Fiber Bragg gratings have become an important element in the fields of telecommunications and fiber optical sensing. Their small size, light weight and high tunability have made them ideal for many unique applications. In this paper the fabrication of these devices is investigated.

Following a review of current literature and a discussion of the mechanisms underlying the photosensitivity of optical fibers, a new technique for writing fiber Bragg gratings is presented. This technique uses a diode-pumped Nd:YAG laser operating at 266 nm with pulse energies up to 137 $\mu$J per pulse to write high quality gratings in standard optical fiber. This technique allows for the writing of variable wavelength gratings using a standard diffractive optical element (phase mask). The new technique has much lower setup and laser stability requirements than the conventional methods of writing variable wavelength fiber Bragg gratings. Furthermore, it is found to be very tunable and extremely robust, allowing for extended writing times.

A preliminary study of the time evolution of the writing process is also presented. It is evident that the process of grating inscription is very complicated and is not always adequately described by current models. In addition, it appears that the process is strongly dependent upon pulse energy and is accelerated by simultaneous heating of the fiber with a CO$_2$ laser and by heating due to the writing laser.
A brief study of the thermal stability of different gratings is then given to determine some of the thermal stability properties of the fiber Bragg gratings written at OSU.
The Fabrication of Fiber Bragg Gratings

by

Kurt Stump

A Thesis Submitted to
Oregon State University

In Partial Fulfillment of
the Degree of

Master of Science

Presented on June 30, 2000
Commencement June 2001

Approved:

Redacted for Privacy

Major Professor, Representing Physics

Chair of Department of Physics

Redacted for Privacy

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University Libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for Privacy

Kurt Stump, Author
Acknowledgement

While this paper bears my name the work presented here is the result of the contributions of many people. It is not possible to thank each for the support or assistance they have given me. However, there are several people who have made such large contributions that their efforts merit special mention.

First and foremost I would like to thank Dr. Thomas K. Plant. Dr. Plant has served as my advisor, mentor, and friend throughout my graduate experience at Oregon State University. He has given me support, both financially and intellectually, throughout my research. He showed a great deal of faith and confidence in me even when mine was waning. Dr. Plant has given me the opportunity to perform original and meaningful work without ever feeling pressured to produce. I have been allowed to pursue my own areas of interest and to make my own mistakes and learn from them. Dr. Plant’s advising has made my graduate experience all that it should be. I thank him for giving me such a rich and rewarding research topic.

Dr. Yunlong Sun and Mr. Ed Swenson from Electro Scientific Industries, Inc. have generously donated their time and the equipment. This has made our research possible. They originally donated a lamp-pumped UV laser and UV optical components. They donated their own time and ESI’s staff and facilities to keep our equipment working. When the lamp-pumped laser didn’t work out they modified one of their diode-pumped lasers for this work and gave us a long term loan. All of their contributions are greatly appreciated.

Mr. Eric Udd and the staff of Blue Road Research have also made generous contributions to this work. They have patiently worked with us while we were on the steep portion of the fiber Bragg grating learning curve and have donated many fiber optical components to help us get under way. In addition, they have included OSU in grant proposals and contracts to help ensure that this research will continue.
Dr. William Hetherington has been a teacher and an excellent resource for all things optical. He has always had an open door and made the time to talk with me whenever I had questions or needed a fresh perspective. He has also helped me to understand some of the photochemistry involved in the photosensitivity of optical fibers. Dr. Joe Nibbler of the Chemistry Department has loaned us an optical spectrum analyzer and various optical components which has enhanced our work considerably. Dr. Henri Jansen has been my minor advisor and has helped me finish my degree in a timely fashion by allowing wide latitude in the courses to complete my minor in Computational Physics.

Dr. Clay Widmayer and Dr. John Hunt at Lawrence Livermore National Laboratory (LLNL) have both given a great deal of support and encouragement to me. The opportunity that they gave me to work at LLNL is the reason I became interested in optics and lasers in the first place. They taught me a great deal about the field of physics, how to work on a problem as a member of a team, and to ask “what’s the graph I want to draw?” This is a lesson I will carry with me for the rest of my life.

I would also like to thank all of my classmates for their encouragement and support. Specifically I would like to thank Robert Hawkins who has become a very good friend. He has always listened with great interest concerning my research and has offered many fresh opinions. Additionally, he has helped me preparing two of the presentations I have given concerning this work. I would also like to thank Michele Winz. Since Michele has begun working on the project he has contributed many excellent ideas and insights. I am happy that he will be continuing this work and hope that it will bring him as much joy and fulfillment as it has me.

Personally, I would like to thank my parents, Mike and Jane Stump, who have supported me in every way and in everything I have done. Without their understanding I would never have been in the position to complete this work. Finally, and perhaps most importantly, I would like to thank Carrie
Cessaro. She has been my best friend and my greatest supporter throughout this experience. She has been extremely understanding and supportive, even when things were not going smoothly and I was less than pleasant to be around. She has always given a concerned and sympathetic ear whenever I wanted to talk about “blah, blah, blah, physics stuff”.

While there are others whose contributions have not been singled out here, their efforts are certainly appreciated. All of those who helped me, both mentioned and not, have made this time of my life very rewarding and fulfilling. For that you have my deepest thanks.
# Table of Contents

1. Introduction .................................................. 1

1.1. Early Developments: The Internal Writing Method .......... 3

1.2. The Ultra-Violet Age: The Transverse Holographic Method .................................................. 4

1.3. Diffractive Optical Elements: The Phase Mask Method .................................................. 6

1.4. Long Period Fiber Gratings: The Point-by-Point Method .................................................. 7

1.5. Lasers Used for Fabricating Fiber Bragg Gratings .......... 9

1.6. Enhancing the Photosensitivity of Optical Fibers .......... 10

1.7. Applications of Fiber Bragg Gratings ...................... 13

1.7.1. Wavelength Division Multiplexing ...................... 13
1.7.2. Fiber Optical Sensing ................................ 14
1.7.3. Optical Filters .......................................... 14
1.7.4. Optical Taps .............................................. 15
1.7.5. Fiber Laser Resonators ................................ 15
1.7.6. Reflectors for Fiber Amplifiers ....................... 15
1.7.7. Dispersion Compensation .......................... 16
1.7.8. Distributed Feedback Laser Output Couplers .......... 16

2. The Nature of the Photosensitivity of Optical Fibers .......... 18

2.1. Color Center Formation Model .......................... 18

2.1.1. Reactions Associated with UV Exposure .......... 20
2.1.2. Relationship Between GeE' Formation and Index Change .................................................. 22

2.2. Densification of SiO₂:GeO₂ Glass Due to UV Exposure .......................... 24
# Table of Contents (Continued)

2.3. Mechanisms of Photosensitivity in Hydrogen-Loaded Optical Fibers ........................................ 26

2.4. Thermally Enhancing the Photosensitivity of Optical Fibers .................................................... 28

2.5. Summary ................................................................................................................................. 29

3. The Modified Phase Mask Writing Technique ........................................................................... 31

3.1. Coherence and Stability Requirements of the Transverse Holographic Technique ................. 31

3.2. Early Attempts at Writing Fiber Bragg Gratings .................................................................... 34

3.3. The Modified Phase Mask Writing Technique ....................................................................... 36

3.4. Comparison Between the Transverse Holographic and Modified Phase Mask Writing Techniques ......................................................... 40

3.5. Experimental Verification of the Modified Phase Mask Technique ........................................ 41

3.6. Conclusion ............................................................................................................................ 47

4. Time Evolution of Writing Fiber Bragg Gratings .................................................................. 48

4.1. Current Theories of the Evolution of FBG Formation .......................................................... 49

4.2. Experimental FBG Writing Studies at Oregon State University ........................................... 51

4.2.1. The Effect of Hydrogen on Grating Inscription ............................................................. 53

4.2.2. The Effect of Pulse Energy on Grating Formation ......................................................... 62

4.2.3. The Effect of CO₂ Exposure During Grating Writing. ..................................................... 68
Table of Contents (Continued)

4.3. Discussion of Experimental Observations .......................... 73
   4.3.1. Discussion of Hydrogen Loading Experiments ............... 73
   4.3.2. Discussion of the Pulse Energy Experiments ............... 76
   4.3.3. Discussion of the Effect of CO$_2$ Exposure
       During Grating Formation ............................................ 77

4.4. Summary ................................................................. 78

5. The Thermal Stability of Fiber Bragg GRATings ................. 79
   5.1. Current Theories Concerning Fiber Bragg Grating
       Erasure ................................................................. 79
   5.2. Thermal Erasure Studies at Oregon State University ......... 82
   5.3. Results of the Thermal Erasure Studies ....................... 85
   5.4. Discussion of the Thermal Erasure Studies .................... 89
   5.5. Annealing Hydrogen Loaded Fibers ............................... 91
   5.6. Summary ................................................................. 93

6. Summary of Results and Future Work ............................... 94
   6.1. Results of Year One of the OSU Fiber Bragg Grating
       Project ................................................................. 94
   6.2. Future Work ............................................................ 96

Bibliography ........................................................................... 99

Index ..................................................................................... 106
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>Example of two interfering Gaussian laser beams.</td>
<td>2</td>
</tr>
<tr>
<td>1.2.1.</td>
<td>Transverse holographic setup for writing fiber Bragg gratings of variable wavelengths.</td>
<td>5</td>
</tr>
<tr>
<td>1.3.1.</td>
<td>Experimental set up for writing fiber gratings with a diffractive optical element.</td>
<td>8</td>
</tr>
<tr>
<td>1.4.1.</td>
<td>Experimental set up for writing fiber gratings using the point by point method.</td>
<td>9</td>
</tr>
<tr>
<td>1.6.1.</td>
<td>Absorption spectrum of Ge:SiO₂ glass prior to and following grating inscription.</td>
<td>11</td>
</tr>
<tr>
<td>2.1.1.</td>
<td>Typical defects in Ge:SiO₂ glass.</td>
<td>19</td>
</tr>
<tr>
<td>2.1.2.</td>
<td>Color center model of the bleachable GeE' forming mechanism.</td>
<td>21</td>
</tr>
<tr>
<td>2.3.1.</td>
<td>Mechanism for the enhanced photosensitivity in hydrogen loaded fibers.</td>
<td>27</td>
</tr>
<tr>
<td>2.5.1.</td>
<td>Flow chart for the mechanisms of photosensitivity and grating types written for various writing conditions.</td>
<td>30</td>
</tr>
<tr>
<td>3.1.1.</td>
<td>Surface plot of $\lambda_{Bragg}$ for different $\lambda_{laser}$ and $\theta$ values for the transverse holographic technique.</td>
<td>33</td>
</tr>
<tr>
<td>3.3.1.</td>
<td>The experimental set up for the modified phase mask writing technique.</td>
<td>37</td>
</tr>
<tr>
<td>3.3.2.</td>
<td>Surface plot of $\lambda_{Bragg}$ for different $\lambda_{laser}$ and $\beta$ values for the modified phase mask technique.</td>
<td>39</td>
</tr>
<tr>
<td>3.5.1.</td>
<td>Photograph of the hydrogen loading apparatus.</td>
<td>42</td>
</tr>
<tr>
<td>3.5.2.</td>
<td>Comparison of gratings written with the modified phase mask technique ($\lambda_{Bragg} = 1302$ nm) and the traditional phase mask technique ($\lambda_{Bragg} = 1286$ nm).</td>
<td>44</td>
</tr>
<tr>
<td>3.5.3.</td>
<td>Plot of eight gratings written in the same fiber to assess the tunability of the modified phase mask</td>
<td>44</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.4. 1550 nm grating written with the modified phase mask technique and a phase mask which would traditionally only write 1286 nm gratings.</td>
<td>46</td>
</tr>
<tr>
<td>4.1.1. The three-energy-level system for the formation of fiber Bragg gratings.</td>
<td>50</td>
</tr>
<tr>
<td>4.2.1. Evolution of the writing process of a grating in boron codoped fiber.</td>
<td>52</td>
</tr>
<tr>
<td>4.2.2. Evolution of a grating written in a fiber without any photosensitivity enhancement.</td>
<td>54</td>
</tr>
<tr>
<td>4.2.3. Evolution of a grating written in a fully hydrogen-loaded fiber.</td>
<td>55</td>
</tr>
<tr>
<td>4.2.4. Writing evolution of fibers with various concentrations of hydrogen.</td>
<td>56</td>
</tr>
<tr>
<td>4.2.5. Typical evolution of a fiber Bragg grating in moderately hydrogen-loaded fiber.</td>
<td>57</td>
</tr>
<tr>
<td>4.2.6. The effect of different levels of hydrogen on wavelength shift and grating evolution.</td>
<td>59</td>
</tr>
<tr>
<td>4.2.7. Two plots which demonstrate the thermal effects seen in moderately hydrogen loaded fibers.</td>
<td>60</td>
</tr>
<tr>
<td>4.2.8. Extended writing time of a partially hydrogen loaded fiber.</td>
<td>61</td>
</tr>
<tr>
<td>4.2.9. Writing evolution of gratings written in unloaded fiber with pulse energies ranging from 69 to 123(\mu J) per pulse.</td>
<td>63</td>
</tr>
<tr>
<td>4.2.10. Writing evolution of gratings written in hydrogen-loaded fiber with pulse energies ranging from 68 to 112(\mu J) per pulse.</td>
<td>64</td>
</tr>
<tr>
<td>4.2.11. Writing evolution of gratings written in boron-codoped fiber with pulse energies ranging from 50 to 137(\mu J) per pulse.</td>
<td>66</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4.2.12.</td>
<td>Writing evolution of gratings written in boron-codoped fiber with pulse energies of 95 μJ per pulse and pulse repetition rates ranging from 3 kHz to 5 kHz.</td>
</tr>
<tr>
<td>4.2.13.</td>
<td>Writing evolution of gratings written in standard fiber (no photosensitivity enhancement) with and without simultaneous CO₂ laser beam exposure.</td>
</tr>
<tr>
<td>4.2.14.</td>
<td>Writing evolution of gratings written in hydrogen-loaded fiber with and without simultaneous CO₂ laser beam exposure.</td>
</tr>
<tr>
<td>4.2.15.</td>
<td>Writing evolution of gratings written in boron codoped fiber with and without simultaneous CO₂ laser beam exposure.</td>
</tr>
<tr>
<td>5.2.1.</td>
<td>Photograph of the fiber heating oven.</td>
</tr>
<tr>
<td>5.3.1.</td>
<td>Erasure of gratings written in hydrogen-loaded fiber.</td>
</tr>
<tr>
<td>5.3.2.</td>
<td>Erasure of gratings written in boron codoped fiber.</td>
</tr>
<tr>
<td>5.3.3.</td>
<td>Erasure of gratings written in untreated germanium fiber.</td>
</tr>
<tr>
<td>5.5.1.</td>
<td>Results of the annealing study of hydrogen loaded fiber.</td>
</tr>
</tbody>
</table>
Preface

The field of fiber optics has undergone remarkable growth in the past 30 years. Since low loss optical fibers were developed, their use has spread to new and exciting areas. Several applications and devices have been developed which were previously unimaginable. While fiber optics are traditionally associated with the telecommunications industry, they are also invaluable in several other applications. The fields of medicine, sensing, optics, and aerospace, as well as many others, have been tremendously impacted by the advances in optical fibers. One of the most important and versatile devices to result from these advances is the fiber Bragg grating, a periodic variation in the refractive index in the core of the fiber.

Fiber Bragg gratings have found applications in optical sensing, telecommunications, and optical engineering. By all accounts the current applications have only scratched the surface of their potential. New applications are appearing continuously and there is no end in sight. Techniques are being developed which allow these simple devices to accomplish various tasks with accuracy and ease previously unattainable. Their small size and chemical inertness has made them ideal for several unique applications such as in the construction of “smart buildings” and in other sensing applications. As the popularity of fiber gratings continues to grow, so does their importance to engineering and applied physical science research.

In 1999, Dr. Thomas K. Plant of the Oregon State University Department of Electrical and Computer Engineering, with funding from the A.V. Smith Faculty Development Fund, began a research program in the fabrication and applications of fiber Bragg gratings. Dr. Plant had many contacts with Oregon industry which placed him in an ideal position to begin this project. He had a preexisting relationship with Blue Road Research (BRR) of Troutdale, Oregon. BRR is an innovative company concerned with fiber optical sensing
and the design and fabrication of fiber Bragg grating-based devices and has a reputation for pioneering new techniques and devices based upon fiber optics. This reputation has forged a relationship between BRR and several governmental and industrial entities as well as other research institutions. These include the US Navy, Air Force, Army, NASA, Sandia National Laboratories, Oregon Department of Transportation, and Boeing. The capability of fabricating fiber Bragg gratings would place OSU in a unique position to participate in joint research with BRR and many of its affiliates. In addition to expanding OSU’s visibility and activity in multi-institutional research projects, this program would also allow collaboration between many of OSU’s Engineering and Physical Sciences Departments.

In assembling the elements necessary for this project Dr. Plant was also able to use an existing relationship between OSU and Electro Scientific Industries, Inc. of Portland, Oregon to obtain a high power UV laser and optical components. This laser is central to the research program as it provides the means of writing fiber gratings. This relationship also helps solidify Oregon State University’s involvement in Oregon’s industrial community. By conducting research far from ESI’s primary field, laser cutting and trimming, OSU may provide an application for their products that has not yet been explored.

The work presented in the following chapters is the result of this research project. It provides the first step in achieving the goals outlined above. The project has so far succeeded in strengthening the relationship between Blue Road Research, ESI, Inc and Oregon State University. By establishing the ability to fabricate fiber gratings and develop novel techniques, Dr. Plant’s group has created a unique position for itself in both industrial and academic research. The group has already been included on a Phase II SBIR research contract with BRR and Boeing for Wright Patterson Air Force Base and has also been funded by NASA Glenn Research Labs to develop techniques to
create high temperature and short wavelength fiber Bragg gratings. In addition, the group has attracted a new Ph.D. graduate student from the Physics Department and has funding for at least one more student.
Fiber Bragg gratings (FBGs) are optoelectronic devices which consist of an optical fiber with a periodic perturbation in the index of refraction in the core of the fiber. This perturbation causes coupling between forward- and backward-propagating modes in the optical fiber (counter-directional coupling). In the case of single mode (SM) fibers, the grating couples the forward propagating mode into a backward propagating mode with the same bounce angle [1]. For this condition the reflected wavelength $\lambda_{\text{Bragg}}$ is related to the period of the grating by the familiar Bragg equation

$$\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda$$

where $\lambda_{\text{Bragg}}$ is the "Bragg wavelength", $n_{\text{eff}}$ is the effective index of the single propagating mode in the core, and $\Lambda$ is the grating period.

The change in index in the core of the fibers is a permanent change caused by exposure to intense UV laser irradiation [2]. This index change is periodic and is caused by the interference of two laser beams. An example of two interfering Gaussian beams is shown in Figure 1. This change has been found to be stable up to 800°C for type II gratings (see below) [3]. Because of these properties, in addition to the fiber's small size and low loss in a fiber optic circuit, FBGs have received a great deal of attention from the fiber sensing and telecommunication industries as strain sensors and laser wavelength stabilizers [2].

---

1 It is also possible to couple forward propagating modes into cladding or radiation modes by tilting the grating with respect to the fiber axis.
Figure 1.1: Example of two interfering Gaussian beams. Above the beam is a section through the half maximum.

The change in index of refraction can be either an increase in the index or a decrease in the index. These changes in index lead to gratings of type I and type II respectively. Generally, when writing a grating there is first an increase in the index of refraction and the formation of a type I grating. Further irradiation will lead to a saturation of the grating followed by the grating’s erasure. Under continued irradiation of the fiber with a high laser fluence ($\sim 20\text{mJ/cm}^2$), a second grating will appear; a type II grating [4]. This phenomena does not occur in all fibers and is not completely understood. During the inscription of type I gratings, the Bragg wavelength has been seen to shift as much as .12 nm to longer wavelengths. The subsequent erasure of the type I grating and writing of a type II grating will either shift the Bragg wavelength slightly to shorter values or not at all [4].
1.1. Early Developments: The Internal Writing Method

The development of fiber Bragg gratings began in 1978 when Hill et al. launched an Ar\textsuperscript{+} laser operating at 488 nm into the core of a germanium-doped optical fiber [5]. This pioneering work was performed in an effort to find a means of creating optical wave guide filters for applications in lightwave communications. Such devices could then be used in wavelength-division-multiplexing (WDM) as a means of separating individual channels from a signal. These filters would then allow much higher data capacities in standard single mode fibers. However, in order to be able to separate the individual channels in a fiber optic link, a filter would require a high degree of wavelength discrimination and tunability.

The fiber used by Hill was single-mode fiber with a germanium-doped core. After a few minutes of exposure it was noted that the beam was increasingly being reflected back. It was determined that the Fresnel-reflected light from the cleaved end of the fiber had set up a standing wave inside, and the areas of high intensity had undergone an increase in index of refraction. As the percentage of the light which was reflected back grew, so did the intensity of the standing wave which resulted in further increase of the index of refraction. This continued until nearly 100% of the input light was reflected back. Hill used this technique to build the first distributed feedback gas laser in the visible range [5]. This was done by removing the output reflector of the Ar\textsuperscript{+} laser and replacing it with a microscope objective which launched the light into a fiber which was 1 meter long. The “Hill Grating”, as they later came to be known, would reflect only one wavelength and allow all others to be transmitted. Therefore, only the reflected wavelength would oscillate and make a stable laser.

In the paper Hill et al. went on to discuss the sensitivity of the gratings to various environmental factors present at the time of writing. These factors
included temperature and strain which form the basis of fiber optical sensing using fiber Bragg gratings. The investigators also noted that the change in the index of refraction seemed to be related to the concentration of germanium in the core. In one brief paper, Hill et al. laid the groundwork for what has become an important element in modern telecommunications and fiber optical sensing.

1.2. The Ultra-Violet Age: The Transverse Holographic Method

While Hill’s pioneering work laid the foundation for fiber grating technology, there were still several technical problems to be addressed before these devices made their way into commercial applications. These problems included (1) having a writing wavelength at or near the reflection wavelength, (2) having an efficient means of writing gratings, and (3) being able to write a wide range of reflection wavelengths [2].

In the period from 1978 to 1989 relatively little work was done to improve the state of fiber Bragg gratings. Some researchers were investigating the nature of the absorption of light in germanosilicate glasses but little was done to address the previously mentioned technical problems. Then in 1989 Meltz et al. proposed a new technique for writing gratings using side illumination of the fiber by two interfering UV laser beams [6]. The experimental setup for this technique is shown in Figure 1.2.1. Writing with UV beams from the side was possible because the silica cladding of the fiber was transparent to the beam while the core was very absorptive [3]. This technique was termed the transverse holographic method and had several distinct improvements over the internal writing method proposed by Hill [2]. First, this method utilized UV light which was one half the wavelength of the light used by Hill in 1978. It had been previously found by Lam and Garside that for gratings written by green Ar\textsuperscript{+} lasers, the grating strength was proportional to the square of the
writing power, suggesting a two photon process [7]. By using a photon with twice the energy, Meltz was able to use a one photon process which proved to be much more efficient.

Figure 1.2.1: Transverse holographic setup for writing fiber Bragg gratings of variable wavelengths.

The second advantage of this technique was that the writing wavelength was far from the reflected wavelength. This is extremely important because many commercial applications for these devices would be in telecommunications where the most common wavelengths are 1300 nm and 1550 nm [2]. The absorption region related to the change of index of refraction had been well studied [7] and was known not to be near these wavelengths. Therefore,
in order to make fiber gratings for telecommunication applications, a writing wavelength far from the reflection wavelength was required. Using the transverse holographic technique, gratings were written with a variable (with \( \theta \)) reflection wavelength given by

\[
\lambda_{\text{Bragg}} = \frac{n_{\text{eff}} \lambda_{\text{laser}}}{\sin \left( \frac{\theta}{2} \right)}
\]  

(1.2)

where \( \lambda_{\text{laser}} \) is the writing wavelength and \( \theta \) is the angle between the two beams. This proved to be the key that was necessary for the fiber Bragg grating industry to take off.

1.3. Diffractive Optical Elements: The Phase Mask Method

Meltz's work with the transverse holographic method ushered in renewed interest in fiber gratings as is evident from the flurry of papers published in the early 1990's. While Meltz made it possible to write gratings at various wavelengths, which made the prospect of grating applications in telecommunication possible, there were still limitations to using the transverse holographic method. The major technical difficulty was the high stability requirement placed upon the writing setup and the coherence of the laser.

In order to create an interference pattern, the laser coherence length must be longer than the difference in optical path lengths of the two beams [8]. This requirement meant that a high quality laser with a long coherence length was needed in order to write gratings capable of operating at the telecommunication wavelengths. This translated into a large investment in the laser in order to make fiber gratings.

In 1993 two groups independently presented new a method which removed this requirement [9-10]. This development made the practice of manufacturing fiber gratings very easy and affordable.
This phase mask method made use of photolithography to make a holographic optical element called a “phase mask” which was, in essence, a transmission diffraction grating. This grating was designed to have most of the beam split into the ±1 diffraction orders. The 0th order diffraction was suppressed. The fiber was then placed next to the phase mask and the ±1 diffractions crossed at the core, creating an interference pattern. A grating was formed which had a reflection wavelength given by

\[ \lambda_{Bragg} = n_{eff} \Lambda_{Mask} \]  

(1.3)

where \( \Lambda_{Mask} \) is the period of the phase mask. The experimental set up is shown in Figure 1.3.1. Notice that, the operation of the phase mask is independent of the writing wavelength! This allows the use of any laser wavelength which would be absorbed in the fiber core [10]. Additionally, since the phase mask acts as a template for fiber gratings, each grating is identical.

While this technique presented several important advances in manufacturing fiber gratings, it still had one major drawback: gratings were limited to the single wavelength reflected by the period of the phase mask. There was a very limited amount of flexibility in the wavelength possible by stretching the fiber while writing the grating. However, in general, separate phase masks were needed for each wavelength grating written.

1.4. Long Period Fiber Gratings: The Point-by-Point Method

Another common technique used to write fiber gratings was introduced by Hill in 1990. This method is known as the point-by-point method [11]. In this technique each index perturbation is written separately. By writing the grating point by point it is easy to tailor the period of the grating which
Figure 1.3.1: Experimental set up for writing fiber gratings with a diffractive optical element.

makes it very easy to incorporate aperiodicity into the grating. The technique is shown in Figure 1.4.1.

In this method the writing beam passes through an aperture and is incident on the fiber. As each point is written, the fiber is indexed by an amount equal to the period of the grating. This technique is generally used to write so-called long-period gratings which couple light into a codirectional mode [12-13]. These gratings are technically not Bragg gratings and are only mentioned here for the sake of completeness. Neither fabrication of these gratings nor their properties will be presented.
Figure 1.4.1: Experimental set up for writing fiber gratings using the point by point method.

1.5. Lasers Used for Fabricating Fiber Bragg Gratings

The array of lasers that have been used to write fiber gratings spans almost the entire gamut of modern lasers. Argon ion visible lasers were used by Hill. Meltz did his pioneering transverse writing work with an excimer-pumped dye laser. Several other authors have used solid state lasers [14-16]. An even more popular choice has been the excimer laser due to its high gain and its 248 nm wavelength (which is near the peak of the germanium absorption) [17-20]. In fact, CO₂ lasers have even been used to write codirectional coupling gratings [12,13].

The recent developments in nonlinear, frequency-converting crystals has made the use of many of these lasers possible. For example, the solid state
lasers now used are quadrupled in order to get the wavelength at or near the strong UV absorption peak near 242 nm (discussed in the next chapter). Also, using ion lasers in the deep UV is only possible by employing these crystals. Without frequency conversion only excimer lasers would be able to write fiber Bragg gratings.

The most common ion lasers used currently are frequency-doubled Argon ion lasers. These lasers have very good coherence and beam quality as well as moderately high continuous wave power levels.

The solid state lasers used in the fabrication of fiber gratings are Nd$^{3+}$:YLF and Nd:YAG, with Nd:YAG being the more popular. These are characterized by excellent beam quality and moderately high power levels. The major drawback to each is that they operate near the outer limits of the absorption band (see Figure 1.6.1): 262 nm for Nd$^{3+}$:YLF and 266 nm for Nd:YAG.

1.6. Enhancing the Photosensitivity of Optical Fibers

As the methods of fabricating fiber gratings were refined, the question of the exact nature of the change in index remained. Further, it was found from the very beginning of fiber grating technology that the change in absorption was related to the concentration of germanium in the core of the fiber. This change in absorption was first demonstrated experimentally by Atkins and is shown in Figure 1.6.1 [21]. While highly reflective gratings have been produced in standard telecommunication fibers, the writing times are very long ($\sim 30$ min) even when writing at the peak of the UV absorption curve [22]. Since standard telecommunication fibers have a low ($\sim 3$ mol%) germanium content, only those researchers who had access to fiber drawing facilities to make higher Ge-content fibers were able to efficiently write high quality gratings. This created a strong desire to find methods of enhancing the photosensitivity of standard telecom fiber.
The research concerning the mechanisms underlying the change in index of the fiber is discussed in detail in the next chapter. Therefore, only the research pertaining to the enhancement of the photosensitivity will be mentioned here.

The most obvious means to increase the photosensitivity of optical fibers was to simply increase the germanium content of the fiber. This was done in several studies [23-25] which did indeed produce a larger increase in the change in index of refraction. However, this technique comes with the price of reducing the mode field diameter due to the increase in the germanium content. This limits the grating’s usefulness in telecommunication networks because of increased losses at the points the grating is spliced into the network [22].

Another attempt to increase the photosensitivity of optical fibers was to find other dopants which would allow writing of fiber gratings. Investigators
were able to create gratings with higher index changes than with germanium-only doped fibers. While this technique was successful in finding alternative dopants such as boron, the problem still remained that only those who could draw their own fibers could make these gratings. Therefore, a method of enhancing the photosensitivity of standard telecom fiber was still actively sought.

Previous work had suggested an increase in absorption for various wavelengths due to the presence of hydrogen in an optical fiber [26-29]. In 1993 Lemaire et al. extended this notion to using this increase in attenuation to enhance the photosensitivity of standard telecommunication fibers [30]. This technique involved exposing the fibers to 70-80°C, high pressure (∼4000 psi) hydrogen prior to writing the grating. This technique provides a simple means to dramatically enhance the photosensitivity of all germanium-doped optical fibers. Furthermore, once the grating is written, the unreacted hydrogen diffuses out of the fiber making the grating the only permanent change to the fiber. The exact mechanism of this enhancement is still under investigation and the current theories will be discussed in the next chapter.

In an article published shortly after Lemaire’s work on hydrogen loading, Atkins et al. sought to explain the mechanism behind this increase in photosensitivity [31]. In this article the investigators noted that there appeared to be a temperature component in this induced sensitivity. They discovered that hydrogen-loaded germanosilicate fiber underwent a larger change in index of refraction when the glass was allowed to be heated by the writing laser than when the glass was cooled during writing. Further, they showed that, when a fiber was exposed to UV laser light then heated with a CO₂ laser to >800°C, the UV attenuation increased from about 20 dB/mm to approximately 360 dB/mm. This indicated that there may be a role of temperature in the enhancement of the photosensitivity. This was followed up in 1995 by Lemaire et al. [32]. In this experiment the fiber was heated by blowing hot air on it during writing. This report confirmed that heating the fiber to 400°C
during UV irradiation did, in fact, increase the photosensitivity of the fiber. An additional paper regarding the effect of temperature on photosensitivity was presented in 1999 by Brambilla et al. [33]. In this work a nonhydrogen-loaded fiber was exposed to CO\textsubscript{2} laser radiation prior to writing the grating. This paper demonstrated a marked improvement in photosensitivity with increasing CO\textsubscript{2} irradiation.

1.7. Applications of Fiber Bragg Gratings

While the methods of fabricating fiber gratings are still being refined, most current research is concerned with gaining a thorough understanding of the mechanism of the index change, new grating design and developing new applications for these devices. Also a great deal of work has been done to develop gratings of various profiles in order to tailor the response of the grating to the desired application. As a result chirped, gaussian, tilted, raised cosine, and discrete phase shifted gratings have been developed. As discussed earlier, fiber Bragg gratings were developed primarily for wavelength division multiplexing. However, since their introduction they have also attracted interest in the areas of fiber optical sensing, optical filters, taps, optical resonators for fiber lasers, reflectors for fiber amplifiers, dispersion compensation and output gratings for laser stabilization [34]. Each of these applications provides many research topics and will only be introduced briefly here. For further treatment the reader is referred to the literature [2,3,34].

1.7.1. Wavelength Division Multiplexing

As was discussed in section 1.1, the primary reason for investigating the possibility of in-fiber gratings was to find a means of separating the individual
channels in an optical fiber [5]. It is of great benefit to have a passive element which has low loss and is easily manufactured. The implementation of such devices allows much higher data capacities and very low insertion loss.

1.7.2. Fiber Optical Sensing

The field of using fiber optics as sensing devices has grown considerably since the development of fiber Bragg gratings. Fiber grating-based sensors are ideal in many applications because of their small size and high sensitivity. The basis of the operation of fiber grating sensors is the dependence of the reflected wavelength on the grating period. Subjecting the grating to stress, strain, temperature variations, or pressure changes the grating period. The shift in the reflected wavelength determines the amount of the period change and, therefore, the magnitude of the environmental cause of the change.

As an example of the high sensitivity of these devices, the wavelength shift of a fiber grating has been shown to be 0.01 nm/°C. For strain sensing applications, resolution of 0.3 microstrain has been demonstrated. Wavelength changes as small as $10^{-4}$ have been detected [3]. It has also been shown that two 50% reflecting gratings can have a 1 GHz difference simply by stretching the fiber [35].

1.7.3. Optical Filters

Closely related to the WDM application is the use of fiber gratings as optical filters. Gratings can be fabricated to function as either reflection or transmission filters. By using a standard grating one can create a selective and highly tunable reflection or rejection filter depending upon where the detector is. Introducing a $\frac{\pi}{2}$ phase shift in the center of the grating, makes
a transmission filter [3]. Additionally, long-period fiber gratings have been used as band rejection filters [13].

1.7.4. Optical Taps

Another application of fiber gratings, which has received relatively little attention, is that of an optical tap. Tilting the grating with respect to the fiber axis, causes the grating to couple light from a forward propagating mode to radiation modes [1,36-38]. These devices have the same selectivity as standard gratings but allow the signal to be coupled out of the fiber rather than be reflected. This could be used to couple the signal into another fiber, thereby providing a means of branching off a desired frequency from a signal.

1.7.5. Fiber Laser Resonators

A very interesting application of fiber gratings is to use them as resonator mirrors for erbium-doped fiber lasers [34]. These devices have demonstrated gigabit/s transmission rates [39]. Because of their high wavelength selectivity, fiber gratings make possible low cost distributed feedback fiber lasers with single-frequency operation.

1.7.6. Reflectors for Fiber Amplifiers

There have been a variety of different configurations proposed which utilize fiber gratings to enhance the performance of fiber amplifiers. An example given in [34] would replace the common practice of using a broadband reflector to reflect the pump light for an erbium-doped amplifier with one that would
reflect only the pump light. This would increase the amplifier output power, especially when the amplifier has marginal pump power. By using these reflectors in a repeaterless system, span lengths can be extended by pumping the erbium-doped amplifiers with 1485 nm light from high power lasers at the terminal station [34].

1.7.7. Dispersion Compensation

One of the major issues with fiber optic communication is dispersion. In many cases chromatic dispersion can cause a great deal of distortion in propagating signals. In order to control this dispersion, compensators must be added to the fiber optical network. This is not as crucial when operating at 1300 nm but can be crucial when trying to carry high data rates at 1550 nm. The standard means of combating this problem is to introduce a component in the network which has the same dispersion as the fiber but is opposite in sign. Fiber Bragg gratings have been designed which can act as an all pass filter with the proper dispersion by introducing the proper chirp in the grating. These gratings generally must be fairly long (~ 5 cm) which requires special fabrication techniques [34].

1.7.8. Distributed Feedback Laser Output Couplers

The utility for creating distributed feedback lasers is not limited to fiber lasers. In fact, as mentioned in Section 1.2, Hill et al. used one of the first fiber gratings to create the first visible distributed feedback gas laser [5]. These devices have been used as output couplers in semiconductor lasers as well [34]. In fact, these narrow-line-grating feedback mirrors have made possible the
dense WDM transmission of terabits/second of data over a single fiber at 1.3 microns wavelength.
Chapter 2
The Nature of the Photosensitivity of Optical Fibers

The photosensitivity of optical fibers has been a topic of intense research ever since its discovery by Hill in 1978 [5]. In the search for the mechanism underlying the change in index of refraction, several theories have been proposed. It appears that the change in index is a complicated process and that multiple mechanisms may be involved. Also, evidence indicates that the mechanism for the photosensitivity of non-hydrogen loaded fibers differs from that of hydrogen loaded fibers. The question regarding the nature of the photosensitivity of optical fiber has not yet been decisively answered.

In order to create fiber gratings, it is important to have an understanding of the mechanisms underlying their formation. Different fluence levels and different writing wavelengths appear to cause different effects. Also, pre-exposure processing such as thermal annealing and hydrogen loading appear to alter the mechanisms involved. In order to optimize the writing conditions, more complete knowledge of these separate processes is needed. In this chapter the models which are thought to contribute the greatest to the photosensitivity of optical fibers will be discussed.

2.1. Color Center Formation Model

Shortly following the discovery of the photosensitivity of optical fibers, the Color Center model was proposed [40]. In the Color Center model, the photosensitivity in the optical fiber arises from defects in the glass matrix which are caused by introducing a dopant into the glass in order to increase the index
Figure 2.1.1: Typical defects in Ge:SiO$_2$ glass. (a) undoped SiO$_2$ matrix, (b) adding Ge to SiO$_2$, (c) Ge–Si defect, (d) Ge–Ge defect, (e) Si–Si defect, (f) Ge(1), (g) Ge(2), (h) GeE'.

\ *= ionic electron
of refraction. The most common dopant used in telecommunication fibers is germanium and the normal concentration is approximately 3-5% [3]. Figure 2.1.1 (a) represents the SiO₂ matrix without any germanium doping. Rather than simply replacing a Si atom with a Ge atom as shown in Figure 2.1.1 (b), several defects can occur. These defects are shown in the figure as (c) through (g). The most important of these for the Color Center model are (c) and (d) which form so-call Germanium Oxygen-Deficient Centers (GODCs) [41-42]. This Ge–Ge bond is known to have an absorption which is centered near 242 nm and extends from about 230 nm to approximately 260 nm [43]. Upon UV exposure this bond is broken and a GeE' center and one free electron are created [21,44]. The GeE' center is shown in the figure as (h). This formation of a GeE' center is accompanied by a decrease in the UV absorption [45]. This change in absorption was first observed experimentally by Atkins in 1992 [21]. The measured absorption prior to and following UV exposure was shown in Figure 1.6.1. The following sections will discuss the relationship between this change of absorption and formation of fiber Bragg gratings and observed photoluminescence of the core of the fiber.

2.1.1. Reactions Associated with UV Exposure

Irradiation of germanosilicate glass by UV laser light has been shown to cause dramatic changes in the glass. These changes are accompanied by a change in the absorption of ultraviolet light in the glass and photoluminescence during irradiation [41,45,46-47]. This luminescence has been found to exist near 400 nm and in the UV region [35]. It has been shown experimentally that the absorption near 5 eV has two components [42]. One of these components was found to be bleachable and was centered at 5.06 eV. The other is not bleachable and is centered at 5.16 eV.
The general idea behind the absorption of UV light by the Color Center model is shown in Figure 2.1.2. A photon with sufficient energy to break the Oxygen Deficient bond interacts with the Ge–Ge (or Ge–Si) portion of the matrix. The result of this reaction is a GeE’ center plus a free electron. This reaction accounts for the bleachable component of absorption and has an energy of approximately 5.06 eV. This model is consistent with the observation that the number of GeE' centers increases as the 5.06 eV absorption becomes bleached [42].

![UV Photon](image)

**Figure 2.1.2:** Color center model of the bleachable GeE' forming mechanism.

The nonbleachable band is believed to be connected with a Ge^{+2} ion located in the core of the fiber. This ion consists of a Ge connected to two oxygen atoms and has an ion pair of electrons in the uppermost level [42]. Divalent germanium defects have singlet-to-singlet excitation energies of 5.1 eV and singlet-to-triplet excitation energies of 3.4 eV [47]. During irradiation with UV light both of these excitations occur. When these electrons relax they emit 4.1 eV photons for the singlet-to-singlet transition and 2.7 eV photons for triplet-to-singlet; thus accounting for the observed luminescence. This
luminescence has been seen to decrease to nearly 40% of its initial value during the writing process. This indicates that the divalent germanium defects arise from the manufacturing process. One can imagine that the decrease in luminescence could be caused by ionization of these defects.

The above model is consistent with experimental observations by many investigators. First of all, it explains the bleaching of the absorption band near 240 nm observed by Williams et al. [48]. Second, it accounts for the decrease in UV absorption found by Atkins and Mizrahi [21]. Also, by following the method of determining the change in index of refraction presented in the next section, this accounts for an increase in the index of refraction. The Color Center model is also in agreement with several investigators' observations (including the experimental work presented later in this paper) that luminescence continues after the grating has saturated, although it may be decreased as noted by Duval [46].

The findings of Hosono et al. which were summarized above, were based upon experimental observations. Recently, the conclusions reached were explained theoretically by Zhang et al. using first-principles quantum-chemical techniques [47].

2.1.2. Relationship Between GeE' Formation and Index Change

As was discussed in the previous section, the creation of GeE' centers by UV exposure leads to a decrease in the fiber's ultraviolet absorption. This was first shown by Atkins [21] and has since been verified by several researchers. The question arises as to the connection between this change in absorption, $\Delta \alpha$, and the change in index of refraction, $\Delta n$. In order to connect these two events one must look to the Kramers-Kronig dispersion relations [3].

According to these relations, the index of refraction is complex. The real part is determined by the phase velocity while the imaginary part is related
to the absorption. The real part of the index of refraction can be expressed
by an integral of the imaginary part [49]. In this context the relation would be

$$\Delta n(\omega') = \frac{c}{\pi} \varphi \int_0^\infty \frac{\Delta \alpha d\omega}{\omega^2 - \omega'^2} \quad (2.1)$$

where $\varphi$ is the principle part of the integral and $c$ is the speed of light in vacuum. Therefore, by the Kramers-Kronig relation, the decrease in absorption predicted by the Color Center model results in an increase in the index of refraction at infrared wavelengths, as experiment demonstrates [46]. When using the Kramers-Kronig relation, the change in index of refraction calculated is often less than the one measured experimentally. There are several reasons for this discrepancy. First, as Eqn (2.1) shows, the integral must be taken over all frequencies. It is not possible to have all of this information, so a theoretical extrapolation is necessary. Another reason could be the presence of more than one mechanism at work. Kramers-Kronig only accounts for the changes in index due to changes in absorption. There can also be changes due to structural changes in the matrix as will be discussed in the next section. Therefore, caution is needed when applying Kramers-Kronig relations [35].

While the Color Center model successfully explains several of the key observations concerning the photosensitivity of optical fiber, it is certainly not the only mechanism by which the index of refraction is changed. Several experiments have demonstrated that there must be other effects on the fiber. These include discovering changes in strain after exposure [50] and volume changes in the fiber [51]. Hence, other explanations for the change in index must be pursued.
2.2. Densification of SiO$_2$:GeO$_2$ Glass Due to UV Exposure

The failure of the Color Center model to predict the total change in index of refraction has prompted researchers to develop additional theories concerning the formation of fiber gratings. Of these new theories, the densification model has been particularly successful. Additional credibility can be lent to this model because the effect has been confirmed experimentally.

The densification model is based upon the idea that UV irradiation causes a strong modification of the glass matrix. This modification leads to a change in volume of the matrix. Because Poumellec et al. showed that there is no ablation occurring [52], this change in volume results from a change in density where the bright parts of the interference pattern are located. This change in density is related to the change of index by the Lorentz-Lorentz relation and is given by Poumellec [35] as

$$\Delta n = \frac{\left( n^2 - 1 \right) \left( n^2 + 2 \right)}{6n} \left( \frac{\Delta \rho}{\rho} \right)$$

where $\rho$ is the molecular volume and $n$ is the core index.

The densification model has been based upon experiments concerning the effect of high pressure on silica. In these experiments it was found that the matrix compresses irreversibly to a density which is about 22% higher [53]. This same effect has been seen under laser irradiation [53]. It has been shown that the compaction of the matrix follows a quadratic dependence on the pulse fluence [54]. Therefore, this effect is much more pronounced with high fluence lasers.

The volume change which is responsible for the UV-induced densification may be caused by several microscopic mechanisms: a phase transformation, a change of polymerization in the glass, and/or a change in coordination [35]. The structure of glass is generally divided into three ranges: short range, medium range, and long range [55]. The short range structure would consist
of the individual tetrahedra, medium range order is the relationship between the tetrahedra, and long range order is the phase of the matrix.

The change in short range order can occur under UV irradiation as bonds are broken. The breaking of these bonds will lead to a change in the local structure of the glass. This in turn can lead to a change in the volume or a compaction of the matrix as the molecules reorganize themselves [35].

Silica has a medium range order which consists of a distribution of ring sizes. These can vary from 2-member rings to 6-member rings [56]. The high pressure experiments described above demonstrated that the change in volume of silica exposed to high pressures was caused by a change in the ring structure of the glass, most likely changing from 4, 5, or 6-member rings to lower member configurations [57].

The long range change is thought to occur only when writing with a pulse density which is high enough to cause fusion in the glass. Poumellec and Kherbouche [35] suggest that this occurs as a multi-step process. In their model a photon is absorbed causing photoconductivity and broad band absorption, then a second photon is absorbed in the conduction band, releasing all of its energy as heat which leads to fusion.

The densification model has been confirmed experimentally by transmission electron microscopy (TEM), interferometric microscopy (IM), and atomic force microscopy (AFM) [58]. The densification model not only accounts for a large portion of the index change in these fibers but also accounts for the observation made by Limberger et al. that there is an increase in the axial strain of the fiber following grating inscription [59]. While densification plays a major role in the photosensitivity of non-hydrogen loaded fibers written with high pulse energy, it has been shown by TEM that densification plays a very small role in hydrogen loaded fibers [60].
2.3. **Mechanisms of Photosensitivity in Hydrogen Loaded Optical Fibers**

As was discussed in Chapter 1, standard telecommunication optical fiber has relatively poor photosensitivity. Therefore, in order to write high quality gratings in such fibers their photosensitivity must be enhanced. The most popular method of doing this is through hydrogen loading.

Hydrogen loading consists of placing the optical fiber in a high pressure hydrogen environment. Molecular hydrogen is then allowed to diffuse into the fiber for several days. The fiber is then removed from this hydrogen environment and exposed to UV irradiation. The use of hydrogen loading in the fabrication of fiber Bragg gratings has improved the change in index of refraction by one or two orders of magnitude [30].

The publication of several recent papers on the mechanisms underlying the enhanced photosensitivity which results from hydrogen loading indicates that this is still an area of intense research [61-63]. As such, there is not yet one universally accepted theory. There are subtle differences in each, but a general agreement appears to have been reached. The major discrepancy appears to be whether Ge–OH, Ge–H, or a GeE' center is formed in the reaction. It has been proposed that Ge–H leads to a GeE' center, leaving only the difference in Ge–OH or GeE' formation. However, this point appears to be minor in the context of this paper and Grubsky's method will be presented. For treatment concerning the formation of Ge–OH the reader is referred to Cordier [60]. This section will discuss the major points concerning these theories.

The overall mechanism believed to be behind the enhanced photosensitivity of hydrogen-loaded fibers is not unlike that of the Color Center model. However, instead of only having the GODCs active in the formation of GeE' centers, the hydrogen allows every germanium atom to contribute to the change in absorption. As was shown in Figure 2.1.1, several defects can occur
when SiO₂ is doped with germanium. The Color Center model is concerned with the GODCs seen in (c) and (d) of the figure as previously discussed. These defects occur in a hydrogen-loaded fiber and will react with the UV light as described by the Color Center model. However, introducing hydrogen to the fiber allows a different reaction to occur. This reaction is described by Grubsky et al. and is shown in Figure 2.3.1. In addition to the reaction at the GODCs, a UV photon can also react with the standard Ge–O bond in a germanium tetrahedral. This excites the bond which is shown in the figure as red. The H₂ then attacks the excited bond creating Si–OH, a GeE' center and atomic hydrogen [61].
The above model is remarkably simple yet it explains several of the observations made regarding the products of the photochemical reaction. Itoh et al. used electron spin resonance techniques to investigate the by-products of the reaction. They found a marked OH loss increase following grating formation. This persisted even after the molecular hydrogen had diffused out of the fiber [64]. Also, the model explains the theoretical prediction by Zhang concerning the formation of Si–OH as a result of hydrogen loading [62].

2.4. Thermally Enhancing the Photosensitivity of Optical Fibers

In a paper published shortly after the discovery of hydrogen loading, Atkins et al. demonstrated that there appeared to be a thermal enhancement in the photosensitivity of optical fiber [31]. In this paper the fiber was hydrogen loaded and then exposed to a CW CO$_2$ laser for 10 s. The core was heated to $> 600^\circ$C. This caused a dramatic increase in the photosensitivity for wavelengths less than 275 nm.

It has long been known that the UV edge of silica can be moved to longer wavelengths by heating the glass [65]. In the first study focused upon the thermal enhancement of photosensitivity, Lemaire et al. [66] found that there was a significant enhancement in the photosensitivity in H$_2$ loaded fibers. In this work the fiber was heated to either 250°C or 400°C by directing hot air onto the fiber during UV exposure.

The thermal enhancement of photosensitivity has been demonstrated by Brambilla et al. using CO$_2$ laser radiation [33]. In this work non-hydrogen loaded fibers were treated with CO$_2$ laser irradiation prior to grating inscription with a KrF excimer laser operating at 248 nm. The fiber was cooled with either air or liquid nitrogen between heating and inscription. Again, the heating treatment caused a significant increase in the photosensitivity of the fibers.
Relatively little work has been done in explaining the mechanisms behind the thermal enhancement of photosensitivity. Brambilla et al. [33] propose that heating the core of the fiber to high temperature causes the formation of GODC from the normal Ge tetrahedron shown in Figure 2.1.1 (b). This reaction would facilitate the Color Center model allowing each germanium site to become active. In this paper the authors note that the enhancement appears to be dependent upon the UV writing laser intensity. For intensities $< 50 \text{ mJ/cm}^2$ per pulse the photorefractivity was the same for heated and unheated samples. For pulse intensities $> 200 \text{ mJ/cm}^2$ the change in index was approximately 2 times higher. The authors attribute this to the existence of two types of GODC defects. One of which is bleached only at high UV intensities. This defect concentration would then have to increase from the CO$_2$ exposure.

2.5. Summary

This chapter has discussed the two mechanisms which are thought to contribute the most to the observed photosensitivity in germanium-doped optical fibers. Each is caused by dramatically different reactions. The Color Center model depends upon the existence of defects which occur as a result of the doping of the core. The densification model concerns a rearrangement of the glass matrix to a more compact state. Both of these models have been confirmed experimentally. It appears that there is a clear separation between the two mechanisms based upon the energy of the writing laser. The mechanisms of photosensitivity and the type of gratings formed in germanium-doped fiber are summarized in Figure 2.4.1. This chart is based upon a similar flow chart presented in reference [35].

Based upon currently held contentions, both hydrogen loading and thermal treatment of fibers appear to enhance the Color Center model. Therefore,
because of the low writing intensities used in the work presented in the fol-
lowing chapters, these techniques will be employed and the grating formation
will be thought to arise from the enhanced Color Center model.

**Figure 2.5.1:** Flow chart for the mechanisms of photosensi-
tivity and grating types written for various writing conditions.
Chapter 3

The Modified Phase Mask Writing Technique

As was discussed in Chapter 1 there are generally three techniques used in writing fiber Bragg gratings. These are the internal writing, transverse holographic, and the phase mask techniques. Of these only the transverse holographic and phase mask are generally used. However, while both techniques have been shown to produce high quality gratings, each has distinct disadvantages. The transverse holographic technique places high requirements on the laser coherence and setup stability, while the phase mask only allows one grating wavelength to be written.

In order to maximize research and application options, it is desirable to have the capability to write various wavelength gratings. However, the writing scheme must be robust and invariant under different writing conditions and laser fluctuations. Therefore, a new technique has been developed which maximizes the advantages of both the transverse holographic and phase mask technique while at the same time minimizes the disadvantages of each. This technique may be thought of as a modified phase mask technique and is actually a hybrid of the two writing schemes.

3.1. Coherence and Stability Requirements of the Transverse Holographic Technique

The experimental set up for the transverse holographic technique was shown in Figure 1.2.1 in Chapter 1. This method was the first side writing technique and is still widely used for writing different wavelength fiber Bragg gratings. The coherence and stability requirements will now be discussed.
In the transverse holographic writing technique, an ultraviolet laser beam is incident upon a 50% beamsplitter. Both beams then propagate and are recombined at a given angle, \( \theta \). The fiber Bragg grating created by the interference of these two beams has a wavelength given by

\[
\lambda_{\text{Bragg}} = \frac{n_{\text{eff}} \lambda_{\text{laser}}}{\sin \left( \frac{\theta}{2} \right)}
\]

As was stated in Chapter 1, in order to create an interference pattern, the difference in optical path length must be much less than the coherence length of the laser. This constraint is the largest coherence requirement put upon the laser using the transverse holographic technique. The experimental setup used at Oregon State University resulted in a difference in optical path length of only 6.88 cm. This is small compared to the coherence length of a solid state laser. However, this may be a factor when using excimer lasers which frequently have coherence lengths as short as 1 cm.

As is evident from Equation 3.1, however, there is a strong dependence upon the wavelength of light used. Therefore, the transverse holographic method places a high requirement upon the longitudinal mode stability of the laser. A drift of \( \pm 1 \) nm in the wavelength of the laser corresponds to a change in \( \lambda_{\text{Bragg}} \) of more than 10 nm when writing a 1300 nm grating using 266 nm laser light.

Another area which can cause difficulty in writing Bragg gratings with the transverse holographic technique is the mechanical stability of the experimental apparatus. Because of the geometry of the set up, both arms of the apparatus have an optical lever arm of greater than 44 cm. This can become important especially when writing with a low pulse fluence laser which requires tight focusing of the beam. Mechanical instabilities can cause the core of the fiber to drift in and out of the focal point.

Equation 3.1 also shows that the Bragg wavelength also has a strong dependence upon the angle of intersection between the beams. For example, when writing a 1300 nm grating with a 266 nm laser a 0.1° change in the angle
can correspond to a 4 nm shift in $\lambda_{Bragg}$. If there is any appreciable vibration in the mirrors the interference pattern can easily be wiped out. The dependence of $\lambda_{Bragg}$ on the laser wavelength and the angle of intersection of the two beams is shown in Figure 3.1.1.

Figure 3.1.1: Surface plot of $\lambda_{Bragg}$ for different $\lambda_{laser}$ and $\theta$ values for the transverse holographic technique.
3.2. Early Attempts at Writing Fiber Bragg Gratings

The last section discussed several of the coherence and stability issues involved with the transverse holographic technique for writing fiber Bragg gratings. In order to maximize Oregon State University’s research capabilities, it was of primary importance to be able to write gratings of various wavelengths. This meant that either a highly stable laser would have to be used or else a new means of writing gratings of variable wavelengths would need to be developed.

The laser that was originally allocated to fiber Bragg grating research was donated to the university by Electro Scientific Industries, Inc. in Beaverton, Oregon. This laser was a lamp-pumped Nd:YAG which was frequency quadrupled to operate at 266 nm. The pulse width was 75 ns. The power was measured to be 300 mW average power at 2 kHz which was determined to be sufficient to write fiber gratings. The laser was designed for use in the micromachining industry and special mounts were fabricated in order to adapt the laser for the current research objectives. As a result, research was begun to develop the techniques necessary for the writing of fiber Bragg gratings in standard telecommunication fiber using the Nd:YAG laser.

Several attempts were made to write gratings using the transverse holographic technique. Despite the resolution of several stability issues including custom fabrication of mirror mounts, a custom fiber mounting assembly and the use of a floating the optical table, the transverse holographic technique failed to produce any gratings. The reason for this is believed to be low longitudinal mode stability in the laser. It is thought that the aluminum chassis which houses all of the laser components transmits vibrations from the cooling system to the optical components. It is likely that this is the major cause for the longitudinal mode instability. The instability of the laser was verified by creating a Michelson interferometer. This resulted in an interference pattern
which drifted excessively and was observed to jump. In order to eliminate the possibility of this behavior being caused by vibrations in the table, the entire assembly was mounted on a floating table. In addition, a second Michelson interferometer was created on the same table with a HeNe laser. There was no movement seen in the fringe pattern of the HeNe laser, verifying the stability of the optical table.

Because of the difficulties experienced with the transverse holographic method, a phase mask was purchased. The phase mask is a Lasiris model with a period of 886.2 nm. Using a phase mask would at least demonstrate that one could write a grating with 266 nm light and the power levels that were available. Using the standard method of placing the phase mask close to the fiber, there was still no evidence of grating formation. It was then determined that the photosensitivity of standard (~ 3% germanium-doped) telecommunication fiber was too poor to support grating formation. Therefore, in order to create fiber gratings, one of the techniques for enhancing the photosensitivity of optical fiber discussed in Chapter 2 had to be employed. Because of both great success and abundance of literature concerning the hydrogen loading technique, it was chosen. Following hydrogen loading, gratings could quickly be written using the phase mask technique. However, the transverse holographic method still produced no gratings.

As was stated previously, having the ability to write gratings at various wavelengths is extremely important in order to maximize potential research applications. Therefore, a new technique had to be developed in order to create a diverse and well rounded research program using existing OSU resources. This new technique is the modified phase mask technique and will be discussed in the following sections.
3.3. The Modified Phase Mask Writing Technique

In 1993 Armitage presented a technique for writing fiber gratings using a phase mask that was set a distance away from the fiber [15]. The ±1 order diffractions were internally reflected off of the sides of a fused silica block and were then allowed to recombine. Where these beams crossed, there would be an interference pattern with a period equal to the period of the phasemask.\footnote{Provided the block faces were perfectly parallel and the block was aligned perpendicular to the phase mask.} This technique had several advantages over the standard use of a phase mask.

First, it allowed the complete blocking of the 0th order diffraction. This is important because, as Xiong et al. recently demonstrated [67], the 0th order beam can interfere with the pattern. This can result in decreased visibility of the fringe patterns or even a change in the period of the interference pattern.

Second, by having the phase mask far from the fiber no debris from the fiber will collect on the mask. Often, if not all of the coating is stripped from the fiber prior to writing, the remaining material may be ablated or burned which can damage the phase mask. Another advantage to having the phase mask far from the fiber is that alignment is much easier when tight focusing on the core of the fiber is required. This is often the case when using a solid state laser which generally has a pulse fluence much lower than an excimer laser.

While the technique used by Armitage has advantages over the typical use of the phase mask, it is still only able to write one wavelength grating. Therefore, it still has the major limitation of the phase mask. Also, the fused silica block is expensive and difficult to fabricate. There will also be a power loss if the ends of the block are not antireflection coated.
Figure 3.3.1: The experimental set up for the modified phase mask writing technique. Top: schematic diagram of the set up. Bottom: Photograph of the experimental apparatus.
The modified phase mask technique, shown in Figure 3.3.1, replaces the fused silica block with two mirrors. These mirrors can then be rotated, causing the angle of intersection to vary. The Bragg wavelength for gratings written with the modified phase mask technique is given by

\[ \lambda_{\text{Bragg}} = \frac{n_{\text{eff}} \lambda_{\text{laser}}}{s} \sqrt{4d^2 + s^2} \]  

where \( d \) is the distance between the point the beam strikes the mirror and the fiber. \( s \) is the distance between the mirrors, \( \lambda_{\text{laser}} \) is the writing wavelength, and \( n_{\text{eff}} \) is the effective index of the fiber.

To obtain a simpler and perhaps more fundamental equation for \( \lambda_{\text{Bragg}} \), the following expression may be substituted into Equation 3.2 for \( d \)

\[ d = \frac{s}{2} \tan \left( \frac{\pi}{2} - \sin^{-1} \left( \frac{\lambda_{\text{laser}}}{\Lambda_{\text{mask}}} \right) - 2\beta \right) \]  

The term \( \sin^{-1} \left( \frac{\lambda_{\text{laser}}}{\Lambda_{\text{mask}}} \right) \) comes from the grating equation and is the angle the ± 1 diffraction make with the normal of the phase mask and \( \beta \) is the angle that the mirrors have been rotated from perpendicular to the phase mask. Rotating the mirrors toward the phase mask is defined to be a positive value of \( \beta \) and rotating the mirrors to the fiber gives a negative value. If both mirrors are rotated by the same angle \( \beta \), Equation 3.2 can be rewritten in the simple form

\[ \lambda_{\text{Bragg}} = \xi n_{\text{eff}} \Lambda_{\text{mask}} \]  

with \( \Lambda_{\text{mask}} \) being the period of the phase mask, \( n_{\text{eff}} \) still the effective index of the fiber. and the term \( \xi \) being defined as

\[ \xi = \frac{1}{\cos (2\beta) + \left( \sqrt{\left( \frac{\Lambda_{\text{mask}}}{\lambda_{\text{laser}}} \right)^2 - 1} \right) \sin (2\beta)} \]  

It is apparent that for \( \beta = 0 \) Equation 3.4 reduces to the familiar phase mask equation obtained from the traditional use of a phase mask placed in close proximity to the fiber. If this condition is met, \( \xi \) is equal to one and
there is no dependence upon the writing wavelength and the period of the grating is equal to the period of the phase mask. However, in order to write variable gratings, the mirrors must be rotated which introduces a wavelength dependence. A plot showing the dependence upon the writing wavelength, $\lambda_{\text{laser}}$ and the angle of rotation, $\beta$, is shown in Figure 3.3.2. In the next section a theoretical comparison between the stability and coherence requirements of the modified phase mask and transverse holographic techniques will be given.

Figure 3.3.2: Surface plot of $\lambda_{\text{Bragg}}$ for different $\lambda_{\text{laser}}$ and $\beta$ values for the modified phase mask technique.
3.4. Comparison Between the Transverse Holographic and Modified Phase Mask Writing Techniques

One of the great advantages to using a phase mask versus the holographic method is that there are lower stability and coherence requirements placed upon the laser. However, in order to determine whether the modified phase mask technique will produce variable wavelength fiber gratings with the equipment available at Oregon State University, a comparison between the stability and coherence requirements of the new technique and those of the transverse holographic technique must be made.

In Section 3.1 the coherence and stability requirements of the transverse holographic writing method were given. A similar analysis may be made of the modified phase mask technique in order to compare the stability and coherence requirements of this new technique to that of the transverse holographic technique. First of all, there is virtually no optical path length difference between the two beams. Therefore, the coherence length requirement of the method is much lower than that of the transverse holographic method. This means that the new method may be used when writing with a low coherence light source such as an excimer laser.

To assess the effect of longitudinal mode instability on the modified phase mask technique, consider writing a grating with a 266 nm laser wavelength, a $\Lambda_{\text{mask}}$ of 886.2 nm, and $\beta$ equal to $-0.1^\circ$. This setup will write a grating at 1300 nm. If again it is imagined that there is a $\pm$ 1 nm drift in the laser wavelength, Equation 3.4 predicts no shift in $\lambda_{\text{Bragg}}$. Therefore, the modified phase mask technique has much greater tolerance to laser fluctuations than does the transverse holographic method.

The dependence of the modified phase mask technique on mirror rotation may be determined in a similar matter as was done for the transverse holographic technique. Using the same values of $\Lambda_{\text{mask}}$, $\lambda_{\text{laser}}$, and $\beta$ as before and using a change in $\beta$ of $0.05^\circ$ for each mirror as was done for the transverse
holographic method. Equation 3.4 predicts a change in $\lambda_{\text{Bragg}}$ of 4 nm. This is the same as the transverse holographic technique.

In summary, the modified phase mask technique theoretically has superior tolerance to fluctuations in the writing laser as well as much lower coherence requirements. The major factor precluding the writing of fiber gratings of variable wavelengths has been the longitudinal mode instabilities of the writing laser. The modified phase mask technique should, in theory, remedy this problem. In order to compare the characteristics of each method for other parameters, the reader is referred to Figures 3.1.1 and 3.3.2.

3.5. Experimental Verification of the Modified Phase Mask Technique

The previous section theoretically predicted that, even with the longitudinal mode instabilities of the Nd:YAG laser, it would be possible to write variable wavelength fiber gratings for research purposes at Oregon State University. The experimental work to verify the predictions of the previous section will now be discussed. In the first part of this work the lamp-pumped Nd:YAG laser previously mentioned was used. This laser has an average output of 300 mW operating at 2 kHz with a pulse width of 75 ns. In the later part of this work a new diode-pumped Nd-YAG laser was received from ESI, Inc. This laser has an average output of 275 mW at 4 kHz and a pulse width of 24 ns. It was manufactured by Lightwave Electronics and was modified by ESI specifically for the fabrication of fiber Bragg gratings. This modification was to add a focusing lens and a quadrupling crystal to the laser. This allowed the generation of the fourth harmonic of the Nd:YAG laser and caused the beam to be elliptical with the major axis along the axis of the fiber.

It had previously been stated that in order to write gratings in standard telecommunication fiber with 266 nm light at the present fluence levels the
photosensitivity of the fiber must be enhanced. Therefore, standard Corning SMF-28 fiber was placed in a 12.93 atm environment at 21°C for approximately 280 hours. The apparatus used for the hydrogen loading is shown in Figure 3.5.1. This consists of a tube furnace with a piece of \( \frac{1}{4} \) in. stainless steel tubing placed inside. The tubing is connected to a hydrogen tank and the optical fiber is placed inside.\(^3\)

![Figure 3.5.1: Photograph of the hydrogen loading apparatus.](image)

After the fiber was hydrogen loaded, it was mounted in a custom fiber holder and exposed to 266 nm laser light. A grating was quickly seen to appear

\(^3\) With the furnace operating at 90°C the loading time has been reduced from 280 hours to less than 40 hours.
at 1262 nm. Therefore, the modified phase mask technique had succeeded in writing a variable wavelength fiber Bragg grating even with a laser with low longitudinal mode stability. Shortly after the first grating was written the diode-pumped laser was delivered. Therefore, the rest of the experimental work in this paper was conducted with this laser.

Once it was confirmed that the modified phase mask technique would allow the writing of fiber Bragg gratings with existing OSU equipment, a study was conducted to determine the range, stability, and tunability of the technique.

For this study Corning SMF-28 fiber was again loaded at 12.93 atm at 21°C. This time the fibers were loaded for 528 hours to ensure saturation. The laser was operating at 275 mW average power and the focal spot on the fiber was 10 mm × 0.1 mm. Because of the operation of the phase mask, only about 70% of the power was left in the ±1 diffraction orders. Due to beam expansion and the limited size of the mirrors only 60% of the original power was transmitted to the fiber. This results in a pulse fluence of 4.125 mJ/cm².

The phase mask used in this work is manufactured by Lasiris, Inc. and has a period of 886.2 nm. There is 4.6% transmission in the 0th order diffraction which is unimportant because the modified phase mask technique allows the 0th order to be completely blocked. This has the advantage of higher fringe visibility.

The first investigation was to compare the quality of a grating written with the modified phase mask technique to that of a grating written with the traditional application of a phase mask. Both gratings were written in the same fiber. The grating written with the modified phase mask technique has a \( \lambda_{Bragg} \) of 1302 nm and is 82.7% reflective. The grating written with the standard phase mask technique has a \( \lambda_{Bragg} \) of 1286 nm and is 75.8% reflective. Both gratings had writing times of 35 minutes giving a total fluence of \( \sim 35 \text{ kJ/cm}^2 \). Both gratings have a full width half maximum reflection of 0.4 nm.
and are shown in Figure 3.5.2. Because the LED used for this plot peaks at 1280 nm, both peaks appear to be the same height even though the grating at 1302 nm is more reflective. There may be two different reasons for the higher reflectivity. First, as predicted by Xiong [67], there may be a higher fringe visibility using the modified phase mask technique. Erdogan showed that the maximum reflectivity of the grating is directly related to the fringe visibility [1]. Another possible explanation of the difference in reflectivity is that, because of the tight focusing requirements of the low fluence laser and the fact that alignment is more difficult with the traditional phase mask method, not all of the core was exposed to the interference pattern.
The next element of the modified phase mask technique investigated was the tunability of the system. It is highly desirable to be able to write gratings at a desired wavelength with accuracy. In order to determine this, several gratings were written in the same fiber. Each was exposed for 15 minutes and the resulting plot is shown in Figure 3.5.3. The reflected signal is plotted with an over-plot of the source LED. It is readily apparent that the method allows the writing of any wavelength within the bandwidth of the LED. It was also determined that the gratings can be written with a great deal of accuracy once the current position of the apparatus is known. Accuracy of greater than 2 nm has been achieved.

**Figure 3.5.3:** Plot of eight gratings written in the same fiber to access the tunability of the modified phase mask technique. Also plotted is the spectrum of the source LED.
Figure 3.5.4: 1550 nm grating written with the modified phase mask technique and a phase mask which would traditionally only write 1286 nm gratings.

The next characteristic to be evaluated of the modified phase mask technique was the range over which gratings could be written. For future research projects, a major emphasis of a writing scheme was to have the flexibility to write gratings over a wide range of wavelengths. Therefore, in determining the characteristics of the new technique, this needed to be addressed. Figure 3.5.4 shows a grating written at 1550 nm with the same setup altered only by decreasing $\beta$ from -0.10° to -1.525°. This demonstrates that the technique is very flexible and can be used over a wide range of wavelengths. The current setup and components can write gratings from less than 800 nm to over 2000 nm.
The last feature of the modified phase mask technique to be tested was the stability of the technique for extended writing times. One of the major difficulties with using 266 nm light is that it is far from the known absorption of the GODCs (see Chapter 2). This can often create prolonged writing times when using low photosensitivity optical fiber. In order to determine the extended stability of the system, optical fiber with a reduced hydrogen content was used as well as a lower pulse fluence. With these changes gratings with reflectivities greater than 98% were written with exposure times of greater than 4 hours. Therefore, this technique has proven to be very stable for extended writing times.

3.6. Conclusion

This chapter has introduced a new writing technique which allows fabrication of variable wavelength fiber Bragg gratings using a single diffractive optical element. This method requires less stability and coherence than the transverse holographic method and also allows writing gratings of various wavelengths using a single, fixed phase mask. The new technique has been found to be much more tolerant to longitudinal mode instabilities in the writing laser. Also, the modified phase mask technique allows for the complete blocking of the 0th order diffraction, which produces higher reflective gratings than with a standard phase mask technique. Also, gratings for virtually any desired wavelength can be written using a single phase mask. The method also has proven to be very stable for extended writing times.

The modified phase mask technique maximizes the strengths of the two most common writing techniques while minimizing their disadvantages. Also, it has proved to be much easier to align given the tight focusing requirements required of the OSU writing laser.
Chapter 4

Time Evolution of Writing Fiber Bragg Gratings

With the success of the modified phase mask technique in writing FBGs, research concerning the writing characteristics of fiber gratings was begun. The goal of this research was to characterize the process of grating inscription. By gaining an understanding of this process, new techniques can be developed which will allow for the optimization of the fabrication of FBGs.

In this chapter the current understanding of grating formation will be discussed. Since there have been no published papers concerning the extended writing evolution for hydrogen-loaded fibers, the discussion will be limited to nonhydrogen-loaded fibers and boron codoped fibers. The introduction to the current theories concerning grating formation are presented in an effort to gain familiarity with the typical writing processes reported in the literature. As will be evident shortly, the grating formation processes observed here are much too complicated to allow for a meaningful comparison to be made with the three-energy level system based solely on the results of writing experiments. Chapter 6 will suggest future work which may help shed light on the fascinating and complex results seen in the studies presented here.

Following this discussion, the results of studies conducted at Oregon State University will be presented. These studies include the evolution of gratings for extended writing periods (up to 11 hours), the effects of different levels of hydrogen loading, exposure of the grating to various levels of CO$_2$ irradiation and the effects of writing gratings with different pulse energies. These experiments are conducted using hydrogen-loaded and unloaded fibers as well as boron codoped fiber. These experiments are designed to categorize the effects that the above parameters have on grating formation.
4.1. Current Theories of the Evolution of FBG Formation

Chapter 1 introduced the idea of type I and type II gratings. The first grating seen during the writing process (type I) is thought to be created by the Color Center model as discussed in Chapter 2. This grating is characterized by an increase in the index of refraction. By further irradiating the fiber a type II grating is formed. This phenomenon has been documented by many researchers [35,58,68]. This grating is believed to arise from a densification of the glass matrix (see Chapter 2) and a concomitent decrease in the index of refraction. Further irradiation has been shown to cause the grating to decay back to zero. This has been attributed to a loss in index modulation [69]. Most studies indicate that the type II gratings have a higher reflectivity and are more thermally stable than type I gratings [68].

The evolution of the writing process has been described by Dong and Liu as a three-energy-level system [68,69]. This process is shown diagramatically in Figure 4.1.1. The idea behind the three-energy-level system is that a UV photon is absorbed and causes an excitation. This causes a higher energy level to be populated (Level 2 in the diagram). This level then undergoes a fast decay and populates a slightly lower energy level (Level 2A). This is the energy level which gives rise to type I gratings. As the fiber continues to be irradiated, level 2A continues to be populated. As Level 2A begins to fill, further irradiation causes the population to be excited to an even higher level (3). Again, a fast decay to a slightly lower energy level (3A) occurs. It is the 3A energy level that is thought to give rise to type II gratings. This type of theory accounts for the higher thermal stability of type II gratings [68]. In addition, this would account for the erasure of one type of grating in favor of another. As discussed by Dong and Liu, since type I gratings are a net positive index change and type II gratings are a net negative index change.
there will come a point when the magnitudes of the two types are equal. At this point the net index change will be zero and there will be no grating. Therefore, the three-energy-level system explains why there is no reflection even though the system is still in an excited state. Using the three-energy-level system model, Dong et al. found very good agreement between theory and experimental data [69]. It is important to note that Dong et al. observed a decrease of type II gratings with continued exposure. This is believed to arise from a less-than-100% fringe visibility in the interference pattern. After
the type II grating has saturated, continued irradiation will cause an increase in the index of the “background” of the grating.

A similar model was proposed by Erdogen et al. in an article which explains the decay of fiber Bragg gratings (see Chapter 5) [70]. In this model, electrons are excited into the conduction band by UV irradiation. From this conduction band the carriers are thought to be trapped in a continuous distribution of energy traps rather than the single energy level given by Dong et al.. While this model is important in the thermal decay of FBGs, as will be discussed in Chapter 5, it does not account for the dynamic effects seen in the writing of fiber gratings. Therefore, emphasis will be placed upon the three-energy-level system when discussing the results of the OSU research.

4.2. Experimental FBG Writing Studies at Oregon State University

In order to characterize the FBGs written at OSU and to optimize the writing process, the time evolution of grating formation has been investigated. In these experiments an ESI diode-pumped Nd:YAG laser operating at 266 nm and the writing technique described in Chapter 3 were used. The laser used is similar to the one discussed in chapter 3 in that it is a Lightwave Electronics diode pumped Nd:YAG laser which has been modified by ESI for the fabrication of fiber gratings. This laser, however, has an output of up to 8 W at 532 and is capable of 521 mW at 266 and 4 kHz. Also, a cylindrical lens has been added to the output of the quadrupling crystal which collimates the elliptical beam. This corrects the beam expansion problem which caused some of the UV beam to spill over the mirrors and create excess power loss. Therefore, approximately 70% of the original beam is incident upon the fiber with an estimated spot size of approximately 6 mm × 0.05 mm.
Standard Corning SMF-28 telecommunication fiber was used with varying degrees of hydrogen loading and thermal processing as was commercially available boron codoped fiber. Data was acquired using an HP 79015 Optical Spectrum Analyzer controlled by a personal computer with a National Instruments General Purpose Interface Bus (GPIB). Data concerning the grating’s amplitude and wavelength was collected every 15 seconds throughout the writing process.

![Graph](chart.png)

**Figure 4.2.1:** Evolution of the writing process of a grating in boron codoped fiber showing the typical characteristics of grating formation.

The studies presented in this chapter are primarily concerned with investigating the roles of the following in the FBG writing process: 1) pulse energy
of the writing beam, 2) the hydrogen content of the fiber, and 3) the simultaneous heating of the fiber while the grating is being written. As was discussed earlier, the typical evolution of a FBG writing process is that a type I grating appears quickly after exposure is begun. Continued irradiation causes this grating to erase. Then a second grating appears which is typically called a type II grating. An example of this type of behavior is shown in Figure 4.2.1. This grating is written in a boron codoped fiber with a 266 nm laser operating at 3 kHz and a pulse energy of 123 \( \mu \text{J} \) per pulse. There is some unexplained transient behavior prior to the formation of the type I grating. However, the evolution of the grating follows the typical pattern for germanium doped silica fibers quite well.

### 4.2.1. The Effect of Hydrogen on Grating Inscription

As a first step in determining the effect of hydrogen on the writing evolution of a fiber grating, a grating was written in a fiber without any processing (e.g. hydrogen or thermal). The evolution of this grating is shown in Figure 4.2.2. As may be expected due to the low germanium concentration and the 266 nm writing light, the grating did not have a very high reflectivity. The UV writing laser had a repetition rate of 4 kHz and a pulse energy of 68 \( \mu \text{J} \) per pulse. A small grating appeared shortly after exposure began. This quickly decayed and there was no grating evident for some time. Continued exposure caused a grating to slowly appear in about 95 minutes. This grating may be a type I grating. As the exposure continued the grating began to decay until there was no reflected signal. Then, after about 160 minutes of total exposure, a second grating appeared. This is believed to be a type II grating.
One interesting observation is that the photoluminescence of the fiber changed dramatically during the writing of the grating. The photoluminescence began as a bright blue, which was attributed to the Ge$^{+2}$ defect in Chapter 2, and switched to a redish-violet near the end of the writing. This is a phenomenon which is not seen in hydrogen loaded or boron doped fiber and has not been previously reported. It is not clear whether this spectral change is due to thermal effects or a new process. Further research is planned to explore this effect.

Having demonstrated that the fiber used in this experiment does follow the typical pattern for germanium doped glass, the effects of hydrogen on the
writing process must be determined. The first step in this study was to record the grating evolution in a fully hydrogen-loaded fiber. This fiber was loaded in 13 atm of hydrogen for 4 days at 100°C. The evolution of the grating is shown in Figure 4.2.3. As may be expected, the grating is much stronger than the grating produced in a nonhydrogen-loaded fiber. However, what is not expected is the writing of a second grating after the first peak disappears. The nature of this peak will be discussed in Section 4.3.1.

In order to gain an understanding of the manner in which the dynamics of writing a grating depend upon hydrogen, an experiment was conducted in which the evolution of gratings written in fibers with different levels of hydrogen was recorded. In this experiment several pieces of fiber were placed
Figure 4.2.4: Writing evolution of fibers with various concentrations of hydrogen. The numbers if the figure indicate the number of hours left in the hydrogen loader.

in the hydrogen loading apparatus. They were loaded at 13 atm and 100°C. At different time intervals a fiber was removed and a grating was written. Each grating was written with a repetition rate of 4 kHz, a pulse energy of 112 μJ per pulse and fluence of approximately 37 mJ/cm² per pulse. The results of this experiment are shown in Figure 4.2.4.

The initial gratings seen in the fiber loaded for 64.67 hours are somewhat larger than what would be expected if the mechanism for hydrogen loading enhancement were to simply increase with increasing hydrogen content, thus indicating a more complicated process. Also, there is evidently a change in the writing mechanism when the fiber is loaded for greater than ≈ 80 hours.
Figure 4.2.5: Typical evolution of a fiber Bragg grating in a moderately hydrogen-loaded fiber.

It is evident from this graph that the moderate level of hydrogen (loaded for less than 88 hours) produces transient oscillations in the grating's strength. Clearly, there is some threshold hydrogen concentration below which the transient oscillations occur and above which an enhancement of the typical grating formation is predominant. The figure also shows a large bump on the plot for the fiber loaded for 140 hours. The nature of this bump is not known, although it is probably an effect of the increased hydrogen concentration in the fiber. A graph demonstrating the oscillations which are observed in a fiber with a moderate hydrogen concentration is shown in Figure 4.2.5.

Inspection of the evolution of the reflected wavelength of the grating during the writing process reveals that the wavelength shifts to longer wavelengths as the fiber is exposed to UV light. This is thought to arise from heating of the
fiber. As was discussed by Patrick et al. [71] and Poumellec [35], as a grating is heated, the Bragg wavelength shifts to longer wavelengths. This effect is due to both thermal expansion and a thermo-optic effect and is described by

$$\frac{\Delta \lambda_{\text{Bragg}}}{\lambda_{\text{Bragg}}} = (\alpha + \xi) \Delta T$$

(4.1)

where $\alpha$ is the thermal expansion coefficient of the glass and $\xi$ is the thermo-optic coefficient. The values of these coefficients are given as $0.55 \times 10^{-5} \degree C^{-1}$ and $6.68 \times 10^{-6} \degree C^{-1}$ respectively. In order to determine the exact magnitude of this effect in the fiber used, several fibers were heated to various temperatures and allowed to come to thermal equilibrium. A plot of the wavelength shift versus temperature was then made. From the slope of this plot it was determined that there is a wavelength shift of $0.0137 \, \text{nm/°C}$. This is in close agreement with the value of $0.014$ found by Patrick et al. [71] and the value of $0.01 \, \text{nm/°C}$ given by Agrawal [3].

Examination of the evolution of reflected wavelengths of the gratings written during this experiment reveals that the grating wavelength is strongly affected by the hydrogen concentration of the fiber. The evolution of the wavelength and the reflectivity of the gratings written for this experiment are shown in Figure 4.2.6. Fibers which were hydrogen loaded for 1, 3, 5, and 6 days are shown to give an example of the effects of different levels of hydrogen on the wavelength shift. There is not much shift in the wavelength for low concentrations of hydrogen (less than 2 days of loading). However, when the fiber is loaded for 3 days, the reflected wavelength begins to shift to longer wavelengths during the writing process. After 5 days of hydrogen loading the fiber heats gradually as the grating grows. With more hydrogen, the fiber heats very rapidly and the onset of the large grating formation is greatly accelerated.
This effect may also be significant in that, as mentioned earlier, as a fiber is heated, its UV absorption band shifts to longer wavelengths [65]. This is an important effect in writing with 266 nm because the absorption band is known to occur at shorter wavelengths. As the grating is written and the fiber is heated, the absorption band is shifted nearer to the 266 nm writing wavelength. Careful comparison between the plots in Figure 4.2.7 reveals that, for fibers with moderate hydrogen concentrations written with high pulse energies, the sharp rise in Bragg wavelength coincides with the sharp rise in reflectivity. This effect is more apparent when the grating is also heated with a CO₂ laser during the writing process. In fact, the effect is even more pronounced than shown in these figures because the source LED peaks at 1282 nm and as the fiber is heated the grating moves farther from the peak power. A common
Figure 4.2.7: The grating evolution for two different gratings, one with CO$_2$ laser heating and one without. The right plot shows the grating reflected wavelength evolution for each fiber.

The feature between these plots and the plot of the wavelength shift for the fiber which was hydrogen loaded for 140 hours (shown in Figure 4.2.6) is that when the wavelength has shifted by about 1.1 nm there is a sharp rise in both the wavelength shift and the grating reflectivity. From this it may be inferred that when the fiber temperature increases by approximately 73°C there is an increase in the absorption in the glass for 266 nm light.

To investigate the extended writing behavior of moderately hydrogen-loaded fiber, a grating was written in a mildly loaded fiber. This grating was allowed to write for over 8 hours and its evolution is shown in Figure
Figure 4.2.8: Extended writing time of a partially hydrogen loaded fiber.

4.2.8. This plot is remarkable in that there are several small peaks seen which erase and give rise to two large peaks. It is not entirely clear which type of grating each of the large peaks is. Based upon these observations, it is possible that the ripples seen in the beginning of the grating formation may either be due to thermal effects or the low concentration of hydrogen (or both). It is thought the first large peak is a type I grating and that the second large grating is a type II grating. If this is the case, then these observations are in direct contradiction with the findings of Poumellec [35] who found that hydrogen only enhanced the formation of type I gratings. It appears that low pressure hydrogen loading may not only enhance type I grating formation, but also the formation of type II gratings. As the second large grating saturated, the full width half maximum (FWHM) of the grating broadened from
1.2 nm to 3.2 nm. Hill and Metlz describe a broadening of the grating upon saturation of a type II grating, further suggesting that this may be a type II grating [2]. When the irradiation was stopped and the fiber allowed to cool for a few seconds, the long wavelength edge of the grating shifted toward shorter wavelengths, leaving the final grating with a FWHM of 2.2 nm.

4.2.2. The Effect of Pulse Energy on Grating Formation

Previous work has suggested that the mechanisms of grating formation are the same whether pulsed or continuous wave UV irradiation is used [4,35]. However, Niay found that pulsed writing sources write much faster with a much lower total fluence [4]. Therefore, it is reasonable to assume that the pulse energy will have an impact on the evolution of grating formation. In order to determine the effect that the pulse energy has on grating formation, a study was conducted where the pulse energy was varied over a series of gratings. The study was conducted in hydrogen loaded and unloaded fibers as well as boron codoped fibers. The pulse energies ranged from 50 to 137 µJ per pulse.

The first fibers studied had no photosensitizing enhancement (thermal or hydrogen). Gratings were written with pulse energies from approximately 69 to 123 µJ per pulse and a rep rate of 4 kHz. The results are shown in Figure 4.2.9. As is evident from the figure, there is a strong dependence on the pulse energy for unloaded fibers. Increasing the pulse energy appears to either remove the formation of the first peak, possibly a type I grating, or cause the second grating to grow much more rapidly and more strongly.

When writing at low pulse energies there is only a slight grating seen at the beginning of the writing process. The small grating that does appear is quickly erased. Another grating appears after about 95 minutes of exposure
and then erases, giving rise to a final grating. This is not the case with the higher pulse energy gratings. There is a grating seen quickly and this grating does not erase at all during the writing times investigated (> 9 hours). These observations indicate that a different process is occurring between low and high pulse energies. Also, there must be some threshold pulse energy below which the typical type I grating evolution is seen and above which a different process occurs.

**Figure 4.2.9:** Writing evolution of gratings written in unloaded fiber with pulse energies ranging from 69 to 123 μJ per pulse.
The next fibers investigated were hydrogen loaded fibers. These fibers were hydrogen loaded in 13 atm of hydrogen at 100°C for over 8 days. The pulse energies ranged from 75 to 135 μJ per pulse at a repetition rate of 3.96 kHz. The results are shown in Figure 4.2.10. A long fiber was used and each grating was written in the end of the fiber. After the grating evolution was recorded the end was broken off and the next grating was written. By using this technique there is no uncertainty in the quality of the splice between the fiber being written and the coupler. There is, however, a slight change in hydrogen content due to outgassing while previous gratings are written. These changes are thought to be small over the time of the experiment. The first grating was written at 135 μJ per pulse. There is a small grating is
seen immediately which erases within 10 minutes. This is followed by the formation of a grating which grows rapidly for the rest of the writing process. The grating’s wavelength shifts by more than 2 nm during the writing process, indicating the fiber is being heated. This is also seen from the grating’s FWHM growing from 1.1 to 3.0 nm during the writing process. For the 120 μJ grating, a larger initial grating is seen than with the 135 μJ one. This partially erases and then begins to grow again rapidly. Again, there is a large wavelength shift and a broadening of the signal. When the writing laser is turned down to 100 μJ per pulse, a small grating is again written and erased followed by the increase of another grating. However, in this grating the wavelength shift is not nearly as dramatic and the pulse only widens from 1.1 to 1.9 nm. This indicates that the fiber is not being heated as much. In the last fiber written the pulse energy was 75 μJ and the evolution was close to that of the 100 μJ grating. In this grating the wavelength shift was even less and there was no measurable increase in the FWHM. It is likely that both the wavelength and the signal broadening are results of the increased temperature of the fiber.

Next, the pulse energy dependence of boron codoped fiber was investigated. These fibers were exposed to UV laser light with pulse energies ranging from 50 to 137 μJ per pulse with a rep rate of 3 kHz. The technique to eliminate splice variation, as was used in the hydrogen loaded fiber experiment, was also employed. The results of this experiment are shown in Figure 4.2.11. It is clear that the pulse energy has a very different effect on boron codoped fiber than it does for hydrogen-loaded or unloaded standard telecommunication fiber. The strongest grating written was at 100 μJ and was seen to shift in wavelength by about 1 nm. The 50 μJ grating was seen to have the lowest reflectivity and the lowest wavelength shift, as expected. The 75 μJ grating was the second strongest and only shifted in wavelength by 0.5 nm. With the higher pulse energies there are some unexpected results. There is
a very dynamic behavior for the 128 \( \mu J \) grating (note the comparison to the 123 \( \mu J \) grating in Figure 4.2.1). This is accompanied by a wavelength shift of about 1.4 nm. The 137 \( \mu J \) grating has a slightly more dynamic evolution than the 100 \( \mu J \) grating and also has a slightly larger wavelength shift. The 132 \( \mu J \) grating has qualitatively the same evolution and roughly the same wavelength shift. These observations indicate that there may be a strong thermal component to the dynamic behavior of boron codoped fiber.
To further investigate the role of heating in the formation of gratings in boron codoped fiber another experiment was done. This time the pulse energy was held at 95 μJ per pulse but the pulse repetition rate was varied from 3 kHz to 5 kHz by changing the current to the pumping diodes. Using a higher repetition rate should cause greater heating of the fiber. The results of this experiment are shown in 4.2.12. It is clear from the figure that increasing the repetition rate does increase the wavelength shift. Again, the grating with the largest wavelength shift exhibits the most dynamic behavior. The grating written at 4 kHz is the most reflective and has the middle amount

Figure 4.2.12: Writing evolution of gratings written in boron-codoped fiber with pulse energies of 95 μJ per pulse and pulse repetition rates ranging from 3 kHz to 5 kHz.
of wavelength shift. This was also the case for the 100 μJ grating in Figure 4.2.11. Both had approximately 1 nm of wavelength shift. This corresponds to a fiber heating of about 73°C. Therefore, it is apparent that, not only is boron codoped fiber very sensitive to thermal variations during the writing process, but also there seems to be an optimization when the total fiber heating is about 73°C. It is interesting that this is also the temperature which marked the onset of large wavelength and reflectivity change in hydrogen loaded fibers. This may be a further indication that the absorption band is shifting toward longer wavelengths.

4.2.3. The Effect of CO₂ Exposure During Grating Writing.

The final parameter investigated in the evolution of the writing process is the effect of simultaneous CO₂ exposure during the writing process. As was mentioned earlier, the exposure of an optical fiber to a CO₂ laser prior to grating inscription has been found to dramatically enhance the photosensitivity of the fiber. This is thought to arise from the formation of additional GOBCs following the heating of the fiber. As was discussed earlier in this chapter, heating of the fiber is thought to shift the UV absorption to longer wavelengths, thereby increasing the writing efficiency at 266 nm. An additional outcome of simultaneously heating the fiber during UV exposure is that, as is discussed in Chapter 5, it may be possible to increase the thermal stability of the gratings by allowing only deep energy levels to be filled.

The CO₂ laser used is manufactured by Synrad and is capable of 10 W continuous wave operation. In the following studies, a fiber was exposed to CO₂ laser irradiation only during the first 5 minutes of the writing process. The average power density present at the fibers was about 2.5 W/cm². The CO₂ exposure time was limited due to the fact that prolonged continuous operation caused the power of the CO₂ laser to drop. This is thought to be a
consequence of over-heating. Also, the laser is currently powered by batteries and there may be a drop in power as the laser operates. To remedy this problem improvements in the cooling system as well as the acquisition of a power supply and a rebuild of the laser are planned.

![Graph showing writing evolution of gratings written in standard fiber (no photosensitivity enhancement) with and without simultaneous CO₂ laser beam exposure.](image)

**Figure 4.2.13:** Writing evolution of gratings written in standard fiber (no photosensitivity enhancement) with and without simultaneous CO₂ laser beam exposure.

The first fibers tested with simultaneous CO₂ heating were unloaded fibers. The results of these experiments are shown in Figure 4.2.13. Both fibers were written with 266 nm light with a pulse energy of 123 μJ per pulse. The results are unexpected and not entirely clear. As was seen in the Section 4.2.2, increasing the pulse energy greatly increases both the speed and the reflectivity of the grating. Also, higher pulse energies appear to alter the
writing mechanism. However, it is evident that exposing the fiber to CO\textsubscript{2} laser light during the first 5 minutes of the grating writing process alters the grating formation. As is seen in the plot, there appears to be the formation of a type I grating which is then erased. This effect is not seen in the unexposed fiber with the same pulse energy. With the unexposed fiber a small grating is seen immediately and grows continuously. However, with the fiber exposed to CO\textsubscript{2} there is only a very slight grating evident which quickly disappears. There is no grating seen for approximately 40 minutes. This grating then erases and a second grating appears. These observations indicate that simultaneous CO\textsubscript{2} exposure in the beginning of the writing process enhances the standard mechanisms for grating formation. However, gratings written in the fiber without CO\textsubscript{2} exposure using the same high UV writing intensity grow much quicker and the reflectivity is much stronger.

The next fibers tested were hydrogen loaded fibers. These fibers were loaded in 13 atm of hydrogen at 100°C for over a week. A fiber was exposed to UV irradiation with a pulse energy of 123 μJ at 4 kHz. Another fiber was then exposed to CO\textsubscript{2} irradiation with a power density of 2.5 W/cm\textsuperscript{2} for the first five minutes of writing before having a grating written with the same UV pulse energy. The results of this experiment are shown in Figure 4.2.14. From the graph it is evident that CO\textsubscript{2} exposure greatly accelerates the writing process. In addition, both the CO\textsubscript{2} exposed and the unexposed fiber exhibit similar writing characteristics. It is believed that the CO\textsubscript{2} exposure speeds the heating of the fiber which increases the writing efficiency. This is obvious when the wavelength shifts of both the exposed and unexposed fibers are compared. This plot also shows, as was seen in Figure 4.2.7, that when the wavelength shift gets to about 2.2 to 2.5 nm, both the grating wavelength and reflectance increase dramatically. This indicates that some process occurs at a fiber temperature of about 170°C that greatly increases the glass’ absorption.
The last fiber type studied with simultaneous CO₂ exposure was boron codoped fiber. There has not been a published report of the enhancement of photosensitivity in boron codoped fiber due to thermal treatment. However, it is generally thought that the mechanisms of photosensitivity in boron codoped fiber are similar to those of germanium fiber. Therefore, it is reasonable to expect that the effects of CO₂ treatment would be similar to those seen in the unloaded fiber. However, as is seen in Figure 4.2.15, this is not the case. By exposing the boron fiber to CO₂ laser light for the first 5 minutes of grating inscription the evolution is noticeably altered. The typical type I grating is replaced by the oscillating behavior similar to that seen in some of the low concentration hydrogen loaded fibers. Following these small oscillations, the
grating reflectivity begins to grow quickly. When the grating reaches about 58% of its maximum it begins to erase. This continues to nearly 50% of the maximum. The grating then begins to grow again until it saturates (not shown). Therefore, it is evident that the mechanism controlling the formation of Bragg gratings in boron doped fiber is not affected by thermal enhancement in the same manner as in standard germanium fiber. This is in agreement with the observations made in the pulse energy studies. The reasons for this variation are not clear, but it is likely that the mechanisms of grating formation in boron fiber are different from those in germanium fiber.

**Figure 4.2.15:** Writing evolution of gratings written in boron codoped fiber with and without simultaneous CO$_2$ laser beam exposure.
4.3. Discussion of Experimental Observations

In the preceding section the results of a series of long writing experiments were given. As is evident from these studies, there are many complex processes occurring during the writing of a fiber grating. It is also apparent that altering any of the parameters investigated alters the writing process. These experiments were intended only as a preliminary examination of the different writing techniques, enhancement processes and fiber types available at Oregon State University. This is particularly necessary since there is a lack of published data regarding the use of 266 nm laser light to write gratings. These studies were far from exhaustive and have raised many questions regarding the FBG process. Emphasis has been placed upon gaining a qualitative understanding of the interplay between these parameters. More research is needed to gain a quantitative measure and interdependencies of each of the writing and processing techniques. Chapter 6 will present suggestions for future work which may help to explain many of the observations given here which have not been reported previously.

4.3.1. Discussion of Hydrogen Loading Experiments

The investigation of the role of hydrogen loading in the enhancement of fiber photosensitivity has demonstrated that the formation of type I gratings is dramatically enhanced, as has been reported in the literature. However, these investigations have also turned up several previously unseen effects. Rather than simply enhancing the typical formation of a grating which has previously been believed, the incorporation of hydrogen in the glass matrix appears to make a much more complicated process occur. For lower hydrogen concentrations the process is marked by small oscillations in the grating strength prior to the formation of two large gratings. One possible explanation for this effect
not being reported previously is that the pressures used for hydrogen loading here are only about 13 atm where typically reported pressures are around 280 atm. Increasing the pressure will increase the hydrogen concentration in the fiber. It is likely that increasing the loading pressure causes the concentration of hydrogen in the fiber to increase so rapidly that there has never been a grating written with low enough hydrogen concentration to see the thermal effects reported here.

Based upon these observations and the extended writing of hydrogen loaded fibers, it is thought that the enhancement in photosensitivity due to low pressure molecular hydrogen loading is two fold. First, there is an enhancement due to the enhanced GeE center mechanism discussed in Chapter 2. This is thought to cause the first peak seen in strongly loaded fibers. It is likely that as the loading pressure, and thus the concentration of hydrogen, increases this peak will grow and combine with the onset of the large grating seen after the partial erasure of the first grating. This would be an extension of the trend seen in Figure 4.2.4 and could be an explanation for the additional hump in the evolution of grating reflectivity for the fiber which was hydrogen loaded for 140 hours. If this behavior is observed by increasing the hydrogen loading pressure, then it is probable that the large increase after the first peak's erasure would be the formation of a type I grating. This would be consistent with the observation of two large gratings being formed in Figure 4.2.8.

It is also possible that low hydrogen concentration acts to increase the temperature of the fiber under UV exposure. Increasing the fiber temperature results in the observed wavelength shift. This may also serve to move the absorption region closer to the writing wavelength of 266 nm. This would result in more absorption and a larger index change as has been observed. It is possible that as the fiber continues to be irradiated with a sufficient pulse energy and repetition rate, the temperature could increase to drive that absorption curve past 266 nm. This would cause a decrease in absorption and
possibly explain the drop in wavelength seen in Figure 4.2.7. As the temperature drops the absorption curve begins to shift back to shorter wavelengths. Then the absorption increases again and so does the temperature. This may lead to the system reaching an equilibrium, as is indicated in the plots concerning hydrogen loaded fiber. Based upon the equilibrium wavelength shift seen and the temperature dependence given earlier, this equilibrium would appear to occur at about 263°C. A possible reason that these effects have not been observed previously is that when the fiber has a large concentration of hydrogen, the enhancement of type I grating formation is large enough that a type I grating of sufficient reflectivity is achieved quickly so the exposure is stopped or perhaps that the standard model of hydrogen enhancement (with larger hydrogen concentrations) does not cause the same heating effects seen here.

It is interesting to note the qualitative similarity between the evolution of gratings written in fibers with low hydrogen concentrations and the boron fiber exposed to the CO₂ laser during the beginning of the writing process. When both are written with high pulse energy UV laser light neither demonstrates the distinct type I grating formation. Instead both show the oscillations noted earlier. Following the oscillations there is a much stronger grating formed. This grating then erases slightly and then grows again until it saturates. In both cases it appears that the mechanism for the formation of type I gratings has been altered and the formation of either a type II grating or a previously unseen grating type has been enhanced. The grating in the boron codoped fiber is, however, much more reflective than the grating in the hydrogen loaded fiber. It is not clear what causes these changes.
4.3.2. Discussion of the Pulse Energy Experiments

As may be expected, the pulse energy of the writing light has profound effects upon the evolution of a grating's formation. In untreated fibers a much stronger and faster process occurs with higher pulse energies. With lower energy pulses a relatively strong grating is not seen until after about 95 minutes of exposure. By increasing the pulse energy a grating is seen immediately and grows much stronger without any erasure, even after 9 hours of exposure. It is possible that with the current focal spot size there is a threshold between 75 and 90 μJ pulse energies. This may be the threshold between a type I and type II grating formation. As was shown in Figure 2.5.1 in Chapter 2, high writing intensities bring about the formation of type II gratings directly. The observation that the gratings written with higher pulse energies have higher reflectances and that there is no erasure seen during the evolution, seems to support this notion.

In hydrogen loaded fiber, increasing the pulse energy causes an increase in wavelength shift. This is believed to be thermal in nature. As the wavelength shift increases so does the grating strength. These observations lend support to the idea that heating the fiber shifts its absorption band to longer wavelengths. In this case it would mean shifting the absorption band closer to the writing wavelength and, thus, increasing the writing efficiency.

Increasing the pulse energy for boron codoped fibers causes dramatic changes in the evolution of the grating. There appears to be a middle range of pulse energies where the grating fabrication is optimized with a wavelength shift of about 1 nm. A wavelength shift above this level causes the onset of dynamic properties which resemble the typical grating formation reported in the literature. Whether or not these evolutions are, in fact, type I and type II gratings is the subject of future work. For pulse energies which cause a wavelength shift below this range there is a rather slow and steady increase
in the reflected signal. The slope of this increase appears to increase with increasing pulse energy.

4.3.3. Discussion of the Effect of CO₂ Exposure During Grating Formation

The experiments presented here indicate that the simultaneous exposure of the fiber to UV and CO₂ laser light causes radically different responses in each fiber type. While it appears to accelerate and amplify the writing process in hydrogen loaded fiber, the processes in the other two types are completely changed. The reasons for this require further investigation.

In untreated fiber, the addition of CO₂ exposure seems to bring about the formation of a type I and type II grating. Using the same pulse energy without the CO₂ laser may cause the formation of a type II grating directly. It is not clear why the addition of CO₂ would cause this change in the writing scheme. It may be that the addition of CO₂ causes the creation of many more GODCs, as was previously thought, and the mechanism of formation of a type I grating is more energetically favorable, as predicted by the three-energy-level model. In this case the mechanism would switch from the type II formation to the type I/type II formation.

The fact that CO₂ exposure accelerates the writing process in hydrogen loaded fiber indicates that there is a strong thermal component to the reaction. Heating the fiber enhances the grating evolution, indicating that the process observed with low pressure (< 280 atm) hydrogen loading has a large thermal component. The wavelength shift is seen to be much greater in a CO₂ exposed fiber than an unexposed fiber when both are strongly hydrogen loaded. As is seen in Figure 4.2.7, the wavelength shift is comparable with and without exposure in weakly loaded fibers. However, the reaction takes place much faster. This seems to confirm that the CO₂ enhances the heating of the fiber.
On the other hand, if boron codoped fiber has the same type of photosensitivity as germanium fiber, and if the UV absorption band does shift to longer wavelengths with increased temperature as is believed, the addition of CO₂ laser exposure should cause an enhancement of type I grating formation. As was seen earlier, this is not the case. By adding CO₂ exposure during the beginning of the writing process, the typical type I grating is replaced by the oscillations seen in low concentration hydrogen loading. This indicates that somehow increasing the temperature of boron doped fiber alters the mechanism which causes the type I grating formation. However, it is seen to enhance the onset of a second grating. It is not yet clear if this second grating is type I or type II. The idea that increased temperature dramatically alters the grating evolution in boron codoped fiber is also supported by the pulse energy experiments.

4.4. Summary

This chapter has presented the results of several experiments conducted at Oregon State University to determine the characteristics of the formation of fiber Bragg gratings written with 266 nm laser light. These experiments have investigated the effects of changing the pulse energy, hydrogen content and temperature of both standard germanium fiber and boron codoped fiber.

The work presented here is merely a collection of experimental observations. Possible explanations have been given when appropriate. However, there is a great deal of work to be done to gain an understanding of the processes described and to achieve a true optimization of the writing process. Suggested further work to help determine the nature and effects of these observations will be given in addition to the conclusions presented in Chapter 6.
Chapter 5
The Thermal Stability of Fiber Bragg Gratings

Many research applications of fiber Bragg gratings demand that the gratings be stable for extended periods of time at elevated temperatures. However, it has been demonstrated that heating the fiber can cause a partial or complete erasure of the grating. Therefore, in order to develop techniques for increasing the thermal stability of fiber gratings, it is important to gain an understanding of the mechanisms underlying this erasure.

In this chapter the current theories regarding the thermal erasure of fiber gratings are presented. This review is then followed by the results of preliminary experiments performed at Oregon State University. These experiments are a first step in developing high temperature fiber Bragg gratings for many unique sensing and research applications. These experiments are designed to gain information concerning the short term thermal stability of the fiber gratings written at OSU. In order to completely characterize the thermal characteristics of these gratings, long term studies are necessary.

5.1. Current Theories Concerning Fiber Bragg Grating Erasure

The thermal erasure of FBGs is closely related to the writing process. Previous work had demonstrated that, when heated to a high temperature, FBGs erase. Following the erasure of either type of grating a new grating could be formed with the same photosensitivity as the original grating [21]. This suggests a reversal of the mechanism by which the grating is initially formed. This observation has only been reported for nonhydrogen-loaded fibers. It is likely that following the erasure of a grating in hydrogen-loaded fiber and
subsequent reloading with hydrogen the original photosensitivity will return.

As was the case with the evolution of writing gratings presented in Chapter
4, the main two theories concerning the thermal erasure of fiber gratings
are the three-level-system [68] and the continuous energy trap distribution
model [70]. Both of these theories are similar and the continuous energy
trap theory may be thought of as a more general form of the three-energy-
level model. The mathematical features of both features are identical so the
notation of Dong will be used here. In the thermal decay of FBGs, the
population of carriers (electrons) in trapped sites, \( g(E, t) \), can be described as

\[
g(E, t) = g_0(E) \exp[-v(E)t]
\]

where \( E \) is the energy, \( t \) is time, \( g_0(E) \) is the initial population, and \( v(E) \) is
given by

\[
v(E) = v_0 \exp(-E/k_BT)
\]

and may be thought of as the release rate from a given energy \( E \). In Eqn (5.2)
\( k_B \) is the Boltzmann constant and \( T \) is the absolute temperature. The total
population in all of the traps may then be written as

\[
N(t) = \int_0^\infty g_0(E) \exp[-v_0t \exp(-E/k_BT)] \, dE.
\]

If the demarcation energy, which may be defined as the energy below which
all of population has been thermally depleted, is given by

\[
E_d = k_BT \ln \frac{v_0t}{\ln 2},
\]

and it is assumed that the initial population distribution is broader than \( k_BT \) then,

\[
\exp[-v_0t \exp(-E/k_BT)] \approx \begin{cases} 0, & \text{for } E < E_d \smallskip \\ 1, & \text{for } E > E_d. \end{cases}
\]

If a Gaussian distribution centered at \( E_0 \) is assumed for the initial population,
then

\[
g_0(E) = \exp\left[\frac{-(E - E_0)^2}{\Delta E^2}\right]
\]
Table 5.1.1: Results of thermal erasing experiments given in the references. The first two rows are taken from [68] and rows 3 and 4 are from [70] and [72] respectively.

<table>
<thead>
<tr>
<th>Grating</th>
<th>$A$</th>
<th>$\alpha$</th>
<th>$E_0$</th>
<th>$\Delta E$</th>
<th>$v_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron, I</td>
<td>$0.00173e^{0.00824T}$</td>
<td>$T/2200$</td>
<td>0.4 eV</td>
<td>1.2 eV</td>
<td>$7.2 \times 10^6$ Hz</td>
</tr>
<tr>
<td>Boron, II</td>
<td>$3 \times 10^{-10}e^{0.027T}$</td>
<td>$T/2900$</td>
<td>5.5 eV</td>
<td>0.6 eV</td>
<td>$1.3 \times 10^{32}$ Hz</td>
</tr>
<tr>
<td>Erbium, I</td>
<td>$0.0186e^{0.00764T}$</td>
<td>$T/5250$</td>
<td>2.8 eV</td>
<td>1.08 eV</td>
<td>$2.5 \times 10^{15}$ Hz</td>
</tr>
<tr>
<td>Boron, I</td>
<td>$6 \times 10^{-6}e^{0.0076T}$</td>
<td>$T/1667$</td>
<td>1.7 eV</td>
<td>0.34 eV</td>
<td>$3.3 \times 10^{-3}$ Hz</td>
</tr>
</tbody>
</table>

and the normalized population takes the form

$$n(x) = 1 - \frac{1}{\sqrt{\pi}} \int_{-\infty}^{x} e^{\left(-w^2\right)} dw \quad (5.7)$$

where $x = (E_d - E_0)/\Delta E$. Dong and Liu [68] found that $n(t)$ was fit closely by a power law giving

$$n(t) \approx \frac{1}{(1 + At^{\alpha})} \quad (5.8)$$

where the parameters are given as

$$\alpha = 2.4 \frac{k_BT}{\Delta E}$$

$$A = e^{\left(-2.4 \frac{E_0}{\Delta E}\right)} e^{\left(2.4 \frac{v_0}{\Delta E} ln \frac{v_0}{ln2k_BT}\right)} \quad (5.9)$$

These last two terms, $A$ and $\alpha$, may be determined by thermally erasing gratings at a constant temperature. From the experimentally determined values of $A$ and $\alpha$, the parameters $E_0$, $\Delta E$, and $v_0$ may be calculated. Table 5.1.1 summarizes the results of this type of analysis from references [68,70,72].

In the table, both experiments using boron codoped fiber obtained different values. The only difference mentioned was that each experiment used different writing wavelengths. Dong and Liu used 193 nm [68] and Williams and Smith used 262 nm [72]. This suggests that there may be a dependence
upon writing wavelength or that the three-energy-level model may need to be altered. However, it is currently the only proposed model for the erasure of FBGs at high temperature and holds the promise of gaining an understanding of the properties of different grating types. There has yet to be a clear explanation of the mechanism underlying the erasure of gratings in hydrogen loaded fiber. As such, it is not clear that the three-energy-level model is applicable.

Due to time constraints and the lack of a large number of gratings to erase, the calculation of the above parameters for the fibers tested here is left for future work. The theory is presented here to give a sense of the erasing mechanisms involved and a feeling of the energy levels that are dealt with.

The evaluation of these parameters will be beneficial in many ways. First, the calculation will reveal for which type of fibers the model is appropriate. Also, by calculating these values, a more fundamental understanding of the grating formation mechanism may be achieved. If the model is appropriate and these values are known, predictions can be made concerning the grating’s lifetime at a given operating temperature.

5.2. Thermal Erasure Studies at Oregon State University

As a first step toward fabricating fiber gratings which can operate at high temperatures, a study was conducted concerning the thermal erasure of different fiber gratings. By studying the decay behavior of different gratings in different fibers and at different parts of the writing process, it is hoped that the processes involved can eventually be identified. In this section the results of this study will be presented. A discussion of these results will be given in the following section.

In order to conduct thermal erasure studies a custom fiber heating oven was constructed. A picture of this oven is shown in Figure 5.2.1. The oven consists of two copper blocks, each of which contain a HotWatt cartridge
heater capable of heating to over 650°C. The blocks are each connected to a lead from a power supply. This allows for the application of up to 2 kV across the fiber during the heating process to investigate the effect of static electric fields upon the erasure of the grating. This may be important because high static fields applied during grating formation have been shown to enhance the grating strength [73]. Specifically, when the electrons are thermally excited into the conduction band during the grating’s erasure, it may be possible to apply a field such that the electrons are prevented from reforming the bonds which will discourage the decay of the grating. The temperature of the blocks is monitored by an Omega K type thermocouple. The thermocouple is connected to an Omega digital readout and a Fluke 45 digital multimeter. The multimeter reads the voltage generated by the thermocouple and transmits the data to a PC via a GPIB controller.

An additional feature of the fiber heating oven is that only the portion of the fiber which contains the grating is heated. Typically, when a grating is annealed it is placed inside of a tube furnace. Optical fibers are coated with a polymer coating to prevent damage due to water vapor. Generally this coating is only stable up to 125°C. In the case of polyimide coated fibers the coating can last for short times to 400°C. Many times it is desirable to anneal the grating to temperatures well in excess of these values. Therefore, by only heating the portion of the fiber which already has had the coating stripped in order to write the grating, the fiber may be annealed to the desired temperature and leave the protective coating intact.

The gratings studied in these experiments were written during the research that was presented in Chapter 4. By using these gratings, the thermal properties of the strikingly different writing processes can be explored.

---

4 Figure 5.2.1 shows aluminum blocks. These have been replaced with copper blocks to allow for higher temperature operation.
Figure 5.2.1: Photograph of the oven used to heat fibers to greater than 600°C.

In each of these experiments fibers were placed in the oven with the stripped portion in between the heater blocks. The oven was then turned on and the reflectivity of each grating was monitored as the temperature increased. The oven temperature went from 25°C to approximately 500°C in about 15 minutes. The reflectivity and wavelength of the peak was measured at each 25°C interval.
5.3. Results of the Thermal Erasure Studies

Fiber gratings in hydrogen loaded fibers have been found to be less thermally stable than those written in other photosensitive fibers [71]. Because of the various possible research applications of fiber gratings, it is important to gain an understanding of their thermal characteristics and their operating range. Therefore, a study was conducted to assess the thermal properties of fiber gratings written in hydrogen loaded fiber.

The fibers chosen for this experiment were written during the experiment concerning the effect of pulse energy on grating formation. The gratings selected were the ones written with 100, 120, and 135 μJ pulse energies. These three fibers represent the major grating evolution types seen. The 135 μJ per pulse grating grows fast and has very high reflectance. There is not a great deal of dynamic behavior seen during the grating formation. The 120 μJ pulse energy grating is marked by a very dynamic evolution and is moderately reflective. The 100 μJ pulse energy grating has a relatively low reflectance and little wavelength shift and, thus, heating. The results of this experiment are shown in Figure 5.2.2. An important note concerning all of these experiments is that as the gratings are heated they shift to longer wavelengths, as was discussed in Chapter 4. Moving to longer wavelengths moves the grating to a lower power portion of the source LED. Therefore, the decrease in the reflected signal seen in the graphs overstates the grating’s erasure. The reflectance drop as calculated after the fiber has come back to room temperature following heating will be given.

As is seen in the plot, the grating written with the most dynamic writing evolution was the most thermally stable. This is the grating written with a 120 μJ pulse energy. In fact, this grating did not decrease in reflectivity at all after being heated to 500°C. This observation does not seem to be
consistent with the generally accepted notion that hydrogen loaded fibers are less thermally stable than ordinary fibers. The grating written with 135 $\mu$J pulse energy decayed by 26% as a result of the heating while the 100 $\mu$J grating decayed by 37%. It is interesting that the grating with the greatest overall thermal stability decayed the most in the beginning of the heating. Also, the early decays of the other two are almost identical.

The thermal erasure of boron codoped fibers was also investigated. Again, gratings were selected so that most of the different evolution types would be represented. The first fiber selected was the one whose evolution was used
as an example of the typical grating evolution in Figure 4.2.1. It is not clear which type of gratings each of the large signals are. However, if the second grating is a type II, there should be very little erasure by heating to 500°C. The second grating selected was the grating written with a 128 μJ pulse energy in the pulse energy experiment. This fiber also showed a dynamic evolution during the grating formation; however, it was not as strong as the first fiber selected. The last fiber selected was also written during the pulse energy experiment and was written with a 100 μJ pulse energy. This fiber did not exhibit a dynamic evolution. However, it was very reflective. The results of the heating of these fibers are shown in Figure 5.2.3.

**Figure 5.3.2:** Erasure of gratings written in boron-codoped fiber.
The fiber which appeared to demonstrate the onset of a type I grating followed by the formation of a type II grating erased the most during the heating study. By heating the fiber to 500°C the grating lost 51% of its reflectivity. This indicates that this is most definitely not a type II grating. The grating written with a 128 μJ pulse energy is seen to lose 33% of its reflectivity. Only 21% of the reflectivity of the 100 μJ pulse energy grating is lost by the heating process. It appears that the gratings written with a dynamic evolution are much less thermally stable than the gratings which grow monotonically.

![Figure 5.3.3: Erasure of gratings written in untreated germanium fiber.](image-url)
The last fibers included in this study were untreated germanium fibers. Only two were available for this study due to breakage and the fact that fewer of these gratings have been written because of the long exposure times required. The results of the heating experiment are shown in Figure 5.2.4. The first fiber used was the one exposed for over 9 hours to determine if the gratings written in unloaded fiber with high pulse energies showed any dynamic behavior. The other fiber was written during the pulse energy study and was written with 95 μJ per pulse. This pulse energy appeared to be near the threshold between the two different writing mechanisms. It is evident that both gratings have very good thermal stability up to 300 degrees. Dong and Liu reported a 4% loss in grating strength by heating a type II grating to 300°C. This would be in good agreement with these findings. However, the sharp fall off after 300°C does not seem to follow the expected behavior for type II gratings. As a result of the heating process, the grating written for over 9 hours lost 17% of its reflectivity while the other fiber lost only about 9% of its original reflectivity.

5.4. Discussion of the Thermal Erasure Studies

The studies presented here were conducted primarily to get a first glimpse at the thermal erasure of the fiber gratings written with the techniques developed so far. As such, these studies are not intended to definitively determine any of the thermal properties of these gratings. The sample size was too small to be able to draw any definite conclusions. More elaborate studies with a larger number of samples are needed before any grating characterization can be made based upon thermal erasure. Therefore, only a summary of the experimental observations will be given here.

The study concerning hydrogen loaded fibers indicated that these fibers have a better thermal stability than was previously thought. In fact, the most
A thermally stable grating tested was written in a hydrogen loaded fiber. The fiber written with a pulse energy of 120 μJ did not erase at all when heated to 500°C. This is not expected and the reasons for this are far from obvious. The other two fibers demonstrated moderate loss as a result of the heating experiment. This type of erasure is to be expected in hydrogen loaded fiber. Chapter 4 demonstrated that low pressure hydrogen loading appears to cause different grating formation mechanisms to occur. It is possible that one of these new mechanisms may actually enhance the thermal stability of fiber gratings when certain pulse energies and repetition rates are used. Of course, these speculations are made after only erasing 3 fibers. Much more work is needed to confirm these observations.

The heating of boron codoped fibers shows that these fibers are very thermally unstable. This observation would appear to be consistent with the observations made in Chapter 4 concerning the strong thermal dependence of boron codoped fiber during grating formation. It appears that the fibers which experienced the greatest wavelength shift during formation are the most thermally unstable. This also indicates that increased temperatures during grating formation have dramatic effects on the grating. This does not necessarily seem to be true for the hydrogen loaded fibers. The 120 μJ/pulse and the 137 μJ fibers had similar wavelength shifts but had very different responses to heating.

In the two untreated fibers which were heated there seemed to be very good thermal stability, especially to 300°C. After that both fibers began to erase. The fact that both fiber were stable to 300°C would seem to indicate that there may be at least a component of the grating which is type II. Again, much more research is needed to determine the exact nature of these gratings.
5.5. Annealing Hydrogen Loaded Fibers

As was discussed in Section 5.1, there has not yet been a good explanation for the thermal erasure of hydrogen loaded fibers. It is not clear if the idea presented by Erdogan et al. [70] consisting of carriers being thermally excited to the conduction band and then recombining with defect sites is applicable to hydrogen loaded fibers. If this is the case then thermally annealing the fibers to a certain temperature should release all of the carriers in traps which have an energy below the demarcation energy. Reheating the fiber to the same temperature should show little erasure as the carriers in the lower energy traps have already been freed.
An experiment to test whether hydrogen loaded fibers exhibit this behavior was conducted. In this experiment gratings were written in two hydrogen loaded fibers. These gratings were then heated to 400°C and held at this temperature for 45 minutes. During the heating process the grating’s reflectivity was monitored. The gratings were then allowed to cool to room temperature for 1 hour. The gratings were then reheated and their reflectivity was again recorded. They are then held at 400°C for an additional 45 minutes. The results of this experiment are shown in Figure 5.4.1. In this figure both of the heatings are shown. The plots which are seen to decrease the most are the first heating and the ones which decrease less are the second heating. As was discussed previously, when the gratings are heated their wavelength shifts to a lower power part of the source LED’s spectrum. This is even more evident with these two gratings since they were written at 1300 nm. The plotting symbols in the graph are used to help differentiate between the two gratings.

During the first heating both fibers lose approximately 40% of their reflectivity. During the annealing they both lose an average of about 3%. As the fibers are reheated, again the signal drops. However, when the gratings are allowed to cool their reflectivities return to their original values. These results are, to some extent, consistent with the continuous energy distribution model. However, it is not known what the erasure mechanism is and, therefore, caution must be used when comparing these results to the model. The similarities between these results and the model may only be qualitative. The mechanisms of each may be, and probably are, very different. This experiment does show that gratings which are thermally stable for short periods of time can be written in hydrogen loaded fibers. Longer heating intervals are needed to further the understanding of this process.
5.6. Summary

In this chapter the thermal stability of fiber gratings has been discussed. First a discussion was given which summarized the current model for grating erasure. This included a review of the mathematical formalism as well as the results of experiments presented in the literature.

Following this discussion the results of thermal erasing investigations conducted at Oregon State University were given. These investigations have been only a first step in an attempt to understand the thermal erasure of different gratings. The results of these experiments indicate that, as seen in Chapter 4, the gratings written with low pressure hydrogen appear to have different characteristics than those written with high pressure hydrogen which have been reported in the literature. Specifically, the survival of a grating written in hydrogen-loaded fiber to 500°C without any decrease in the grating strength suggests that the grating formation is not the same as that of high pressure hydrogen-loaded fibers. However, there is much more work needed in this area before any conclusions should be made.

Following a brief discussion of these experiments, an experiment concerning the annealing of hydrogen loaded fibers was presented. This experiment indicates that the hydrogen loaded fibers written at OSU appear to follow the qualitative picture provided by the continuous energy band model. By annealing hydrogen loaded fibers at an elevated temperature, the thermal stability of the grating can be increased, for short times at least.
Chapter 6
Summary of Results and Future Work

The research presented in this paper has primarily been concerned with developing fiber Bragg grating fabrication capabilities at Oregon State University. A major goal of this research has been to use existing equipment and resources to accomplish this task. Through the generous support of Oregon State University, Electro Scientific Industries, Inc. and Blue Road Research, these goals have been reached. In this chapter the results of this research will be summarized. Following this a section describing current and future work will be given.

6.1. Results of Year One of the OSU Fiber Bragg Grating Project

This work was primarily focused upon being able to make fiber gratings at Oregon State University. Because of the resources available at OSU and the relationship between the university and Oregon industry, funding was provided by the OSU College of Engineering A.V. Smith Faculty Development Fund to begin this work. Most of the work presented in this document was supported by this grant.

Because of the availability of 266 nm lasers from Electro Scientific Industries, Inc., this was the type of laser selected for this work. Using these lasers presented several benefits such as good beam quality, long coherence length, high power levels and high stability. However, their use also presented several challenges. First of all, the lamp pumped laser did not have sufficient longitudinal mode stability to use the transverse holographic technique. Since writing multiple different wavelength gratings is vital to a broad research program, a new writing technique had to be developed. This has been referred to
as the modified phase mask technique and has been published in *Electronic Letters* [74]. This technique proved to be robust, compact and allowed very simple alignment.

Writing gratings at 266 nm also presents the challenge of being on the very edge of the UV absorption band in germanium doped optical fibers. This meant that some photosensitivity enhancement was required. Hydrogen loading was the first technique used. The use of boron codoped fibers as well as thermal enhancement techniques have also been explored. The hydrogen loading techniques employed make use of low pressure hydrogen loading ($\approx 13 \text{ atm}$). This may have dramatic effects upon the writing mechanism and warrants further investigation. Thermal enhancement has also been successful in increasing the photosensitivity of optical fibers. The use of thermal techniques may prove to be extremely valuable when writing at 266 nm if it is confirmed that heating the fiber shifts the absorption band to longer wavelengths.

Following the establishment of a viable writing technique, experiments were conducted to try to document and categorize some of the previously unreported effects which were seen during grating formation. It is hoped that an understanding will be reached and optimization of the desired effects will be possible. These experiments indicated that the writing processes involved are more complicated than has been presented in the literature. Gratings written in fibers loaded in lower pressure hydrogen appear to follow the same writing evolution as is typically reported. It is most likely that this technique makes use of some intermediate enhancement which still allows the formation of type II gratings. Once the techniques to characterize the grating type are established, the general writing process should be much clearer. Also, previously unseen results were obtained concerning the wavelength shift during grating formation. This is very apparent in both boron codoped and hydrogen-loaded fibers. This wavelength shift is thought to be thermal in nature and corresponds to radically different writing behaviors in the fibers. Further investigation should help to develop an understanding of the exact relationship
between the wavelength shift and the grating’s formation. With the current writing setup there appears to be a change in the writing mechanism for untreated germanium fibers near 90 $\mu$J/pulse writing energies. It is not yet clear if this marks the onset of type II grating formation or not.

Finally, a brief introduction and preliminary experiments were presented concerning the thermal stability of the fiber gratings written at OSU. These studies indicate that boron codoped fiber gratings are not very thermally stable, which may lend support to the observations concerning the effect of wavelength shift on grating formation. These studies also indicate that low pressure hydrogen loading may in some way allow for the writing of thermally stable gratings in standard telecommunication fiber. The reasons for this are not clear and require more research.

6.2. Future Work

While the work presented here does establish the capability of fabricating fiber Bragg gratings at Oregon State University, there have been many questions raised concerning the grating formation process. Additionally, new applications and properties of these gratings also require further work. In this section some of the current or currently planned work will be presented.

1. A major step in understanding the grating writing processes observed in Chapter 4 would be the development of a technique to observe the index of refraction changes caused by UV exposure. The most likely method would be an interferometric technique such as the method used by Hand and Russell [75]. Also, spectroscopic studies of the glass prior to and following exposure may lead to a higher level of understanding of the mechanisms involved.

2. Many of the experiments in Chapter 4 suggest that increasing the temperature of the fiber during grating formation increases the writing efficiency
at 266 nm. The shift of the absorption band centered at 242 nm, which arises from germanium defects, has not yet been experimentally observed. By repeating the experiment of Atkins and Mizarahi [21] while increasing the temperature of the sample, the thermal shift should be observable. This research should begin soon by Michele Winz and Dr. Thomas Plant at OSU. By determining the quantative shift, a heating apparatus can be built into the writing setup to allow for a much more efficient writing technique.

3. Much more work is needed to investigate the thermal stability of fiber gratings; specifically, those loaded with low pressure hydrogen. The fact that one of these gratings was heated to 500°C without any erasure suggests that there are different mechanisms at work. These gratings could be very useful for future research experiments.

4. As was also seen in Chapter 4, when the fiber is heated during the writing process the FWHM of the grating increases considerably. In addition, the top of the resulting grating reflection spectrum is sloped. Presumably the slope of this grating is dependent upon the rate of heating of the fiber and the speed of grating growth. By gradually either heating or stretching the fiber during the writing of a grating, it may be possible to create a wide grating with a smooth and sloped top. This would be of considerable interest to Blue Road Research for their high speed demodulation devices.

5. Another area of research interest is creating tilted gratings in optical fibers. These can then be used to couple a desired wavelength out of the fiber. It may be possible to then attach a multimode fiber to the grating and create an optical tap. These devices could also be useful in creating low loss demodulators.

6. With the ability to write multiple wavelength gratings comes the possibility of creating gratings in the visible region. These are of interest because this would allow for grating applications using less expensive sources and
silicon detectors. Some preliminary work has been done in this area; however, visible source LEDs are needed to continue this work.

7. Upon neutron irradiation boron has been known to undergo decay to a lithium atom and an alpha particle. This is useful in medical applications for cancer therapy and is known as Boron Neutron Capture Therapy. The effect of neutron radiation on the photosensitivity of boron codoped fibers or on gratings written in boron codoped fibers is also a possible subject of future work. If noticable effects are seen, there may be applications for fiber gratings in neutron dosimetry and detection.

The above research topics are but a few of the myriad of proposed experiments either currently underway or planned at Oregon State University. There seems to be no shortage of research ideas in this fascinating field. As has been the case with this research project, there are bound to be many more potential research topics which appear over the next couple of years.
Bibliography


Index

A (grating parameter), 82
α (grating parameter), 82
β (angle of rotation), 39
absorption, bleachable, 20, 21
absorption, nonbleachable, 20, 22
atomic force microscopy, 25
boron codoped fiber, 49
effect of CO₂ irradiation on, 74, 79
effect of pulse energy on, 68, 78
effects of heat, 69
erasure of gratings in, 88, 91
Bragg equation, 1
Bragg grating, 8
Bragg gratings
variable wavelength, 31, 35
Bragg wavelength, 1
CO₂ laser, 29, 69
color center model, 18, 22, 27, 50
compaction, see densification
continuous energy trap model, 52, 81
counter-directional coupling, 1
densification, 24, 50
dispersion compensation, 16
distributed feedback laser, 3, 17
divalent germanium defects, 22, 55
dopants, alternative, 12
dye laser, 9
Electro Scientific Industries, Inc., 34, 41, 52, 96
excimer laser, 9, 32, 40
fiber amplifier
reflectors for, 16
fiber gratings
writing evolution of, 49, 54
annealing, 84
evolution of writing, 97
thermal stability of, 80, 97
fiber heating oven, 84
fiber lasers, 15
fiber optical sensing, 14
frequency converting, 34, 41
frequency converting crystals, 10
fringe visibility, 36, 43, 52
fusion, 25
gas laser, 9
Ge⁺² ion, see divalent germanium defects
GeE' center defect, 20, 26
Germanium Oxygen Deficient Center, 20, 21
Germanium Oxygen-Deficient Centers, 69
glass
structure of, 25
Hill Grating, 3
Hill, K.O., 3, 8, 18
hydrogen loaded fiber
annealing of gratings in, 91
effect of CO₂ irradiation on, 72, 78
effect of pulse energy on, 66, 77
erasure of gratings in, 86, 91
moderately, 58, 63
oscillations in grating strength, 58
hydrogen loading, 12, 26, 35, 55, 96
apparatus for, 42
effects on grating evolution, 56, 59, 75
photosensitivity mechanism, 26
interferometric microscopy, 25
Kramers-Kronig dispersion relations, 22
long-period gratings, 8
longitudinal mode stability, 32, 35, 40
Lorentz-Lorentz relation, 24
Meltz, G., 4, 9
modified phase mask technique, 31, 36, 38, 49, 96
coherence requirements of, 40
stability of, 47
tunability of, 45
Nd³⁺:YLF laser, 10
Nd:YAG laser, 10, 34, 41
diode pumped, 41, 52
optical filters, 15
optical taps, 15
phase mask, 7, 31, 35
photoluminescence, 20, 22, 55
photosensitivity
enhancement of, 10
increased germanium, 11
thermal, 13, 28
hydrogen, *see* hydrogen loading
thermal enhancement of, 69
point-by-point technique, 8
pulse energy
effects on grating evolution, 63
ring structure of glass, 25
solid state laser, 9, 32
three-energy-level model, 50, 81
transmission diffraction grating, *see* phase mask
Transmission Electron Microscopy, 25
transverse holographic method, 4, 6, 31, 35
transverse holographic technique
coherence requirements of, 6, 31
type I grating, 1, 50, 54, 65
type II grating, 1, 50, 54, 65
untreated fiber
effect of CO₂ irradiation on, 78
effect of CO₂ irradiation on, 71
effect of pulse energy on, 64
erasure of gratings in, 91
untreated fibers
erasure of gratings in, 90
UV absorption band, 5, 10, 20, 62, 96
wavelength division multiplexing, 3, 14
wavelength shift, 2, 14, 59, 62, 72, 76