This research investigates the use of fiber Bragg gratings (FBGs) as thermal sensors in high temperature environments with rapidly changing and complex thermal or structural loads. To test the capabilities of FBGs in complex environments, a proof of concept experiment where two FBG arrays were embedded in a thermal protection system (TPS) material exposed to a steady state 200°C temperature load was conducted. One embedded FBG array was horizontally embedded in the specimen near the surface exposed to the temperature load and the second array was embedded diagonally, sloping away from the temperature load. The FBGs behaved well during the experiment and output realistic temperature data and fast response time. The response of the FBGs was consistent between two repeated tests.

Due to the presence of the diagonal array in the proof of concept test, the question arose as to what happens when a nonuniform, dynamically changing, varying temperature load is applied over the length of a grating. An experiment involving two different temperature fluid baths was designed to investigate the effect of temperature gradients on FBG response. The difference in temperature between the two baths forced a dynamically changing temperature gradient over the length of a FBG located in the partition separating the baths. The spectrum deformation of the FBG response due to the gradient was recorded and compared to a numerical model. A mathematical equation between temperature difference over the grating length and bandwidth change was developed to quantify the magnitude of the temperature difference between ends of a FBG given an observed bandwidth change.
Since FBGs are sensitive to both temperature and strain, mathematical models discriminating between the temperature and strain response of a FBG were derived for free, bonded, and embedded FBGs when both strain and temperature loads are present. These models were validated by placing a FBG array with free, bonded, and embedded FBGs in an oven and monitoring the wavelength response of each FBG to a known temperature load. The validated models were applied to Bragg wavelength shifts of FBGs subjected to nonuniform strain and temperature gradients, and the reflected FBG spectra calculated from the temperature and strain gradients determined by the mathematical models were compared to the experimentally observed reflected spectra.

Finally, the response of FBGs exposed to dynamic flame loads were tested. FBGs were embedded in a cube shaped, generic TPS specimen. The specimen was initially exposed to steady state and transient temperature loads provided by a hot plate. The hot plate tests were designed to be similar to the experiments conducted in the proof of concept tests to show FBGs would respond well to high temperature loads regardless of the host material. The cube specimen was also exposed to a dynamic flame load. Different sensor geometries and flame loads were tested, and in some experiments FBGs were embedded next to thermocouples and the response of the two sensor systems were compared. In all tests, FBGs output accurate temperature measurements with a response time that exceeded that of the thermocouples.
Characterization of Fiber Bragg Gratings as Thermal Sensors in Complex Environments

by
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DEDICATION

This dissertation is dedicated to those in my life to whom this dissertation would not have been possible without. To my parents Steve and Paige for their patience and continuous encouragement throughout my life and this process. To my dad for encouraging a love of math, science and a wonder at exploring new things all the while asserting I remain a balanced individual. To my mom for raising me in a safe and loving household, assuring my needs were always met and handling three sometimes rowdy sons like a champ. To my brothers, Eric and Brian for their constant companionship and friendship through childhood into adulthood, and for remaining competitive while consistently beatable in Mario Kart. Finally, I would like to thank my Lord and my God, Jesus Christ. In him I can do all things for he strengthens me, and through him all things hold together.
BIOGRAPHY

Drew Alexander Hackney was born on April 1st, 1986 in Rockville, Maryland to Stephen and Paige Hackney before moving to Houghton, MI before his first birthday. Drew was joined in his childhood by two brothers, Eric who is one year older and Brian who is one year younger. Drew received his B.S. in Mechanical Engineering in May of 2008 from Cedarville University in Cedarville, OH. Drew continued his formal education under the guidance of Dr. Kara Peters at North Carolina State University where he obtained his M.S. in Mechanical Engineering in May 2010. After receiving his M.S., Drew moved to Colorado Springs, CO to work for the United States Missile Defense Agency as a Contracting Officer’s Technical Representative. After a year in Colorado Springs, Drew returned to Raleigh, NC and North Carolina State University to complete his formal education by pursuing a Doctorate of Philosophy in Mechanical Engineering under the continued direction of Dr. Kara Peters. In his spare time, Drew enjoys reading, spending time outside hiking, and playing the banjo.
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CHAPTER 1

INTRODUCTION

1.1 FIBER BRAGG GRATINGS

1.1.1. Theory and Overview

Fiber Bragg gratings (FBGs) are a periodic change to the refractive index of a portion of an optical fiber. Initially developed in 1978 as filters, FBGs cause a narrow peak of light centered on a specific wavelength to be reflected back to the original source (Hill et al., 1978). The periodic change can be expressed mathematically by equation 1.1.

\[
n_{\text{eff}}(z) = \bar{n}_{\text{eff}} + \delta n_{\text{eff}} \left\{ 1 + \nu \cos \left( \frac{2\pi}{\Lambda} + \phi(z) \right) \right\}
\]  

\(\bar{n}_{\text{eff}}\) is the effective refractive index of the fundamental model of the optical fiber, \(z\) is the distance along the axis of the fiber, \(\delta n_{\text{eff}}\) is “dc” average index change, \(\nu\) is the fringe visibility, \(\Lambda\) is the period of the period change to the refractive index, and \(\phi(z)\) is the grating chirp which is defined as any variation in the period along the grating length (Erdogan, 1997). A diagram of the reflected and transmitted spectra due to an FBG is shown in Fig. 1.1.

FBGs began to be investigated for use as sensors in the early 1990’s (Morey et al., 1990). As a temperature change or strain is applied to the grating, the location of the reflected Bragg peak shifts by amount \(\Delta \lambda_B\) as given by Equation 1.2.

\[
\Delta \lambda_B = \lambda_B (C_s \epsilon + C_T \Delta T)
\]  

\(\lambda_B\)
\( \lambda_B \) is the initial Bragg wavelength of the FBG, \( C_s \) is the coefficient of strain, \( \varepsilon \) is the applied strain on the grating, \( C_T \) is the coefficient of temperature, and \( \Delta T \) is the temperature change on the grating. In the case of a pure temperature load applied to a grating initially at room temperature, the change in Bragg wavelength can be determined using equation 1.3.

\[
\Delta \lambda_B = \lambda_B [\alpha + \beta] \Delta T
\]  

(1.3)

\( \alpha \) is the coefficient of thermal expansion of the silica and \( \beta \) is the thermo-optic coefficient of the grating. The thermo-optic coefficient is defined as the proportional shift of the Bragg wavelength due to the material index of refraction change. From equation 1.3, the change in temperature measured by the grating can be calculated using equation 1.4.

\[
\Delta T = \frac{1}{(\xi + \alpha)} \left[ \frac{\Delta \lambda_B}{\lambda_B} \right]
\]  

(1.4)

FBG sensors have advantages over traditional sensors. Multiple gratings can be written on a single fiber optic strand and interrogated at the same time by a single laser and photodetector. This multiplexing of FBGs reduces the amount of instrumentation needs to interrogate the sensor suite, interrogation time, and the weight of the sensor network.

### 1.1.2. Durability of FBGs at High Temperatures

While FBGs have proven themselves as adequate temperature and strain sensors, their applications at high temperature environments have been limited. However, FBGs have been used for high temperature applications such as down hole oil wells where temperatures can range from 50°C to as high as 400°C as well as gas turbines, coal boilers, aluminum smelting furnaces, and power plants (Åslund et al., 2010, Sun and Ma, 2010; Chen et al., 2011).
The main limitations of the maximum temperature range for FBG sensors are the material temperature limit for the silica, the temperature limit of the coating material, and the chemical stability of the index of refraction increase in the FBG. The silica of conventional optical fibers can survive temperatures as high as 1190°C. The temperature range of FBGs can be extended by replacing the silica of the fibers with sapphire. Fibers made out of sapphire do not melt until 2040°C; however, acquiring sapphire fibers in long lengths is difficult as is adding additional cladding (Grobnic and Mihailov, 2004). Therefore, these fibers have been limited to research applications.

Optical fibers are coated with a protective layer to increase their resistance to wear and prevent moisture ingress into the silica. The most common coating for optical fiber sensors is polyimide. While polyimide has a large temperature range, from -190°C to as high as 385°C, it is unsuitable for the temperature ranges commonly found in high temperature applications such as turbines or furnaces. Commonly, gold is used as a coating when an optical fiber is in a high temperature environment as the melting temperature of gold is approximately 800°C. One issue with gold is that it is a very soft metal and is normally applied as a coating in a gold-nickel alloy. For environments with temperatures exceeding the melting point of gold, a common coating is platinum which has a melting point of 1772°C (Black and Moslehi, 2010). Though metallic coatings do generally have high melting temperatures, some metals chemically react with silica at high temperatures (Butov et al., 2006). In addition to externally applied coatings, fibers can also be “self-coated,” which is an unusually thick cladding. Advantages of an unusually thick cladding are cost as metallic coatings such as gold and platinum are expensive. However, using a self-coating fiber increases the fiber diameter which
generates larger stress concentrations during the embedding process, and does not protect the fiber as well as a separate coating.

While the fiber material and applied coatings both limit the temperature range at which FBG sensors can be used, the grating itself is the primary limiting factor for using FBGs at high temperatures. The Bragg grating response in gratings of Type I gratings written with traditional methods such as the phased mask technique tends to decay under high temperature thermal loads due to the index of refraction of the written grating relaxing. As a result, traditionally written gratings should not be used at temperatures exceeding 300°C (Butov et al., 2006; Barrera et al., 2011). The operational temperature of FBGs can be increased up to 1150°C by using nitrogen doping to create the basis for the chemical reaction during FBG fabrication, rather than germanium which is more common (Butov et al., 2006).

Traditionally written gratings begin to decay as a power law function of time at approximately 300°C (Butov et al., 2006; Barrera et al., 2011); however, high temperature gratings such as Type IIA gratings can provide accurate readings at temperatures as high as 500°C (Canning et al., 1999) or 700°C (Groothoff and Canning, 2004). The equation defining the power law decay is seen in equation 1.5.

\[ f(t) = at^k \]  \hspace{1cm} (1.5)

The exponent, \( k \), and the coefficient of multiplication of the decay, \( a \), both depend on the applied temperature. Furthermore, as a result of decaying as a power law, the grating decay can be somewhat mitigated by writing initially strong gratings. Erdogan \textit{et al.} (1994) did an experiment where they wrote two gratings, the first grating had twice the strength of the second. A high thermal load was applied to the first grating so it decayed to the strength of the
second grating. Upon further temperature based decay, the initially stronger grating decayed significantly less than the initially weaker grating over the same period of time. Furthermore, the larger the change in the photoinduced change of refractive index of the fiber, the larger the decay in the reflectivity of the FBG with temperature (Morey et al., 1994).

Long term temperature exposure also causes a permanent Bragg shift in the sensor due to germanium moving out of the fiber core. The rate of the shift is proportional to the temperature. At 370°C, a permanent 0.01 nm shift in the Bragg wavelength would require 10 million years; however, at 800°C, a permanent 0.01 nm shift only requires 100 hours (Morey et al., 1994).

1.1.3. Behavior of FBGs at High Temperatures and Thermal Gradients

While often assumed to be linear near room temperature, the temperature response of FBGs is in fact non-linear over a much wider range. Reid and Özcan (1998) showed the relationship between wavelength shift and temperature change for FBGs becomes increasingly non-linear as the temperature approaches absolute zero for germanium doped silica fibers. For these temperatures, a third order polynomial is best used to fit the temperature shift-wavelength dependence. Furthermore, they showed the relationship between wavelength shift and temperature change is second order whether the FBG is embedded or free (Reid and Özcan, 1998). At temperatures near room temperature, the wavelength shift due to temperature was found to be best fit by a second order equation between -70°C and 80°C (Flockhart et al., 2004) for gratings written into Ge-doped fibers. Pal et al. (2004) expanded the temperature range to 250°C, which is near the maximum service temperature for Ge-doped Type I FBGs, and found
a second order fit continued fit the data well. Over the temperature range investigated by Flockhart et al. (2004) and Pal et al. (2004), the coefficient of thermal expansion of silica, \( \alpha \), is near constant. The variation in temperature response must therefore be due to the thermo-optic coefficient of the FBG, \( \beta \). By applying a linear temperature dependence, the difference in wavelength shift between measured wavelength and the wavelength given by the linear fit can be as high as 30 pm (Flockhart et al., 2004) or 60 pm (Pal et al., 2004). These residuals result in errors of approximately 3°C or 6°C, respectively. Therefore, applying a second order fit to the data is important and has a consequential effect on the accuracy of the temperature response.

When exposed to high temperatures, a temperature gradient can also develop over the length of the FBG. Gradients of temperature or strain can result in a chirped response by the FBG. Chirps due to strain are a well-known issue first investigated by Hill and Eggleton where they forced a non-uniform strain to develop over the length of an FBG by applying a varying tensile load to the optical fiber as the FBG was bonded to a host material and observed the spectrum deformation (Hill and Eggleton, 1994). Strain gradients are common in FBGs embedded in composite laminates (Kuang et al. 2001a; 2001b; Minakuchi et al, 2007; Hackney and Peters, 2011). The resulting deformed spectrum shape can overwhelm peak wavelength tracking interrogation (Peters et al. 2001; Webb et al. 2011). To accurately determine information from distorted spectra, dynamic full spectrum interrogation is required (Webb et al. 2011; Webb et al. 2012). Chirped spectra due to temperature gradients are not as prevalent due to the small sensing length of FBGs and the severity of the temperature gradients that would be required to develop a significant chirp.
FBG chirp due to temperature has been produced by Lauzon et al. (1994) by setting an optical fiber with a written FBG in a 250 μm deep V-groove machined into a brass plate spanning two temperature controllers, one temperature controller with an attached heat sink to act as the “cool” side of the brass bridge. Lauzon et al. (1994) used their setup to apply temperature gradients across the length of the FBG of 5.6°C and 26.1°C which increased the full width half maximum bandwidth of the reflected FBG spectrum by 0.027 nm and 0.137 nm, respectively. Chen et al. (2001) produced a thermal gradient over the length of an FBG by encasing the FBG in a metal sleeve and wrapping the sleeve in a heating wire. The coil spacing varied with distance along the FBG. By altering the current through the heating wire, Chen et al. (2001) were able to vary the bandwidth of the FBG spectrum. Higher temperature gradients, of the magnitude to be presented in this work, have not been presented in the literature.

1.1.4 Discrimination Between Strain and Temperature in Embedded FBGs

As equation 1.2 showed, FBGs are sensitive to both strain and temperature. The separation of the temperature and strain responses of FBGs has been the focus of research for the past 15 years, especially when monitoring curing temperatures and strains in composite laminates (Tanaka et al., 2003; Frazão et al., 2005; Yoon et al., 2005; Waris et al., 2014). Xu et al. (1994) first discriminated the strain and temperature response for an FBG using a dual wavelength grating with wavelengths of 850 nm and 1300 nm and equation 1.6.

\[
\begin{bmatrix}
\Delta \lambda_{B1} \\
\Delta \lambda_{B2}
\end{bmatrix} = \begin{bmatrix}
K_{\varepsilon 1} & K_{T 1} \\
K_{\varepsilon 1} & K_{T 2}
\end{bmatrix} \begin{bmatrix}
\Delta \varepsilon \\
\Delta T
\end{bmatrix}
\] (1.6)
Δλ_{B1} and Δλ_{B2} are the Bragg wavelength shifts of each wavelength in the dual wavelength FBG, Δε and ΔT are the strain and temperature changes applied to the FBG, and K_{ε1}, K_{T1}, K_{ε2} and K_{T1} are the experimentally determined coefficients for the strain and temperature dependence of both wavelengths in the grating. To determine the K-matrix, strain and temperature were independently applied to the grating (Xu et al., 1994).

While discriminating between the temperature and strain response can be a challenge, a single sensor able to measure both temperature and strain does have advantages. Waris et al. (2014) used FBGs to measure the residual strains present in composite laminates after curing due to the differing thermal expansion coefficients of the mold and the laminate for different molds and curing temperatures. The authors were able to separate out the strain and temperature response of the FBG mathematically using the known material properties of the mold and laminate.

If the material properties of the host material are unknown, commonly arrays of multiple FBGs are used to discriminate between the strain and temperature response of each FBG. Discrimination is often achieved by closely splicing two FBGs together with optical fibers that are doped differently. The different dopings result in different temperature dependencies for the two gratings (Cavaleiro et al., 1999; Yoon et al., 2005). Another common method to discriminate between temperature and strain using multiple gratings is to bond one grating to the host material and encase a second grating in a thermally conductive sleeve. The bonded grating measures both temperature and strain from the host material while the second grating is affected by temperature but free of strain in the sleeve (Hayat and Ha, 2013).
There are several methods to discriminate between the temperature and strain response of a FBG using a single sensor. Chehura et al. (2007) used a single tilted FBG. A tilted FBG refers to the grating not being written orthogonal to the longitudinal axis of the fiber. Using a tilted FBG, Chehura et al. (2007) were able to separate the wavelength shift due to temperature change from the wavelength shift due to an applied strain by comparing the wavelength shift in the core of the fiber and the wavelength shift of the core-cladding mode of the fiber. The drawback of using a tilted FBG is the FBG spectrum must be recorded and analyzed in transmission which eliminates the single ended operation benefit of FBGs. A second method to separate the strain and temperature response using a single FBG is to use a superstructured FBG. As temperature or strain is applied to the grating, the wavelength shifts as does the intensity of the superstructuring. Monitoring both the wavelength shift and the change in the superstructuring intensity allows discrimination between temperature and wavelength (Guan and Tam, 2000). A single, conventionally written, FBG is able to discriminate between the temperature and strain response by analyzing the wavelength response given by the primary and secondary harmonic wavelengths, though the secondary harmonic is usually weak (Brady et al., 1997). Another way to discriminate temperature and strain using a single, traditionally written FBG is with the aid of an erbium-doped fiber amplifier (EDFA). The transmission power of the EDFA varies almost linearly with temperature. When multiplexed in series with a FBG, the EDFA alters the intensity of the FBG output. Based on the change in intensity, temperature data can be determined independently from strain (Jung et al., 1999).
1.2 THERMAL PROTECTION SYSTEM (TPS) APPLICATIONS

During atmospheric reentry, spacecraft undergo high thermal loads. For example, NASA’s space shuttle orbiter would commonly experience temperatures as high as 1640°C on the nose and leading edges of the wings during reentry (Hanlon et al., 2006). Unlike the orbiter which used lifting reentry, currently designed spacecraft reenter the atmosphere using ballistic reentry. In lifting reentry, the spacecraft enters the atmosphere with a nonzero angle of attack, whereas the angle of attack during ballistic reentry is zero (Schlee and Atkinson, 2009). As a result, the thermal loads experienced by currently designed spacecraft are considerably higher than those experienced by the Shuttle Orbiters, and non-reusable ablative thermal protection systems (TPS) materials which can protect reentry at these higher temperatures must be used (Marra et al., 2010).

Due to the importance of TPS, instrumenting these materials to determine the temperature profile at heat flux through the thickness of the material during reentry conditions has been a recent research focus (Hanlon et al., 2006; Schlee and Atkinson, 2009; Black and Moslehi, 2010; Moslehi et al., 2012a; Moslehi et al., 2012b; White et al., 2011). In current NASA testing, metallic thermocouples are embedded in TPS materials using instrumented plugs. An example of such a plug is shown in Fig. 1.2.

Plugs are made out of the same TPS materials as the rest of the heat shield to eliminate material inaccuracies. The plug is inserted into the host TPS material and held in place using an adhesive. Typically, instrumented plugs are placed throughout the heat shield to provide spatially distributed information on its performance. The process of instrumenting a TPS with plugs requires significant post production alterations to the material (White et al., 2011).
Similarly, other researchers have also applied metallic thermocouples to measure temperature profiles within the TPS material (Milos and Karunaratne, 2003). However, the accuracy of temperature or heat flux profiles within TPS materials reconstructed from metallic thermocouple data is limited for a few reasons. First, the response time of metallic thermocouple is relatively slow due to the high thermal mass of most thermocouples. Second, each thermocouple requires its own lead-in and lead-out wire, therefore the number of thermocouples and equipment necessary to effectively measure a TPS can add significant weight to the spacecraft which drives up launch costs. For the same reason, the number of thermocouples that can be integrated into a volume of TPS material is limited. Finally, there is a large discrepancy in the thermal properties of metallic thermocouples and typical TPS materials. The thermal conductivity of many TPS materials ranges between 0.1-0.2 W m\(^{-1}\)K\(^{-1}\) (Pulci et al., 2010), whereas the thermal conductivity of mechanical thermocouple materials is significantly higher and can range from 20-200 W m\(^{-1}\) K\(^{-1}\) (Bejan, 1993). Therefore, the temperature measured by the thermocouple may not accurately match the surrounding TPS material to be monitored.

The heat shield of the Mars Science Laboratory (MSL) was instrumented with seven TPS plugs, five with four thermocouples and the remaining two with only two thermocouples. During Martian entry on August 5\(^{th}\), 2012, the thermocouple suite on the MSL recorded and transmitted temperature data to earth. During entry, the temperature output by the leeside plugs exceeds the modeled temperatures at the surface by approximately 400°C while the surface temperatures are approximately 100°C less in the experimental data than what is present in the
models. The deeper thermocouples show generally good agreement between the model and the TPS plug data (Little et al., 2013).

FBGs can serve as an alternative temperature sensor to metallic sensors for TPS applications (Milos and Karunaratne, 2003; Black and Moslehi, 2010; Rapp and Baier, 2010). FBGs have several advantages for structural health monitoring in TPS materials as compared to metallic thermocouples. First, due to the small radius of optical fibers, FBGs can be embedded within materials such as composite laminates with minimal structural impact (Askins et al., 1994). Furthermore, multiple sensors can be written on a single fiber and simultaneously interrogated using a single interrogator in what is known as multiplexing (Spencer and Braun, 1996). Multiplexing capability can drastically reduce the weight of the sensor suite and the instrumentation required to interrogate the network during operation (Black and Moslehi, 2010). An example of a multiplexed spectrum is shown in Fig. 1.3.

Additionally, sensors can be embedded at a high spatial density. For example, Black and Moslehi reported measurements from an array of 8 FBGs in a single optical fiber embedded in a TPS panel, along with a metallic thermocouple placed near one of the gratings. Under an applied heating load, the FBGs measured a temperature increase at different rates depending on the distance between the heat load and the individual gratings. With values between 0.8 and 1.1, the thermal conductivity of silica is also much closer to that of TPS materials (Bejan, 1993) than thermocouples. In their experiment, Black and Moslehi observed the thermocouple recorded a higher rate of temperature change than the nearest FBG and also cooled at a faster rate. This can be attributed to the higher thermal conductivity of the metallic thermocouple compared to that of the silica fiber (Black and Moslehi, 2010).
Rapp and Baier (2010) embedded an array of nine FBG sensors at the interface between the carbon fiber reinforced polymer facesheets and metallic honeycomb core of sandwich panels commonly used in satellites and applied thermal hot spots to six different locations on the surface of the sandwich panel using heat resistors. The FBG array was used to determine the location and intensity of each hot spot while the location and intensity of each hot spot was independently measured and verified using an IR camera. The FBG array was able to accurately measure the both the location and the intensity of each hot spot.

1.3. SCOPE OF RESEARCH

The goal of this research is to investigate the behavior and use of FBGs at high temperatures, using FBGs as embedded sensors in TPS materials as a specific case study. This research looks to build upon the work previously done into embedding FBGs in TPS materials by authors such as Black and Moslehi (2010). Due to their availability and low cost compared to other gratings, Type I FBGs written into standard 125 μm diameter optical fiber will be used in this work. This will limit the maximum temperature the gratings can be exposed to approximately 300°C which is well below temperatures experienced by TPS materials during reentry (Little et al., 2013); however, the FBG behavior at temperatures below 300°C can reveal many of the behaviors expected at higher temperatures and the physical principles behind these behaviors. Developing response models at lower temperatures can serve as preliminary models for future high temperature testing. Additionally, this research will explore some of the sources of data error encountered when FBGs are used at high temperatures.
Therefore, the research presented in this document has been divided into the following objectives:

1. Investigate the temperature response of FBGs in a high temperature, complex loading application and characterize the response. To achieve this objective, FBG arrays were embedded in an irregularly shaped block of a TPS material known as super lightweight ablator (SLA) provided by NASA’s Ames Lab.

2. Characterize the effects of sources of data error in high temperature applications. The sources of data error explored in this work are some of the errors that are likely to be encountered when FBGs are used at high temperatures. The error sources specifically investigated in this work are as follows.
   - The non-linear FBG response to a change in temperature. This error source has been well characterized by previous work such as Adamovsky et al. (2012), Flockhart et al. (2004) and Pal et al. (2004). While the general second order relationship between temperature change and wavelength shift is well understood, the specific relationship for a given FBG depends on the doping used in the silica and the ultraviolet induced change to the index of refraction of the silica. Therefore, a calibration must be completed for a given FBG, though the calibration should be the same for all FBGs produced by the same manufacturing process.
   - The chirped response of the FBG output due to applied temperature gradients over the length of the FBG. Temperature gradients over FBG length, especially
dynamic or changing gradients, have not been adequately investigated by previous literature.

- Strain transfer between adhesives and FBGs. Due to differing thermal coefficients of expansion between the silica in optical fibers, host materials and bonding agents, strains will be applied to a bonded or embedded FBGs whenever a temperature is applied.

3. Test the response of FBGs under steady state and dynamic loading and compare the grating response.

The completion of these goals will be presented in detail in this dissertation. This dissertation is organized into 6 chapters which are broken down as follows. Chapter 1 provides an introduction to the research including a brief discussion of the fundamentals of FBGs, some of the applications of FBGs as temperature sensors, and a survey of the challenges of using FBGs at elevated temperatures. Chapter 1 provides the motivation for using FBGs as temperature sensors in TPS materials and provides a short discussion of the historical use of FBGs embedded in TPS materials. Chapter 2 discusses the results of proof of concept testing of FBGs embedded in a TPS material. The specimen discussed in Chapter 2 is exposed to a steady state load and the temperature response of the FBG arrays over time is presented, analyzed and discussed. The temperature profile of the specimen at the end of the test is captured using an IR camera. Chapter 2 also includes a second order temperature calibration for the FBG arrays used. The calibration for the arrays presented in Chapter 2 is also valid for the arrays used in some of the experiments presented in Chapter 5.
Chapter 3 investigates the effect of temperature gradients on FBG response. Chapter 3 begins with a full spectrum calibration of a Micron Optics sm130 dynamic swept laser optical interrogator that is used in Chapters 3, 4 and 5, and the temperature calibration for Micron Optics os1100 fiber Bragg gratings which are used in Chapters 3, 4 and portions of Chapter 5. The temperature gradient presented in Chapter 3 is driven by the temperature difference of two water baths. The FBG is embedded in a 1 cm thick polytetrafluoroethylene (PTFE) wall between the baths. Because the temperatures of the baths are not actively maintained at a consistent temperature, the gradient present in the fiber is dynamically changing during the experiment. The experimental gradient is recorded and compared to numerical calculated gradients developed by a combination of a mathematical 2D heat transfer model, a finite element simulation completed in ANSYS, and the transfer matrix method.

Chapter 4 explores how strain transferred to a FBG by a host or bonding material affects the FBG response, through both wavelength shift and spectrum deformation. Chapter 4 derives mathematical equations to discriminate the temperature and strain induced wavelength response of the grating given known material properties. The mathematical models were validated with an experiment that compared the response of free, bonded and embedded FBGs exposed to the same temperature load in an oven. Next, the mathematical models were applied to a specimen with four FBGs bonded to the surface. A thermal gradient was applied to the specimen. Three FBGs in the array were oriented orthogonal to the temperature gradient and measured point temperature while the fourth FBG was oriented parallel to the gradient and measured the gradient over its length. Due to the difference in thermal expansion between the FBG, host material and bond materials, strain was applied to all four FBGs in addition to
temperature. The FBG oriented parallel to the temperature gradient had combined temperature and strain gradients present over its length. The transfer matrix method was used to numerically predict the bandwidth change of the applied gradients on the FBG. The numerically predicted bandwidth values were compared to the experimentally observed bandwidth.

Chapter 5 examines the response of FBGs embedded in a generic TPS material subjected to steady state hot plate loads, transient hot plate loads, and dynamically changing flame loads. The purpose of the hot plate tests is to compare the response of the FBGs to the experiments presented in Chapter 2. Additionally, Chapter 5 includes the temperature output of a FBG array with close, 0.15 cm, spacing between adjacent FBGs. Embedded at an angle, this array provides millimeter sensing resolution through the height of the specimen. The flame loading presented in Chapter 5 include cyclical exposure of the specimen to the flame to qualify the response time of FBGs to a rapidly changing temperature load. Chapter 5 concludes with a direct comparison of the temperature response of FBGs and thermocouples for a given temperature load. Finally, Chapter 6 presents the conclusions of the research presented in this dissertation and recommendations for future work.
Figure 1.1. The reflected and transmitted spectrum response due to a fiber Bragg grating written in an optical fiber.

Figure 1.2. Standard TPS plug with four embedded thermocouples (White et al., 2011).
Figure 1.3. Reflected spectrum response of an optical fiber with seven written fiber Bragg gratings with Bragg wavelengths spaced 5 nm apart (Spencer and Braun, 1996).
CHAPTER 2

INITIAL TPS MATERIAL TESTING

This chapter describes the initial temperature testing of a TPS material with embedded FBG arrays under a steady state temperature load of approximately 200°C and discusses the FBG response.

2.1 EXPERIMENTAL METHODS

A small, abnormally shaped specimen of a TPS material was supplied by NASA Ames Laboratory. Fig. 2.1 shows a photograph of the specimen. The specimen was a type of ablative TPS material known as super-lightweight ablator (SLA). A type of SLA, SLA-561V was the material shield used on the Mars Pathfinder (Spencer and Braun, 1996). SLA is a low density ablator consisting of ground cork, phenolic micro-balloons, reinforcing glass fibers, eccospheres, and elastomeric silicone contained in a phenolic honeycomb support structure (Tran et al., 1996). The properties of the SLA in the specimen provided by Ames Research Lab are unknown. The specimen was instrumented with two optical fibers with four FBG sensors in each fiber. A 3-D sketch of the specimen with the embedded arrays is given in Fig. 2.2, and Fig. 2.3 is diagram of the vertical cross-section of the specimen at the location where the arrays were embedded with the wavelengths of each sensor and the spacing dimensions of the FBGs in the fibers. The arrays were embedded in the specimen by threading the fiber through a hollow metal tube then inserting the tube into a guide hole drilled into the specimen. Once the
tube and fiber were embedded, the tube was pulled out around the fiber and removed. The TPS material expanded back around the fiber holding it in place and providing a good thermal contact between the specimen and the fiber. One array was embedded horizontally in the specimen near the surface to be subjected to the heat load. The second array was embedded diagonally in the same vertical plane as the horizontal array. The FBGs were spaced 1.4 cm apart in the horizontal array and 1.25 cm apart in the diagonal array. This spacing resulted in the FBGs in the horizontal array being nearly vertically aligned with the FBGs in the diagonal array creating sensor pairs. Table 2.1 shows the correlation between sensor designation and Bragg wavelength.

The temperature response from the FBG pairs was used to calculate the heat transfer rate through the thickness of the specimen. Heat transfer rate is defined as the change in temperature over a given time. The equation for heat transfer rate is given by equation 2.1.

\[
\varphi = \frac{1}{\alpha + \xi} \frac{1}{t} \left[ \frac{\Delta \lambda_B^A}{\lambda_B^A} - \frac{\Delta \lambda_B^B}{\lambda_B^B} \right]
\]  

(2.1)

Applied strains due to the mismatched coefficients of thermal expansion between the fiber and TPS material could be ignored because while the TPS material was in contact with the fiber, the fiber was not constrained along the length of the fiber and was free to expand.

Heat was applied to the specimen using a hot press with the platens fully opened. The test setup is shown in Fig. 2.4 and the interrogators are shown in Fig. 2.5. The distance between the platens during the test was 15.9 cm. The lower platen was heated to temperatures between
195°C and 205°C, which are below the ablation temperature of the provided SLA specimen. The upper platen was not heated and remained off.

After the lower platen reached a steady state, the specimen was placed on the platen. While the specimen was subjected to the applied temperature load from the heated platen, the shifts in the Bragg wavelength of each sensor was measured and recorded by a FBG interrogator provided by IFOS, while the full reflected spectrum of the arrays were monitored to confirm the accuracy of the wavelength data. Images from an infrared camera were taken immediately before the specimen was removed from the hot platen to provide an independently measured temperature profile of the specimen. The initial temperature of the specimen before each test was room temperature, 22°C.

Three tests were conducted, though the data from the first test was corrupted during data acquisition. Between Tests 2 and 3, the experimental setup was disassembled, the hot press was turned off and allowed to cool, then the test setup was reassembled. During the first two tests, the temperature of the lower platen was set to 195°C and during the third test, it was set to 205°C. The specimen remained on the hot platen for 400 s during Test 2 and 500 s in Test 3. After the specimen was removed from the heat source, it was placed on a room temperature metal table and allowed to passively cool.

2.2. FIBER BRAGG GRATING TEMPERATURE CALIBRATION

The coefficient of thermal expansion and thermo-optic coefficients of silica at room temperature are known to be equal to $0.55 \times 10^{-6} \, ^\circ \text{C}^{-1}$ and $8.6 \times 10^{-6} \, ^\circ \text{C}^{-1}$, respectively. However, the thermo-optic coefficient is known to be dependent on temperature at higher temperatures.
(Reid and Özcan, 1998; Flockhart et al., 2004; Pal et al. 2004; Adamovsky et al., 2012). To determine how the Bragg wavelength shift of the FBGs corresponds to temperature change at higher temperatures, two of the FBGs from the embedded arrays were placed in a tube oven while in tension. As the temperature in the oven was increased to 300°C, the Bragg wavelength shift in the grating array was recorded, as was an independent temperature reading from a thermocouple. A schematic of the test setup is shown in Fig. 2.6, and a photograph of the setup is shown in Fig. 2.7. The temperature calibration curves resulting from the experiment for two FBGs are shown in Fig. 2.7. For the gratings embedded in the TPS specimen, the temperature dependence of the Bragg wavelength shift is well approximated by the second order polynomial given in equation 2.2.

\[
\Delta T = 26.9 \degree C + (1.58 \times 10^5 \degree C) \left( \frac{\Delta \lambda_B}{\lambda_B} \right) - (1.56 \times 10^7 \degree C) \left( \frac{\Delta \lambda_B}{\lambda_B} \right)^2
\]  

(2.2)

Fig. 2.8 shows the calibration curves for both FBGs within the oven are nearly identical.

2.3 RESULTS AND DISCUSSION

The peak Bragg wavelength shift data from each FBG array collected during the experiments were transformed into temperature change using Equation 2.2. The temperature vs. time data collected from the FBG sensors for Test 2 is shown in Fig 2.9, and the FBG data from Test 3 is shown in Fig. 2.10. The horizontal array was longer than the dimension of the specimen resulting in the FBG designated h1 being partially embedded in the specimen. As a result, the data given by grating h1 was noisy and inaccurate. FBG d1 exhibits a higher than expected rate of temperature increase for the first 100 s of each test. In fact, the temperature
increase observed by d1 is higher than that of FBG d2, even though d2 is closer to the heat source than d1. As the temperature profile of the specimen approaches an equilibrium state, the rate of temperature increase shown by d1 slows to a more expected rate. Approximately 200 s into the test, d1 shows a temperature lower than that of d2, which is expected. This behavior is highlighted in the first 200 s of each test. Fig. 2.11 shows the first 200 s for Test 2 and Fig. 2.12 shows the first 200 s for Test 3. One possible explanation for this behavior a local void or impurity in the specimen near d1 that results in an increased rate of heat transfer. However, this explanation is unlikely because the rate of heat transfer eventually slows to a more expected rate. A more plausible explanation for this behavior of an initially elevated rate of temperature increase due to natural convection from the surrounding air heated by the platen. Since d1 is located near the edge of the specimen, it measures heat transfer due to natural convection in addition to conductive heat transfer through the thickness of the specimen. As the through specimen heat flux nears the location of d1, the temperature change due to edge effects becomes less dominant. Eventually, the temperature in the specimen due to the radiant heat load becomes greater than that of the surrounding air, and the natural convection acts to transfer heat away from the specimen rather than to add heat. Similarly, FBG d4 is not affected by the edge effects even though it is located at the specimen edge due to its proximity to the heat source. The conductive heat load is initially dominant.

Figs. 2.9 and 2.10 show excellent agreement between the two tests and that the test was repeatable even though the test setup was torn down and reassembled between the tests. The agreement between the tests is further highlighted during the first 200 s of each test. This is the initial loading phase, after this time the test begins to near an equilibrium condition.
An IR camera was used to validate the temperature response from the FBG arrays. A thermal image from Test 3 after the specimen had been on the hot platen for approximately 460 s is shown in Fig. 2.13. The temperature profile through the thickness of the specimen agrees with the temperature data shown in Fig. 2.7. In addition to the temperature profile through the thickness of the specimen, Fig. 2.10 shows the temperature profile of the hot platen is fairly uniform at the location of the specimen.

Heat flux could not be calculated based on the data shown in Figs. 2.9 and 2.10 because the material properties of the specimen are unknown. Instead, the heat transfer rate equation given in Equation 4 was used to calculate the rate of heat transfer through the thickness of the specimen using the vertical grating pairs. Due to the poor data output from grating h1, the data from grating h4 was used instead of grating h1 when calculating the heat transfer rate for the first FBG pair. The plot of heat transfer rate as a function of the experimental time for Test 2 is shown in Fig. 2.14, and the heat transfer rate for Test 3 is shown in Fig. 2.15.

The heat transfer rate plots are separated into heating and cooling regions where the specimen was being actively heated and passively cooled, respectively. The heat transfer rate data was passed through a moving average filter six times to reduce the noise in the data and reduce the magnitude of the vertical spikes in the plot. The spikes are the result of sudden, large wavelength changes in the raw data. The heat transfer rate is highest in pair 4 which consists of gratings h4 and d4. Heat transfer rate is expected to be highest in pair 4 because h4 and d4 are closest in proximity to each other and d4 is the closest grating to the heat source in the diagonal array. As expected, the heat transfer rates during the heating cycle in Test 3 are slightly higher than those during the heating cycle in Test 2 because the hot platen was hotter.
in Test 3. During the heating phase, the heat transfer rate briefly becomes negative for pairs 2, 3, and 4. The negative regions occur between 120 s and 180 s for pair 2, 90 s and 130 s for pair 3, and 40 s and 74 s for pair 4. These negative regions are due to the temperature increasing in the diagonal grating at a faster rate than in the horizontal grating. After approximately 200 s, the heat transfer rate plot for all pairs becomes constant and zero designating the specimen has reached and equilibrium condition and the horizontal and diagonal gratings are experiencing equal rates of heating. The first 200 s of the heat transfer rate plots highlighting the heating cycle are given in Fig. 2.16 for Test 2 and Fig. 2.17 for Test 3. In addition to the regions of negative heat transfer rate, Figs. 2.16 and 2.17 also highlights the data thermally loaded by a radiant heater. FBGs have the potential to overcome many of the issues encountered when using thermocouples to measure heat transfer in TPS materials. Optical fibers have a significantly better thermal property match than thermocouples and acquire data at faster acquisition rates. Furthermore, optical fibers can be embedded within a TPS tile with little thermal or structural impact to the tile, and multiple FBGs can be written on a single fiber and interrogated simultaneously. By using a single interrogator to read a network of sensors, little sensing instrumentation is required to monitor the system reducing the weight added by the FBG network which is vital in space applications. The temperature change measured by the FBGs embedded in the TPS material were shown to be accurate and highly repeatable across tests. The data given by the sensor arrays gave insights into heat transfer through a typical TPS material and were sensitive enough to show how the thermal properties changed with temperature.
2.4. CONCLUSIONS

This chapter demonstrated the accuracy and repeatability of a FBG sensor network embedded in a TPS material thermally loaded by a radiant heater, and showed FBGs have the potential to overcome many of the issues encountered when using thermocouples to measure heat transfer in TPS materials. Optical fibers have a significantly better thermal property match than thermocouples and acquire data at faster acquisition rates. Furthermore, optical fibers can be embedded within a TPS tile with little thermal or structural impact to the tile, and multiple FBGs can be written on a single fiber and interrogated simultaneously. By using a single interrogator to read a network of sensors, little sensing instrumentation is required to monitor the system reducing the weight added by the FBG network which is vital in space applications. The temperature change measured by the FBGs embedded in the TPS material were shown to be accurate and highly repeatable across tests. The data given by the sensor arrays gave insights into heat transfer through a typical TPS material and were sensitive enough to show how the thermal properties changed with temperature.
Figure 2.1. Photograph of the SLA specimen used in the experiments.

Figure 2.2. Three dimensional drawing of the specimen showing specimen dimensions and Bragg grating array placement.
Figure 2.3. Diagram of the cross-section of the specimen at the location of the embedded fibers showing the initial Bragg wavelengths of each sensor and the distance between fiber Bragg gratings. Distances are in millimeters and wavelengths are in nanometers.
Figure 2.4. Test instrumentation including the hot press and IR camera.
Figure 2.5. Test instrumentation showing the interrogators.
Figure 2.6. Schematic of the tube oven test setup used for fiber Bragg grating temperature calibrations.
Figure 2.7. Test setup for fiber Bragg grating calibration.
Figure 2.8. Temperature calibration curve for both fiber Bragg gratings.
Figure 2.9. The temperature output from the horizontal and diagonal FBG arrays for test 2 during a 400 second steady heating load.

Figure 2.10. The temperature output from the horizontal and diagonal FBG arrays for test 3 during a 500 second steady state heating load.
Figure 2.11. The temperature output from the horizontal and diagonal FBG arrays for the first 200 seconds of Test 2.

Figure 2.12. The temperature output from the horizontal and diagonal FBG arrays for the first 200 seconds of Test 3.
Figure 2.13. IR image of the specimen on the hot platen in Test 3 after 460 seconds showing the temperature distribution through the thickness of the specimen. Temperatures are in degrees Celsius.
Figure 2.14. Heat transfer rate over the duration of the experiment for Test 2.

Figure 2.15. Heat transfer rate over the duration of the experiment for Test 3.
Figure 2.16. First 200 s of the heat transfer rate plot for Test 2.

Figure 2.17. First 200 s of the heat transfer rate plot for Test 3.
Table 2.1. Sensor designation and corresponding Bragg wavelength.

<table>
<thead>
<tr>
<th>Sensor Designation</th>
<th>$\lambda_B$ (nm)</th>
<th>Sensor Designation</th>
<th>$\lambda_B$ (nm)</th>
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<tr>
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<td>d1</td>
<td>1530</td>
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<td>d2</td>
<td>1539</td>
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<td>d3</td>
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<tr>
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<td>1533</td>
<td>d4</td>
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CHAPTER 3

FBG RESPONSE DUE TO DYNAMIC THERMAL GRADIENTS

Due to the angled FBG array present in the experiments presented in Chapter 2, the question arose as to how a FBG would respond if a dynamic temperature gradient was present over the length of the sensor. The goal of this chapter is to investigate the chirping of a FBG spectrum when a temperature gradient is applied over its length and how the presence of a chirped spectrum affects FBG wavelength response. Initially, a four FBG array was bonded to a cylindrically shaped specimen which was placed between two platens of a hot press set to different temperatures. Unfortunately, the strains were transferred to the FBGs due to the different coefficients of thermal expansion between the optical fiber, host material of the specimen and bonding epoxy. The adhesive strain transfer present in this experiment will be presented in Chapter 4. To avoid the presence of an adhesive strain transfer, a second experiment was designed and conducted using a free FBG located in the partition separating two fluid baths at different temperature. The experimental deformation of the spectrum due to the temperature gradient forced by the different temperature baths is presented in this chapter. Furthermore, a numerical model was developed to simulate the FBG spectrum response given a thermal gradient present in the FBG. This model is described in section 3.4.

First, sections 3.1 and 3.2 present calibrations for the spectrum data output move of the Micron Optics sm130 interrogator and the temperature dependence of a Micron Optics os1100 fiber Bragg grating. All wavelength shifts presented in this chapter were calculated from the
spectrum data output mode of the sm130 interrogator. os1100 FBGs were used for all measurements in this chapter as well as Chapter 4 and portions of Chapter 5.

3.1. MICRON OPTICS INTERROGATOR FULL SPECTRUM OUTPUT CALIBRATION

The Micron Optics sm130 optical interrogator has a wavelength interrogation range of 1510 nm to 1590 nm, with both peak wavelength tracking and full spectrum analysis data collection modes. For sm130 models, the tracking feature is accurate to absolute wavelength, but the spectrum data output is not the primary measurement mode of the x30 core and therefore absolute wavelength information for the collected data points is not provided. The x-axis of the spectrum output is given in terms of fractional counts (Micron Optics, 2012). To determine the correlation of the fractional counts output by the sm130 interrogator and wavelength, the spectrum output from the Micron Optics sm130 was calibrated using a 31 FBG array and a high resolution optical spectrum analyzer (OSA). The FBG array consists of 31 FBGs with nominal Bragg wavelengths between 1530 nm and 1590 nm with a 2 nm nominal spacing between FBGs. A rough comparison of the full spectrum response between the OSA (red line) and the Micron Optics interrogator (blue line) is shown in Fig. 3.1. To convert the Micron Optics fractional counts to wavelength, a linear calibration with end points of 1510 nm and 1590 nm was applied to the x-axis data points for Fig. 3.1.

Fig. 3.1 shows applying a linear calibration to the Micron Optics data with endpoints of 1510 and 1590 nm results in a poor calibration of the Micron Optics spectrum output, with as much as a 1 nm difference between the two measurement systems. A plot of the difference
between a linear Micron Optics scaling between 1510 and 1590 nm and the peak wavelengths as determined by the OSA is given in Fig. 3.2.

To determine a better data fit, peak wavelengths given by the high resolution OSA for all 31 FBGs were plotted as a function of the raw Micron Optics fractional counts as shown in Fig. 3.3. The MATLAB curve fitting tool was used to fit a first, second, third, and fourth order polynomial fit to the peak wavelength data from the OSA to the fractional count data from the sm130 shown in Fig. 2, for each FBG. The equations from the four fits are shown from equation 3.1a-d respectively where \( x \) represents the fractional count output by the Micron Optics interrogator.

\[
\lambda = (0.003883 \text{nm})x + 1508.4 \text{nm} \quad (3.1a)
\]
\[
\lambda = (9.7128 \times 10^{-9} \text{nm})x^2 + (0.0036316 \text{nm})x + 1509.875 \text{nm} \quad (3.1b)
\]
\[
\lambda = (3.3541 \times 10^{-13} \text{nm})x^3 + (2.2979 \times 10^{-8} \text{nm})x^2 + (0.0034692 \text{nm})x + 1510.47 \text{nm} \quad (3.1c)
\]
\[
\lambda = (1.3011 \times 10^{-17} \text{nm})x^4 - (1.0212 \times 10^{-12} \text{nm})x^3 + (3.5839 \times 10^{-8} \text{nm})x^2 + (0.003685 \text{nm})x + 1510.75 \text{nm} \quad (3.1d)
\]

All four of these fits were applied to the raw Micron Optics spectrum data, and the resulting peak wavelength values were compared to those of the high resolution OSA. The difference between the OSA data and the calibrated Micron Optics data for all 31 peaks is shown in Fig. 3.4. Fig. 3.4 shows that the linear fit results in the most variation between the Micron Optics peak wavelengths and the OSA wavelengths. Fig. 3.5 is to Fig. 3.4, but with the linear fit removed highlighting the differences between the different order polynomial fits.
The average distance between the second order fit peak wavelengths and the high resolution OSA is 0.0264 nm, the average distance for the third order fit is 0.0155 nm and the average difference is 0.0144 nm for the fourth order fit. Fig. 3.5 shows that the second order fit had significantly more error than the third and fourth order fits, while the difference between the third order and the fourth order fits was not sufficient to justify the increased computation time required of the fourth order fit. Based on these results, the third order fit of equation 3.1 c was used when converting the Micron Optics spectrum output to wavelength.

3.2. FIBER BRAGG GRATING TEMPERATURE CALIBRATION

To calibrate the relationship between the Bragg wavelength of the FBG and temperature change, the peak wavelength of a Micron Optics os1100 FBG was recorded while the FBG was in a Fisher Isotemp 737G Oven. As the manufacturing process for all Micron Optics os1100 FBGs is identical, the calibration of one FBG is expected to be accurate for all Micron Optics os1100 FBGs. The temperature of the oven was set to 200°C. As the temperature of the oven increased to 200°C, the temperature of the oven was recorded along with the reflected spectrum given by the FBG at 5 s intervals. Once the oven reached 200°C, data collection continued for an additional 205 seconds. The test set-up is shown in Fig. 3.6. The seal between the oven door and the oven body is a soft, rubbery material that sealed tightly around the 125 micron diameter optical fiber while allowing the fiber to pass through with no noticeable signal loss.
The oven temperature over time is given in Fig. 3.7 and the temperature change as a function of wavelength shift is given in Fig. 3.8. A quadratic equation was used to fit the curve shown in Fig. 3.8. This equation is given in equation 3.2.

\[ T = (-2.2455 \times 10^7 \degree C) \left( \frac{\Delta \lambda}{\lambda} \right)^2 + (1.6389 \times 10^5 \degree C) \left( \frac{\Delta \lambda}{\lambda} \right) + 22.778 \degree C \tag{3.2} \]

The R squared value of equation 3.2 is 0.9953 which signifies a good fit between the fitted curve and the data. It is currently unclear why there is increased noise in the FBG data after the temperature exceeds 100\degree C. The oven temperature curve in Fig. 3.7 is less smooth as the temperature increase per time decreases, but not as much as is observed in the FBG wavelength shift response to temperature. Increased variation in the temperature response of Micron Optics os1100 FBGs above 100\degree C should be investigated further.

### 3.3. TEMPERATURE GRADIENT BANDWIDTH EXPERIMENT

#### 3.3.1. Experimental Setup

To force a temperature gradient over the length of a FBG, a container constructed out of polytetrafluoroethylene (PTFE), commonly known as Teflon, was constructed. PTFE was chosen because it has a similar thermal conductivity to the silica of the optical fiber and a broad temperature range of -73\degree C to 260\degree C, which exceeds the temperature loads induced by this experiment. It is also easily machinable. The walls, ends, and center partition of the container were attached and held in place using a clear silicone caulk with an operating temperature range of -51.11\degree C to 204.44\degree C. The container included a partition located at the halfway point of its length that split the container into two equally sized compartments. The partition was 1
cm thick, the same thickness of the FBG. The compartments were filled with water at different temperatures, $T_H$ and $T_C$. A small, 0.0254 cm, diameter hole was drilled into both ends and the center partition. The hole allows for the optical fiber to freely move through the walls while remaining small enough to prevent water escaping the two compartments. No bonding agents were used to hold the fiber in place. A schematic of the container is given in Fig. 3.9 and Fig. 3.10 shows a photograph of the completed container. Fig. 3.10 includes an optical fiber running through the two compartments, but the optical fiber is difficult to see in the image.

To induce a temperature gradient, one compartment was filled with boiling water, and the second compartment was filled with ice water. Over time, the temperature of the water in both baths would cool or heat respectively to room temperature. To reduce the rate of temperature change in both baths, a thin layer of low density polyethylene (LDPE) was wrapped around the upper surface of the container to insulate the fluid in the two compartments from the surrounding air. The LDPE layer reduced, but did not prevent heat transfer between the water baths and the lab environment. Reducing the heat transfer between the water baths and the lab environment allowed for a more consistent temperature load between the baths and the FBG in the partition; however, because the temperature of the baths was still variable, different thermal gradients were measured across the FBG. Two experiments were conducted to determine how the current setup would affect the reflected FBG spectrum, one steady state and one transient. In the steady state experiment, a single FBG was immersed in the hot bath, placed in the center partition, and immersed in the cold bath. In all three cases, the reflected spectrum of the FBG was recorded. The transient test utilized a 3 FBG array. One FBG was fully immersed in the hot bath for the duration of the experiment, the second FBG was placed
in the partition to measure the temperature gradient through the PTFE partition, and the third FBG was fully immersed in the cold bath. In both experiments, a Micron Optics os130 interrogator was used to record the reflected spectrum of the FBG or the three FBG array. Fig. 3.11 shows the experimental setup.

3.3.2. Steady State Experiment Results

The initial wavelength of the FBG used in the steady state experiment was 1575.99 nm. The three reflected spectra recorded while the FBG was immersed in the hot bath, located within the center PTFE partition, and fully immersed within the cold bath are plotted in Fig. 3.12. The peak wavelength of the three spectra are given in Table 3.1 and the full width half maximum (FWHM) and full width quarter maximum (FWQM) bandwidths of the three spectra are given in Table 3.2. The FWHM is defined as the width of the spectrum at half the intensity, whereas the FWQM is the width of the spectrum at one quarter of the maximum intensity. The peak wavelength shifts make sense given the temperatures of the hot and cold baths. When the FBG is located in the partition under the temperature influence of both temperature baths, the reflected spectrum shows an obvious broadening of the spectrum. Table 3.2. also shows the percent increase of the bandwidth of the spectrum when the FBG is located within the partition compared to when the FBG is fully immersed in one of the two baths under a uniform temperature load.
3.3.3. Transient Experiment Results

The initial spectrum of the multiplexed 3 FBG array used in the transient thermal gradient experiment is shown in Fig. 3.13, and Table 3.3 gives the designation of each FBG and its initial wavelength.

FBG 1 was immersed in the cold bath and FBG 3 was immersed in the hot bath. FBG 2 was to be placed in the center partition, but initially remained outside of the container exposed to the laboratory environment. Once the baths were filled and covered with a layer of LDPE, an initial spectrum was recorded with FBG 2 remaining in the lab environment. Once data collection began, FBG 2 was moved into the center partition between the two baths. The second reflected spectrum was recorded at 15 second intervals and spectra were recorded every 5 seconds afterwards. The maximum reflectivity of FBG 2 is shown in Fig. 3.14, and the FWHM and FWQM bandwidths are shown for FBG 2 over the duration of the experiment in Fig. 3.15.

The goal of this work is to demonstrate a relationship between the bandwidth of the FBG spectrum and the temperature gradient applied across the FBG gauge length. However, the maximum reflectivity information is also plotted for completeness. Generally the reflectivity information is not useful for sensing applications since it is highly sensitive to laser power and bending loss fluctuations in the optical fiber. At 330 seconds, the magnitude of the FWHM bandwidth of FBG 2 returns to within 5% of its initial value. Given the noise present in the data, this can be considered an insignificant change. The FWQM bandwidth returns to within 5% of its initial value after 435 seconds. The bandwidth and reflectivity have a roughly inverse relationship, which can be seen in Fig. 3.12 and more obviously in Fig. 4.28. The
maximum reflective of FBG 2 is overlaid with the FWQM of FBG in Fig. 3.16, to show that
the expected behavior was observed.

Fig. 3.17 shows the temperature responses of FBG 1, FBG 2, and FBG 3 over the
duration of the experiment. Fig. 3.18 shows the temperature response of all three FBGs plotted
on the same axis. The temperature is calculated from the peak wavelength change of each FBG
using equation 3.2. Figs. 3.17 and 3.18 show a delay in the temperature change of FBG 2 due
to it being located within the center partition rather than directly exposed to the temperature
baths. Furthermore, due to its location within the PTFE partition, the temperature response of
FBG 2 remains stable compared to FBG 1 and FBG 3. After 350 seconds, the temperatures
registered by FBG 2 and FBG 3 are within 1°C of each other, and at 530 seconds, the
temperature of FBG 3 is warmer than the temperature of FBG 3. The temperature of the cold
bath is above 20°C after approximately 420 seconds, and consistently within 1°C of 23°C (room
temperature) after 515 seconds.

While there is still an obvious difference in the temperature of the two baths after 300
seconds, this temperature is not reflected in an increased FWHM bandwidth of FBG 2 after
300 seconds or the FWQM after 350 seconds. This is likely due to the thermal load produced
by the hot bath conducting through the center partition and the thermal load from the cold bath
being too weak to counter the load from the hot bath. Numerical simulations of this effect will
be presented later. At 350 seconds, FBGs 2 and 3 are outputting same temperature values, and
by 400 seconds it is possible that the temperature of the partition is equal to the temperature of
the hot bath through the thickness of the partition.
Fig. 3.19 shows a scatter plot of the FWHM and FWQM bandwidth of FBG 2 as a function of the temperature difference between FBG 3 and FBG 1. The dashed line on each plot represents the initial FWHM or FWQM of FBG 2. The bandwidth behaves as expected for most of the temperature difference range, however peaks at approximately 75°. This behavior cannot be explained by a simple linear temperature gradient across the FBG gage length, but instead requires a more detailed modeling of the heat transfer between the two baths and through the partition thickness. This modeling should capture the heat transfer through the partition, the applied thermal loading to the FBG gage length due to the heat transfer, and finally the two-mode coupling along the FBG length in the presence of a varying temperature field, which determines the reflected spectrum. These components of the simulation will be presented in the following sections.

3.4. NUMERICAL BANDWIDTH MODEL

A numerical model was therefore developed to determine the bandwidth change of a FBG under the experimental conditions presented in section 3.3. The numerical model consists of three components. The first is a two dimensional, finite element thermal model constructed in ANSYS. The second component is the transfer matrix (T-matrix) method, which used the numerical temperature profile determined by the ANSYS model to calculate numerical bandwidths over the length of a simulated FBG. The third component is a 2D heat transfer model used to calculate the hot side and cold side wall temperatures of the center partition.
3.4.1. Two Dimensional ANSYS Model

The geometry of the ANSYS model represents a cross section of the partition with dimensions 3.175 cm tall and 1 cm wide. A two dimensional model was considered sufficient because if the two temperature baths are full, the temperature load on the partition due to the baths should be consistent through along the width of the partition. Bisecting the model geometry was a 0.0125 cm thick strip used to numerically represent the silica optical fiber. Above and below this area were two larger areas used to represent the PTFE of the partition. The material properties used for the PTFE, which remain constant throughout the temperature range of the experiment, are given in Table 3.4. The material properties for the silica used in the model are given in Tables 3.5 and 3.6. Unlike PTFE, the thermal conductivity of silica does show noticeable variation across the temperature range induced by the experiment. The relationship between temperature and thermal conductivity for silica given in Table 3.5 is plotted in Fig. 3.20.

Plane77 elements were used to mesh the model. Plane77 elements are an 8-node two dimensional thermal element. The meshed model geometry is shown in Fig. 3.21. A curve was fit to the time dependent cold and hot bath temperatures from the experiment given in Fig. 3.17(a) and 3.17(c). The transient temperature profile from these curves, which were taken directly from the experimental data, were applied to the right and left sides of the ANSYS model, respectively. The equations for these curves as a function of time are given in equations 3.3a and 3.3b.
\[ T = \left( 4.4906 \times 10^{-11} \frac{^\circ C}{s^4} \right) t^4 - \left( 1.9869 \times 10^{-7} \frac{^\circ C}{s^3} \right) t^3 \]
\[ + \left( 3.4420 \times 10^{-5} \frac{^\circ C}{s^2} \right) t^2 + 0.04152 \frac{^\circ C}{s} t + 1.9120 \frac{^\circ C}{s} \]

\[ T = -\left( 9.9987 \times 10^{-8} \frac{^\circ C}{s^3} \right) t^3 + \left( 1.4346 \times 10^{-4} \frac{^\circ C}{s^2} \right) t^2 + 0.09235 \frac{^\circ C}{s} t \]
\[ + 83.8444 \frac{^\circ C}{s} \]

(3.3a)

(3.3b)

All nodes were set to an initial temperature of 23°C, and a 600 second long transient analysis was conducted in ANSYS. The time dependent temperatures at 21 nodes in 0.05 cm increments along the silica strip were recorded by ANSYS and output. The temperature profiles of 11 of these nodes with a spacing of 0.1 cm is shown in Fig. 3.22.

### 3.4.2. T-Matrix and Modified T-Matrix Models

The temperature output from the ANSYS model was input into the transfer matrix (T-matrix) method. The T-matrix method is a computationally fast technique used to approximately solve the coupled mode equations in an optical fiber at the location of an index refraction perturbation (such as at a FBG). The T-matrix method can be applied to calculate the reflected spectrum of a FBG given a non-uniform period change in the refractive index along the FBG, by reducing the grating into piecewise approximations (Yamada, 1987). The T-matrix method can be applied when the number of grating segments is large enough such that the piecewise approximation to the strain or temperature field is sufficient, however the number of grating segments is smaller than the number of FBG periods (by a factor of 100), such that complete coupling of the forward and backward propagating modes can be assumed.
in each segment. The T-matrix method was used to approximate the response of a FBG under a non-uniform strain load by Huang et al. (1995). The T-matrix method was modified by Prabhugoud and Peters in 2004 to include the strain gradient into the calculation of each FBG segment and therefore properly calculate the effect of large strain gradients (Prabhugoud and Peters, 2004). Including the gradient improved the accuracy of the numerical calculation of bandwidth to experimental data. The equations used in the modified transfer matrix method and modified transfer matrix method for strain are presented below.

\[ \tilde{\Lambda}(z) = \Lambda_o \left[ 1 + (1 - p_e)\varepsilon(z) + (1 - p_e)z\varepsilon'(z) \right] \]  \hspace{1cm} 3.4

\( \tilde{\Lambda} \) is the modified segment period due to the applied strain, \( \Lambda_o \) is the initial period of the FBG, \( p_e \) is the strain-optic coefficient, \( \varepsilon \) is the strain, \( \varepsilon' \) is the change in strain with respect to distance along the FBG segment, \( z \). The term modified segment period is used because it is not the actual segment period after deformation, but is an equivalent segment period that produces the same spectrum as solving the coupled mode equations directly in the presence of a strain gradient. In equation 3.4, the third term within the brackets, \( (1 - p_e)z\varepsilon'(z) \), is the term due to the modification by Prabhugoud and Peters (2004).

For a free sensor under a temperature load, varying along the length of the FBG, as present in the FBG bandwidth experiment, we can write an equivalent to equation 3.4, given as equation 3.5.

\[ \tilde{\Lambda}(z) = \Lambda_o \left[ 1 + (\alpha + \beta)\Delta T(z) + (\alpha + \beta)z\Delta T'(z) \right] \]  \hspace{1cm} 3.5

\( \Delta T \) is the piecewise approximation to the temperature change in each segment, \( z \), \( \alpha \) is the coefficient of thermal expansion for silica, and \( \beta \) is the thermo-optic coefficient for the FBG.
When calibrating a FBG, both $\alpha$ and $\beta$ are calculated, though $\alpha$ remains constant over the temperature range. The derivation for equation 3.5 will be presented in Chapter 4.

The effective grating period due to applied temperature, $\Lambda$ is used to calculate the general “dc” self-coupling coefficient, $\hat{\alpha}$, as defined by equation 3.6 and the “ac” coupling coefficient, $\kappa$, defined in equation 3.7.

$$\hat{\alpha} = \frac{2\pi}{\lambda} (n_{eff} + \delta n_{eff}) - \frac{\pi}{\Lambda(z)}$$ \hspace{1cm} 3.6

$$\kappa = \frac{\pi}{\lambda} \nu \delta n_{eff}$$ \hspace{1cm} 3.7

$\lambda$ is the wavelength of the propagating lightwave, $n_{eff}$ is the effective refractive index of the fundamental mode in the optical fiber, $\delta n_{eff}$ is the “dc” index change of the optical fiber over the grating period, and $\nu$ is the fringe visibility. The “ac” and “dc” coupling coefficients are then input into the components of the optical transfer matrix, $F_i$ which is given in equation 3.8.

$$F_i = \begin{bmatrix}
cosh(\gamma_B \Delta z) - i \frac{\hat{\alpha}}{\gamma_B} \sinh(\gamma_B \Delta z) & -i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) \\
\frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) & \cosh(\gamma_B \Delta z) + i \frac{\hat{\alpha}}{\gamma_B} \sinh(\gamma_B \Delta z)
\end{bmatrix}$$ \hspace{1cm} 3.8

where $\gamma_B$ is calculated using equation 3.9.

$$\gamma_B = \sqrt{\kappa^2 - \hat{\alpha}^2}$$ \hspace{1cm} 3.9

The optical transfer matrix, $F$, is used in equation 3.10 to calculate the amplitudes of the forward- and backward-propagating modes in the fiber, $R(z)$ and $S(z)$, respectively. The T-matrix method is based on the concept that the optical transfer matrix for the complete FBG is the multiplication of the optical transfer matrix for each segment.
\[
\begin{bmatrix}
R \left( -\frac{L}{2} \right) \\
S \left( -\frac{L}{2} \right)
\end{bmatrix} = F 
\begin{bmatrix}
R \left( \frac{L}{2} \right) \\
S \left( \frac{L}{2} \right)
\end{bmatrix}
\]  \hspace{1cm} 3.10

\( L \) is the length of the FBG where the midpoint of the grating is located at \( L = 0 \). For a broadband of lightwaves, with constant reflectivity of 1, the known boundary conditions for the FBG are the forward propagating mode input, \( R \left( -\frac{L}{2} \right) = 1 \) and the backward propagating mode input, \( S \left( -\frac{L}{2} \right) = 0 \). From these boundary conditions, the reflectivity of the FBG as a function of wavelength can be calculated as the amplitude of the output propagating mode divided by the input forward propagating mode, using equation 3.11.

\[
 r(\lambda) = \left| \frac{S \left( -\frac{L}{2} \right)}{R \left( -\frac{L}{2} \right)} \right|^2 = \left| \rho \left( -\frac{L}{2} \right) \right|^2 \hspace{1cm} 3.11
\]

For spectra determined by the T-matrix and modified T-matrix methods, changing the value of the coefficient of thermal expansion, \( \alpha \), and the FBG thermo-optic coefficient, \( \beta \), alters the magnitude of the wavelength change due to temperature. Increasing \( \alpha \) and \( \beta \) increases spectrum deformation and decreasing \( \alpha \) and \( \beta \) decreases spectrum deformation due to temperature change. For the model the value of \( \alpha \) was \((0.55 \times 10^{-6}) \frac{1}{\degree C}\) and the value of \( \beta \) is dependent on temperature as defined by equation 3.12 (Leviton, 2006).

\[
\beta = (-3.6422 \times 10^{-11} \degree C^{-2})T^2 + (1.9619 \times 10^{-8} \degree C^{-1})T + 7.896 \times 10^{-6} \hspace{1cm} 3.12
\]

The values for \( \beta \) used in the T-matrix method model were not the values calculated from Fig. 3.8 and equation 3.2 because the MATLAB script used to calculate the T-matrix and modified
T-matrix method results was completed before the calibration. The line in the code was not updated with the actual $\beta$ values.

Changing the segment length in equation 3.8 alters the initial bandwidth of the FBG. Increasing the segment length results in a narrower peak, and decreasing $z$ results in a broader peak. The fringe visibility, $\nu$, affects the amplitude of the simulated spectrum. By decreasing $\nu$ the simulated peak has a larger intensity and less noticeable fringes. Increasing $\nu$ reduces the intensity of the spectrum while transferring power from the center peak to the fringes to each side of the peak. For the simulated spectra, the values of $z$ and $\nu$ were chosen so the initial simulated spectra would closely match the initial experimental spectrum before any temperature loads were applied. Furthermore, because the initial spectrum is the spectrum before any applied temperature loads, the spectra given by the T-matrix and modified T-matrix methods are identical because $\Delta T$ in equation 3.5 is zero. The initial simulated spectrum as determined by the T-matrix and modified T-matrix methods is shown in Fig. 3.23 along with the initial experimental spectrum.

The FWQM bandwidth of the spectra given by the T-matrix and modified T-matrix methods over the experimental time compared with the experimental FWQM bandwidth is given in Fig. 3.24. There are two noticeable differences between the numerical and experimental bandwidth plots. First, the time dependent behavior of the bandwidth given by the T-matrix and modified T-matrix methods have a stepped behavior. The drops in bandwidth are due to deformations in the shape of the simulated spectrum as seen in Fig. 3.25. The black dashed line represents the location of the FWQM bandwidth.
The FWQM, as denoted by the dashed line in Fig. 3.25a, includes the minor peak along the right-hand side of the reflected peak while this peak is not captured by the FWQM in Fig. 3.25b. To smooth the simulated bandwidth plots a first order Gaussian fit was applied to the simulated spectra. The equation for a Gaussian fit is given in equation 3.13.

\[
f(x) = \sum_{i=1}^{n} \left[ a_i \exp \left( -\frac{(x - b_i)^2}{c_i} \right) \right]
\]  

(3.13)

\(a, b,\) and \(c\) are the coefficients from the Gaussian fit. For a first order fit, \(i\) is equal to 1. The Gaussian fits for the modified T-matrix compared to the raw simulated spectra are given in Fig. 3.26.

The Gauss fit spectrum does not have the significant spectrum deformation present in both the T-matrix and modified T-matrix simulations, though the significant deformations in the spectrum shape is not present in the experimental spectra. The excess deformation present in the spectra is due to a combination of the increased the fringe visibility and the reduced FBG segment size in the numerical model. Decreasing the fringe visibility reduces the deformations in the spectrum shape while increasing the segment size decreases the bandwidth to be deformed. The bandwidth of the Gauss fit T-matrix and modified T-matrix spectra along with the raw T-matrix and modified T-matrix spectra is given in Fig. 3.27.

3.4.3. Two Dimensional Heat Transfer Model

The second noticeable difference between the experimental results and the bandwidth results from the numerical simulation is the numerical bandwidth as seen in Fig. 3.25 overestimates the bandwidth response. The overestimation of the bandwidth is due to the
temperature loads applied to the model as described by equation 3.3 assuming a perfect heat transfer between the fluid baths and the PTFE partition. This is not a physically accurate assumption. To correct for the imperfect heat transfer between the fluid baths and the PTFE partition, the wall temperatures were calculated using a 2D heat transfer model as described in equation 3.14 which is derived from the heat transfer problem given in Fig. 3.28.

\[ h_h(T_h - T_{hw}) = \frac{k(T_{hw} - T_{cw})}{L} = h_c(T_{wc} - T_c) \] (3.14)

\( T_h \) and \( T_c \) are the temperatures of the hot and cold baths as described in equation 3.3, \( h_h \) and \( h_c \) are the convective heat transfer coefficient between the hot and cold baths and the hot and cold sides of the PTFE partition, respectively, \( k \) is the thermal conductivity of the PTFE, and \( T_{hw} \) and \( T_{cw} \) are the wall temperatures of the PTFE partition.

Equation 3.14 can be split into two equations with two unknowns, \( T_{hw} \) and \( T_{cw} \) to describe the hot and cold sides of the partition.

\[ h_h(T_h - T_{hw}) = \frac{k(T_{hw} - T_{cw})}{L} \] (3.15a)

\[ h_c(T_{wc} - T_c) = \frac{k(T_{hw} - T_{cw})}{L} \] (3.15b)

These two equations can be solved simultaneously for \( T_{hw} \) and \( T_{cw} \).

\[ T_{hw} = \frac{T_h k + T_c k + LT_h h_h}{2k + L h_h} \] (3.16a)

\[ T_{cw} = \frac{T_c k + T_h k + LT_c h_c}{2k + L h_c} \] (3.16b)

Equations 3.14-3.16 are valid for a linear temperature gradient through the thickness of the PTFE. The convective heat transfer coefficients, \( h_h \) and \( h_c \) are not constant and depend on a
combination of the Rayleigh Number \((Ra)\) of the fluid, the temperature difference between the wall and the fluid, the thermal conductivity of the fluid, and the Prandl Number \((Pr)\). For laminar flow \((Ra < 10^9)\) a vertical plate with submerged length \(L_p\), the convective heat transfer coefficient can be calculated using equation 3.17.

\[
h = \frac{k}{L_p} \left( 0.68 + \frac{0.67Ra_1^{1/4}}{1 + \left( \frac{0.492}{Pr} \right)^{9/16}} \right)^{4/9} \tag{3.17}
\]

Assuming the center partition is fully submerged, \(L_p\) is 0.03175 m. The Rayleigh number is calculated using equation 3.18.

\[
Ra_h = \frac{g\alpha}{k_v\phi} (T_h - T_{wh})L_p^3 \tag{3.18a}
\]

\[
Ra_c = \frac{g\alpha}{k_v\phi} (T_{cw} - T_c)L_p^3 \tag{3.18b}
\]

g is the acceleration due to gravity, \(\alpha\) is the thermal expansion coefficient, \(k_v\) is the kinematic viscosity, \(\phi\) is the thermal diffusivity, \(T_{wh}\) is the hot wall temperature, \(T_{wc}\) is the cold wall temperature, and \(T_h\) and \(T_c\) are the hot and cold bath temperatures, respectively. For the initial calculation of the Rayleigh number before the fluid baths are filled, the wall temperature is assumed to be room temperature, 23°C. The value of \(\frac{g\alpha}{k_v\phi}\) for water is temperature dependent and can be calculated using equation 3.19 (Bejan, 1993).

\[
\frac{g\alpha}{k_v\phi} = (8.4412^{\circ}C^{-2})T^2 + (590.34^{\circ}C^{-1})T \tag{3.19}
\]

Given the values of \(\frac{g\alpha}{k_v\phi}\) over the temperature range of 0°C to 100°C, the temperature difference between the PTFE surface and the fluid bath, and \(L_p\), \(Ra\) never approaches \(10^9\), so
the laminar flow calculation for $h$ presented in equation 3.17 holds. The Prandl number for water is also temperature dependent and can be calculated using equation 3.20 (Bejan, 1993).

$$Pr = (2.92 \times 10^{-7} {^\circ}C^{-4})T^4 - (7.969 \times 10^{-5} {^\circ}C^{-3})T^3 + (8.422 \times 10^{-3} {^\circ}C^{-2})T^2 + (0.4521 {^\circ}C^{-1})T + 13.309$$  \hspace{1cm} (3.20)

Finally, the thermal conductivity of water depends on temperature and can be described by equation 3.21 (Bejan, 1993).

$$k = \left(-7.881 \times 10^{-6} \frac{W}{m \cdot K^3}\right)T^2 - \left(1.984 \times 10^{-3} \frac{W}{m \cdot K^2}\right)T + 0.5593 \frac{W}{m \cdot K}$$  \hspace{1cm} (3.21)

Equations 3.18 through 3.21 were used to calculate $h_h$ and $h_c$ from equation 3.17, then the values of $h_h$ and $h_c$ were used to calculate $T_{hw}$ and $T_{cw}$ in equations 3.16a and 3.16b, respectively. The comparison between the temperature of the baths and the wall temperatures is shown in Fig. 3.29.

Fig. 3.29 shows the temperature of the hot wall is initially approximately 20°C cooler than the hot bath at the beginning of the test. By the end of the test, the difference in temperature between the hot bath and the hot side of the PTFE partition is reduced to approximately 10°C. Initially, the cold wall is significantly warmer than the cold bath due to a combination of lower $h_c$ values and temperature conduction through the PTFE partition. Due to conduction through the PTFE, the cold bath never drops below room temperature. Additionally, the timescale on the x-axis in Fig. 3.28 is the timescale of the experiment presented in section 3.4 where data collection begins at time 0. In reality, the baths were filled 15 seconds before time 0. Since equation 3.18 depends on the wall temperature of the previous timestep, the temperatures of
the hot and cold baths were extrapolated back 15 seconds using equation 3.3 and the wall temperatures when time was at -15 seconds were set to room temperature, 23°C.

The calculated hot and cold wall temperatures were input into the ANSYS model as the temperature loads as defined by equation 3.22a and 3.22b for the cold and hot walls, respectively.

\[
T = -\left(9.918 \times 10^{-7} \frac{\circ C}{s^3}\right) t^3 + \left(1.029 \times 10^{-4} \frac{\circ C}{s^2}\right) t^2 + \left(0.01950 \frac{\circ C}{s}\right) t + 29.220 \circ C
\]  
(3.22a)

\[
T = -\left(9.959 \times 10^{-8} \frac{\circ C}{s^3}\right) t^3 + \left(1.341 \times 10^{-4} \frac{\circ C}{s^2}\right) t^2 + \left(0.07268 \frac{\circ C}{s}\right) t + 65.886 \circ C
\]  
(3.22b)

Since the temperature gradient was developing for 15 seconds before data collection in the experiment, the ANSYS model calculated temperature between 0 and 615 seconds. Spectra were only calculated using the T-matrix and modified T-matrix method from times between 15 and 615 seconds to better match the experimental data. The temperature profile of 11 nodes as given by the ANSYS model is shown in Fig. 3.30.

The bandwidth over time determined by the raw T-matrix and modified T-matrix of the numerical data compared to the experimental data is given in Fig. 3.31. The Gauss fit bandwidths for the T-matrix and modified T-matrix method spectra compared with the experimental data is given in Fig. 3.32. Fig. 3.33 shows the bandwidths given by the T-matrix and modified T-matrix methods as a function of the numerically calculated temperature difference between the walls. A third order fit was applied to the modified T-matrix curve in
Fig. 3.33 when the temperature difference of the walls was between 15°C and 32°C. This temperature range excludes the initial development of the bandwidth change and only captures decay of the bandwidth change. Based on this fit given in equation 3.23, the magnitude of the temperature difference on the ends of the FBG can be determined from the bandwidth change.

\[
\delta T = \left( 1237 \frac{\circ C}{nm^3} \right) \delta \lambda^3 - \left( 693.95 \frac{\circ C}{nm^2} \right) \delta \lambda^2 + \left( 1.6348 \frac{\circ C}{nm} \right) \delta \lambda + 15.647 \circ C \tag{3.23}
\]

\(\delta T\) is the magnitude of the temperature difference and \(\delta \lambda\) is the change in bandwidth.

The bandwidth of the Gauss fits to the T-matrix and modified T-matrix spectra shows excellent agreement with the experimental data. Figs. 3.24, 3.27, 3.31, and 3.32 show that the magnitude of the bandwidth of the spectra determined by the modified T-matrix method initially exceeds that of the bandwidth of the spectra calculated by the T-matrix method, but as the simulation progresses the spectra determined by the modified T-matrix method becomes almost identical to the spectra determined by the T-matrix method. As the difference in temperature between the hot and cold walls becomes less pronounced, the gradient component of the modified T-matrix method has less of an effect on the numerically determined spectra. After 165 seconds, the Gauss fit bandwidths have the same value and the temperature difference between the hot and cold walls is 27.714°C and as Fig. 3.34 shows, the temperature profile through the ANSYS modeled FBG is nearly linear.

Fig. 3.35 provides Gauss fit spectra as calculated by the T-matrix and modified T-matrix method with experimentally determined spectra at different times during the experiment along with the numerically determined temperature profile through the FBG at those locations.
Fig. 3.35 shows that the Gaussian fit of the numerically determined spectra does an excellent job of simulating the shape of the experimental spectra; however, the wavelength shift determined by the temperature profile output by ANSYS and the T-matrix and modified T-matrix methods slightly underestimates the wavelength shift during the experiment. After the spectrum image in Fig. 3.35d, there is no discernable difference in the T-matrix and modified T-matrix determined spectra which confirms the output shown in Fig. 3.32.

The equation used to calculate the wall temperatures presented in equations 3.15 and 3.16 assume a linear temperature gradient through the PTFE thickness. The temperature profile curves in Fig. 3.35 show that the temperature profile is highly nonlinear for the first 100 seconds of the test. The temperature profiles shown in Fig. 3.35d-h are not perfectly linear though they are approximately linear. The bandwidth fit shown in Figs. 3.31 and 3.32 is worst for the first 100 seconds.

3.5. CONCLUSIONS

This chapter began with the full spectrum output calibration of the Micron Optics sm130 optical interrogator. Not calibrating the full spectrum output and applying a linear fit to the x-axis data points with endpoints of 1510 nm and 1590 nm (the manufacturer specified wavelength range of the interrogator) results in errors of between -0.4 nm and 0.3 nm at various points in the wavelength range of the interrogator. These errors in wavelength translate to approximately -4°C to 3°C errors in temperature. Applying the calculated third order calibration to the interrogator’s output reduces the error to an average of 0.0155 nm, or approximately 0.155°C across the wavelength range.
Though not groundbreaking, previous research has shown the temperature change – wavelength shift calibration of the Micron Optics os1100 FBG is necessary for accurate temperature calculations (Reid and Özcan, 1998; Flockhart et al., 2004; Pal et al. 2004; Adamovsky et al., 2012). Within the temperature range of the grating, a second order calibration was determined.

The two bath experiment presented in this chapter demonstrated the effect of a thermal gradient on FBG spectrum response. The FBG located within the partition between the baths showed significant sensitivity to the thermal gradient created by the differing temperatures of the baths as both the FWHM and FWQM bandwidths nearly doubled due to a gradient with a magnitude less than 100°C. The experimental bandwidth as a function of temperature difference between the baths was determined and plotted.

The experimental results were compared to a numerical model consisting of a two dimensional heat transfer model, an ANSYS model, and the T-matrix method. The two dimensional heat transfer model is necessary because it is used to calculate the hot and cold wall temperatures of the partition. The temperature difference of the partition wall temperature more directly affect the spectrum deformation of the FBG than the temperature difference of the baths. The heat transfer model assumed a linear temperature gradient through the thickness of the partition, and this is valid for the ANSYS determined temperature gradients after approximately 100 seconds. The bandwidths of the numerically determined spectra matched the bandwidths of the experimentally observed spectra well, though the model did underestimate the Bragg wavelength shift of the spectra. The numerical model showed the sensitivity a FBG to a temperature gradient was more significant than what was experimentally
observed because the experimental data relied on the larger temperature difference between
the baths. According to the numerical model, a FWQM bandwidth change of 0.25, nearly
double the initial bandwidth, is due to only a 32°C temperature difference over the length of
the FBG.
Figure 3.1. Reflected spectrum of the 31 FBG array as given by the high resolution OSA and the Micron Optics sm130 when a linear scale with end points of 1510 nm and 1590 nm is applied to the Micron Optics data.
Figure 3.2. The difference between the peak wavelength given by the Micron Optics os130 interrogator and the high resolution OSA for all 31 peaks in the FBG array for an 80 nm wide linearly scaled window.

Figure 3.3. Peak wavelength as given by the OSA as a function of the fractional count location of the peak from the raw Micron Optics data.
Figure 3.4. Difference in peak wavelength between the data from the OSA and the Micron Optics interrogator for each peak when different calibrations are applied to the Micron Optics spectrum data in terms of (a) FBG array peak number and (b) wavelength.
Figure 3.5. Difference in peak wavelength between the data from the OSA and the Micron Optics interrogator with the linear calibration removed in terms of (a) FBG array peak number and (b) wavelength.
Figure 3.6. Test set-up for the Micron Optics os1100 FBG temperature calibration.
Figure 3.7. Temperature of the oven over the duration of the calibration

Figure 3.8. Temperature in degrees Celsius as a function of wavelength shift.
Figure 3.9. Diagram showing the dimensions and configuration of the thermal gradient experiment using two different fluid baths separated by a 1 cm thick central partition.

Figure 3.10. Photograph of the PTFE container with an optical fiber.
Figure 3.11. Photograph of the experimental setup.
Figure 3.12. FBG reflected spectra taken seconds apart with the FBG at three locations within the thermal bath experiment.
Figure 3.13. Initial reflected spectrum of the three FBG array used in the transient thermal gradient experiment.

Figure 3.14. Intensity of FBG 2 during the experiment.
Figure 3.15. The (a) FWHM and (b) FWQM bandwidth of FBG 2 during the experiment.
Figure 3.16. Maximum reflectivity of FBG 2 during the experiment plotted on the same axis as the FWQM bandwidth highlighting the relationship between the two.
Figure 3.17. Temperature response of (a) FBG 1, (b) FBG 2, and (c) FBG 3 during the transient bandwidth deformation experiment.
Figure 3.18. Temperature response of all three FBGs during the experiment.
Figure 3.19. The (a) FWHM bandwidth and (b) FWQM bandwidth of FBG 2 plotted against the temperature difference of FBG 1 and FBG 3.
Figure 3.20. Thermal conductivity for silica as a function of temperature.

Figure 3.21. Meshed model geometry used in the numerical ANSYS model.
Figure 3.22. Temperature output from 11 nodes located within the silica from the ANSYS model.
Figure 3.23. Initial experimental spectrum of FBG 2 compared with the simulated spectra from the T-matrix and modified T-matrix methods.

Figure 3.24. Comparison of T-matrix and modified T-matrix spectrum FWQM bandwidth with experimental spectrum FWQM bandwidth.
Figure 3.25. Simulated reflected spectra given by the T-matrix and modified T-matrix methods at (a) 123.46 seconds and (b) 128.46 seconds as calculated from temperature data given by the ANSYS model.
Figure 3.26. Simulated reflected spectra given by the modified T-matrix method along with the first order Gauss fit for the data at (a) 123.46 seconds and (b) 128.46 seconds as calculated from temperature data given by the ANSYS model.
Figure 3.27. Comparison of the FWQM bandwidth of the T-matrix and modified T-matrix methods with first order Gauss fits of the T-matrix and modified T-matrix curves.
Figure 3.28. Diagram of the combined conduction-convection model described by equation 3.14.
Figure 3.29. Comparison of the hot and cold bath experimental temperatures and the calculated wall temperatures using equation 3.16.

Figure 3.30. Temperature output from 11 nodes located within the silica from the ANSYS model as determined by using a reduced temperature load.
Figure 3.31. Comparison of T-matrix and modified T-matrix spectra FWQM bandwidth with experimental spectrum FWQM bandwidth for the recalculated ANSYS temperature loads.

Figure 3.32. Comparison of Gauss fit of the T-matrix and modified T-matrix spectra FWQM bandwidth with experimental spectrum FWQM bandwidth for the recalculated ANSYS temperature loads.
Figure 3.33. Values for the FWQM bandwidth given by the T-matrix and modified T-matrix methods plotted as a function of temperature difference between the numerically calculated values for $T_{wh}$ and $T_{wc}$.

Figure 3.34 Temperature profile across the length of the FBG as calculated by the ANSYS model with reduced temperature loads.
Figure 3.35. Numerical temperature profile across the length of the FBG as determined by the ANSYS model with the experimental and numerically determined spectra at (a) 15 seconds, (b) 50 seconds, (c) 100 seconds, (d) 150 seconds, (e) 200 seconds, (f) 250 seconds, (g) 300 seconds, and (h) 600 seconds.
(c) and (d) show the experimental data and the calculated results using the T-Matrix and Modified T-Matrix methods, respectively. The data is plotted against FBG length in millimeters and temperature in degrees Celsius. The wavelength reflectivity is also depicted, with experimental data and modelled curves for T-Matrix and Modified T-Matrix.
Table 3.1. Reflected Bragg wavelength of the FBG when in the temperature baths and the center partition.

<table>
<thead>
<tr>
<th>FBG Location</th>
<th>Bragg Wavelength [nm]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Bath</td>
<td>1576.40</td>
<td>80.959</td>
</tr>
<tr>
<td>Partition</td>
<td>1576.20</td>
<td>60.435</td>
</tr>
<tr>
<td>Cold Bath</td>
<td>1575.97</td>
<td>9.360</td>
</tr>
</tbody>
</table>

Table 3.2. Comparison of bandwidths when the FBG is located at different locations within the container and the bandwidth is taken at different percentages of the maximum intensity.

<table>
<thead>
<tr>
<th>FBG Location</th>
<th>FWHM [nm]</th>
<th>FWQM [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Bath</td>
<td>0.2060</td>
<td>0.2670</td>
</tr>
<tr>
<td>Partition</td>
<td>0.2289</td>
<td>0.3243</td>
</tr>
<tr>
<td>Cold Bath</td>
<td>0.2060</td>
<td>0.2632</td>
</tr>
<tr>
<td>Percent Increase</td>
<td>11.11</td>
<td>21.43</td>
</tr>
</tbody>
</table>

Table 3.3. Definition of the three FBGs in the multiplexed array and their initial Bragg wavelengths.

<table>
<thead>
<tr>
<th>FBG</th>
<th>Initial Bragg wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1536.05</td>
</tr>
<tr>
<td>2</td>
<td>1560.23</td>
</tr>
<tr>
<td>3</td>
<td>1573.90</td>
</tr>
</tbody>
</table>
Table 3.4. PTFE material properties used in the numerical ANSYS model (Bejan, 1993).

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>$2200 , \frac{kg}{m^3}$</td>
</tr>
<tr>
<td>Specific Heat, $c_p$</td>
<td>$1040 , \frac{J}{kg , K}$</td>
</tr>
<tr>
<td>Thermal Conductivity, $k$</td>
<td>$0.245 , \frac{W}{m , K}$</td>
</tr>
</tbody>
</table>

Table 3.5. Material properties for density and specific heat for silica used in the numerical ANSYS model (Bejan, 1993).

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>$2210 , \frac{kg}{m^3}$</td>
</tr>
<tr>
<td>Specific Heat, $c_p$</td>
<td>$730 , \frac{J}{kg , K}$</td>
</tr>
</tbody>
</table>
Table 3.6. Temperature dependent thermal conductivity for silica used in the ANSYS model (Touloukian, 1977).

<table>
<thead>
<tr>
<th>Temperature(°C)</th>
<th>Thermal Conductivity ($\frac{W}{m \cdot K}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.3984</td>
</tr>
<tr>
<td>10</td>
<td>1.4045</td>
</tr>
<tr>
<td>20</td>
<td>1.4108</td>
</tr>
<tr>
<td>30</td>
<td>1.4175</td>
</tr>
<tr>
<td>40</td>
<td>1.4244</td>
</tr>
<tr>
<td>50</td>
<td>1.4316</td>
</tr>
<tr>
<td>60</td>
<td>1.439</td>
</tr>
<tr>
<td>70</td>
<td>1.4468</td>
</tr>
<tr>
<td>80</td>
<td>1.4548</td>
</tr>
<tr>
<td>90</td>
<td>1.4632</td>
</tr>
<tr>
<td>100</td>
<td>1.4718</td>
</tr>
</tbody>
</table>
CHAPTER 4

ADHESIVE STRAIN TRANSFER BETWEEN HOST MATERIALS AND FIBER BRAGG GRATINGS

The goal of this chapter is to develop mathematical models to analyze the adhesive strain transfer between a bonded FBG, the host material and the bonding material. The work presented in this chapter was motivated by the results of the initial thermal gradient experiment consisting of a four FBG array bonded to a specimen using epoxy. Mathematical models were derived to determine FBG response to coupled silica, host systems. These models were developed in section 4.1.

An experiment consisting of a three FBG array placed in an oven was conducted and is discussed in section 4.2. The purpose of the oven test was to validate the accuracy of the mathematical models for a known, uniform, applied temperature. In the array, one FBG was free, the second was embedded in an isotropic material, in this case epoxy, and the third FBG was bonded to a host material, in this case a small aluminum bar.

Section 4.3 discusses the application of the mathematical models developed in section 4.1 to the initial thermal gradient test briefly described in the introduction to Chapter 3. Based on the temperatures calculated by the mathematical model, temperature and strain gradients and their effect on the spectrum response of the FBGs in the array were calculated using the modified T-matrix method.
4.1. THEORETICAL DERIVATION OF THE RESPONSE OF FBGS TO COUPLED SILICA, HOST MATERIAL SYSTEMS

In addition to temperature, FBGs are sensitive to strain components. This coupled sensitivity to strain and temperature is not unique to FBG sensors, however the properties of silica are strongly sensitive to temperature, relative to electrical resistance strain gages. In this section, we applied a thermal load $\Delta T$ to the sensor and determine the Bragg wavelength sensitivity to the thermal loading. The coupled sensitivity depends on the mounting configuration of the FBG sensor, therefore the apparent gage factor to temperature, $G_T$, must be derived for each mounting configuration. For example, when FBGs are embedded in a host material with a different coefficient of thermal expansion than the silica of the optical fiber, the different thermal expansion of the two materials will result in a mechanical strain applied to the fiber that will be detected by the FBG.

The change in Bragg wavelength due to thermal and mechanical loading can be defined using equation 4.1.

$$\frac{\Delta \lambda_B}{\lambda_B} = G_T \Delta T = \frac{\Delta n_{eff}}{n_{eff}} + \frac{\Delta \Lambda}{\Lambda}$$  \hspace{1cm} (4.1)

$\Delta \lambda_B$ is the change in Bragg wavelength, $\lambda_B$ is the initial Bragg wavelength, $n_{eff}$ is the effective refractive index of fundamental mode of the optical fiber, $\Delta n_{eff}$ is the change in effective refractive index and the term $\Delta \Lambda$ is the change in grating period. The refractive index and grating period are each affected by both the mechanical and thermal loading. The term $\Delta \Lambda/\Lambda$ can be rewritten as, $\varepsilon_1^T$, the total axial strain along the length of the FBG.
\[
\frac{\Delta \lambda_B}{\lambda_B} = \frac{\Delta n_{eff}}{n_{eff}} + \varepsilon_1^T
\] (4.2)

It is necessary, therefore, to calculate \( \Delta n_{eff} \) for each mounting case. We assume small strains and temperature changes. Therefore the linear thermoelastic strain-optic equation for the silica dielectric constants, \( B_i \), can be applied, given in equation 4.3, using tensor notation for strain components (Nye, 1985),

\[
\Delta B_i = p_{ij}(\varepsilon_j - \alpha_j \Delta T) + W_i \Delta T
\] (4.3)

\( \varepsilon_j \) is the total normal strain in the \( j^{th} \) direction. \( p_{ij} \) are the strain-optic coefficients of silica, \( \alpha_j \) are the coefficients of thermal expansion in the 1-, 2- and 3-directions of silica and \( W \) is the free-expansion thermo-optic coefficient, measured only due to temperature changes. The first term of equation 4.3 is the stress induced change in the dielectric constants and the second term is the temperature induced change. \( W \) is measured at a constant stress and is defined using equation 4.4.

\[
W_i = \left( \frac{\partial B_i}{\partial \Delta T} \right)_{\sigma=constant}
\] (4.4)

For an isotropic material (as we assume for the unloaded optical fiber), the initial properties are \( B_1 = B_2 = B_3 = 1/n^2_{eff} \) and \( B_4 = B_5 = B_6 = 0 \). The strain-optic coefficients are given in equations 4.5 and 4.6.
The index of refraction for a lightwave propagating in the 1-direction, in the optical fiber axial
direction, is calculated by equation 4.7 (Van Steenkiste and Springer, 1997).

\[
\frac{1}{n^2} = \frac{1}{n_{\text{eff}}^2} + \frac{1}{2} (p_{11} + p_{12}) \left( \varepsilon_1 + \frac{1}{2} (p_{11} - p_{12}) \sqrt{(\varepsilon_2 - \varepsilon_3)^2 + \varepsilon_4^2} \right) + W_1 \Delta T
\]  

(4.8)

Shear strains are typically not transferred well through adhesives to the optical fiber sensor,
therefore we typically neglect their effect on equation 4.8. Assuming shear strains are zero,
\( \varepsilon_4 = \varepsilon_5 = \varepsilon_6 = 0 \), equation 4.8 further reduces to equation 4.9.

\[
\frac{1}{n^2} = \frac{1}{n_{\text{eff}}^2} + \frac{1}{2} (p_{11} + p_{12}) \left( \varepsilon_1 + \frac{1}{2} (p_{11} - p_{12})(\varepsilon_2 - \varepsilon_3) \right) + W_1 \Delta T
\]  

(4.9)
4.1.1. Mechanical Strain on a Free FBG

The effects of temperature induced strain on a free FBG can also be considered as the calibration case for a sensor. Applying a known temperature to a FBG is how the thermo-optic coefficient of the FBG, $\beta$, is calculated. An experimental calibration of a Micron Optics os1100 FBG sensor was discussed in section 3.2 (although here we limit ourselves to the linear response region). We apply a constant thermal load $\Delta T$ to the sensor. For the case of a free sensor, the total strain is defined in equation 4.10 and the mechanical strain in equation 4.11.

$$\varepsilon_1^T = \varepsilon_2^T = \varepsilon_3^T = \alpha_s \Delta T$$  \hspace{1cm} (4.10)

$$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$$  \hspace{1cm} (4.11)

$\alpha_s$ is the coefficient of thermal expansion for silica. Equations 4.10 and 4.11 are substituted into equation 4.9 to give equation 4.12 and the index of refraction, $n$, is solved for in equation 4.13.

$$\frac{1}{n^2} = \frac{1}{n_{eff}^2} + W_1 \Delta T$$  \hspace{1cm} (4.12)

$$n = \left[ \frac{1}{n_{eff}^2} + W_1 \Delta T \right]^{-1/2}$$  \hspace{1cm} (4.13)

As we are considering the small temperature change region, we can linearize equation 4.13 about $\Delta T = 0$.

$$\Delta n \approx \left( \frac{\partial n}{\partial \Delta T} \right)_{\Delta T=0} \Delta n_{eff} = -\frac{1}{2} n_{eff}^2 W_1 \Delta T$$  \hspace{1cm} (4.14)

For the free FBG case, equation 4.14 becomes equation 4.15.

$$\frac{\Delta n_{eff}}{n_{eff}} = -\frac{1}{2} n_{eff}^2 W_1 \Delta T$$  \hspace{1cm} (4.15)
Rearranging equation 4.15 to solve for $W_i$ gives equation 4.16.

$$W_1 = \frac{-2 \Delta n_{\text{eff}}}{n_{\text{eff}}^3} \frac{\Delta T}{\Delta} = \frac{-2 d n_{\text{eff}}}{n_{\text{eff}}^3} dT$$

(4.16)

For convenience, we define the thermo-optic coefficient for silica, $\zeta$, in equation 4.17.

$$\zeta = \frac{dn_{\text{eff}}}{dT}$$

(4.17)

Substituting equation 4.17 into 4.16 defines $W_i$ in terms of the thermo-optic coefficient of silica.

$$W_1 = \frac{-2}{n_{\text{eff}}^3} \zeta$$

(4.18)

Substituting equation 4.18 and 4.15 into equation 4.1 defines the change in Bragg wavelength of the FBG in terms of the effective refractive index of the FBG and the thermo-optic coefficient of the fiber.

$$\frac{\Delta \lambda_B}{\lambda_B} = -\frac{1}{2} n_{\text{eff}}^2 \frac{2}{2} n_{\text{eff}}^3 \zeta \Delta T + \varepsilon_1^T$$

(4.19)

For the free sensor, the total axial strain on the fiber is wholly due to the thermal expansion of the silica so equation 4.19 reduces to equation 4.20.

$$\frac{\Delta \lambda_B}{\lambda_B} = \left( \frac{1}{n_{\text{eff}}} \zeta + a_s \right) \Delta T$$

(4.20)

The first term of equation 4.20 can be further simplified by defining the thermo-optic coefficient of the FBG, $\beta$, using equation 4.21. This property is typically provided in reference material property tables.

$$\beta = \frac{1}{n_{\text{eff}}} \zeta$$

(4.21)
Equation 4.21 reduces the Bragg wavelength change due to temperature change given in equation 4.20 to the form shown in equation 4.22. Therefore, when free calibration of a FBG is performed, the thermal gage coefficient $G_T= (\beta + \alpha_s)$ is measured.

\[
\frac{\Delta \lambda_B}{\lambda_B} = (\beta + \alpha_s) \Delta T
\]  \hspace{1cm} (4.22)

4.1.2. Mechanical Strain on a Surface Bonded FBG

When an FBG is surface bonded to a host material, additional mechanical strains are included in the calculation of the Bragg wavelength change. Assuming the volume of the adhesive is small relative to the volume of the host material, strain effects from the adhesive can be ignored. The total strains for this case are given in equation 4.23 and the mechanical strains are given in equation 4.24.

\[
\begin{align*}
\varepsilon^T_1 &= \alpha_h \Delta T, \quad \varepsilon^T_2 = \varepsilon^T_3 = \alpha_s \Delta T \\
\varepsilon_1 &= (\alpha_h - \alpha_s) \Delta T, \quad \varepsilon_2 = \varepsilon_3 = 0
\end{align*}
\]  \hspace{1cm} (4.23)

\[
\alpha_h \text{ is the thermal expansion coefficient of the host material. The fiber is assumed to be bonded to the host in the 1-direction (the axial direction of the optical fiber). In the model, the host material forms a tangent plane to the surface of the fiber. The silica in the fiber is free to expand in the 2- and 3- directions independent of the host, however, the thermal coefficient mismatch between the host material and the silica optical induces a mechanical strain in the fiber along the 1-direction.}

The boundary conditions given in equations 4.23 and 4.24 along with the relationship for $W_f$ and $\beta$ given in equations 4.18 and 4.21 are plugged into equation 4.9 to calculate the
index of refraction for a lightwave propagating along the 1-direction of the fiber, which is
given in equation 4.25.

\[
\frac{1}{n^2} = \frac{1}{n_{\text{eff}}^2} + p_{12}(\alpha_h - \alpha_s)\Delta T - \frac{2}{n_{\text{eff}}^2} \beta \Delta T
\]  \hspace{1cm} (4.25)

Equation 4.25 is linearized about \(\Delta T=0\) to give equation 4.26.

\[
\Delta n \approx \left( \frac{\partial n}{\partial \Delta T} \right)_{\Delta T=0} \Delta n_{\text{eff}} = \frac{1}{2} \left( \frac{1}{n_{\text{eff}}^2} \right)^{-3/2} \left[ p_{12}(\alpha_h - \alpha_s) - \frac{2}{n_{\text{eff}}^2} \beta \right] \Delta T
\]  \hspace{1cm} (4.26)

The relationship between Bragg wavelength change and temperature dependence for the case
of a surface bonded sensor is given in equation 4.27.

\[
\frac{\Delta \lambda_B}{\lambda_B} = \left[ \beta - n_{\text{eff}}^2 p_{12}(\alpha_h - \alpha_s) + a_h \right] \Delta T = G_T \Delta T
\]  \hspace{1cm} (4.27)

The strain effect due to the difference in thermal expansion coefficients between the silica and
the host material is dependent upon one of the Pockel’s constants, \(p_{12}\), not the strain-optic
coefficient, \(p_e\), which is a combination of both Pockel’s constants and the Poisson’s ratio of
silica.

4.1.3. Mechanical Strain on a Surface Bonded FBG with an Included Prestrain in the 1-
Direction

When there is an additional pre-stress, \(\varepsilon_a\), along direction of the optical fiber in addition
to a bond between an optical fiber and host material, the boundary conditions presented in
equations 4.23 and 4.24 become equations 4.28 and 4.29 for total and mechanical strain.

\[
\varepsilon_1^T = \alpha_h \Delta T + \varepsilon_a, \hspace{0.5cm} \varepsilon_2^T = \varepsilon_3^T = \alpha_s \Delta T - \nu \varepsilon_a
\]  \hspace{1cm} (4.28)
\[ \varepsilon_1 = (\alpha_h - \alpha_s)\Delta T + \varepsilon_a, \quad \varepsilon_2 = \varepsilon_3 = -\nu \varepsilon_a \quad (4.29) \]

\( \varepsilon_a \) is the prestrain along the axial direction of the fiber due to the pre-stress (equal to \( \sigma_a/E \) where \( E \) is the host material elastic modulus) and \( \nu \) is the Poisson’s ratio of the host material. Inputting the boundary conditions into equation 4.9 gives equation the relationship between the index of refraction of a propagating lightwave along the axial direction of the optical fiber.

\[
\frac{1}{n^2} = \frac{1}{n_{\text{eff}}^2} + p_{12}[(\alpha_h - \alpha_s)\Delta T + \varepsilon_a] + \frac{(p_{11} + p_{12})}{2}(-2\nu \varepsilon_a) + \frac{2}{n_{\text{eff}}^2} \beta \Delta T \quad (4.30)
\]

Linearizing equation 4.30 about \( \Delta T=0 \) we find equation 4.31.

\[
\Delta n \approx -\frac{1}{2} \left( \frac{1}{n_{\text{eff}}^2} + p_{12}\varepsilon_a - \nu(p_{11} + p_{12}) \right)^{-3/2} \left[ p_{12}(\alpha_h - \alpha_s) - \frac{2}{n_{\text{eff}}^2} \beta \right] \Delta T \quad (4.31)
\]

\[
\frac{\Delta n}{n_{\text{eff}}} = -\frac{1}{2} n_{\text{eff}}^2 \left[ 1 + n_{\text{eff}}^2(p_{12} - \nu(p_{11} + p_{12}))\varepsilon_a \right]^{-3/2} \left[ p_{12}(\alpha_h - \alpha_s) - \frac{2}{n_{\text{eff}}^2} \beta \right] \Delta T \quad (4.32)
\]

The strain-optic coefficient, \( p_e \), is often defined using equation 4.33.

\[
p_e = \frac{n_{\text{eff}}^2}{2} (p_{12} - \nu(p_{11} + p_{12})) \quad (4.33)
\]

Using equation 4.32 is used to calculate the Bragg wavelength change, given in equation 4.1, along with the definition of \( p_e \).

\[
\frac{\Delta \lambda_B}{\lambda_B} = (1 + 2p_e \varepsilon_a)^{-3/2} \left[ \beta - \frac{1}{2} n_{\text{eff}}^2 p_{12}(\alpha_h - \alpha_s) \right] \Delta T + \alpha_h \Delta T + \varepsilon_a \quad (4.34)
\]

The \( \alpha_h \Delta T + \varepsilon_a \) term in equation 4.34 represents the total axial strain, \( \varepsilon'_T \), given in equation 4.28. For realistic values of prestrain, \( \varepsilon_a \).
Equation 4.35 simplifies equation 4.34.

\[
\frac{\Delta \lambda_B}{\lambda_B} \approx \left[ \beta - \frac{1}{2} n_{eff}^2 p_{12} (\alpha_h - \alpha_s) + \alpha_h \right] \Delta T + \epsilon_a = G_T \Delta T + \epsilon_a
\]  

(4.36)

The pre-strain term, \( \epsilon_a \), becomes a constant independent of temperature. Therefore the slope of the change in wavelength as a function of the change in temperature curve remains the same as for the previous case.

4.1.4. Mechanical Strain on a FBG Embedded in an Isotropic Material

For a FBG embedded fully within an isotropic material, the total strain and mechanical strain are given by equations 4.37 and 4.38.

\[
\varepsilon^T_1 = \varepsilon^T_2 = \varepsilon^T_3 = \alpha_h \Delta T
\]  

(4.37)

\[
\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = (\alpha_h - \alpha_s) \Delta T
\]  

(4.38)

Inputting these boundary conditions into equation 4.9 gives equation the relationship between the index of refraction of a propagating lightwave along the axial direction of the optical fiber.

\[
\frac{1}{n^2} = \frac{1}{n_{eff}^2} + p_{12} (\alpha_h - \alpha_s) \Delta T + (p_{11} + p_{12}) (\alpha_h - \alpha_s) \Delta T + \frac{2}{n_{eff}^2} \beta \Delta T
\]  

(4.39)

Equation 4.40 is the result of linearizing equation 4.39 about \( \Delta T=0 \).

\[
\Delta n \approx -\frac{1}{2} \left( \frac{1}{n_{eff}^2} \right)^{3/2} \left[ (\alpha_h - \alpha_s)(p_{11} + 2p_{12}) - \frac{2}{n_{eff}^2} \beta \right] \Delta T
\]  

(4.40)

The Bragg wavelength change due to an applied temperature change is given in equation 4.41.

\[
\frac{\Delta \lambda_B}{\lambda_B} = \left[ \beta - \frac{1}{2} n_{eff}^2 (p_{11} + 2p_{12}) (\alpha_h - \alpha_s) + \alpha_h \right] \Delta T = G_T \Delta T
\]  

(4.41)
For a germanium doped silica optical fiber, values for the different constants present in equations 4.1 through 4.41 are shown in Table 4.1.

4.2. OVEN TEST

4.2.1. Experimental Setup

A three FBG array was constructed consisting of three Micron Optics os1100 FBGs. Each FBG was located in a different physical state. FBG 1 was free, FBG 2 was embedded within a block of Duralco™ 4525IP epoxy and FBG 3 was bonded to a small aluminum block using Duralco™ 4525IP epoxy. The Duralco™ epoxy is a room temperature cure epoxy that is dark grey in color, electrically resistant, and has a service temperature up to 260°C. The designation of each FBG, their state and initial Bragg wavelengths given in Table 4.2 and the thermal expansion coefficients for the Duralco™ 4525IP epoxy and aluminum is given in Table 4.3.

The initial spectrum of each FBG in the array, before embedding or bonding, is given in Fig. 4.1. Embedding or bonding the FBGs had no effect on Bragg wavelength or bandwidth of the FBG.

The array was placed in a Fisher Scientific Isotemp oven. The array in the oven is shown in Fig. 4.2. The temperature of the oven was set to 200°C. As the temperature of the oven was increased to 200°C, the temperature of the oven was recorded along with the reflected spectrum given by the FBG at 5 s intervals. Once the oven reached 200°C, data collection continued for an additional 205 seconds. The seal between the oven door and the oven body is a soft, rubbery material that sealed tightly around the 125 micron diameter optical
fiber while allowing the fiber to pass through with no noticeable signal loss. The oven and the test setup is shown in Fig. 4.3. This is the same image seen in Fig. 3.6, as the free FBG was used to calibrate the temperature response of the Micron Optics os1100 FBGs as discussed in section 3.2.

The temperature of the oven over time is given in Fig. 4.4 and the wavelength change of each FBG in the array over time is given in Fig. 4.5. As predicted earlier, a clear difference in apparent thermal gage factor can be seen in the three different FBGs.

### 4.2.2. Experimental Results: Free FBG

The results for the free FBG were previously presented in section 3.2, but are repeated here. Fig. 4.6 shows wavelength shift as a function of temperature change. The curve in Fig. 4.6 is used to calculate $\beta$ for the FBG. The second order fit of the curve in Fig. 4.6 is given in equation 4.42.

$$\frac{\Delta \lambda}{\lambda_B} = \left( 8.080 \times 10^{-9} \frac{1}{\sigma_C^2} \right) \Delta T^2 + \left( 5.969 \times 10^{-6} \frac{1}{\sigma_C} \right) \Delta T$$

(4.42)

The linear coefficient in equation 4.43, $5.969 \times 10^{-6}$ °C$^{-1}$ is $(\alpha_s + \beta)$. The properties of silica used for optical fiber fabrication is well controlled and reported. Therefore the thermal expansion of silica, $\alpha_s = 0.55 \times 10^{-6}$ °C$^{-1}$, was taken from the literature. From equation 4.43, the linear $\beta$ term becomes $5.419 \times 10^{-6}$. As explained in chapter 3, the thermal expansion coefficient of silica is reported to be constant over a large temperature range. Therefore, we assume that the second order term in 4.42 is entirely due to the temperature dependence of $\beta$ and define the nonlinear thermo-optic coefficient $\beta$, as equation 4.43.
\[ \beta = \left(8.080 \times 10^{-9} \frac{1}{\alpha C^2}\right) \Delta T^2 + \left(5.419 \times 10^{-6} \frac{1}{\alpha C}\right) \Delta T = a_\beta \Delta T + b_\beta \Delta T^2 \quad (4.43) \]

Using equation 4.42 to convert the wavelength shift from the free curve in Fig. 4.4 to temperature gives the FBG curve in Fig. 4.8 plotted along with the oven temperature, demonstrating the good approximation of the second order polynomial fit to \( \beta \). At this point, it is important to point out that the temperature gage factors, \( G_T \), derived in sections 4.1 are based on linearizing the index of refraction response about \( \Delta T = 0 \). Applying these equations over the large temperature range of figure 4.7 may not be properly represented by simply adding the nonlinearity to the coefficient \( \beta \). Transferring the calibration may instead be better modeling using the nonlinear equations for \( \Delta n_{\text{eff}} \) such as equation 4.25. This could be tried in future studies.

4.2.3. Experimental Results: Embedded FBG

The Bragg wavelength over time measured for the embedded FBG is given in Fig. 4.8. The embedded FBG has a slower initial wavelength change than the other FBGs in the array. The embedded FBG is located deep within the epoxy specimen and is initially insulated from the heating load by the epoxy. The embedded FBG also experiences the largest wavelength shift of any FBG in the array. Due to the second order nature of \( \beta \), equation 4.41 is represented as equation 4.44.

\[ \frac{\Delta \lambda_B}{\lambda_B} = \frac{a_\beta}{\lambda_B} \Delta T^2 + \left[b_\beta - \frac{1}{2} n_{\text{eff}}^2 (p_{11} + 2p_{12})(\alpha_h - \alpha_z) + \alpha_h\right] \Delta T \quad (4.44) \]

\( a_\beta \) and \( b_\beta \) are the second and first order coefficients for the FBG thermo-optic coefficient defined in equation 4.44. To determine the temperature change, \( \frac{\Delta \lambda_B}{\lambda_B} \) was subtracted from each
side of the equation and the quadratic equation was used with the coefficients defined in equation 4.46. The roots of the quadratic equation were the temperature change. The two roots calculated by the quadratic equation over time are shown in Fig. 4.9.

The temperature change in Fig. 4.9b is unrealistic given the physical constraints of the experiment. The temperature change plotted in Fig. 4.9a was added to the initial temperature of the FBG and the temperature profile over time of the embedded FBG is plotted along with the oven temperature in Fig. 4.10.

The temperature of the embedded FBG is below the oven temperature, but is still increasing when the test concludes. Unfortunately, because spectrum data was saved, it was impossible to determine if all three FBGs in the array had reached a steady state temperature before the test concluded. For the final 500 seconds of the test, the temperature of the embedded FBG was increasing steadily and would potentially reach steady state at 200°C if the test was not stopped prematurely. However, the embedded sensor test was not conclusive.

4.2.4. Experimental Results: Bonded FBG

The bonded FBG specimen is shown in Fig. 4.11. The dimensions of the aluminum host specimen are 10.2 cm x 2.54 cm x 0.3175 cm, with a total volume of 8.23 cm³. The approximate dimensions of the epoxy on the specimen are 4.5 cm x 2.4 cm x 0.2 cm with a volume of 2.16 cm³. The total volume of the combined aluminum/epoxy system is 10.34 cm³, of which 79.2% is aluminum. The bonded FBG equation given in equation 4.27 assumes the volume of the host material is significantly larger than the volume of the bonding agent. In this case, that is not a valid assumption. To compensate, the coefficient of thermal expansion of the
host material, \( \alpha_h \), is adjusted to be a combination of the host and bonding agent coefficients of thermal expansion as defined in equation 4.45.

\[
\alpha_{hc} = V_f \alpha_h + (1 - V_f) \alpha_b
\]  

(4.45)

\( \alpha_{hc} \) is the corrected coefficient of thermal expansion for the host material, \( V_f \) is the volume fraction of the host material, in this case 0.792, and \( \alpha_b \) is the coefficient of thermal expansion of the bonding agent. Substituting equation 4.47 into equation 4.27 along with accounting for a second order \( \beta \) relationship gives equation 4.46.

\[
\Delta \lambda_B = a_\beta \Delta T^2 + \left[ b_\beta - n_{eff}^2 p_1 \right] \Delta T^2 + \alpha_{hc} \Delta T + \varepsilon_a
\]  

(4.46)

Fig. 4.12 gives the wavelength over time for the bonded FBG.

Between 310 seconds and 375 seconds, there is a plateau present in the wavelength response. The plateau is due to a compressive strain being induced by the epoxy. The epoxy, while room temperature cured, has a recommended post cure cycle consisting of 1 hour at 121.1\(^\circ\)C followed by 1 hour at 176.7\(^\circ\)C. The epoxy was not post cured in this experiment. To compensate for the presence of the compressive strain, the compressive strain was treated as a constant prestrain that exists after 450 seconds. To compensate for the prestrain, equation 4.36 was used with the coefficient of thermal expansion correction presented in equation 4.45. The resulting relationship between Bragg wavelength shift and temperature change is given in equation 4.47.

\[
\Delta \lambda_B \approx a_\beta \Delta T^2 + \left[ b_\beta - \frac{1}{2} n_{eff}^2 p_1 \right] \Delta T^2 + \alpha_{hc} \Delta T + \varepsilon_a
\]  

(4.47)

Fig. 4.13 shows the wavelength response of the bonded FBG between 225 and 600 seconds highlighting the plateau. The dashed line represents the slope of the wavelength
response curve before the development of the compressive strain and has a slope of $0.004545 \frac{nm}{s}$.

To calculate the value of the compressive strain, the wavelength of the temperature response curve at 375 seconds was compared to the wavelength of the dashed line at 375 seconds. The dashed line is defined with equation 4.48.

$$\lambda = t \left( 0.004545 \frac{nm}{s} \right) + 1581.677nm$$

(4.48)

The wavelength output by the bonded FBG at 375 seconds is 1583.113 nm while the predicted wavelength using equation 4.50 is 1583.380 nm. The difference between the two wavelengths is -0.2668 nm. The value of -0.2668 nm is used in equation 4.49 to calculate the stress.

$$\varepsilon_a = \frac{\Delta \lambda_B}{\lambda_B} \frac{1}{1 - p_e}$$

(4.49)

$p_e$ is calculated using equation 4.33. For the given Pockel’s constants, $p_e$ is equal to 0.213. The value of the compressive strain, $\varepsilon_a$, is therefore equal to $-2.142 \times 10^{-4} \frac{m}{m}$.

Equation 4.46 was used to calculate the temperature from the wavelength shift before 375 seconds, and equation 4.47 was used to calculate the temperature from the wavelength shift after 375 seconds. The value of the two roots from each equation over time is given in Fig. 4.14. The temperature change seen in Fig. 4.14b is unrealistic given the physical constraints of the experiment. The temperature change plotted in Fig. 4.14a was added to the initial temperature of the FBG and the temperature profile over time of the embedded FBG is plotted along with the oven temperature in Fig. 4.15.

Unlike the embedded FBG, the bonded FBG eventually reaches a steady state of approximately 200°C. The bonded FBG reaches steady state because it is not embedded deep
in the specimen and it in contact with aluminum which has a high thermal conductivity. However, as the bonded FBG is not directly exposed to the oven environment, the response time of the FBG is still slower than that of the free FBG. The temperature response of all three FBGs is given in Fig. 4.16.

4.3. THERMAL GRADIENT TEST

The calibration results for the surface bonded sensors were then applied to experimental data from a test designed to measure the temperature variation through an epoxy cylinder. The experiment was originally designed to apply controlled thermal gradients to the FBG, however sufficient thermal gradients were not achieved. This experiment was later replaced with the two water-bath experiment presented in chapter 3. However, in this chapter, the previous analysis is used to interpret the effects of epoxy cure on the apparent thermal response in a surface mounted FBG.

4.3.1. Experimental Setup

A 6.5 cm tall cylindrical specimen was constructed out of Duralco™ 4525IP epoxy. The specimen had a slight taper with the diameter ranging from 7 cm at the bottom to 5.5 cm at the top. An array consisting of four FBGs was epoxied to the surface of the specimen using the same Duralco™ 4525IP epoxy. One FBG was aligned vertically with the center of the FBG located halfway up the height of the specimen. The other three FBGs in the array were attached horizontally to the specimen at 1 cm intervals. An image of the specimen is shown in Fig. 4.17, and a schematic of the specimen is shown in Fig. 4.18. The difference in appearance between
the epoxy in the specimen which is matte, and the epoxy used to bond the array to the specimen, which is glossy and darker, is because the specimen did not release cleanly from the mold so it was sanded to remove some surface roughness, and the specimen had been heated previously to the test. The appearance of the epoxy becomes less glossy as temperature is applied.

The specimen was placed in a hot press with the lower platen set to a temperature of 50°C, and the upper platen set to a temperature of 200°C. The specimen was not placed in the hot press until the upper and lower platens had reached a steady state temperature. The full spectrum of the array was sampled at 5 second intervals. Spectra were recorded for 1800 seconds. A photograph of the specimen in the hot press is shown in Fig. 4.19 the FBG spectrum before loading is shown in Fig. 4.20 and the initial Bragg wavelength of each FBG is given in Table 4.4. The loss of reflectivity between successive peaks in the spectrum response is due to losses in optical power due to the splice between FBGs.

### 4.3.2 Experimental Results

The Bragg wavelengths of FBGs 2, 3, and 4 from the experiment is given in Fig. 4.21. The wavelength drop occurring in each wavelength shift curve between 450 seconds and 800 seconds is assumed to be due to the post-curing of the epoxy used to bond the array to the specimen. Because the specimen had undergone previous heating cycles, but the epoxy used to bond the array to the specimen had not, the post-curing response of the epoxy used to bond the array to the specimen induced a compressive strain on the FBGs which resulted in a negative wavelength shift.
To compensate for the compressive strain, the difference in wavelength between the Bragg wavelength at the bottom of the drop and the projected value of the Bragg wavelength at that point in time had the drop not developed was calculated for each FBG. Fig. 4.22 demonstrates this difference for FBG 2. Fig. 4.23 shows the wavelength response for FBG 3 and 4 highlighting the drop. The dashed line represents the projected wavelength response of both FBGs without the drop. The dashed line is based off the slope of the wavelength response curve immediately before the development of the drop. The wavelength shift and the resulting strain as calculated using equation 4.49 for each FBG is given in Table 4.5.

The residual strains were used in the calculation of the temperature change due to wavelength shift for FBGs 2, 3, and 4. To calculate temperature change, the bonded FBG case described by equation 4.27 without a prestrain was used for each FBG. After the development of the compressive strain, which was modeled as a prestrain, equation 4.36 was used to calculate temperature. The resulting temperature profile for FBGs 2, 3, and 4 during the experiment is given in Fig. 4.24.

Fig. 4.24 shows that the temperatures in the array never exceed 100\(^\circ\)C for the FBG closest to the hot platen, FBG 2, after 1800 seconds. At the end of the experiment, the difference between the temperatures recorded by FBG 2 and FBG 4 is 17.91\(^\circ\)C. The unexpectedly low temperatures are due to a combination of convection and poor thermal contact between the hot press platens due to surface roughness. The FBGs were located on the outer surface of the specimen with only a thin layer of epoxy separating them from the laboratory air.
Once the temperature change of FBGs 2, 3, and 4 were known, equation 4.43 was used to calculate the expected wavelength shift due to the temperature change. The difference between the calculated wavelength shift and the actual wavelength shift during the experiment would be the wavelength shift due to strain. Fig. 4.25 shows the raw wavelength shift, the wavelength shift due to temperature, and the wavelength shift due to strain for FBGs 2, 3, and 4. The calculated strain as determined by the wavelength shift due to strain for FBGs 2, 3 and 4 is given in Fig. 4.26.

FBG 1, which was oriented vertically on the specimen, in line with the temperature and strain gradients, showed significant deformations in bandwidth during the experiment. The FWQM bandwidth of FBG 1 is shown in Fig. 4.27 during the experiment. The bandwidth response has a drop between 1080 and 1175 seconds. A sampling of reflected spectra from FBG 1 is shown in Fig. 4.28. Fig. 4.28 shows that the initial peak deformation between 300 seconds and 1050 seconds in Fig. 4.28(b) – Fig. 4.28€ is primarily due to spectrum broadening with little peak splitting. Once the peak begins to split after 1050 seconds, the bandwidth decreases as the secondary peak develops. Fig. 4.29 shows a sampling of reflected spectra in the trough region between 1050 seconds and 1175 seconds. Fig. 4.29 shows that as the bandwidth response enters the drop, a secondary peak in the spectrum develops and separates from the primary peak. As the secondary peak continues to grow after Fig. 4.29(h), the bandwidths to its maximum value at 1250 seconds where the peaks have a near equal magnitude as seen in Fig. 4.29(h). After 1250 seconds, the primary peak continues to decrease in magnitude as the secondary peak continues to grow. Eventually, the primary peak disappears
completely, and only the secondary peak remains. When this occurs, the bandwidth has returned to its initial value.

4.3.3 Numerical Bandwidth Results

The temperature and strain values calculated from the wavelength response from FBGs 2, 3, and 4 were used to construct second order temperature and strain profiles over the length of FBG 1. These profiles were used to simulate the spectra of FBG 1 using the modified T-matrix method described in section 3.4. The modified T-matrix method was used because it is shown to be more accurate for high strain gradients (Prabhugoud and Peters, 2004), and while there was not much difference between the modified T-matrix and T-matrix method curves shown in Fig. 3.32, the modified T-matrix curve matches the experimental data slightly better. The distance between FBG 2 and FBG 4 is 20 mm while the length of FBG 1 is only 10 mm. Only the profiles calculated at points between 5 mm and 15 mm were input into the modified T-matrix method to calculate bandwidth. A sample of a calculated strain gradient over the length of the FBG and the modified T-matrix method calculated spectrum is shown in Fig. 4.30.

The modified T-matrix method bandwidth due to the calculated strain profile is given in Fig. 4.31. The data in Fig. 4.31 is noisy. The measurement first appears to be limited by the wavelength resolution of the interrogator, however the bandwidth jumps are approximately 0.1 nm, which is well above the wavelength resolution of the interrogator. A few sources contribute to the noise present in the data. First, the wavelength resolution of the simulated spectrum is 0.01 nm between points, whereas the resolution of the interrogator is
approximately 0.004 nm between points. FWQM bandwidth is calculated by determining the wavelength of a point on the spectrum with a reflectivity equal to 25% of the peak reflectivity. Due to the discrete nature of the data, a data point may not exist at a reflectivity of exactly 25% of the peak reflectivity. To compensate, data points within ±25% of the reflectivity of the FWQM reflectivity were used to calculate bandwidth. While this did introduce an error, the error is not large enough to explain the approximately 0.1 nm jumps in the calculated bandwidth. As Fig. 4.32 shows, the shape of the spectrum calculated by the modified T-matrix varies widely in shape and bandwidth in adjacent points. This is the dominant cause of the noise in the calculated FWQM bandwidth. A moving average filter was applied to the data to reduce the noise. The filtered data is shown with the unfiltered data in Fig. 4.33. The same filtering was applied to the bandwidth due to temperature. The strain calculated bandwidth and the temperature calculated bandwidth is plotted along with the experimentally observed bandwidth in Fig. 4.34.

The temperature profiles have no effect on the bandwidth response. This agrees with the bandwidth experiment discussed in Chapter 3. Fig. 3.19 shows that if the temperature difference on each end of the FBG is less than 40°C, there is no noticeable change in the FWQM bandwidth.

The bandwidth response due to calculated strain also differs from the experimentally observed bandwidth. While the experimental FWQM bandwidth does not show a change until after 300 seconds, the strain bandwidth shows an increase within the first 150 seconds. Between 550 seconds and 700 seconds, the bandwidth change due to strain is zero. This region aligns with the development of the compressive stresses due to the post-curing of the bonding
epoxy. Fig. 4.26 shows near identical strains from FBG 3 and FBG 4 at this time in the experiment. After 700 seconds, the strain determined bandwidth rapidly increases and between 800 and 1100 seconds has a similar slope to the experimentally observed bandwidth before the trough in the experimental bandwidth data. The strain determined bandwidth continues to increase after the experimentally observed bandwidth returns to its initial value. The strain field present in this problem is complex, and was not analyzed in depth. The spectra calculated by the modified T-matrix assume the determined second order strain and temperature gradients are accurate over the length of the vertically aligned FBG. The experimental gradients may vary greatly from the fits used. For example, the fitted strain and temperature gradients assumed there were gradients present after 1400 seconds, but some yet undetermined mechanism caused the gradients to be removed in the experiment as the bandwidth of FBG 1 returned to zero.

4.4 CONCLUSIONS

Mathematical models for the temperature response of free, embedded, and bonded FBGs were determined in this chapter and validated in an oven test. The free FBG in the oven test was used to calibrate the Bragg wavelength shift – temperature change relationship of Micron Optics os1100 FBGs. Due to the depth the embedded FBG was located in the epoxy, the FBG never achieved a steady state temperature in the oven; however, the calculated temperature of the FBG was less than the known temperature of the oven and the temperature output by the embedded FBG made sense given the temperature loads. The calculated temperature of the bonded FBG did reach a steady state temperature equal to the temperature
of the oven. Due to the ratio of volume of the host material and the volume of the bonding epoxy, a modification to the derived equation for a bonded FBG was necessary.

The modified T-matrix method was used to determine the spectrum deformation due to the numerically calculated temperature and strain gradients based on the response of FBGs 2, 3 and 4 in the thermal gradient test. The thermal gradient due to the temperature difference was not significant enough to affect the reflected spectrum of FBG 1. This agrees with the results determined in Chapter 3 where a temperature difference of less than 15°C over the length of a FBG does not result in spectrum deformation. The spectra calculated by the modified T-matrix method due to the strain gradient did show significant deformation. Unfortunately the spectra calculated by the modified T-matrix method did not match the experimentally observed spectra well. The largest possible source of error is the second order strain gradient approximation determined by the strains at the locations of FBGs 2, 3 and 4 did adequately model the strain gradient present in the experiment. The mechanism of the strain release observed in the experiment at approximately 1400 seconds into the test currently unknown.
Figure 4.1. Initial spectrum of the three FBG array.

Figure 4.2. Array in the oven showing the bonded specimen on the far left, the embedded specimen and the free FBG to the right.
Figure 4.3. Test set-up for the Micron Optics os1100 FBG temperature calibration.
Figure 4.4. Temperature of the oven over the duration of the calibration.

Figure 4.5. Wavelength change for each FBG in the array.
Figure 4.6. Non-linear wavelength shift as a function of temperature change.

Figure 4.7. Temperature data output by the oven with the temperature data of the free FBG.
Figure 4.8. Wavelength change for the embedded FBG.
Figure 4.9. Temperature change due to the wavelength shift as determined by the (a) first and (b) second roots given by equation 4.44.
Figure 4.10. Temperature output by the oven along with the temperature data from the embedded FBG.

Figure 4.11. FBG bonded to a small aluminum plate using Duralco™ 4525IP epoxy.
Figure 4.12. Wavelength change for the bonded FBG.

Figure 4.13. Wavelength response of the bonded FBG highlighting the effect of the compressive strain on wavelength response.
Figure 4.14. Temperature change due to the wavelength shift as determined by the (a) first and (b) second roots given by the coefficients in equations 4.52 and 4.53.
Figure 4.15. Temperature output by the oven along with the temperature data from the bonded FBG.

Figure 4.16. Temperature output by the oven along with the temperature data from the bonded FBG.
Figure 4.17. Photograph of the Duralco™ 4525IP epoxy specimen with attached FBG array.

Figure 4.18. Schematic of the Duralco™ 4525IP epoxy specimen showing FBG location, spacing and orientation. The small radius bends in the fiber strand are not replicated in the specimen.
Figure 4.19. Photograph of the thermal gradient specimen between the hot press platens.

Figure 4.20. Initial reflected spectrum of the four FBG array before an applied heating load.
Figure 4.21. Bragg wavelengths for the horizontal FBGs in the array.

Figure 4.22. Wavelength difference due to the compressive strain for FBG 2.
Figure 4.23. Wavelength response of (a) FBG 3 and (b) FBG 4 at the drop in Bragg wavelength.
Figure 4.24. Temperature profile from the 3 horizontal FBGs in the array during the experiment.
Figure 4.25. Experimental wavelength shift plotted with the calculated wavelength shift due to temperature and the wavelength shift due to strain for (a) FBG 2, (b) FBG 3 and (c) FBG 4.
Figure 4.26. Temperature profile from the 3 horizontal FBGs in the array during the experiment.

Figure 4.27. FWQM bandwidth of FBG 1 during the experiment.
Figure 4.28. A sampling of reflected spectra from FBG 1 at (a) 0 seconds, (b) 300 seconds, (c) 600 seconds, (d) 900 seconds, (e) 1050 seconds, (f) 1100 seconds, (g) 1200 seconds, (h) 1250 seconds, (i) 1275 seconds, (j) 1300 seconds, (k) 1350 seconds, and (l) 1600 seconds.
Figure 4.29. A sampling of reflected spectra from FBG 1 taken at (a) 1080 s, (b) 1100 s, (c) 1110 s, (d) 1120 s, (e) 1130 s, (f) 1140 s, (g) 1160 s, and (h) 1175 s in the trough of the bandwidth response.
Figure 4.30. Strain gradient and resulting FBG spectrum as given by the modified T-matrix method at 1175 seconds.
Figure 4.31. FWQM bandwidth of the spectra calculated by the T-matrix method for a strain across FBG 1.

Figure 4.32. Spectra calculated by the modified T-matrix method at adjacent data points. Dashed lines represent the quarter maximum for each spectrum.
Figure 4.33. Filtered and unfiltered FWQM bandwidth of the spectra calculated by the T-matrix method for a strain across FBG 1.

Figure 4.34. The experimentally observed bandwidth of FBG 1 plotted with the calculated bandwidth of a spectrum subjected to the temperature and strain profiles calculated from the response of FBGs 2, 3, and 4.
Table 4.1. Common constants and properties of germanium doped silica.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pockel’s Constant, $p_{11}$</td>
<td>0.113 (Bertholds and Dändliker, 1988)</td>
</tr>
<tr>
<td>Pockel’s Constant, $p_{12}$</td>
<td>0.252 (Bertholds and Dändliker, 1988)</td>
</tr>
<tr>
<td>Index of Refraction, $n_{eff}$</td>
<td>1.482</td>
</tr>
<tr>
<td>Poisson’s Ratio of Silica, $\nu$</td>
<td>0.16</td>
</tr>
<tr>
<td>Thermal Expansion of Silica, $\alpha_s$</td>
<td>$0.55 \times 10^{-6}$ °C$^{-1}$</td>
</tr>
</tbody>
</table>

Table 4.2. Bragg wavelengths of Micron Optics FBGs used in the oven test.

<table>
<thead>
<tr>
<th>FBG</th>
<th>State</th>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Free</td>
<td>1532.313</td>
</tr>
<tr>
<td>2</td>
<td>Embedded</td>
<td>1561.960</td>
</tr>
<tr>
<td>3</td>
<td>Bonded</td>
<td>1582.086</td>
</tr>
</tbody>
</table>

Table 4.3. Coefficients of thermal expansion for the epoxy and aluminum.

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficient of Thermal Expansion [°C$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duralco™ 4525IP Epoxy</td>
<td>$64 \times 10^{-6}$ (Cotronics, 2014)$^1$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$22.2 \times 10^{-6}$ (Touloukian, 1975)</td>
</tr>
</tbody>
</table>

$^1$ There is uncertainty surrounding this value. The data sheet packaged with the epoxy gave a value of coefficient of thermal expansion of $64 \times 10^{-6}$ °C$^{-1}$. Data sheets found provided online by manufacturer Cotronics give a value of the coefficient of thermal expansion of $33 \times 10^{-6}$ °C$^{-1}$. For this paper, the value of $64 \times 10^{-6}$ was used.
Table 4.4. Initial Bragg wavelength for each FBG in the array.

<table>
<thead>
<tr>
<th>Grating Designation</th>
<th>Bragg Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG 1</td>
<td>1581.934</td>
</tr>
<tr>
<td>FBG 2</td>
<td>1560.210</td>
</tr>
<tr>
<td>FBG 3</td>
<td>1568.116</td>
</tr>
<tr>
<td>FBG 4</td>
<td>1572.263</td>
</tr>
</tbody>
</table>

Table 4.5. Initial Bragg wavelength for each FBG in the array.

<table>
<thead>
<tr>
<th>Grating Designation</th>
<th>Wavelength Shift [nm]</th>
<th>Strain $\frac{m}{m_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG 2</td>
<td>-0.2472</td>
<td>-2.0131*10^{-4}</td>
</tr>
<tr>
<td>FBG 3</td>
<td>-0.1841</td>
<td>-1.4917*10^{-4}</td>
</tr>
<tr>
<td>FBG 4</td>
<td>-0.3609</td>
<td>-2.9163*10^{-4}</td>
</tr>
</tbody>
</table>
CHAPTER 5

FIBER BRAGG GRATING RESPONSE TO DYNAMIC TEMPERATURE LOADING

This chapter examines and discusses the response of FBGs embedded in a generic TPS material when the material is exposed to dynamic temperature loads provided by a flame. The initial sections of the chapter test the specimen on a hot plate under static and transient loads. The purpose of the hot plate tests is to compare the output of the FBGs embedded in the generic TPS material to the output of the FBGs embedded in the SLA as seen in Chapter 2.

Before an instrumented TPS specimen was tested, initial flame tests were conducted to characterize the response of a free and bonded FBG. Three tests with FBGs embedded in a TPS material were completed. The first test consisted of two FBG arrays, while the second and third tests were done on the specimen instrumented with both a FBG array and thermocouples.

5.1. HOT PLATE TESTS

5.1.1. Experimental Setup

An FBG array was embedded diagonally in a generic phenolic TPS specimen. An image of the specimen is shown in Fig. 5.1 and a schematic of the specimen with the embedded array is shown in Fig. 5.2. The specimen has dimensions of 5 cm wide, 5.5 cm thick, and 4.5
cm tall and was slightly charred during the initial test. The FBG array consists of four FBGs each 0.4 cm in length spaced 1 cm apart with the first FBG 0.3 cm from the end of the optical fiber. The length of the array is 4.9 cm from the end of the optical fiber to the end of the fourth FBG on the strand. When the array was embedded in the specimen, the end of the fiber was aligned with the edge of the specimen. Given the geometry of the specimen and the array, Table 5.1 gives the distance from the bottom surface of the specimen (as shown in Fig. 5.2) to the center of each FBG in the array.

An IFOS iSense interrogator was used to record the spectrum output by the FBG array during the experiment. The iSense interrogator recorded the shape of the reflected spectrum in a dynamically swept wavelength range between 1510 nm and 1590 nm. Table 5.2 shows the designation given by each FBG during data analysis and the initial wavelength of each FBG for both steady state experiments. FBG 1 is the FBG located closest to the heat source which is applied to the bottom surface of the specimen, and FBG 4 is located furthest from the heat source.

Two sets of experiments were run. In the first set of experiments, the temperature of the hot plate was set to a steady state temperature of approximately 200°C. Once the steady state temperature of the hot plate was reached, the specimen was placed on the hot plate. In the second set of experiments, the specimen was placed on the hot plate while the specimen and the hot plate were both at room temperature. Once the specimen was placed on the hot plate, the temperature of the hot plate was set to approximately 200°C. The temperature of the hot plate was monitored by a type K thermocouple attached to the surface of the hot plate using Kapton® tape. The hot plate and specimen were placed in a portable fume hood with vacuum
suction to contain and remove any off-gassing from the specimen in the event of charring or ablation.

Additionally, three transient tests were run using the same experimental setup as the steady state tests. The first two transient tests had the same specimen geometry as the steady state tests. For the third test, in addition to the diagonal embedded FBG array, a second, horizontal array was embedded in the specimen as seen in Fig. 5.3. The horizontal array consisted of 5 FBGs each 0.15 cm in length closely spaced 0.1 cm apart. The two arrays were simultaneously interrogated by two IFOS optical interrogators connected to the two arrays through a 2x2 splitter. One IFOS interrogator recorded the reflected spectrum of the two arrays at 5 second intervals, and the second IFOS interrogator recorded the peak wavelength of each array and had the capability to switch back and forth between the arrays. The second IFOS interrogator could record each array individually. The initial spectrum of the combined arrays is shown in Fig. 5.4. The reflected spectrum of each FBG in the 5 FBG array is broader due to the shorter length of the FBG.

For the purpose of data reduction for the spectrum data, the 9 FBG peaks were labeled FBG 1 through FBG 9 from left to right. Additionally, each FBG was given a second designation based on their position in either the horizontal or vertical array. Table 5.3 gives the initial wavelength of each FBG in the array along with their numbered designation and their designation within the horizontal and diagonal arrays.

The specimen was placed on the hot plate with the hot plate off. 25 seconds after data collection was begun, the hot plate was turned on and set to approximately 200°C. As in previous experiments, the temperature of the hot plate was monitored with a type K
thermocouple attached to the surface of the hot plate using Kapton® tape. At 1830 s, the hot plate was turned off, though the specimen remained on the hot plate and was allowed to cool with the hot plate.

The reflected peak wavelength of each FBG was determined from the spectra files like those seen in Fig. 5.4. Though the wavelength range of the FBGs in the two arrays overlapped, the peaks never crossed. Figs. 5.5 and 5.6 show the experimental setup used during the hot plate experiments. Fig. 5.7 shows the initial reflected spectrum of the four FBG array.

The IFOS Interrogator collected data at 512 points along the 1510 nm to 1590 nm wavelength range resulting in a low resolution of 0.157 nm between data points. To compensate for the poor resolution, a Gaussian distribution was fit to the profile of each FBG peak. A Gaussian distribution should accurately predict the location of the FBG peak because each of the FBG spectra closely matched an ideal Gaussian curve shape. A Gaussian fit is defined using equation 5.1. Equation 5.1 was also presented in Chapter 3 as equation 3.13.

\[
f(x) = \sum_{i=1}^{n} \left[ a_i \exp \left( -\frac{(x - b_i)^2}{c_i} \right) \right]
\]

(5.1)

First, second, and third order Gaussian fits were applied to both the data. Before the fits were applied, each of the four reflected peaks recorded by the interrogators were separated so the fits were applied to individual peaks rather than the complete four peak spectrum. An example of the three Gaussian fits is shown in Fig. 5.8.

Fig. 5.8 highlights the poor resolution output by the IFOS iSense interrogator. The first order fit cannot reconstruct the noise floor, which sets nonzero reflectivity values away from the peak. However the maximum peak location reconstructed by the first order fit is reasonable,
therefore it is plotted in Fig. 5.8. The second and third order Gaussian fits are nearly identical with little variation between them. The two curves are barely distinguishable. The first order fit has a lower maximum intensity than both the second and third order fits, a larger bandwidth, and begins and at a normalized intensity level of zero rather than the noise level. An example of the peak wavelengths of the Gaussian fits applied to the data over the test range is given in Fig. 5.9 for FBG 1.

The first order Gaussian fit has a lot of noise and variation with the data because the points in the noise floor are equally weighed with points in the peak. The third order FBG fit is generally good, but results in some significant outliers from the raw data such as the large spike present at 120 seconds. The spike is present in the fit data seen in Fig. 5.10, and is due to momentary measurement errors present in the IFOS interrogator output as discussed in Fig. 5.12. The second order Gaussian fit consistently fits the data best and is used to fit the data.

5.1.2. Steady State Test Results

Two steady state tests were conducted. Figs. 5.10 and 5.11 show the temperature profiles measured from the FBG array during the first and second steady state tests. The spectrum from the array was recorded in 5 s intervals, and the specimen was placed on the hot plate between 15 s and 20 s after data collection had begun. After 1200 s, the hot plate was turned off and both the specimen and the hot plate were allowed to cool. Data collection continued through this cooling phase. The temperature calibration for the FBG array is the same as the calibration presented in Chapter 2.
The data generally behaves as expected. There is an inflection point in the data output by FBG 4. Currently there is no explanation for this point as FBG 4 is fully embedded within the specimen. There may be poor contact between FBG 4 and the generic phenolic TPS specimen, or there may be some reaction within the material that occurs at approximately 60°C that is only noticeable at low heating rates. The temperature response given by the FBG array is consistent between the two tests. The localized spikes in the temperature response are due to the interrogator output. The intensity of one of the FBGs would occasionally show a significantly higher amplitude than the other three. During these intensity spikes, the wavelength would also shift. These momentary shifts result in the spikes in the data. Fig. 5.12 highlights the difference between a normal spectrum and a spectrum where one peak has a spike in amplitude. The spikes are therefore measurement errors and not indicative of temperature variations.

5.1.3. Transient Test Results

In addition to the steady state temperature tests, two transient tests were conducted. In both transient tests, the maximum temperature of the hot plate was approximately 200°C, and the hot plate was turned on after 20 seconds. For the first transient test, data was only recorded for 780 seconds as the hot plate was heated. No data was collected during the cooling phase. For the second test, data was collected for 1800 seconds. The hot plate was turned off after 900 seconds. The temperature data plotted against the experimental time for the first transient test is given in Fig. 5.13, and the data for each FBG from the second test is given in Fig. 5.14. The
inflection points seen in the FBG 4 response from the steady state tests is also present in the transient response. Otherwise, the temperature response is as expected.

The temperature measured by each FBG over time is given in Fig. 5.15. Fig. 5.15 shows the temperature response of the 5 FBGs in the horizontal array is tightly spaced as expected, given their near equal distance from the temperature source. FBG h1 reads the highest maximum temperature from the horizontal array and FBG h5 reads the lowest maximum temperature from the horizontal array. Discrepancies could be due to a non-uniform temperature profile on the surface of the hot plate, the horizontal FBG being embedded at a slight angle, or the presence of transverse heat flow through the specimen. Given the distance between FBGs h1 and h5, that the embedded array is able to pick up on either of these variations speaks to the temperature sensitivity of FBGs.

The diagonal array behaves as expected and similarly to the diagonal array of the experiments presented in Figs. 5.8, 5.9, 5.11, and 5.12. D1 outputs the highest maximum temperature as it is located closest to the heat source, and d4 outputs the lowest maximum temperature as it is furthest away. The response of d4 is the least smooth over the experiment. Since it is furthest from the heat source, external factors such as free convection or nearby material defects will have a greater influence on the FBG response. The same inflection point present in the FBG 4 curves of the previous steady state and transient hot plate tests at approximately 60°C is also present in the response of FBG d4.
5.2. FLAME TESTS

Dynamic flame testing was conducted at the Textile Protection and Comfort Center (TPACC) at North Carolina State University (NCSU) to determine how FBG arrays embedded in TPS materials respond to more realistic reentry conditions. The testing fits into two broad categories. The initial testing was conducted on a free FBG and a FBG epoxied to a ceramic plate. The second category of testing consists of FBG arrays embedded in the same generic TPS specimen tested in section 5.1. Three TPS material tests were conducted consisting of different embedded FBG sensor geometry and loading conditions.

5.2.1. Initial Flame Tests

For the initial flame test, an exposed FBG was placed above the flame along with a thermocouple to measure the temperature response of the FBG. A photograph of the FBG and the thermocouple is shown in Fig. 5.16. For this experiment, the FBG was interrogated using a Micron Optics sm130 interrogator due to availability, and two experiments were conducted. The performance of the sm130 interrogator is similar to that of the IFOS iSense, with the exception that the os1100 interrogator is unable to record wavelength and spectrum output simultaneously. Therefore, the first experiment recorded wavelength over time for 10 seconds, and the second experiment recorded the reflected spectrum of the FBG at 1 second intervals for 7 seconds. Fig. 5.17 gives the 10 second wavelength output of the FBG when the flame was exposed to the flame between seconds 6 and 7. Reflected spectra from the second test at different times is given in Fig. 5.18 where the fiber is exposed to the flame between seconds 2 and 3.
Fig. 5.18 shows extreme spectrum deformation due to the applied flame load with two spectra taken 1 second apart appearing very different. Due to the extreme and rapidly changing spectrum deformations, the peak tracking software of the Micron Optics sm130 interrogator has difficulty determining a single peak wavelength for some spectra. The locations where the interrogator and software is unable to determine a peak is represented by the gaps in the curve in Fig. 5.17 as highlighted with the red circle.

To isolate the FBG from the direct effects of the flame and to determine an initial comparison between the FBG response and the response of a thermocouple, an FBG along with a thermocouple was attached to a 0.635 cm thick ceramic plate using a Duralco™ 4525IP epoxy. The Duralco™ epoxy is a room temperature cure epoxy that is dark grey in color, electrically resistant, and has a service temperature up to 260°C. The FBG and the thermocouple were offset 0.64 cm from the centerline of the plate. The FBG had an initial wavelength of 1512.22 nm, and the thermocouple was a bare type K thermocouple with a diameter of 0.0762 mm (0.00762 cm). The specimen was oriented on a swinging plate with a square hole in the bottom such that the flame from the burner would centered between the thermocouple and FBG. Data collection was initiated after the burner was ignited but before the ceramic plate was moved over the burner. The plate was moved over the burner approximately 10 seconds after the beginning of data collection. After approximately 120 seconds, the epoxy began to boil off. A schematic of the plate is shown in Fig. 5.19, Fig. 5.20 shows the specimen near the burner, and Fig. 5.21 shows the experimental setup. The wavelength response given by the FBG due to the flame load is shown in Fig. 5.22.
The wavelength data was recorded in 10 second windows. The gaps in the wavelength curve are not due to poor peak tracking by the Micron Optics interrogator, but due to adjacent recorded windows not overlapping. When the windows did not overlap, the wavelength change between two adjacent windows was assumed to be linear. The wavelength response is due to a combination of the temperature dependent behavior of the FBG, strains due to the thermal expansion of the ceramic tile, and strains due to the post-curing of the epoxy. The thermal expansion of the epoxy is assumed to be minor due to the difference in volume between the epoxy and the underlying ceramic plate. As such, the effect of the epoxy post-cure on wavelength response is treated as a temperature independent strain. The effect of this strain is clearly seen between 10 and 20 seconds in the wavelength response, a region that is highlighted in Fig. 5.23. The resulting wavelength shift is -0.049 nm. The residual strain due to wavelength shift is determined using equation 5.2,

\[ \varepsilon = \frac{\Delta \lambda_B}{\lambda_B} \left(1 - p_e \right) \]  

(5.2)

where \( \Delta \lambda_B \) is the change in Bragg wavelength, \( \lambda_B \) is the initial Bragg wavelength, and \( p_e \) is the effective photo-elastic constant of the SM-28 optical fiber and is equal to 0.29. The calculated residual strain for the wavelength shift of -0.049 nm is \( \varepsilon_a = -45.638 \mu \varepsilon \).

For linear FBG and material responses to temperature, the wavelength change due to temperature for a FBG sensor attached to a host material can be described by equation 5.3. Equation 5.3. was fully derived in Chapter 4.

\[ \frac{\Delta \lambda_B}{\lambda_B} = \left[ \beta - \frac{1}{2} n_{eff}^2 p_{12} (\alpha_h - \alpha_s) \right] \Delta T + \alpha_h \Delta T + \varepsilon_a \]  

(5.3)
\( \beta \) is the thermo-optic coefficient of the FBG, \( n_{\text{eff}} \) is the effective index of refraction of the optical fiber fundamental mode, \( p_{12} \) is one of the Pockel’s constants for silica, \( \alpha_h \) is the coefficient of thermal expansion of the host material (here the ceramic), \( \alpha_s \) is the coefficient of thermal expansion of the silica, and \( \varepsilon_a \) is the residual strain due to the epoxy. Rearranging equation 5.3 to solve in terms of \( \Delta T \) gives equation 5.4.

\[
\Delta T = \frac{\Delta \lambda_B}{\lambda_B} - \varepsilon_a \\
\beta - \frac{1}{2} n_{\text{eff}}^2 p_{12} (\alpha_h - \alpha_s) + \alpha_h
\]

(5.4)

When determining the temperature profile given by the FBG, the residual strain, \( \varepsilon_a \) will only be applied to the wavelength response after 18.25 seconds, as it was assumed that the epoxy was fully cured. Table 5.4 shows values for the constants present in equation 5.4. The host material was an unknown ceramic tile, but was assumed to be porcelain. Fig. 5.24 shows a comparison between the FBG temperature response as given by equation 5.4 and the response of the thermocouple. The dotted horizontal line in Fig. 5.24 represents the manufacturer defined service temperature of the epoxy, 260°C.

Fig. 5.24 shows excellent agreement between the thermocouple and FBG. Both data sets display similar temperature behavior over the first 90 seconds of the test while the temperature is within the operating range of the epoxy. Once the temperature exceeds the service temperature of the epoxy, the data sets continue to show agreement, until approximately 120 seconds when the epoxy begins to boil off. The FBG output showed an immediate increase in wavelength not displayed by the thermocouple data. This is likely due to the fact that the FBG response is a coupled strain-temperature response, whereas the thermocouple is not sensitive to strain. As the epoxy dissolves into a liquid state then boils, the
residual strain state on the FBG changes which is not included in equation 5.3. However, once
the wavelength data jumps, the temperature increase of the FBG follows a similar slope to the
temperature increase output by the thermocouple. At approximately 140s into the experiment,
the thermocouple data begins to level out and the FBG data shows a quick decrease before also
leveling out. At this point, both the thermocouple and the FBG have lost contact with the
ceramic plate. After the experiment, the epoxy was very brittle, less dense, and easily flaked
off the surface of the ceramic plate.

Equation 5.4 and the results in Fig. 5.24 assume a linear relationship between
temperature change and wavelength change in the FBG. This assumption is known to be
invalid for larger temperature values, based on the FBG temperature calibrations presented in
Chapters 2 and 3. The nonlinearity in FBG response is due to the FBG thermo-optic coefficient
and not the thermal expansion coefficient of silica, as demonstrated by Pal et. al. (2004).
Therefore the experimental data was processed again using the updated thermo-optic
coefficient from the calibration data. First the Micron Optics os1100 FBG calibration from Fig.
3.8 and equation 3.2 was rearranged to a proportional wavelength shift as a function of
temperature change similar to the linear calibration given in equation 5.3 as seen in Fig. 5.25.
A quadratic fit to the curve in Fig. 5.25 gives equation 5.5.

\[
\frac{\Delta \lambda_B}{\lambda_B} = \left(8.080 \times 10^{-9} \frac{1}{\sigma C^2}\right) \Delta T^2 + \left(5.969 \times 10^{-6} \frac{1}{\sigma C}\right) \Delta T \\
= (\beta_2) \Delta T^2 + (\alpha_s + \beta_1) \Delta T
\]  

(5.5)
The linear coefficient, 5.969*10^{-6} °C^{-1} is a combination of the coefficient of thermal expansion of silica, \( \alpha_s \) (0.55*10^{-6} °C^{-1}), and the linear portion of the thermo-optic coefficient, \( \beta_l \). Subtracting \( \alpha_s \) from 5.969*10^{-6} °C^{-1} gives the linear \( \beta_l \) term as 5.419*10^{-6}.

The quadratic relationship between wavelength shift and temperature change for the FBG thermo-optic coefficient is applied to equation 5.3. The updated equation 5.3 accounting for a quadratic relationship between wavelength shift and temperature change for \( \beta \) is given in equations 5.6 and 5.7.

\[
\frac{\Delta \lambda_B}{\lambda_B} = a_\beta \Delta T^2 + \left[b_\beta - \frac{1}{2} n_{eff}^2 p_{12} (\alpha_h - \alpha_s) + \alpha_h\right] \Delta T + \varepsilon_a
\]  
(5.6)

\[
0 = a_\beta \Delta T^2 + \left[b_\beta - \frac{1}{2} n_{eff}^2 p_{12} (\alpha_h - \alpha_s) + \alpha_h\right] \Delta T + \varepsilon_a - \frac{\Delta \lambda_B}{\lambda_B}
\]  
(5.7)

where \( a_\beta \) is equal to \( \beta_2 \) and \( b_\beta \) is equal to \( (\alpha_s + \beta_1) \). The quadratic equation was used to solve equation 5.7 for \( \Delta T \) given different values of Bragg wavelength change. The resulting temperature change measured by the FBG compared to the thermocouple is shown in Fig. 5.26.

As in Fig. 5.24, the dotted horizontal line at 260°C represents the manufacturer defined service temperature of the epoxy. The FBG response in Fig. 5.26 overestimates the temperature change with respect to the thermocouple, though the slopes of the two curves are similar after the initial deviation. The temperature calibration outlined in chapter 3 for the Micron Optics os1100 FBG and repeated in equations 5.6 and 5.7 is only valid up to 200°C, however it was extrapolated to higher temperatures. FBG temperatures calculated above 200°C may therefore not be accurate given the temperature calibration. One possible cause for the difference in temperatures is when the specimen is away from the ignited burner and not being actively tested as seen in Figs. 5.20 and 5.21, the temperature of the burner still affects the temperature
of the specimen and the temperature determined by an FBG requires an initial wavelength at a known temperature. Unfortunately, the Bragg wavelength of the FBG used in this experiment was not recorded at room temperature. It was assumed that the FBG and the thermocouple had the same initial temperature when data collection was begun, but if the FBG was at a slightly cooler temperature, then the curves would show much better alignment.

5.2.2. Thermal Protection System Material Flame Tests

The same specimen from the hot plate tests presented in sections 4.1 through 4.3 was tested for a flame exposure at the T-PACC. Two FBG arrays were embedded in the specimen, one horizontal and one diagonal. Both arrays were identical 5 FBG arrays with 0.15 cm long FBGs space 0.1 cm apart. A diagram of the specimen is seen in Fig. 5.27. The specimen was placed on a platform located a distance from the flame so the applied temperature on the lower surface of the specimen would be between 150°C and 250°C. The platform had a circular hole to allow the free stream of heated air due to the flame to directly impact the surface of the specimen. Spanning the hole was a thermocouple located in the free stream to measure the temperature applied to the specimen. Figs. 5.28 and 5.29 show the experimental setup.

Two initial experiments were conducted with the cube specimen. In the first experiment, the flame door was opened for 30 seconds and the air heated by the flame directly impacted the lower surface of the specimen. In the second test, the door was periodically opened and closed in 30 second intervals for five cycles. The FBGs were sampled every second continuously through both tests. The temperature calibration for the FBG arrays is the same calibration presented in Chapter 2. The full FBG array temperature response for both tests is
given in Fig. 5.30. Figs. 5.31 and 5.32 show the response of just tests 1 and 2 respectively with the thermocouple temperature data superimposed.

The FBG arrays behave as expected. The lower maximum temperature in the second test is due to the lower flame load applied by the burner, though the total time the flame load was applied to the specimen was longer than in the first test. The response of the horizontal array is tightly bound within 1°C. Any discrepancies within the horizontal data are due to the horizontal track not being perfectly horizontal, non-uniformities of the flame, material defects within the TPS block and transverse heat flow. The results from the diagonal array are also tightly bound, though the difference between the lowest and highest recorded temperature is significantly more noticeable than the horizontal array. Even though the array is diagonally embedded within the specimen, due to the angle of the embedding (26.6°) and the spacing of the FBGs in the array (2.5 mm between the center of adjacent FBGs), the FBGs are vertically very similar, with only a 1.12 mm height difference between the centers of adjacent FBGs. To highlight the response of the diagonal array, Figs. 5.33 and 5.34 show the response of the diagonal array in the individual tests without the thermocouple data overlaid on the FBG response or the response of the horizontal array. The drop in recorded temperature after 1500 seconds is due to the burner being extinguished. Even though the door between the burner and the specimen was closed, there was still heat flow through the specimen.

5.2.3. Combined FBG and Thermocouple Tests

In the previous tests, the thermocouple provided data on the thermal load to the specimen, however a direct comparison between the FBG and the thermocouple temperature
measurements could not be made. Therefore a new test was performed in which thermocouples were embedded within the specimen, at roughly the same locations as the individual FBG sensors. The cube shaped, generic phenolic TPS specimen was instrumented with a four FBG array and four thermocouples. Each FBG in the array was paired with a thermocouple. Each pair was embedded at the same height in the specimen 0.5 cm apart and 0.25 cm from the midplane of the specimen. The first pair was embedded 1 cm from the bottom surface of the specimen, and each successive pair was embedded 0.5 cm above the previous pair as seen in Fig. 5.35. Fig. 5.36 shows photographs of the specimen.

The thermocouples used were Type K bare thermocouples of 0.0254 cm in diameter. The FBG array was created from four independent Micron Optics os1100 FBGs spliced together. The manner in which the array was created resulted in the array snaking in and out of the specimen. The lead in for the array was connected to FBG 4. During the mounting of the specimen on the test apparatus, the optical fiber between FBGs 1 and 2 was severed resulting in no data output from FBG 1. A Micron Optics sm130 interrogator was used to interrogate the FBGs in the array. Table 5.5 shows the initial wavelengths for each FBG in the array. In addition to the thermocouples in the array, a thermocouple, TC 0 was placed in the free stream below the specimen. The test setup is shown in Fig. 5.37, Fig. 5.38 shows a close image of the mounted specimen, and Fig. 5.39 shows the FBG interrogation setup.

Fig. 5.38 highlights the reduction in the number of lead outs brought on by multiplexing FBGs into an array. There is one lead out optical fiber from the specimen that allows the interrogation of all FBGs in the array. For the four thermocouples, there are eight wires: two positive leads and two negative leads for each thermocouple.
Two tests were conducted. In the first test, the specimen was placed on the platform and data collection from both the thermocouples and the FBG array was begun before the burner was ignited. Once the burner was ignited, the specimen was allowed to heat up for approximately 300 s with the pneumatic actuated door above the burner closed before the door was opened. The door remained open for 180 seconds before being closed again. During the 180 second period, the lower surface of the specimen was directly exposed to the effects of the burner. The door remained closed for approximately 600 seconds before the door was opened and closed in 10 30 second cycles. During the 30 second cycles, the door was opened for 15 seconds and closed for 15 seconds. After the cyclical loading was completed, the burner was extinguished and the door was opened. The heating profile in the first test as given by TC 0 is given in Fig. 5.40.

Data collection from both the thermocouples and the FBG array was continuous during the entire test from before the ignition of the burner until cooling of the specimen after the burner was extinguished. The temperature data from the thermocouples and FBG array is shown in Fig. 5.41. The temperature calibration used to process the FBG array wavelength data is the same calibration presented in Chapter 3.

Fig. 5.41 highlights two differences between the output of the thermocouples and the FBG array. First, the thermocouple array cools at a slower rate than the FBG array. During the cooling phase after the initial heat load, the three FBGs in the FBG array return to a near identical temperature, whereas the thermocouples still show variation with their depth. The final temperature data from hottest to coldest, was in order from TCs 1-4. The temperature response of the first heating phase of the first test is shown in Fig. 5.42. The second difference
in the output between the thermocouples and FBG array is that the thermocouples consistently output lower temperatures than the FBGs. This is more noticeable for at the lower temperature loads on the thermocouple/FBG. The discrepancy between the thermocouple and FBG is greatest for pair 4 which is also the lowest temperature pair. The thermal contact between the sensors and the specimen is not significantly different for the two sensor types. Since the sensor arrays never reached steady state, it is unknown if the maximum temperature recorded by both would be the same or similar. Taken in concert with the slower cooling rate reported by the thermocouples, it is possible the thermocouples response time is noticeably lower than that of the FBG array. The difference in maximum temperature reached by the thermocouples is not as noticeable in the cyclical loading case because the thermocouples began at a higher initial temperature.

For the second test, the specimen was allowed to return to a steady state temperature state before a cyclical temperature load was applied to the specimen. The cyclical load consisted of 24 10 s on/off cycles before a longer final load. The free stream temperature profile given by TC 0 is given in Fig. 5.43.

Similar to the first test, data collection began before the burner was ignited and continued through the duration of the test. Unlike the first test, the cooling region was recorded for a longer time, approximately 720 s. During the cooling region, the burners were extinguished and the door above the burner was opened. The temperature profile of the thermocouples and FBG array is given in Fig. 5.44. Though there was approximately a 30 minute break between tests, the thermocouples did not cool to the same final temperature as the FBG array. Furthermore, the final temperature of the individual thermocouples was nearly
identical, while the FBGs display final temperatures within a range of approximately 1.5°C. Even beginning from a lower initial temperature, FBGs 2 and 4 exceed the temperatures of their paired thermocouples, again showing a shorter response time. FBG 3 has a longer response time. Additionally, the FBG array cools at a faster rate than the thermocouples. The shorter cycle time means that the influence of the cyclical load is less noticeable on the response of both the FBGs and the thermocouples. The cyclical load is less noticeable in the response of TC 1, and is barely noticeable in the response of TC 2 and FBG 2.

A final test was conducted using the thermocouple instrumentation as seen in Figs. 5.35 and 5.36 and the diagonal closely space FBG array as seen in Fig. 5.27. The array was embedded in the specimen such that the center of FBG 1 was located 1.59 cm above the bottom surface of the specimen, and the center of FBG 5 was located 2.04 cm above the bottom surface of the specimen. A schematic of the specimen is shown in Fig. 5.45 and Table 5.6 gives the distance between the bottom surface of the specimen and each FBG and thermocouple. Data collection began before the burner was ignited. A Micron Optics sm130 interrogator was used to interrogate the peak wavelength of each FBG in the array at 1 second intervals. The thermocouple output was recorded every second.

The specimen was placed above the burner at the same height as seen in Fig. 5.37. A photograph of the specimen on a platform above the burner is seen in Fig. 5.46. A variable temperature load was applied to the specimen consisting of three cycles where the specimen was exposed to the flame for 10 second intervals, three cycles where the specimen was exposed to the flame for 15 second intervals, three cycles where the specimen was exposed to the flame for 20 second intervals, three cycles where the specimen was exposed to the flame for 25
second intervals, four cycles where the specimen was exposed to the flame for 30 second intervals, and finally a ten minute span where the specimen was continuously exposed to the flame. Data collection continued for an additional ten minutes while the specimen cooled. Fig. 5.47 shows the heating profile, and Fig. 5.48 shows the specimen on the platform above the ignited burner during the 10 minute heating window. The initial peak in Fig. 5.47 is when the burner was ignited before the door above the burner was closed. Even though the distance between the burner and the specimen was the same for both the heating profiles shown in Fig. 5.43 and Fig. 5.47, the temperature load measured by the free stream thermocouple is approximately 50°C less in Fig. 5.47 showing the unpredictable nature of flames and the need to have a direct test comparison between thermocouples and FBGs.

Fig. 5.49 shows the temperature output by both the FBG array and the thermocouples. The initial output from the initial loading period is highlighted in Fig. 5.50. The initial increase in temperature at approximately 50 seconds is due to the burner being ignited. Once the burner was ignited, the door was closed and the specimen was allowed to achieve a near steady state condition over the following two minutes before loading began. During the initial heating from the ignition of the burner through the beginning of the cyclical loading, the output of FBG 4 aligns very well with the temperature response of TC 2, even though FBG 5 is embedded 0.43 cm further away from the heat source than TC 2. In fact, FBGs 1-4 all show a temperature shift equal to or greater than TC 2 for the first 200 seconds of the test though all FBGs are located further away from the heat source than TC 2. The slope of the temperature response from the FBG array continues to closely follow the slope of TC 2 between 200 seconds and 450 seconds before the temperature output of the array reaches a steady state due to the cyclical loading and
begins to level out. The temperature output by the thermocouples does not reach a steady state due to the cyclical loading until approximately 700 seconds.

FBGs 4 and 5 show little response to the 10 second and 15 second cyclical load, though a response to the initial cycles is present in FBGs 1, 2 and 3 and TCs 2 and 3. The presence of the cyclical load in the response of FBGs 4 and 5 might be hidden by the noisier nature of the FBG data. During the initial cycles, FBG 1 outputs the hottest temperature and FBG 5 outputs the coldest with the temperature of the other three FBGs spaced between them. This is the expected output given that FBG 1 is closest to the flame. As the period of the loading cycle increases, FBG 1 outputs the coldest temperature and FBG 4 outputs the hottest. The switch is due to the FBG 1 being located closest to both the lower surface and the side of the specimen. As the specimen is isolated from the flame and the specimen cools, the center of the specimen closest to FBGs 4 and 5 have the lowest rate of cooling whereas FBG 1 experiences the highest rate of cooling. During the 30 second cyclical loading, FBG 1 is coolest when the specimen is not exposed to the flame, outputting a temperature below that of TC 3 despite being 0.41 cm closer to the heated surface of the specimen; however, once the specimen is exposed to the flame, the temperature response of FBG 1 nearly matches the response of FBG 2.

When the specimen is exposed to the flame for 600 seconds at approximately 875 seconds into the test, the rate of heating output by the FBG array exceeds that of TC 3 and matches the slope TC 2, though the FBG array has a quicker response. When a quasi-steady state was reached after approximately 1200 seconds the temperature output by each FBG in the array is between TCs 2 and 3, though closer to TC 3. During the cooling phase, there is a delay between when the burner was extinguished and when the TCs and FBGs show a
temperature decrease. For TC 1, this delay is insignificant, only a few seconds. TC 2 does not show a cooling trend for 10 seconds after the burner is extinguished, TC 3 20 seconds, and TC 4 approximately 30 seconds before cooling is noticeable. The temperature output by the FBG array shows cooling occurring approximately 10 seconds after the burner is extinguished. Within the array, FBG 1 shows the fastest cooling rate and FBG 5 the slowest. It is similar with the thermocouples, TC 1 shows the fastest cooling and TC 4 the slowest. The FBG array cools faster in general than the thermocouples.

There is less separation in the temperature output from the FBGs in the array than expected given their spacing. For their locations as given in Table 5.6, the temperatures of the FBGs should be distributed between the output of TCs 2 and 3; however, the temperature response of the FBG array is in a tight band throughout the experiment, especially when the slope of the FBG output is near zero. The banded behavior of the array is likely caused by the temperature conducting along the length of the fiber between gratings. This temperature conduction results in the temperature being nearly identical across the entire array. The exception is when the temperature of the gratings is rapidly changing such as during the cyclical loading phase or the cooling phase where separation is present. This behavior can be mitigated somewhat by improving the thermal contact between the array and the specimen. The simplest way to improve the thermal contact is by embedding the array during the manufacturing of the TPS material.
5.3. CONCLUSIONS

This chapter discussed response of FBGs embedded in a generic TPS material when the material was exposed to a dynamic flame load. Initially, the temperature load on the instrumented TPS specimen was provided by a hot plate. The applied temperature loads were both steady state, similar to the load in Chapter 2, and transient. The material tested in this chapter is significantly more insulating than the material used in Chapter 2 as the specimen discussed in this chapter took a longer time to reach steady state when exposed to a similar steady state temperature load. Under both the steady state and transient hot plate tests, the embedded FBGs behaved as expected with the exception of the presence of an inflection point in the temperature response of the FBG located furthest from the heat source. The cause of this inflection point is not known with certainty.

The initial flame tests showed that a dynamic flame can overwhelm the response of an exposed or free FBG. While the FBG response does give details about the turbulent nature of the applied flame, the response is so rapidly changing that little meaningful data can be determined. Separating the FBG from the flame with a host material can eliminate this response.

When embedded in a TPS material exposed to a flame, the FBGs behaved well: outputting reasonable temperatures and responding to rapid changes in application of the flame. When instrumented in proximity to thermocouples, the FBGs responded faster than the thermocouples. For example, the temperature output by the FBG in the thermocouple – FBG pair located 1.5 cm from the heated surface of the specimen exceeded the temperature output by the thermocouple by between 3°C and 5°C during dynamic loading. This temperature
difference increased to greater than 10°C for the thermocouple – FBG pair located 2.5 cm from heated surface of the specimen. However, as the temperature profile of the specimen approached steady state, the difference in temperatures output by the FBGs and thermocouples decreased. Therefore, the temperature difference can be attributed to the faster response time of the FBG. While multiplexed FBGs can greatly decrease the number of lead-out wires and weight necessary to instrument a specimen, angled arrays can serve as conduits for conduction through the thickness of the specimen. These conduits can cause the response of arrays to merge into a single temperature value. When instrumenting TPS materials with FBGs, care must be taken as to how the geometry of the embedded sensors affects the temperature response of the specimen and the temperature profile of the specimen.
Figure 5.1. Photograph of the generic phenolic TPS specimen used in the steady state and transient experiments.

Figure 5.2. 2-D schematic of the generic phenolic TPS specimen showing specimen dimensions, FBG location, and nominal FBG wavelengths.
Figure 5.3. Schematic of the generic phenolic specimen showing specimen dimensions, embedded arrays, FBG locations, Bragg wavelengths for each FBG, and the location of each FBG within the specimen.

Figure 5.4. Initial reflected spectrum of both FBG arrays.
Figure 5.5. Experimental setup highlighting the interrogation system.

Figure 5.6. Experimental setup highlighting the location of the specimen and the hot plate.
Figure 5.7. Initial reflected spectrum output by the FBG array.
Figure 5.8. First, second, and third order Gaussian fits applied to a reflected FBG spectrum.

Figure 5.9. Comparison of the first, second, and third order Gaussian fits to the raw peak wavelength data for the output from FBG 1 in the first steady state test.
Figure 5.10. Temperature vs. time data for all four FBGs in the array during the first steady state test.

Figure 5.11. Temperature vs. time data for all four FBGs in the array during the second steady state test.
Figure 5.12. Reflected spectra from the FBG array taken during the first steady state run at 
(a) 1430 s and (b) 1435 s highlighting the spiked intensity given by FBG 2.
Figure 5.13. Temperature vs. time response for the FBGs in the array and the thermocouple for the first transient test.
Figure 5.14. Temperature vs. time response for the FBGs in the array and the thermocouple for the second transient test.

Figure 5.15. Temperature response for each FBG array over time with the temperature of the hot plate recorded by the thermocouple.
Figure 5.16. Thermocouple and FBG suspended above the burner in the T-PACC facility.

Figure 5.17. Wavelength shift given by the FBG when directly exposed to a flame.
Figure 5.18. Spectrum output by the exposed FBG at (a) 2 s, (b) 3 s, (c) 4 s, (d) 5 s, (e) 6 s, and (f) 7 s.
Figure 5.19. Diagram of the ceramic specimen showing specimen dimensions and the location of the FBG and thermocouple with respect to the centerline of the plate.

Figure 5.20. The ceramic plate specimen with thermocouple and optical fiber on the specimen mount next to the burner.
Figure 5.21. Experimental set-up for the flame load test. Thermocouple data was recorded using a PC to the left of the picture.
Figure 5.22. Wavelength response of the FBG over the duration of the experiment.

Figure 5.23. FBG wavelength response between 10 and 25 seconds highlighting the effect of the epoxy post-cure on the wavelength response.
Figure 5.24. Comparison between the temperature output of the FBG and the thermocouple.

Figure 5.25. Non-linear wavelength shift as a function of temperature change.
Figure 5.26. Temperature comparison between the FBG and thermocouple when calibration data is applied to the FBG.

Figure 5.27. Specimen dimensions and FBG arrays.
Figure 5.28. Specimen on the platform above the flame.

Figure 5.29. Image of the lower surface of the specimen showing the hole in the aluminum plate and the free stream thermocouple.
Figure 5.30. FBG response of the diagonal and horizontal arrays due to the applied flame load.
Figure 5.31. Temperature response from the FBG arrays from the first test with superimposed TC data.

Figure 5.32. Temperature response from the FBG arrays from the second test with superimposed TC data.
Figure 5.33. Temperature response diagonal array in the first test.

Figure 5.34. Temperature response diagonal array in the second test.
Figure 5.35. (a) side and (b) front view of the TPS specimen showing specimen dimensions and locations of the embedded thermocouples and FBGs in the array.
Figure 5.36. Photographs of the instrumented TPS specimen showing (a) the specimen and the thermocouple output and (b) close up of the specimen in the same orientation as Fig. 5.35(b).
Figure 5.37. Test setup used for the combined FBG and thermocouple test.

Figure 5.38. Image of the test setup focused on the mounted specimen.
Figure 5.39. FBG interrogation system.

Figure 5.40. Heating profile for the first test showing the ignition of the burner, the 300 s heating load, and the cyclical heating load.
Figure 5.41. Comparison of the output from the FBG array (solid line) and the thermocouples (dashed line) over the duration of the first experiment.
Figure 5.42. First heating phase of the first test.

Figure 5.43. Free stream temperature profile for the second test given by TC 0.
Figure 5.44. Temperature response of the FBG array and thermocouples during the second test.
Figure 5.45. Diagram of the specimen used showing the dimensions of the specimen, the spacing between the thermocouples, and the approximate location of the five FBG array.

Figure 5.46. Specimen instrumented with four thermocouples and a five FBG array. The orange Kapton® tape is located on the optical fiber as it leaves the specimen.
Figure 5.47. Free stream temperature profile as given by TC 0.
Figure 5.48. Specimen above the ignited burner during data collection.
Figure 5.49. Temperature output given by the FBGs and the TCs for the temperature load shown in Fig. 5.47.

Figure 5.50. Temperature output given by the FBGs and the TCs for the temperature load shown in Fig. 5.47 for the first 900 seconds of the test.
Table 5.1. Distance from the bottom of the specimen to the center of each FBG in the array.

<table>
<thead>
<tr>
<th>Sensor Designation</th>
<th>Distance [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG 1</td>
<td>1.224</td>
</tr>
<tr>
<td>FBG2</td>
<td>1.850</td>
</tr>
<tr>
<td>FBG 3</td>
<td>2.476</td>
</tr>
<tr>
<td>FBG 4</td>
<td>3.102</td>
</tr>
</tbody>
</table>

Table 5.2. Initial wavelength of each FBG in the array for both steady state tests.

<table>
<thead>
<tr>
<th>Sensor Designation</th>
<th>Initial Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
</tr>
<tr>
<td>FBG 1</td>
<td>1533.5</td>
</tr>
<tr>
<td>FBG 2</td>
<td>1542.8</td>
</tr>
<tr>
<td>FBG 3</td>
<td>1551.6</td>
</tr>
<tr>
<td>FBG 4</td>
<td>1559.5</td>
</tr>
</tbody>
</table>
Table 5.3. Designations and initial Bragg wavelengths for the 9 FBGs in the array.

<table>
<thead>
<tr>
<th>FBG Designation</th>
<th>Initial Bragg Wavelength [nm]</th>
<th>Horizontal or Diagonal Array Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG 1</td>
<td>1533.321</td>
<td>d1</td>
</tr>
<tr>
<td>FBG 2</td>
<td>1535.082</td>
<td>h1</td>
</tr>
<tr>
<td>FBG 3</td>
<td>1540.040</td>
<td>h2</td>
</tr>
<tr>
<td>FBG 4</td>
<td>1542.673</td>
<td>d2</td>
</tr>
<tr>
<td>FBG 5</td>
<td>1545.079</td>
<td>h3</td>
</tr>
<tr>
<td>FBG 6</td>
<td>1549.977</td>
<td>h4</td>
</tr>
<tr>
<td>FBG 7</td>
<td>1551.486</td>
<td>d3</td>
</tr>
<tr>
<td>FBG 8</td>
<td>1554.925</td>
<td>h5</td>
</tr>
<tr>
<td>FBG 9</td>
<td>1559.408</td>
<td>d4</td>
</tr>
</tbody>
</table>

Table 5.4. Constants used in equation 5.4 and their associated values.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG Thermo-optic Coefficient, β</td>
<td>8.2*10^{-6} °C^{-1}</td>
</tr>
<tr>
<td>Effective Index of Refraction, n_{eff}</td>
<td>1.456</td>
</tr>
<tr>
<td>Pockel’s Constant, p_{12}</td>
<td>0.36</td>
</tr>
<tr>
<td>Host Thermal Expansion Coefficient, α_h</td>
<td>2.0*10^{-6} °C^{-1} (Morrell, 1987)</td>
</tr>
<tr>
<td>Silica Thermal Expansion Coefficient, α_s</td>
<td>0.55*10^{-6} °C^{-1}</td>
</tr>
</tbody>
</table>

Table 5.5. Initial Bragg wavelength of each FBG in the array.

<table>
<thead>
<tr>
<th>FBG Designation</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1578.26</td>
</tr>
<tr>
<td>2</td>
<td>1571.93</td>
</tr>
<tr>
<td>3</td>
<td>1564.05</td>
</tr>
<tr>
<td>4</td>
<td>1559.95</td>
</tr>
</tbody>
</table>
Table 5.6. Distance of each sensor in the specimen from the bottom surface of the specimen and the initial wavelengths of each FBG in the array.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Distance [cm]</th>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC 0</td>
<td>Free Stream</td>
<td></td>
</tr>
<tr>
<td>TC 1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TC 2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>FBG 1</td>
<td>1.59</td>
<td>1535.234</td>
</tr>
<tr>
<td>FBG 2</td>
<td>1.70</td>
<td>1540.190</td>
</tr>
<tr>
<td>FBG 3</td>
<td>1.81</td>
<td>1545.225</td>
</tr>
<tr>
<td>FBG 4</td>
<td>1.93</td>
<td>1550.128</td>
</tr>
<tr>
<td>TC 3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>FBG 5</td>
<td>2.04</td>
<td>1555.076</td>
</tr>
<tr>
<td>TC 4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>TC 5</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The work presented in this dissertation demonstrated that FBGs are suitable sensors for measuring temperature in high temperature, complex environments. The initial experiments showed FBGs provide accurate temperature measurements when embedded in a TPS material exposed to a steady state temperature load supplied by a hot plate. The two embedded arrays behaved in a reasonable manner outputting expected temperatures given the applied temperature load during the experiment with little noise in the response. The test conditions were repeatable and the response of the FBG sensor network was consistent in both tests. The temperature response from the FBGs was compared to the temperature profile of the specimen provided by an IR camera and showed good agreement. The initial experiments also showed how one interrogator is able to simultaneously measure multiple sensors in two arrays. One interrogator was able to monitor an instrumentation suite of eight FBGs distributed throughout the specimen.

Chapters 3 and 4 investigated the effects of sources of data error that may be present when FBGs are used as temperature sensors in high temperature, complex environment applications. First, Section 3.2 determined the calibration of a Micron Optics os1100 FBG up to 200°C as second order confirming the previous work done by Adamovsky et al. (2012), as Flockhart et al. (2004) and Pal et al. (2004).
Chapter 3 also examined how a dynamic temperature gradient affects the response of a FBG. The temperature gradient was caused by two fluid baths at different temperatures separated by a 1 cm thick partition. An FBG was located lengthwise through the thickness of the partition exposed to both baths. During the experiment, the deformed spectrum of the FBG was recorded as well as the temperature of the fluid baths. The bandwidth change of the FBG in the partition was compared to the difference in temperature between the baths and bandwidth change as a function of experimentally observed temperature difference was determined. Additionally, a three part numerical model consisting of a two dimensional heat transfer representation of the partition and the fluid baths, a finite element model constructed in ANSYS and the T-matrix method was developed and used to calculate numerical spectra given a temperature difference. Because the heat transfer between the fluid baths and the partitions is not perfect, the numerical model determined the sensitivity of FBGs to temperature gradients is greater than experimentally thought. The bandwidth numerically determined by the difference in temperature between the partition walls showed excellent agreement with the experimentally observed bandwidth. Finally in Chapter 3, a third order mathematically relationship between temperature difference over the grating length and bandwidth change was determined. This mathematical relationship can be used to determine the temperature difference between the ends of a FBG given a known bandwidth change.

Next, the strain transfer from the surrounding material to an FBG was investigated in Chapter 4. Mathematical models for free sensors, bonded sensors with and without a prestrain and embedded sensors were developed and validated using an array of three FBGs in an oven where one FBG in the array was free, one was embedded, and the third was bonded. The
mathematical models were used to calculate the temperature of the three FBGs oriented orthogonal to the temperature gradient in the initial four FBG array gradient test. Based on the calculated temperature change from each of these three FBGs, the wavelength change due to strain for each FBG was calculated by subtracting the wavelength shift due to calculated temperature from the total wavelength shift. From the temperature changes and strains calculated for each of the three orthogonal FBGs, temperature and strain gradients over the length of the FBG oriented parallel to the temperature gradient were determined. Simulated reflected spectra for this FBG were calculated using the modified T-matrix method using the determined gradients as inputs. The modified T-matrix method spectrum calculated bandwidths were compared to the experimentally observed bandwidth. The bandwidth of the spectra calculated from the modified T-matrix method due to the temperature gradients showed no variation. Due to the magnitude of the temperature gradients, this simulation agrees with the data determined in Chapter 3. The bandwidth change of the reflected spectra calculated by the modified T-matrix method due to the applied strain gradient does show significant change. The magnitude of the bandwidth change does not agree with what was experimentally observed, though they do have similar slopes at times. The second order strain gradient approximation determined from the strain response of the orthogonal FBGs may not accurately model the strain present in the experiment. While there are still significant hurdles to overcome when characterizing the strain transfer between adhesives and FBGs, the material presented in Chapter 4 showed how a complex loading consisting of strain and temperature gradients can affect the response of a FBG.
Lastly, dynamic temperature loads were applied to FBGs that were free, bonded to and embedded in materials. The response of the free FBG was overwhelmed by the variation present in the flame load, whereas the FBG bonded to a ceramic plate behaved well. Unfortunately, the initial wavelength of the bonded FBG was not recorded. Without this initial baseline Bragg wavelength, a significant source of error exists in the data for that test. Before being exposed to flame loading, the FBG arrays embedded in the generic TPS material were first subjected to hot plate tests to determine their response and compare it to the initial tests in Chapter 2. Similar to the tests in Chapter 2, the arrays behaved as expected and the response of the arrays confirmed that the generic TPS material was more insulating than the SLA discussed in Chapter 2. The initial flame tests demonstrated FBGs are able to respond well to dynamic loads, survive, and return realistic results. Additionally, when embedded next to thermocouples, the FBGs had a significantly quicker response time as evidenced by a much faster temperature increase. Similarly, the FBGs cooled to room temperature at a quicker rate when the temperature load was removed. When the specimen was brought to a steady state, the temperatures output by the thermocouples and the FBGs in the array showed excellent agreement given their locations in the specimen. The slower response time for thermocouples could be a significant source of error causing thermocouples to underestimate the temperatures compared to the experimental models presented by Little et al. (2013). For the structural health monitoring of insulating materials in high temperature environments with the presence of complex thermal loads and temperature states, this study has shown that FBGs are superior to thermocouples in many facets.
Future experiments involving FBGs at high temperature applications should consider and expand upon the adhesive strain transfer work from in this dissertation. The examination of the adhesive strain transfer presented here was brief and did not give the topic the attention it deserved. Due to the limitations of the gratings used, the temperatures present in the TPS material specimens instrumented with FBG sensors were well below the temperatures TPS materials would experience in real world applications. The response of FBG arrays embedded in TPS materials should be investigated at significantly higher temperature loads.
REFERENCES


