core-replaced d-fiber," *Applied Optics*, Submitted for publication.

[14] F. Zhang and J. W. Y. Lit, "Temperature and strain sensitivities of high-birefringence elliptical fibers," *Applied Optics*, vol. 31, no. 9, pp. 1239–1243, Mar 1992.