PHOTOSENSITIVITY RESPONSES AND BRAGG-GRATING IN OPTICAL FIBRES USING 157nm F₂ LASER RADIATION

by

Keith Beckley

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

© Copyright by Keith Beckley, 1997
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author’s permission.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-28841-2

Canada

Abstract

This thesis reports the first study of photosensitivity in optical fibre irradiated with 157nm laser radiation. The largest-per-pulse index changes reported to date were recorded in standard telecommunications fibre with a one-photon process being identified as the driving photosensitivity mechanism. Index changes of $3.5 \times 10^{-9}$ per pulse were registered at an irradiating fluence of 25mJ/cm$^2$. At 450mJ/cm$^2$, a 300% improvement in the per pulse index change was measured for 157nm radiation versus 193nm radiation. Increasing the germanium core concentration had negligible effect on the per pulse index change rate at 25mJ/cm$^2$. Fluences of 100mJ/cm$^2$ to 450mJ/cm$^2$ resulted in a premature index saturation due to a damage mechanism in the core and cladding of the fibre. A Bragg grating with a spectral width of 0.5nm and a 70% peak reflectivity was written in a hydrogen loaded fibre using a phase mask irradiated at a fluence of 360mJ/cm$^2$. 
Acknowledgements

I owe a sincere debt of thanks to Professor Peter Herman for his guidance during the course of the experimental work and the writing of this thesis.

Many people have helped in many little ways toward the completion of this thesis. However certain individuals require special mention. Foremost is Dr. Robin Tam of the OLLRC who gave excellent guidance on the grating work, loaned me (numerous times) the tuneable laser, and most of all gave me precious metres of AT&T fibre. Tino Alavie of Electrophotonics provided useful suggestions with the photosensitivity work and supplying *in-kind* a 3dB coupler and laser diode driver. Professor C. Goh provided the stereo-microscope and fibre light source for about three months longer than the original ‘two weeks’ Professor J. Xu lent me the spectrum analyser. Professor S. Zukotynski made available the stylus profilometer and optical microscope. Their generosity was greatly appreciated.

I owe a special thanks to Takauki Yamanishi for helping me on some of the all-night photosensitivity studies. Jianhao Yang and Brian Jackson were helpful in so many ways - many thanks to them.

I received strong family support during the course of this thesis. Thank you Martha.
## Table of Contents

Chapter 1 Introduction ..................................................... 1

Chapter 2 Photosensitivity and Bragg Gratings ........................ 7
  2.1 Photosensitivity in Optical Fibres .................................. 7
  2.2 Mechanisms of Photosensitivity .................................... 13
  2.3 Measurement of Index Change ...................................... 20
  2.4 Fabrication of Bragg Gratings ..................................... 27
  2.5 Applications of Bragg Gratings .................................... 37
  2.6 Justification of Direction of Exploration ......................... 40

Chapter 3 Experimental Setup .............................................. 46
  3.1 Equipment Modifications ........................................... 46
  3.2 Energy Calibration .................................................. 49
  3.3 Fibre Photosensitivity Measurements ............................ 52
  3.4 Fibre Grating Experiments ....................................... 60

Chapter 4 Results ............................................................. 64

Chapter 5 Discussion ........................................................ 72
  5.1 General Observations ............................................... 72
  5.2 Per Pulse Index Changes .......................................... 74
  5.3 Fibre Gratings ....................................................... 82
  5.4 Repeatability and Error ........................................... 84
  5.5 Significance of Work ............................................... 86

Chapter 6 Conclusions and Future Work ................................. 88
  6.1 Conclusions .......................................................... 88
  6.2 Future Work ......................................................... 89
Chapter 1

Introduction

The relentless growth in global information exchange has resulted in an ever-increasing requirement that the existing technologies move information, by whatever means, at faster speeds. The bandwidth bottleneck has spurred research into such diverse areas as data compression, network protocols, transmission techniques and transmission hardware. In the specific area of optical fibres, currently installed commercial state-of-the-art systems work at a data rate of 10Gbits/s [1]. These remarkable speeds have been achieved by incremental improvements in all of the components of a fibre optic network. Fast detector electronics, optical fibre amplifiers, and stable narrow-bandwidth laser diodes are but three examples of hardware improvements that have permitted the transmission providers to keep pace with demand.

By all accounts, future bandwidth demand will more than eclipse the capacity of current networks. Video-on-demand, internet multimedia, and central server networks are all current or near-term growth industries, and all require tremendous data throughputs. For fibre optic transmission systems there exist several options available to increase capacity: compress or filter the data, increase the bit rate, or move to a multi-wavelength (channel) system. Data compression, while very important, is only able to work on certain types of data and clearly will not be able to handle the capacity requirements in itself. Increasing the data bit rate has been the method of choice to date by telecommunication companies as they struggle to keep up with demand. However, the ability of engineers to double or triple the current bit rate is
becoming increasingly more difficult and expensive as physical limitations are being reached. Specifically, the electronics at both the transmission and detection ends are currently working at speeds near the threshold of room temperature operation. It is becoming apparent that faster bit rates alone cannot be developed to carry future transmission demand.

In light of the capacity limitations imposed by faster bit rates or data compression, multi-wavelength transmission systems are currently favoured to expand the network capacity [1]. Wavelength Division Multiplexed (WDM) networks take advantage of the ~100nm low-loss transmission window of optical fibres centred at 1550nm by employing multiple wavelength transmission channels. Typical demonstration systems reported to date have 16 equally spaced (1nm) channels working at a bit rate of 2.5Gbit/s [1]. One result of the added complexity of guiding multiple wavelengths on a single fibre is the need for new optical devices such as wavelength selectable filters or fixed filters, tuneable narrowband laser sources, top hat broadband optical amplifiers, and optical demultiplexers. One of the more basic components of a number of these devices is the Bragg grating. Bragg gratings are used to narrow or tune the lasing linewidth of a laser diode, for the mirrors of a Erbium doped fibre amplifier, or simply as a filter, forming an integral component of WDM networks.

The fabrication of a fibre Bragg grating requires a periodic modulation of the index of refraction of the core of a fibre [2]. The required modulation is achieved by interfering an intense (laser) light source inside the fibre core thus inducing changes in the stoichiometric properties of the core at the points of constructive interference and no change at the points of destructive interference. This stoichiometric change phenomenon is referred to as photosensitivity and is defined as the susceptibility of a material (in this case germanium-
doped silica), when exposed to laser light, to shift its index of refraction.

Photosensitivity research has progressed rapidly since its initial discovery [3], as the potential for commercial applications was an immediate incentive. The photosensitivity mechanism is driven by linear absorption of short wavelength UV laser light by defect centres in silica glasses. Two primary UV wavelength regions have seen the bulk of photosensitivity research [2]. The first region is centred around a strong 240nm absorption band of germanosilicate glasses. The 248nm krypton fluoride laser has been the primary source for coupling into this absorption region. The second well-studied wavelength region is at 193nm - the lasing wavelength of the argon fluoride laser. Both lasers have produced photosensitivity responses. However, at 248nm maximum index changes saturate at values of \( \Delta n = 2 \times 10^{-4} \) in standard telecommunications fibre after long exposures with large net irradiating energies.

Increased germanium concentration or hydrogenation treatment of the fibre are two techniques that have enabled a tenfold improvement of the photosensitivity response to the 10\(^{-3}\) region [2,4]. While index changes of 10\(^{-3}\) are compatible with producing short strong gratings, the treatments required to achieve these net changes preclude simple manufacturing techniques. At 193nm, a different photosensitivity channel yields large index changes (~10\(^{-3}\)) in low germanium non-hydrogen treated fibres by a two-photon direct excitation of an electron into the silica conduction band [5]. As with any two-photon process it is a relatively inefficient process, so that large index changes at 193nm require long fibre exposure times. At large fluences (>700 mJ/cm\(^2\)) large index changes can be produced by both 248nm and 193nm single laser pulses (these large fluences index changes are termed 'type II' as opposed to the 'type I' changes produced at low fluences). This index change is characterized by
damage at the core-cladding boundary and results in radiation mode losses for wavelengths shorter than the Bragg wavelength. Clearly, a low-fluence photosensitivity mechanism is preferred.

A fast-responding photosensitivity response without fibre damage is highly desirable, especially for low-doped germanosilicate fibres. Such a process may exist if the following mechanism could be initiated in a fibre core: single-photon excitation directly into the conduction band. Theoretically, this would produce non-damage index changes on the order of those available at 193nm, and at much faster rates than a two-photon process. The bandgap of pure fused silica is ~9eV however defects in the glass matrix produce a long tail on the band edge. Electronic excitation by photon energies below the intrinsic bandgap are therefore possible due to the presence of these defects. The addition of germanium as a dopant into silica further reduces the bandgap to 7.1eV (at 5% germanium concentration [6]). The proximity of the 7.9eV-157nm photon to the 7.1eV bandgap of germanosilicate promises strong electronic bandgap excitation. This apparent strong 157nm absorption has been confirmed by ablation work in our laboratory [7] which showed a stronger absorption of 157nm radiation in fused silica and germanosilica as compared with 193nm radiation. The proven strong coupling of 157nm radiation in germanosilicate glasses promises a strong photosensitivity response to the high energy photons afforded by the F₂ laser.

This thesis will report the photosensitivity response of telecommunications fibre to the irradiation by a record short-wavelength 157nm F₂ laser. Measurements were performed on two different types of single mode fibres: standard telecommunications fibre with 3 mol% germanium and a so-called ‘UV sensitive’ fibre with 7-8 mol% germanium concentration.
These fibres were also exposed to multiple pulses of the F$_2$ laser after having received hydrogenation treatment.

Three laser fluences of 25, 100 and 450mJ/cm$^2$ were used to study the fibres. Results showed that low-doped fibres exposed to the 157nm radiation generated per pulse index changes comparable with that produced by 193nm radiation, but for one tenth of the fluence. Further, the 157nm photosensitivity process appeared linear with fluence suggesting that a single-photon mechanism is driving the strong response. Fibres responded more strongly to larger fluences, but core-cladding damage quickly saturated the maximum index change. Hydrogen treatment of the fibres yielded the highest unsaturated index change of $8.1 \times 10^{-4}$ at low fluence but increased the damage mechanism at high fluence. Finally, a Bragg grating was written using a custom-fabricated MgF$_2$ phase mask. This grating had a FWHM spectral width of 0.6nm and a peak reflectance at 1550nm of 70%.

The results of the experiments are significant in two aspects. First and foremost, they set a new short-wavelength boundary on the study of photosensitivity and as such have both practical and theoretical implications. Secondly, they indicate the largest per pulse index change for standard non-hydrogen treated optical fibre for a type I index change.

Chapter two will outline the history, trends, and current status of photosensitivity research. The commercial spinoff of photosensitivity, namely, Bragg gratings, will be discussed from the viewpoint of fabrication, and applications. Chapter three will outline the experimental setup used to perform the 157nm studies as well as to fabricate our Bragg gratings. Details of equipment, experimental procedures, and analysis will be described in this section. Chapter four will present the experimental results. Chapter five will discuss the
implications of this work and compare and contrast our results to other published work. Conclusions will be drawn and future areas of exploration will be explored in the final chapter.
Chapter 2

Photosensitivity and Bragg Gratings

2.1 Photosensitivity in Optical Fibres

This section will outline the historical development of photosensitivity in optical fibres and discuss the current state of the research effort.

Hill et al. [3] inadvertently discovered optical fibre photosensitivity in 1978. Attenuation over time of argon ion laser (488nm) light was observed when the beam was launched into a fibre. Subsequent investigations showed that the Fresnel reflection from the end of the fibre was creating a standing wave in the fibre such that the high intensity nodes were modifying the index of refraction of the material. This spatial modulation created a reflector in the fibre which reduced the output light. Research in the field progressed slowly for a decade as it was thought only certain small core fibres were photosensitive.

At the end of the 1980's, two important breakthroughs occurred. First was the recognition that photosensitivity occurred in many different types of fibre as long as germanium was present as a dopant [8]. The second advance was the fabrication of a Bragg grating in a fibre by the side exposure of interfering 244nm (Argon ion) laser beams by Meltz, Morey and Glenn [9]. The 244nm wavelength is significant since it is one half the 488nm wavelength used by Hill et al. in 1978. At 488nm, the index modulation amplitude was shown to be proportional to the square of the argon-ion laser intensity [10], a strong indicator that a two-photon process at 488nm was driving the index change. On-the-other-hand, UV radiation (tuned directly to a 240nm germanosilicate defect band) drove much stronger photosensitivity
responses through a one-photon process. Successful photolytic index changes were soon reported by a number of groups (see, for example [11,12]) using UV sources. The recognition of the importance of germanium and the successful UV external writing of a grating in a fibre spurred a huge increase in the research effort of fibre photosensitivity and rapid commercial exploitation.

Soon after the work of Meltz, Morey, and Glenn photosensitivity experiments were producing index changes (Δn) of the order of 10⁻⁶-10⁻³ [2]. In light of these small changes, several avenues of research were pursued in order to increase the maximum saturated index change, prolong the permanence of the change, and increase the sensitivity of fibre to the illuminating radiation.

One avenue pursued towards increasing the maximum Δn was selection of the best illuminating wavelength. Due to a strong absorption band at 240.3nm (discussed in more detail in section 2.2) the illumination source of the bulk of photosensitivity work is the krypton fluoride (KrF, 248nm) laser, with nearby [2] sources including a frequency quadrupled Nd:YAG laser (266nm) and a frequency doubled xenon chloride dye-pumped laser (230nm to 255nm). In order to access new defect states with potentially stronger photosensitivity responses, Hill and co-workers [13] also employed the argon fluoride (ArF, 193nm) excimer laser.

Laser fluence (J/cm²) can also be tuned to produce the optimum index modulation. The optimum fluence for a given wavelength depends on a combination of fibre characteristics and dopant concentrations. Typical fluences are ~100's mJ/cm² - higher fluences are limited by fibre and optics damage thresholds. ArF photosensitivity has been measured [5] in the 100-
660 mJ/cm² fluence range. The maximum index change, obtained at the highest fluence, was 9x10⁻⁴ after irradiating the fibre with 54,000 pulses. For the KrF source, the maximum index change of 1.6x10⁻⁴ [14] was achieved by exposing the fibre to a fluence of 300mJ/cm² for 45,000 pulses. These large laser pulse counts are unsatisfactory, as they often require exposure times greater than 10 minutes. For practical applications, such as exposing the fibre in situ on a draw tower, long exposure times are not possible. Low saturated index changes also pose a limitation on the usefulness of the technology since they require either long grating lengths or an acceptance of gratings with low reflectivity. Clearly, with the UV sources available to date, the photosensitivity mechanism is not strong enough for untreated standard telecommunication fibre to suit many applications.

To achieve greater photosensitivity for a given illumination wavelength two different approaches have been investigated. The first approach is to hydrogen treat the fibre before exposure. The second approach is to use fibres with a higher molar content (> 5%) of germanium in the core of the fibre. Hydrogenation treatment can take place in one of two forms. ‘Flame brushing’ involves exposing the bare fibre to a flame (~1700°C) fuelled by a hydrogen oxygen mixture for about 20 minutes. Results from this technique [14] showed a greater than tenfold increase in maximum index change to Δn = 1.75x10⁻³. The second technique, referred to as ‘hydrogen loading’, involves soaking the fibre in hydrogen at pressures up to 200atm for a time period ranging from several days to many weeks. Atkins, Lemaire, and Erogan [4] achieved the highest ever reported index change for a standard telecommunications (low germanium) fibre of 5.9x10⁻³ using this technique.

Enhancement of the photosensitivity response by increased germanium dopant
concentration is the most studied process in a broader investigation into the role of core dopants that underlie photosensitivity mechanism. As mentioned earlier, it was originally thought that germanium was a required dopant for fibre photosensitivity, as no photosensitivity had ever been observed in a pure silica core fibre. Later, it was shown that photosensitivity could be induced in non-germanium doped fibres. Specifically europium [15], and cerium [16] doped fibres have both shown a photosensitive response of $-2 \times 10^{-5}$. A co-doped boron-germanium [17] fibre recently was found to have a strong index modulation in the $\Delta n = 10^{-3}$ range. Another significant result, due to its potential use in erbium fibre amplifiers, was the demonstration of photosensitivity in erbium-germanium doped fibres. Bilodeau et al. [18] obtained an index change of $-3 \times 10^{-5}$ (240mJ/cm$^2$/pulse; 50 pulses) in a erbium-germanium fibre. The strongest germanium-free response was recently reported [19] in a tin doped phosphosilicate fibre which, after hydrogen loading, peaked at $\Delta n = 1.2 \times 10^{-3}$.

Crucial to the commercialization of devices based on photosensitivity effects is the permanence of the index change. The permanence of an index change induced in a fibre has to be measured against its resistance to erasure by temperature as well as erasure by the wavelength designed to travel along the fibre (typically 1550nm or 1300nm). To measure resistance to low temperature annealing, accelerated lifetime (high temperature) tests can be performed. An extensive study by Erdogan et al. [20] demonstrated that the decrease in the peak reflectivity follows a well fitted power law decay curve for a given temperature of the form:

$$\eta = \frac{1}{1 + A(t/t_1)^\alpha}$$

10
Here, $A$ and $\alpha$ (typically $\ll 1$) are functions of temperature, $\eta$ is a normalized index change and $t_i = 1$ minute. As observed experimentally, a small value for $\alpha$ implies that the bulk of the index degradation that will occur takes place very soon after the index change is initiated. For the fibres tested in reference 19, a 90% reflective grating would lose 2% of its reflectivity in 1000 years (at 300K), with the first 1% occurring in the first nine hours. This decay process strongly suggests that the distribution of traps for electrons liberated to the conduction band by an illuminating UV photon occupy a broad spectrum as opposed to there being a single trap level. The index degradation is very stable at a particular temperature once the occupied traps, reachable by thermal excitation, have been liberated. This continuum of traps is corroborated by the broadband increase in UV absorption due to a narrowband UV exposure. This will be discussed further in the next section.

A final characteristic of photosensitivity is that it is an anisotropic process. This anisotropy results in a UV induced Bragg grating having its reflectivity dependent on the polarization of the transmitting light beam. A birefringence of $2\times10^{-6}$ has been observed [21] in standard telecommunications fibre.

Photosensitivity research has now progressed to the point whereby index changes greater than $10^{-3}$ (comparable to the typical $6\times10^{-10}$ core cladding index step) can be reproducibly created in various fibres. Modulations of this magnitude allow useful devices to be produced, some of which will be discussed in section 2.5. It must be stressed that only treated or high germanium fibres can produce large index changes with reasonable laser pulse counts. There remains a strong demand for a technique to write large index changes in
untreated telecommunications fibre. Table 1 summarizes the photosensitivity responses for KrF and ArF illumination of germanosilicate fibres:

**Table 1: Peak index changes for KrF and ArF fibre illumination.**

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Standard Fibre</th>
<th>Hydrogen Treatment</th>
<th>High Germanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krypton Fluoride</td>
<td>Type I</td>
<td>~1x10^-4 (10's kJ/cm²) [2] ‡</td>
<td>1.7x10^-3 (13.5kJ) [14]</td>
</tr>
<tr>
<td>Band (~248nm)</td>
<td>Type II</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Argon Fluoride</td>
<td>Type I</td>
<td>1x10^-3 (7.9kJ/cm²) [5]</td>
<td>N/A</td>
</tr>
<tr>
<td>(193nm)</td>
<td>Type II</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* This table gives figures-of-merit only - different core and cladding compositions yield different index change results for the same irradiating conditions.
† Index change not explicitly given - calculated from peak reflectivity.
‡ Reference [25] gives an index change of 1.2x10^-3 however there is an anomalous result - there is some question about this being a standard fibre as it was highly transmissive at 248nm.

Photosensitivity research has centred around the index changes in optical fibres. However, other potential applications for the phenomenon exist. Foremost is the patterning of planar silica structures with guiding optical channels. Buried waveguides and their spinoff components are a huge potential area of growth. Indeed, as the optoelectronics industry moves from a predominantly electronics base to a predominately optical base, silica devices fabricated by UV photosensitivity are likely to be a seminal technology.
2.2 Mechanisms of Photosensitivity

Closely coupled with the effort to maximize the index change in fibres is a more basic study intended to determine the physical processes occurring in the fibre during exposure. To date, no clear comprehensive picture exists as to the process underlying photosensitivity. Three separate theories exist, each supported by strong experimental evidence. inconsistencies among these theories may simply be due to different exposure conditions which give rise to different photosensitivity mechanisms. It must be stressed that the theories outlined below are all based on the photosensitivity in germanium doped fibres at low fluences (<700mJ/cm²). Other index change mechanisms for higher fluence regimes, different irradiating wavelengths, or for fibres with different core dopants, remain little understood and will be discussed at the end of the section.

The early recognition of the required presence of germanium in the fibre core, and the fact that the refractive index changes were being induced by one-photon processes at 240nm (well below the 148nm-9.0eV bandgap of pure silica), points to a model where germanium point defects were responsible for the index change. Although defects in doped and undoped silica glasses have been studied for years, there is little comprehension of the response of these defects to UV radiation. Understanding the effect of defect irradiation is critical to a comprehensive theory of photosensitivity.

Intrinsic silica has three defects [26], each with an associated absorption band. Figure 1 shows the structures of the important silica and germanosilica defects. The SiE’ centre (‘Silicon E primed centre’) has an absorption peak at 245nm and is characterized by a missing oxygen atom and a weakly bound electron. The Non-Bonded Oxygen Hole Centre (NBOHC)
absorbs at 260nm and is simply a broken O-Si bond with a lone electron on the dangling oxygen atom. The third pure silica defect is the peroxo radical or Si-O-O bond structure with the free oxygen having a bound free electron. This defect absorbs at 160nm - very close to the band edge of pure silica.

![Figure 1: Structure of pure silica (A) and germanosilica (B) point defects [19].](image)

The introduction of germanium into glass produces more point defects mainly because germanium has a stable +2 oxidation state [26]. This gives rise to a GeE' defect which is identical to the SiE' defect except for the exchange of germanium for silica. Two similar defects are termed Ge(1)' and Ge(2)'. They are simply a bound electron on a four-atom bonded germanium atom. The Ge(2)’ defect is distinguished from Ge(1)' by the replacement of one of the nearest neighbour silicon atoms with a germanium atom. The Ge(1)' and Ge(2)' defects absorb at 281nm and 213nm, respectively. The final and most significant defect is the
Germanium Oxygen Deficiency Centre (GODC, also referred to as the Ge-Si wrong bond) which absorbs strongly at 240nm. This defect is a direct Si-Ge bond (The regular Si-O-Ge bond structure is simply missing the oxygen atom).

It has been shown [26] that the Ge-Si bond density increases linearly with germanium concentration and is much more prevalent than the Si-Si defect. The strong absorption and relatively high concentration of GODC's indicate that these defects provide a very efficient method to couple UV radiation into the glass structure. For this reason there is general consensus that GODC's are the catalysts behind the 248nm photosensitivity response of germanosilicate fibres. It is also generally agreed that the breaking of the Ge-Si bond leads to the formation of a GeE' centre. However, what happens to the freed electron and what new defects might be created is an area of intense study, with conflicting results. The GODC defect is simply a conduit of energy into the glass; the true photosensitivity mechanism remains uncertain.

The first theory proposed by Hand & Russell [27] in 1991 is termed the colour centre model. The postulation is that the bleaching of the 240nm band creates new, as yet uncharacterized, defects that absorb at higher energies. This bleaching of the 240nm band by 240nm radiation is well known (see for example [4]) to increase the fibre absorption at shorter wavelengths. A detailed study of the post-irradiation absorption spectrum of a germanosilicate fibre preform [28] showed the creation of a strong band at 195nm and a few weaker bands at longer wavelengths. The absorption change then yields an index of refraction change at longer wavelengths through the Kramers-Kronig relation. An overall increase in the absorption coefficient (imaginary index) creates a positive increase in the real index of refraction on the
long wavelength side. This increase in the index of refraction is partially offset by the bleaching of the 240nm band. The maximum index change that could be produced by a complete bleaching of the 240nm band was ~3x10$^{-4}$. Thermal annealing at 800°C showed that the index change could be completely reversed. This was consistent with the thermal erasure of a Bragg grating reported by Meltz and Morey [29]. While the colour centre model can account for small index-of-refraction modulations, it cannot explain the large (>10$^{-3}$) non-damage index-of-refraction changes that have been observed by Fonjallaz et al. [22]. Finally, the increased photosensitivity due to hydrogenation treatments is thought to be due to the formation of strongly UV-absorbing Si-OH sites by the breaking of Si-O-Ge bonds by H$_2$ molecules. This process would dramatically increase the number of absorbing sites compared with the number of intrinsic GODC's. This process remains to be confirmed.

In an effort to explain the discrepancies of the colour centre model Wong, Poole, and Sceats [30] proposed the stress relief model. The difference in the thermal expansion coefficients between the core and the cladding produces a thermoelastic stress in the core. The bleaching of the GODC by UV radiation allows the relaxation of the glass network since the Ge-Si and Si-Si bonds have a lower binding energy than any oxygen-containing bonds. It has long been known that tension reduces the index of refraction via the stress-optic effect. Therefore the reduced tension (stress relief) should increase the index of refraction. This positive index shift has been experimentally verified by a number of groups. Sceats and coworkers also showed [30] that index changes on the order of 10$^{-3}$ are possible in highly stressed fibres. Recently the stress relief model has suffered a number of setbacks. The ability to erase an index change by thermal annealing is hard to explain with a relaxation of the glass
matrix. A second problem for the stress relief model are the recent results, by Limberger and co-workers [22,25,31], that show a tension increase in the core of the fibre after UV exposure.

The compaction model has been proposed to explain the discrepancy between the observed positive index change (shift of Bragg wavelengths to longer wavelengths during irradiation) and the negative (photoelastic) index change implied by the measured core tension increase. Measurements of axial stress and mean index change in a Bragg grating formed on a 12% Ge fibre indicated that there were in fact two competing processes contributing to the net positive index change [22]. There was a negative index change due to the photoelastic effect which varied sinusoidally along the grating from a peak of $-1.41 \times 10^{-3}$ to a minimum of $-0.23 \times 10^{-3}$. A combination of structural changes, namely, core compaction and colour centre creation, are thought to create a larger, offsetting, positive index change. The 12% Ge fibre was calculated to have a peak compaction induced change of $3.48 \times 10^{-3}$ (the minimum being zero due to no structural changes at the destructive interference nodes). This resulted in the fibre having a net positive index change of $1.15 \times 10^{-3}$ (measured) in the constructive interference nodes and a net negative index change of $-0.23 \times 10^{-3}$ in the destructive nodes. The actual compaction (densification) mechanism remains unclear but has been observed in UV irradiated fibre preforms [32] and UV irradiated thin films. The compaction model explains, through an as yet uncharacterized core densification mechanism, the high index changes observed in untreated fibres. However, questions about thermal annealing remain.

As mentioned earlier, all three theories outlined above attempt to explain the index change observed in germanosilicate fibres exposed to relatively low-fluences ($<700\text{mJ/cm}^2$) KrF radiation. At higher fluences, another mechanism induces damage at the core cladding
interface and produces strong index modulations in the fibre [23]. Gratings made at low fluences are termed type I gratings and those produced at higher fluences are termed type II gratings. Type II gratings produced by KrF laser pulses are characterized by visible core-cladding damage, resistance to thermal anneal up to 700°C, and large effective index changes of $\sim 5 \times 10^{-3}$ per pulse. Due to the core-cladding damage, these gratings have the property that wavelengths shorter than the Bragg wavelength are strongly coupled out of the fibre. Another interesting property of type II gratings written by a phase mask (discussed below) is that the photo-induced grating period is equal to $\Lambda$, the period of the phase mask, and not $\Lambda/2$ which is typical for type I gratings. Furthermore, the reflection spectrums from type II gratings are similar to those seen for surface-etched gratings on the core-cladding boundary which suggests that the damage is only on one side of the core [33]. For commercial applications type II gratings have a number of attractive features: high reflectivity (>99%), single shot production, standard fibre fabrication, and long thermal stability. These assets are in complete contrast to gratings produced by a type I process where weak reflectivities, multiple pulse production, fibre photosensitivity enhancement, and thermal bleaching are the norm. Yet type II gratings suffer from losses due to the coupling out of the fibre of non-Bragg wavelengths. This is a serious impediment to the implementation of type II gratings in WDM systems. Type I gratings do not suffer from this off-resonance wavelength loss and thus, despite the difficulties involved in their fabrication, have received the bulk of commercial interest.

The shift to ArF excimer irradiation was proposed [13] to couple into a weaker 185nm absorption band of the GODC. Experimental results produced two separate photosensitivity responses depending on the germanium content of the fibre [5,34]. At high germanium (>8%
Ge) concentration, the photosensitivity response appears to follow the standard one-photon colour centre model with saturated index changes on the order of $3.5 \times 10^{-4}$. Switching to low germanium fibres (3% Ge) produces unexpectedly high responses of $\Delta n \sim 1 \times 10^{-3}$. More interestingly, the photosensitivity mechanism for low-doped fibres appeared to follow a two-photon process. This indicates that for higher germanium concentrations, resulting in more GODC’s, the one-photon process (which has a larger cross section) dominates and the two-photon process is negligible. One conclusion that can be drawn is that the two-photon defect channel at 12.8eV ($2 \times 6.4$eV - 193nm photons) is more efficient at producing colour centres than the single-photon process. The 12.8eV energy directly releases an electron into the conduction band where it is free to move over a greater distance to a trap location. The large change in low-germanium fibre must involve colour centre defects originating with germanium dopants since the largest achievable index change in pure silica glasses at 193nm is only $5 \times 10^{-5}$. Therefore the freed electron from the two-photon process is most likely being trapped at a germanium dopant site. Thermal annealing results were similar for the one and two-photon processes, as well as for KrF exposed fibres.

Germanium-free phosphorous doped fibre (attractive for fibre laser applications) exhibit yet another photosensitivity mechanism. In general, phosphorous fibres have almost no absorption at 240nm (the addition of phosphorous to germanosilicate fibres suppresses the 240nm absorption band), so little photosensitivity was observed using KrF laser radiation. A combination of hydrogen loading (often deuterium loading) and 193nm irradiation has produced a strong photosensitization response ($\Delta n = 2 \times 10^{-3}$) [35]. The growth of the UV induced index change is markedly different from germanium response. Germanium fibres
typically have over 50% of the total index increases during the first few pulses and a long saturation tail for longer exposures. The phosphorous fibres have little change in the first few pulses and then have a large linear increase before eventually saturating. There are two possible explanations for this phenomenon: an increase in the absorption during exposure or a temperature effect whereby the increased temperature (due to laser pulse heating) drives the photosensitivity mechanism.

This section has outlined the current theories of photosensitivity. From the incongruous results achieved by various groups it is apparent that there are several photosensitivity mechanisms. Different fibre, dopant level, irradiation wavelength, and fluence combinations tap into these different mechanisms. Work remains to be done to understand the state of the glass structure after UV exposure.

2.3 Measurement of Index Change

There exist several techniques for measuring index change in optical fibres. Each method has its merits that trade ease of measurement with accuracy and absolute sensitivity. This section will outline some of these techniques and discuss their relative strengths and weaknesses.

**Writing of Bragg Grating**

The reflectivity of a perfectly periodic grating of length $L$ at the central Bragg wavelength, $\lambda_B$, is given by [36]:

\[ R(\lambda) = \frac{1}{1 + (\frac{\lambda - \lambda_B}{\Delta\lambda})^2} \]
Here \( \eta \) is the fractional mode intensity in the core and has a value of 0.8 for single mode silica fibres. The careful measurement of the reflectance of a grating at the resonant wavelength yields the index modulation. This technique is the one most commonly reported in the literature since the bulk of the reported work is on Bragg grating fabrication. One difficulty with this technique is that it does not classify the maximum index change but only the difference between the peak and minimum. As reported in the compaction model, at the nodes of destructive interference there was in fact a predicted decrease (a negative dc component) in the index of refraction. Furthermore an imperfect interference pattern will result in some modulation at the nulled nodes. Accuracy is also a potential problem as measurement of the grating length, \( L \), is typically somewhat subjective. In conclusion, the grating technique, while simple to perform (the reflection spectrum is a basic component of a grating’s characterization), does not produce a reliable value for the absolute index modulation value.

**Bragg Wavelength Shift**

Related to the measurement of the peak reflectance of a Bragg grating is the technique to monitor the wavelength shift in the peak as the grating is written. This is a more sensitive technique than simply measuring the peak reflectivity. The technique’s accuracy depends on several factors: no dc index change, the grating is not saturated, and the grating is uniform along its length (difficult with non-uniform excimer lasers beams).
**Side Observation of Bragg Reflection**

This technique also requires the presence of a Bragg grating in the fibre but, unlike the two previous techniques, the magnitude of the index modulation is determined by the Bragg reflection of a probe beam incident at a angle to the side of the fibre. By comparing the strength of the reflected beam to the incident probe beam the magnitude of the index change can be calculated. This technique is attractive because it can yield a profile of the grating along its length, thus providing information about the uniformity of the writing UV beam. Another attraction of the technique is its ability to provide an external *in situ* monitor of the growth of a grating as it is being written - a requirement of a draw tower grating fabrication system. Drawbacks include the relative insensitivity of the measurement and the precise alignment required to couple the probe beam into the core.

**Direct Observation**

This technique involves simply measuring the core refractive index profile. The obvious drawbacks are that this is a destructive technique and only index changes greater than 5x10^-5 can be measured. This technique is important for index changes brought about by the type II mechanism, since the index profile is non-uniform across the core and, therefore, damage regions can be identified.

**Far Field Interference** [37]

If two fibres of near identical length are both cleaved at one end and connected via a 3dB coupler at the other end, then coherent light passing through the coupler - along each fibre...
- and out of the cleaved ends will form an interference pattern in the far field similar to a Young's double slit pattern. The path difference, $\Delta \ell$ between the fibres must be less that the coherence length of the laser source. By irradiating only one of the fibres over a length, $\ell$, with UV light any induced index change will increase (or decrease) the optical path length for that arm. The additional phase for the light travelling along the exposed fibre will be:

$$\Delta \phi = \frac{2\pi \Delta n \ell}{\lambda_o}$$

This additional phase will manifest itself as a shift in the interference pattern originating from the fibre ends. Careful measurement of this shift will yield the index change induced in the fibre. This far field interference technique is very sensitive and is only limited by the accuracy of the measurement of the shift in the interference pattern. The tradeoff for such accuracy is the extreme mechanical and thermal stability required to perform the measurements. Another complication is that the measurement of index changes in the infra-red requires an IR sensitive material or a CCD camera with sufficient resolution.

**Mach-Zehnder Interferometer**

The Mach-Zehnder, like all interferometric techniques, is an extremely sensitive method for measuring index change. The basic Mach-Zehnder interferometer consists of two fibres fused together at two locations along their lengths. Each of the two fused sections should be a 50:50 coupler. If one arm of the interferometer is irradiated over a length, $l_1$, so
as to produce an index change, then the corresponding optical path length difference due to
an index change of Δn is: ΔOPL = (nl₁)₁before - (nl₁ + Δnl₁)₁after Δnl₁. The phase change between
the arms of the interferometer is given by:

\[ \Delta \phi(\Delta n) = \frac{2\pi \Delta n l_1}{\lambda_o} \quad (Mach-Zehnder) \] 4

To calculate the intensity of the output signal from the Mach-Zehnder interferometers two
plane waves of equal amplitude are assumed in each arm of respective lengths L₁ and L₂:

\[ E_1 = E_o e^{i(\omega t - \phi_1)}, \quad E_2 = E_o e^{i(\omega t - \phi_2)} \] 5

With \( \phi_1 = 2\pi n L_1/\lambda_o \) and \( \phi_2 = 2\pi n L_2/\lambda_o \) then the total field at the output is:

\[ E_{TOTAL} = E_1 + E_2 = E_o e^{i(\omega t - \phi_1)} (1 + e^{-i\Delta \phi}); \quad (\Delta \phi = \phi_1 - \phi_2 = \frac{2\pi n \Delta L}{\lambda_o}) \] 6

The intensity is then given by:

\[ I_{TOTAL} = \frac{1}{c \mu_o} (E_{TOTAL} \times E_{TOTAL}^*) = \frac{1}{c \mu_o} E^2 (2 + e^{i\Delta \phi} + e^{-i\Delta \phi}) \] 7

Equation (7) can be rewritten:

\[ I_{TOTAL} = 2E^2(1 + \cos \Delta \phi) = 4E^2 \cos^2 \frac{\Delta \phi}{2} \] 8

Normalizing and substituting \( \Delta \phi \) from (6) into (8) the final result is:
Equation (9) gives the variation in the intensity due to a change in the relative lengths of the arms of a Mach-Zehnder interferometer. The relative lengths (ΔL) of the arms is a function of a number of factors: temperature, strain, and index change. A change in index will result in an optical path length for arm 1 of: nL₁ + ΔnL₁. This results in a constant ΔL phase term plus a term dependant on Δn. Combining equation (4) and equation (9):

\[
\frac{I(ΔL)}{I_o} = \cos^2\left(\frac{\pi n ΔL}{λ_o}\right)
\]

Rearranging (10) to solve for Δn:

\[
Δn = \frac{λ_o}{nL₁} \cos^{-1}\left(\left(\frac{I}{I_o}\right)^{\frac{1}{2}}\right) + C_{ΔL}
\]

The constant, C_{ΔL}, is the unchanging phase term from equation (10) and can be ignored. Experimentally a measurement of the evolution of the intensity, I, at a given wavelength, λ₀, will yield a profile of the index change as a function of laser pulse. The Mach-Zehnder approach is attractive due to the relative ease of obtaining an absolute index change value. However, care must be taken to ensure that intensity changes are not a result of temperature fluctuations or fibre strain. Another critical point is to ensure that the illuminating beam is as uniform as possible over the interaction length l₁.
Michelson Interferometer

The Michelson fibre interferometer differs from the Mach-Zehnder in one crucial respect: instead of using two 3dB couplers, only one is employed, and the loose fibre ends are mirrored to reflect the light. This reduces the complication of having to unbalance the path lengths since the arms can easily be made different lengths. The requirement of fabricating only one 3dB coupler simplifies the fabrication. However, the mirroring of the cleaved fibre ends adds a complication. The index change can be measured the same way as with the Mach-Zehnder but the measured index change must be halved since the light in the fibre propagates twice through the irradiated region. Equation (4) becomes:

$$\Delta \phi (\Delta n) = \frac{4 \pi \Delta n l_1}{\lambda_o} \quad (\text{Michelson})$$

Finally, equation (11) becomes:

$$\Delta n = \frac{\lambda_o}{2 \pi l_1} \cos^{-1}\left(\left(\frac{I}{I_o}\right)^{\frac{1}{2}}\right)$$

The Michelson interferometer has the same noise drawbacks as the Mach-Zehnder interferometer: temperature fluctuations, varying strain, and beam non-uniformities will give spurious results for the index change.

Table 2 gives a summary of the advantages and disadvantages of the various photosensitivity measurement techniques outlined above.
Table 2: Comparison of photosensitivity measurement techniques.

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bragg Grating Reflection</td>
<td>+Simple</td>
<td>+Relative $\Delta n$</td>
</tr>
<tr>
<td></td>
<td>+Easy</td>
<td>+Requires grating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+Insensitive</td>
</tr>
<tr>
<td>Bragg Wavelength Shift</td>
<td>+Sensitive</td>
<td>+Relative $\Delta n$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+Requires grating</td>
</tr>
<tr>
<td>Side Observation of Bragg Reflection</td>
<td>+Longitudinal $\Delta n$ profiling</td>
<td>+Difficult to perform</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+Requires grating</td>
</tr>
<tr>
<td>Direct Observation</td>
<td>+Cross-section $\Delta n$ profiling</td>
<td>+Insensitive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+Destructive</td>
</tr>
<tr>
<td>Far Field Interference</td>
<td>+Very sensitive</td>
<td>+Difficult to perform</td>
</tr>
<tr>
<td></td>
<td>+Easy to construct</td>
<td></td>
</tr>
<tr>
<td>Mach-Zehnder Interferometer</td>
<td>+Sensitive</td>
<td>+Stability problems</td>
</tr>
<tr>
<td></td>
<td>+Absolute $\Delta n$</td>
<td>+Difficult to make</td>
</tr>
<tr>
<td>Michelson Interferometer</td>
<td>+Sensitive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+Absolute $\Delta n$</td>
<td>+Stability problems</td>
</tr>
<tr>
<td></td>
<td>+ this thesis</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Fabrication of Bragg Gratings

Since the first weak fibre Bragg grating was written by Meltz and co-workers in 1989 [38], significant progress has been made by numerous groups in developing techniques to produce stable high-reflectance gratings. Research has quickly progressed from the laboratory into industry to the point where there are already a number of new companies dedicated to producing products based on fibre grating technologies. A number of techniques have been developed to write Bragg gratings in fibres; they will be discussed in this section.
A number of general statements can be made about features common to all fibre Bragg grating writing systems. A general requirement is an illumination source with sufficient energy to induce the photosensitive mechanism. In practical terms, this means a UV laser - typically, as mentioned earlier, a KrF excimer. Except for the point-by-point technique, the illuminating source must have a degree of coherence - this enables the creation of a standing interference pattern (of desired pitch) on the fibre core. Finally, to produce strong gratings the writing system must have a high degree of vibrational and thermal stability.

**Internal Writing**

This was the first fabrication method to generate a fibre grating. Light coupled into the fibre interferes with its own back reflection, producing a standing wave. If the intensity is strong enough then a two-photon process can occur and a grating will be created. It is important to stress that this technique requires a two-photon process as only wavelengths that are not strongly absorbed by the fibre are usable. Gratings useful for communication applications cannot be generated with this method. The main advantage of writing gratings internally is that very long (and, hence, highly reflective) gratings can be generated.

**Lloyd's Mirror**

This technique is probably the simplest of all techniques, since it only involves one mirror. A fibre is placed in close proximity to the edge of a UV mirror and the incident UV beam is directed such that half of the beam falls on the mirror and half on the fibre. The portion of the beam incident on the mirror will reflect onto the fibre and generate a standing
interference pattern. This same technique was used by this author in 1994 to etch a surface relief grating ($\Lambda=180\text{nm}$) in PMMA using our $157\text{nm}$ $F_2$ source[7]. Since the beam is, in effect, folded back on itself this technique requires a laser beam with good transverse coherence or else the grating will be washed out. The Lloyd's mirror technique has several drawbacks. Grating lengths are small due to the typically small UV beam dimensions. The grating has an abrupt cutoff at the mirror/fibre apex but slowly washes out along the length of the fibre. The mirror must be held in extreme proximity to the fibre for maximum effectiveness which might damage the fibre. In addition to its simplicity the advantages include a high degree of stability and the ability to alter the period of the induced grating by altering the angle between the mirror and the fibre.

A 16% reflective grating with $\Delta n=6.6\times10^{-4}$ was written in a single mode fibre using the Lloyd's mirror method [39]. Figure 2 shows the physical layout of a Lloyd's mirror interferometer.

Figure 2. Experimental setup for Lloyds’ mirror Bragg grating writing technique [39].
Point-by-Point

The point-by-point grating fabrication technique was first reported by Hill et al. in 1990 and followed up three years later with a more refined methodology [40]. Writing a grating point-by-point involves transversely stepping the fibre (or UV beam) at a precise spacing (A) such that a periodic index modulation is written along the length of the fibre. The clear advantage of this technique is the flexibility it provides in defining both the pitch and length of the grating. Since each period of the grating is written individually, non-uniform (apodized) index changes can be written at different places along the length of the grating. The fact that index change is a nonlinear process means that difficulties associated with translation and alignment are not as severe as they would be in a linear process. However fabrication of small period (<500nm) gratings remains a challenge. A clear drawback of this technique is that it is slow and therefore not suitable for use on a fibre draw tower. Figure 3 shows the arrangement for the point-by-point technique.

Figure 3: Point-by-Point writing technique for fibre Bragg gratings [41].
Prism Interference

There are several variations on this technique. Figure 4 shows one of the variations [42]. If the $\lambda_b$ and $n_b$ are, respectively, the Bragg wavelength and index, and $\lambda_{UV}$ and $n_{UV}$ are the corresponding values for the writing index, then the Bragg wavelength is given, for the geometry of Figure 4, by:

$$\lambda_b = \frac{n_b \lambda_{UV}}{2 \cos \alpha \sin(\alpha - \sin^{-1}[(1/n_{UV}) \sin \alpha])}$$

The angle $\alpha$ is shown in Figure 4. As with the Lloyd’s mirror method, this technique is simple with few optical elements. However, a long coherence length is required due to the prism thickness. Bragg wavelength tunability is achieved by tilting the prism or, on a larger scale, selecting a new prism angle $\alpha$. Interestingly, by moving to more complex shapes than a simple prism this technique holds the potential to form chirped or apodized gratings. Since there is some focusing of the UV beam in the prism there remains a question of incurring damage over multiple uses.

Figure 4: Prism writing technique for fibre Bragg gratings [42].

31
**Phase Mask**

The phase mask approach was demonstrated by two different groups in 1993 [43, 44]. This is a simple one element technique that has proved to be very effective at generating highly reflective stable gratings. A phase mask consists of a periodic surface relief etched into a piece of UV grade silica (for KrF). The key is to obtain as much zeroth order extinction as possible. This is achieved by ensuring that the surface relief has a high degree of uniformity (sharp corners, straight side walls, flat surfaces) and that the depth of the etch is such that a π phase difference exists between the light travelling through the etched portion compared to the non-etched portion. The correct etch depth, d, is given by:

\[
\pi = 2 \pi (n_{UV} - 1) \frac{d}{\lambda_{UV}}
\]

In equation (15), \(\lambda_{UV}\) is the writing wavelength and \(n_{UV}\) is the index of the phase mask material at \(\lambda_{UV}\). For KrF and a silica substrate (\(\lambda_{UV} = 248\text{nm}, n_{UV} = 1.508\)), the required etch depth is a multiple of ~244nm. For a magnesium fluoride (MgF\(_2\)) phase mask (\(\lambda_{UV} = 157\text{nm}, n_{UV} = 1.464\)) the required etch depth is ~169nm. Commercial phase masks are now routinely produced in silica with the zeroth order having less than one percent transmission. With a strong suppression of the zeroth order most of the light, typically 80%, is coupled into the first (+/-) orders. It is the interference of the plus and minus first order beams that causes the periodic grating to be created.

The near field interference pattern of the first order beams has its strongest frequency component at half the phase mask’s period (\(\Lambda_{PM}/2\)). The Bragg condition in a fibre, \(m\lambda_{Bragg}\)
\[ 2n_{\text{fibre}} \Lambda_{\text{grating}}, \text{ (m=1 for first order reflection)} \] directly gives the required phase mask period since \( \Lambda_{\text{grating}} = \frac{\Lambda_{\text{PM}}}{2} \), where \( \Lambda_{\text{PM}} = \frac{\lambda_{\text{Bragg}}}{n_{\text{fibre}}} \). For silica fibres and 1550nm transmission, the correct phase mask period is \( \approx 1.030 \mu m \). The phase mask’s period is independent of the writing wavelength. Therefore, as noted in reference [43], in principal it is possible to write a grating using a phase mask with a broadband source since only the wavelength corresponding to the etch depth will be diffracted into the non-zeroth orders. Phase masks are fabricated using a reactive ion etch technique in conjunction with a photolithographic process. Before reliable zeroth order suppressed masks were available gratings were created by interfering the zeroth and +1 order beams by having the UV incident at an appropriate angle.

A notable attraction of phase mask grating writing is the loose requirement on the

\[ \text{INCIDENT ULTRAVIOLET LIGHT BEAM} \]

\[ \text{SILICA GLASS PHASE GRATING} \text{ (Zero Order Suppressed)} \]

\[ \text{DIFFRACTED BEAMS} \]

\[ \text{ZERO ORDER} \text{ (<1% of throughput)} \]

\[ \text{FIBER CORE} \]

\[ \text{FRINGE PATTERN Pitch = 1/2 Grating Pitch} \]

\[ \text{OPTICAL FIBER} \]

\[ \text{FIRST ORDER = 40%} \]

\[ \text{+1ST ORDER = 40%} \]

**Figure 5**: Phase mask writing technique for fibre Bragg gratings. Silica glass phase masks are used for both 248nm and 193nm wavelengths [41].
transverse coherence of the excimer laser. The transverse coherence can be as low as the width of a few periods of the phase mask since the near field interference pattern is only weakly influenced by distant grating corrugations. The major drawback of the phase mask technique is the inability to tune the Bragg wavelength - each mask is manufactured for a particular UV wavelength and desired fibre grating period, \( \Lambda_{\text{fiber}} \). Recent work [45] has shown that by prestraining the fibre a wavelength shift of \( \sim 3 \text{nm} \) is possible. Another drawback is that, since the phase mask intensity pattern is a near field effect, the phase mask must be brought close to the fibre (typically within 100\( \mu \text{m} \)). The close proximity to the fibre also implies a close proximity to the focus of the UV beam - this can cause degradation of the phase mask over time due to a build-up of low level damage. The previous two problems were partly dealt with by Rizvi et al. [46] who used an imaging objective to interfere the two first-order beams. This allowed the phase mask to be illuminated by a low intensity UV beam, as well as allowing the phase mask to be situated far from the fibre. The drawback was a more complicated optical system.

Despite the limitations outlined above, the phase mask is now the most commonly used technique for mass manufacturing of fibre gratings. This dominance is mainly due to two factors: the technique’s inherent simplicity, and the current demand for many gratings at fixed wavelengths (as opposed to gratings at many wavelengths). Figure 5 shows a schematic diagram of the phase mask writing technique.

**Transmission Mask Projection**

First demonstrated in 1994 [47], gratings can be written by projecting the image of a
mask onto the fibre using a demagnification lens. Figure 6 shows the phase mask projection technique. This method allows the grating period to be changed by simply changing the mask. Strong type II gratings were formed using this technique. However, reflections at 1550nm required a second order (or higher) Bragg reflection since the smallest grating spacing that could be imaged was 1μm. Although simpler than the holographic technique (described below), transmission mask projection requires an aberration-corrected UV imaging lens. Good lateral coherence is required for this technique.

**Holographic Writing**

Holographic writing of gratings involves splitting the UV beam into two separate beams and then intersecting them on the fibre, creating a standing interference pattern on the fibre. Figure 7 shows the layout for the holographic writing technique. The holographic technique was first demonstrated by Meltz in 1989 [9] and has been subsequently developed to the point where type II gratings of high reflectivity can be produced on a fibre draw tower at varying peak wavelengths [48] - very attractive for future WDM applications. The
wavelength tunability is achieved by tilting one of the mirrors so as to affect the angle of interference of the two beams. This technique requires good temporal and spatial coherence. The major problem which precludes wider acceptance of this holographic approach is the high degree of stability required - optical benches and thermal shielding are necessary to produce quality gratings. In addition, any holographic setup requires multiple optical components which makes this the most complex of all the grating fabrication techniques. Nevertheless, the combination of the ability to tune the Bragg wavelength rapidly and the benefit of a large working distance, mean that the holographic method will continue to attract attention.

Figure 7: Holographic technique for writing fibre Bragg gratings on a fibre draw tower with a KrF laser. The period of the grating can be tuned by rotating mirrors M3 and M4 [48].

The advantages and disadvantages of the fibre Bragg grating writing techniques are summarized in Table 3.
Table 3: Comparison of fibre grating writing techniques.

<table>
<thead>
<tr>
<th>Bragg Writing Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Internal Writing        | *Long Gratings  
* Fairly simple | *Slow  
* No IR gratings |
| Lloyd’s Mirror          | * Simple  
* Tuneable | * Short gratings  
* Requires good coherence |
| Point-by-Point          | * Long gratings  
* No coherence requirement | * Slow  
* Less accurate |
| Prism Interference      | * Simple | * No rapid tuning  
* Requires good coherence |
| Phase Mask              | * Stable  
* Simple | * No tuning  
* Close working distance |
| * this thesis *         |            |               |
| Mask Projection         | * Simple to change mask  
* Large working distance | * Long period only  
* Complicated |
| Holographic Writing     | * Tunability  
* Large working distance | * Stability problems  
* Complex |

2.5 Applications of Bragg Gratings

This section will deal briefly with some of the more recent applications of Bragg gratings. This review is by no means comprehensive - it only serves to illustrate the reasons underlying the explosive growth of this industry. Broadly speaking, applications of fibre Bragg gratings fall into two distinct categories: sensors and communication devices. The original focus for spinoff applications of photosensitivity research was centred around the potential of Bragg gratings in WDM networks. While it is still likely that communications
applications will eventually be the largest consumer of fibre grating technologies, it is the sensor applications that have seen the first real commercial usage. Each technology will be briefly discussed below.

Sensor Application

The two main sensor applications where Bragg gratings are currently in use are: strain and temperature gauging. A change in temperature produces a shift in the Bragg wavelength of a grating. The shift is a result of the dependence of index on temperature and the result of thermal expansion of the fibre. The equation governing the shift in the Bragg wavelength is given by [36]:

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

In equation (16) \( \alpha \) is the thermal expansion coefficient and \( \xi \) is the thermooptic coefficient. For standard germanosilicate fibres the wavelength shift is \( \sim 0.006 \text{ nm/}^\circ \text{C} \). The induced Bragg wavelength due to an applied longitudinal strain, \( \epsilon \), on the fibre is given by [36]:

\[
\frac{\Delta \lambda_{\text{Bragg}}}{\lambda_{\text{Bragg}}} = (1 - p_e) \epsilon
\]

The variable \( p_e \) is the photoelastic constant which, for silica, results in a wavelength sensitivity of 0.05 nm/kpsi. Strain gauges are useful for monitoring the long term shift in concrete structures. Typically, the gratings are imbedded in the concrete as it is poured and
the back reflection is monitored over time.

**Communications Applications**

While applications for gratings in the communication field are many a few broad application areas can be identified:

- Mode Conversion
- Dispersion Compensation
- Wavelength Selection and Tapping
- Filtering and Reflecting

Mode conversion involves writing long-period gratings that enable switching between polarization states or fibre modes. Mode conversions that involve switching from one forward propagating mode to another (unlike the Bragg reflector which converts a forward mode into a backward mode) require a large grating period (100's of microns) in order to satisfy the phase-matching condition. Gratings for mode conversion are written by the point-by-point technique [49].

Dispersion compensation is accomplished by chirping a grating (varying the pitch of the grating along its length) so that different wavelengths are each reflected at a different point along the grating. A chirp can be applied by aligning a phase mask at an angle to the fibre before exposing the fibre to the UV writing laser. Chirped gratings can also be used for pulse compression and expansion.

Wavelength selection is performed by tuning a grating to selectively filter a particular wavelength while passing others. Crucial to these devices is the speed that the grating can be
tuned to the desired wavelength and the magnitude of the losses imposed by the device on the non-selected wavelengths. A wavelength selectable tap has been demonstrated [50] by photo-inducing a grating into both arms of a Mach-Zehnder interferometer. By tuning both of the gratings to reflect at a wavelength corresponding to a channel in a WDM system that channel can be either added or dropped. All other wavelengths pass through the interferometer unaffected.

Using Bragg gratings as reflectors has been an important development in the commercialization of erbium-doped fibre amplifiers. Gratings, placed on either side of the erbium-doped amplification region, serve as the lasing cavity mirrors thus permitting a lower pump energy for the fibre laser.

2.6 Justification of Direction of Exploration

Sections 2.1 through 2.5 have outlined the current state of the photosensitivity research effort, highlighting the best results and techniques used to measure these results. This section will present arguments towards justifying the need for a research effort at shorter wavelength UV photosensitivity. Once the grounds underlying the significance of the work had been laid, decisions about the parameter space (fibre types, fluences, fibre treatment) to be explored were made. These decisions will be outlined, as will the decisions relating to the selection of the most appropriate photosensitivity measurement technique. Finally, reasons for the Bragg grating writing technique used in this thesis will be discussed.
**Justification for 157nm Photosensitivity Study**

One of the clear trends of the photosensitivity research effort to date is that a move to a shorter illumination wavelength produces a greater photosensitivity response. For the same net fluence (fluence \(\times\) total pulses) the 193nm **type I** photosensitivity mechanism produces a higher index change than the 248nm mechanism. The same trend is likewise true for the 248nm response as compared with the 488nm response. Two factors point to an even greater photosensitivity response at 157nm. First is the plausible assumption that shorter illumination wavelengths produce an increase in the number of electrons directly excited to the conduction band of silica via an efficient one-photon process. The second factor is the observation, by Hill and co-workers [5] with the two-photon mechanism at 193nm, that conduction band electrons seem to be an efficient photosensitivity pathway (compared to direct defect generation by sub bandgap photons). This leads to the conclusion that 157nm might be a very efficient mechanism owing to the fact that its wavelength lies close to the conduction band edge in silica and, therefore, should efficiently produce conduction electrons via a one-photon process. Adding to the argument of a potentially strong mechanism at 157nm is the absorption band centred at 160nm associated with the peroxy radical. These postulations lead to the belief that an investigation of fibre photosensitivity at 157nm was certainly a worthwhile endeavour. If a strong response was found, there is potential for immediate commercial applications.

**Photosensitivity Parameter Space**

It was decided at the outset that the photosensitivity response should be measured at
a wavelength range common to both the published literature (for comparison purposes) and industrial use (for practical purposes). The second criterion offered a number of wavelength regions. However, the bulk of the published work to date has reported on photosensitivity responses of fibres in the 1550nm telecommunications region. This was therefore the wavelength region chosen for the 157nm study.

The selection of the fibre types which could best give a picture of the 157nm photosensitivity mechanism was again heavily influenced by the desire to compare the responses directly with fibres used in 248nm and 193nm studies. This meant selecting a standard telecommunications fibre with low germanium doping and, conversely, a supposedly more UV sensitive fibre with a higher core germanium concentration. There was thought of studying a pure silica core fibre (in which photosensitivity has never been measured) but this was abandoned since a primary focus of the research was on comparing the 157nm response with the longer UV responses. Pure silica core fibres have not been characterized at either 248nm or 193nm.

To complement the study of the effect of increasing the germanium dopant it was decided to test both fibre types treated with one of the hydrogenation techniques. Low-temperature high-pressure hydrogen loading was chosen because it was the treatment most commonly reported in the literature. As stated in section 2.1, hydrogen loading is typically performed at pressures in excess of 100atm. These high pressures were unobtainable with the equipment in our laboratory, so 10atm was used for a longer period.

The remaining variable to be determined was the laser fluence. Three fluences were selected. The highest fluence was simply the fluence produced near the focal plane of a MgF₂
cylindrical lens purchased for these experiments. Care had to be taken to ensure that this high fluence would not damage the optical materials. The lowest fluence was based on driving a measurable index change within a limited time. The intermediate fluence was chosen to be the mid fluence between the maximum and minimum fluences when plotted on a logarithmic scale.

In summary, the parameter space chosen for this 157nm photosensitivity investigation was:

- Photosensitivity study of 1550nm wavelength region
- Standard (low germanium) single mode telecommunications fibre
- High germanium single mode fibre
- Moderate pressure hydrogen loading for an extended period for both fibre types
- Exposure of each fibre type to three fluences

**Photosensitivity Measurement Technique**

The selection of the photosensitivity measurement technique was achieved by the dual process of elimination and consultation. Since absolute index changes were to be quantified, all of the techniques involving writing Bragg gratings were eliminated. Direct observation of the index change was eliminated since a profile of the evolution of the index change as the fibre was exposed was to be obtained. This left one of the three interferometric techniques. The far field method was initially considered but ultimately eliminated due to the difficulty of physically laying out the interferometer in our vacuum chamber. The Mach-Zehnder approach was considered next. However, as 3dB couplers had to be outsourced, the constant resplicing
of test fibres into the interferometer was going to prove to be expensive. Discussions with T. Alavie (of ElectoPhotonics Corp.) and his subsequent furnishing of a technique to mirror fibre ends finally led to a decision to use the Michelson interferometer for the photosensitivity studies. ElectoPhotonics agreed to supply \textit{in kind} a 3dB coupler. The chemicals needed for fibre mirroring were readily available locally.

**Bragg Grating Writing Technique**

As with the photosensitivity study, the decision about the best technique for producing a Bragg grating was a process of elimination. The internal technique and mask projection technique were eliminated for various reasons, not least of which is that they can not produce gratings in the 1550nm spectral region. The Lloyd's mirror method was considered because of our earlier results with grating writing on PMMA, but was ultimately eliminated due to the low transverse coherence of our laser. The relatively low coherence of the F_2 laser also eliminated the prism method. The holographic and phase mask projection techniques were eliminated as our vacuum system is not large enough to contain optical systems with many optical elements. Finally, the point-by-point method was unattractive from two standpoints: multiple optics required for a tight focus and the lack of an available precision stepper stage. This left only the phase mask approach as a viable technique.

The phase mask was an attractive approach providing direct comparison with the large effort for writing gratings at 248nm and 193nm. A major problem with the phase mask approach was the requirement that a custom non-silica phase mask be constructed with transmission at 157nm.Magnesium fluoride (MgF_2) is the most commonly used optical
material (out of a small range of possible materials) for transmission in the vacuum ultraviolet (VUV) region. Once it was confirmed that an experimental MgF$_2$ phase mask could be produced, the phase mask fibre grating writing technique was solidified as the optimum choice.

The completion of the literature review and subsequent selection of the materials and techniques to be employed finished the planning phase of the investigation. The next step was the actual experimentation, which will be described in the next chapter.
Chapter 3

Experimental Setup

This section will describe the experimental setup and data collecting techniques for the photosensitivity measurements and grating fabrication.

3.1 Equipment Modifications

The F₂ laser used in this project is one of a handful of fluorine lasers available in the world. The laser vessel was home-built in this lab [51] and has been in operation for about five years. Extensive modifications were carried out by this author in 1995 to alleviate a drop in the laser energy that had occurred due to the photo-degradation of the coatings of the internal capacitors. The operating characteristics of the laser used for the present study are summarized in Table 4.

Table 4: F₂ laser parameters.

<table>
<thead>
<tr>
<th>Laser Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>157nm</td>
</tr>
<tr>
<td>Pulse Duration [51]</td>
<td>~15ns (FWHM)</td>
</tr>
<tr>
<td>Spectral Width [51]</td>
<td>0.005nm</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>~40mJ (+/- 20%)</td>
</tr>
<tr>
<td>Beam Area</td>
<td>8mm x 12mm</td>
</tr>
<tr>
<td>Beam Divergence [51]</td>
<td>2×10⁻³ radian</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>1-2 Hz</td>
</tr>
<tr>
<td>Typical Gas Fill</td>
<td>150 mTorr F₂ (10%,He balanced); 9.5atm He</td>
</tr>
</tbody>
</table>
Recently a high-pressure gas recirculator was added to the laser. This dramatically improved the lifetime of a gas fill from ~1 hour to ~6 hours, thereby allowing long duration experiments to be undertaken.

157nm radiation is strongly absorbed in air. As a result, the beam was directed through evacuated beam tubes to the experimental chamber. A schematic diagram of the vacuum assembly is shown in Figure 8. The vacuum system was pumped by a mechanical/turbo pump (Leybold TMP/NT 50) combination which was capable of reaching pressures of 5x10^-7 Torr. Electrical feedthroughs provided external control of an X-Y translation stage. This stage, mounted perpendicular to the incident beam, provided the means to position the sample precisely in the beam path. Beam energy is measured by flipping a MgF₂ optical flat (serving as a beam splitter) into the path of the 157nm beam and redirecting a portion of the beam onto a scintillating detector (Star Tech VHR-0020-1295, SN-0200). Energy calibration was performed to correlate the Star Tech voltage measurement to the actual beam energy (see below). A MgF₂ cylindrical lens (Interoptics, R₁=50mm, R₂=∞), with a focal length of 10.5cm at 157nm, was positioned in the beam and could be translated longitudinally via a micrometer to control the laser fluence on fibre samples.

The X-Y translator was modified by milling a one-inch hole through its breadboard to allow the beam to pass through the translator and out of the experimental chamber through a scintillating (Star Tech - model number not given) window. These modifications allowed the fibre to be accurately positioned in the path of the beam. The inclusion of a scintillation crystal in the output port allowed monitoring of the position of the beam as the fibre was exposed for both the photosensitivity and grating experiments.
Figure 8: Schematic diagram of $F_2$ processing chamber used for photosensitivity and Bragg grating experiments.

Figure 9: Photograph of vacuum chamber showing test bed mounted on X-Y translator and lens at the 4cm exposure position.
The final modification to the existing chamber was the modification of a KF flange to allow for two fibres to be fed into the vacuum chamber. A 1mm by 10mm slot was cut into an existing flange, the fibres were placed in the flange, and vacuum compatible epoxy (Torr-Seal) was used to hold the fibres in place.

A hydrogen loading setup was assembled using stainless steel tubing connected to a pump and hydrogen bottle. Fibres were date-stamped when placed under pressure to ensure that fibres were loaded for at least four weeks. The loading pressure was ten atmospheres.

As stated previously in section 2.5, two fibre types were chosen for study. For the low germanium fibre Corning (SMF-28) single-mode fibre was chosen due to its common usage and its previous citations in the literature. The core germanium content is 3% for this fibre. The high germanium fibre was an AT&T (JRFTV 1066AITV) single-mode fibre having a core germanium content of 7-8%. This fibre was selected because it was used at the Ontario Laser and Lightwave Research Centre (OLLRC) to produce gratings with a KrF laser. Both fibres were sourced from the OLLRC. Each fibre has a core diameter of 25μm and a cladding diameter of 125μm. We were unable to obtain the cladding composition for either fibre.

3.2 Energy Calibration

The F₂ laser beam profile and fluence were characterized at several positions behind the cylindrical lens by measuring ablation profiles produced on PMMA - a material well studied by our group [7]. The cylindrical lens was placed at six different distances from each sample (4cm, 6cm, 8cm, 9cm, 10.5cm, and 10.7cm) and 10-100 laser pulses were irradiated for each sample. A wire mesh was place over each sample prior to ablation to produce a
reference height in determining the etch profile. The beam energy was measured by the Star Tech detector before and after each exposure. The width of the ablated region ranged from 1mm at the 10.5cm lens position (focal plane) to 8mm at the 4cm lens position. The centre beam position was carefully marked on each sample and 1mm scratches were scored on the edge of the sample on either side of the centre mark. A depth profile of the etched surfaces was recorded by a stylus profilometer (Tencor, alpha-step 200) and the maximum etch depth was at eleven points were measured. Fluences were extracted from the data in Figure 10 [52], which shows the etch rate versus fluence on the same type of PMMA. A logarithm fluence dependent fit of the data yielded a threshold fluence of was $F_{th} = 9.7\text{mJ/cm}^2$ and an effective absorption coefficient of $\alpha=2.3\times10^5\text{cm}^{-1}$. The extracted fluence values are shown in Figure 11 as a function of position along the PMMA sample for each cylindrical lens position. The maximum fluence was $\sim450\text{mJ/cm}^2$ at the 10.5cm position and the minimum was $\sim25\text{mJ/cm}^2$ at the 4cm lens position. These two fluences, together with a value of $100\text{mJ/cm}^2$, were selected for the VUV photosensitivity studies. Figure 10 also shows the lateral energy falloff of the beam. It was desirable to maximize the exposed length of the fibre while still maintaining a top-hat beam energy profile. An aperture diameter of 5mm was chosen to best meet these conflicting requirements. A 5mm aperture would give a maximum transverse beam variance of $\sim20\%$ at the lowest fluence lens position - comparable with the 20% pulse-to-pulse variation of the laser energy.
**Figure 10:** Etch rate of PMMA plotted as a function of fluence for irradiation with 157nm laser radiation [52].

\[
\alpha = 2.3 \times 10^5 \text{ (cm}^{-1}\text{)}
\]

\[
F_{th} = 0.0097 \text{ (J/cm}^2\text{)}
\]

**Figure 11:** Calculated fluence versus lateral beam distance for six cylindrical lens positions.
3.3 Fibre Photosensitivity Measurements

Design of Test Bed and Experimental Setup

To perform the fibre photosensitivity study it was necessary to fabricate a fibre test bed. The design was limited by availability of space in the vacuum chamber. The basic components of the test bed were: two excess fibre winding spools, a 3dB coupler fashioning area, an exposure area, and a fibre to fibre coupling area. Schematics for the test bed are shown in Appendix A. The aluminum test bed was nickel plated for vacuum compatibility. A stainless steel plate with V-grooves (to guide the fibres) was inlayed into the main piece, which provided a means to magnetically clamp fibres as shown in Figure 12. Mounting holes for the X-Y translator were drilled in the aluminum block allowing the fibre to be positioned either horizontally or vertically in the beam. All experiments for this thesis were carried out with the fibre mounted horizontally. Once the 3dB coupler had been mounted on the test bed it was not moved for the duration of the photosensitivity measurements.

Figure 13 shows a schematic diagram of diagnostics used for measuring index-of-refraction changes in situ during 157nm laser exposure. A tunable laser source (Radians Innova, Intun 1500) was launched into the Michelson interferometer through a Faraday isolator (ExB H1-140) to prevent back reflections. The isolator output was coupled via a bulkhead connector to one of the two metre fibre lengths that had been epoxied to the KF vacuum flange. Both ends of the two metre lengths of fibre were terminated with FC/APC connectors. To connect the bare fibre output of the isolator to the bulkhead connector, temporary (ExB) connectors were used. Great care was used when connecting the temporary connectors as coupling efficiencies can easily be changed by 200% by wiggling the connector. Once a good
Figure 12: Photograph of photosensitivity test bed showing fibre spools, fibre couplers, magnetic holders, 3dB coupler and the aperture mask.

Figure 13: Schematic diagram of setup used during photosensitivity measurements showing the main diagnostic tools.
coupling was ensured both sides of the bulkhead connector were taped to the table and protected. Inside the chamber the feedthrough fibre was joined to one of the input arms of the 3dB coupler via a second bulkhead connector.

The output of the interferometer was coupled to the second fibre that feeds from the vacuum to the outside of the chamber via a third bulkhead connector. The final connection used a fourth bulkhead connector to join the feedthrough fibre to the detector. The detector (PD/LD PLD-DIN-075-PH1-1FA) was an InGaAs semiconductor photo diode which is sensitive in the 1550nm wavelength region. The detector signal was amplified using an amplification circuit supplied by ElectroPhotonics (T. Alavie) and connected to channel A of a digital oscilloscope (Tektronix, 2439). See Appendix B for details of the amplifier circuit. Channel B of the oscilloscope was connected to the signal from the energy detector. The sensitivity setting for the detector was placed at position three (least sensitive). The detector and amplifier circuit, oscilloscope and tunable laser were all enclosed in a Faraday cage to minimize EMF noise form the high voltage F2 laser discharge. It was found that even with the suppression afforded by the Faraday enclosure measurements were best carried out from 10pm to 7am when noise from sources in the building were at a minimum.

**Preparation of Fibre for Exposure (Michelson Interferometer)**

The procedure for preparing a fibre which is to have its photosensitivity measured is described here:

- Turn on tunable laser, detector amplifier, and oscilloscope at least ten hours prior to exposure and set the built-in temperature controller to 23°C.
- Obtain a ~25cm piece of test fibre and strip the buffer (Lepage Poly Strippa for ~1 minute) from one of the ends. Clean with isopropanol and cleave the end (Fitel, #321). Ensure the end facet of the fibre is flat and particle free.

- Mirror the fibre end (see Appendix C for details) and protect with small diameter PVC tubing cut in 2.5cm lengths.

- Cleave and clean the other end of the test fibre in a similar manner, being careful to ensure that the lengths of the interferometer arms will differ by 2-3cm (discussed below) after the test fibre has been fused onto the interferometer arm.

- Prepare the interferometer arm to receive test piece by cleaving and cleaning end. If the interferometer is becoming too short (~2cm is lost for each test fibre) splice on an extension piece.

- Fuse interferometer arm and test piece (Tritec Developments Ltd, Fase II) and protect with PVC sheath (put sheath on test fibre before making last cleave to ensure a clean end).

- Wrap both arms of the interferometer together ensuring that the fibres remain in contact with each other (a long-period braid is helpful) and the aluminium block - this will dramatically help with thermal stability.

- Coil excess fibre around spools until area to be exposed can be placed between grooves of the stainless steel insert.

- Place fibre to be exposed in bottom V-groove and non-test arm of the interferometer in the top V-groove - this is the only point where the fibres should be separated.

- Remove about 1cm of buffer from the test piece where it is to be irradiated and clean bare fibre.
Secure fibre with magnetic strips and fashion 5mm aperture so that the fibre area to be exposed runs through the diameter of the aperture.

Secure any loose fibre with tape to ensure good contact with the aluminium.

Inspect bare fibre to ensure it is clean - air brush if necessary.

Attach fibre feedthrough connectors for the laser source and detector output to the bulkhead connectors mounted on the test bed.

Turn on tuneable laser and set to 1mW output power at ~1550nm; switch to Δν mode and tune through +/-10Ghz range, ensuring that a good cosine response is mapped out by the frequency tuning.

Output power on the oscilloscope should peak at at least 600mV with a minimum < 50mV.

Unsatisfactory power or large minimum values can be caused by (in order of least to most time consuming to fix): feedthrough cables are overly bent, weak connections, fibres wound too tightly on spools, bad splice, poor fibre mirror.

If power is adequate, mount test bed on X-Y translator and retest interferometer output.

Check fibre position for orthogonality by comparing orientation to side wall and bottom of vacuum chamber - adjust with X-Y translator if necessary.

Position back (flat side) of lens to desired distance from fibre.

Place lid on chamber, position beam splitter so that the 157nm beam is directed to energy metre, and begin pump down.

Best results are obtained if the chamber is allowed to pump for at least eight hours.

The test fibre is now ready to be exposed. Typically it took two hours to prepare a fibre for exposure. The total length of each of the interferometer arms was ~40cm. This allowed up
to three exposure areas per test fibre. All hydrogen loaded fibres were exposed within 12 hours of being removed from the high pressure system. Photographs were taken of the exposed areas of the fibre for each of the three fluences using a microscope (Leica, DMR/ME).

**Interferometer Arm Length Difference**

The need to unbalance the interferometer arms can best be explained by example. If the arms are exactly equal in length then no amount of wavelength tuning will alter the phase of the output of the interferometer. If the arms are unequal in length ($\Delta L$) by exactly one wavelength ($2\lambda$ total difference), to tune through a phase difference of $\pi$ the tuning wavelength has to be shifted by $\lambda/4$ (for the Michelson interferometer). If the length difference is $100\lambda$ then a tuning of only $\lambda/400$ is required to produce a $\pi$ phase shift. A 2cm length difference (4cm total path) equals an $\sim 5300\lambda$ total path length difference. A $\pi$ phase shift can then be created by shifting only $\lambda/10600$. At 1550nm $\lambda/10600 = 0.14\text{nm}$. The tuning resolution of the laser diode driver was 0.001nm so at least a 2cm difference in the interferometer arm lengths was required be able to tune through a few cosine squared periods.

**Measurement of Fibre Photosensitivity (Michelson Interferometer)**

Once the fibre had been pumped for 12 hours and was ready for exposure, the actual photosensitivity measurements were taken in the following manner:

- Fill laser with new gas; fill recirculator with liquid nitrogen.
- Confirm maximum and minimum of interferometer are acceptable by tuning the laser diode.
- Check drift of interferometer (see separate discussion below).
- Start laser.
- Take vacuum energy measurement of $F_2$ laser pulse (ten pulse average).
- Fill vacuum chamber with argon to just under atmospheric pressure (keeping a good seal on the O-rings).
- Wait until drift is within acceptable range (~5-10min) and record laser energy; adjust $F_2$ laser voltage to get a ten pulse average peak reading of 135mV on the oscilloscope.
- Adjust tuneable laser frequency so that the oscilloscope reading is positioned at the midpoint of the peak-to-peak value: $(\text{MAX}-\text{MIN})/2 + \text{MIN}$ - this is the most sensitive position.
- Rotate the beam splitter so that the 157nm beam will irradiate the test fibre.
- Trigger laser pulse.
- Wait 45 seconds (for thermal relaxation) and record oscilloscope reading.
- Repeat previous two steps, gradually increasing the number of pulses between each reading.
- Every 500 pulses, an $F_2$ laser energy reading should be taken and the drift should be monitored. If the measured ten pulse average energy falls below 115mV then the chamber needs to be evacuated by the turbo pump at full speed for five minutes and refilled with argon.
- Two techniques were used to confirm the alignment of the fibre in the UV beam. A strong visible blue-violet fluorescence can be seen emanating from the fibre after each pulse - the fibre is aligned properly when this fluorescence is the strongest. The fibre can also be aligned by monitoring the thermally induced index change per pulse as the fibre is translated though the beam - the fibre is positioned correctly when the thermal index change
is a maximum.

- When the experiment is compete, confirm: interferometer drift, fibre placement, peak-to-peak interferometer values (this will typically have changed - especially for high fluence experiments)

Photosensitivity data is in the form of detector voltage versus laser pulse. The detector voltage can be treated as the intensity once the minimum has been subtracted and the voltage values have been normalized to the maximum value. The index change is calculated using equation (13). At the zero points of the cosine curve, multiples of \( \pi \) phase have to be added to ensure that the index change progresses in one direction.

**Measurement Drift**

During the addition of argon, pumping of the chamber or firing of a pulse, large swings in the interferometer output were observed due to thermal fluctuations in the interferometer arms. However, once the fluctuations had died, down there was a persistent, slower, drift in the detector output. The drift would slowly trace out the cosine response of the interferometer. The drift was observed to travel in both directions. To minimize the effect of the drift, no fibre was exposed until the drift was less than 1% of the maximum value over ten minutes when measured at the midpoint of the cosine response. This corresponded to a maximum false index change of \( \sim 4 \times 10^{-7} \) every ten minutes. A typical 7000 pulse experiment would last about 2.5 hours. The drift decreased the longer the fibre setup was allowed to sit prior to exposure. As a conservative measure, all experiments for this thesis were carried out so that the real index change produced a response in the opposite direction of the drift.
3.4 Fibre Grating Experiments

As a proof of principle of grating writing at 157nm, fibres were initially exposed in our lab then characterized externally using a broadband LED source and a spectrum analyser (Hewlitt Packard, 70951A OSA). The back reflection from these early gratings confirmed the potential of 157nm photosensitivity however, ex-situ characterization was undesirable as it did not allow characterization of a grating’s growth. In order to properly study gratings produced by 157nm illumination an in situ experimental setup was designed.

The same test bed for the photosensitivity study was used for the Bragg grating experiments except that the MgF$_2$ phase mask (Lasiris, PM-152-1.071-24.5) was added. The phase mask has a period of 1.0694μm which is the correct period for producing a grating that reflects at 1550nm. The measured zeroth order energy of the phase mask was 11%. The phase mask was mounted in a kinematic mount (Thorlabs, KCl) which, in turn, was mounted to the test bed by two screws. The kinematic mount was a modification of a traditional mount such that the point of the mount that is normally fixed was replaced by a fine thread screw. This afforded an ~3mm linear travel in the mount. The ability to translate the mount allowed the mask to be brought flush into contact with the fibre. A spectrum analyser, computer and tuneable laser were borrowed for one day to carry out the in situ grating experiments.

The setup used to produce a fibre grating and record in situ index changes is shown in Figure 14. The setup used the 3dB coupler to allow the grating’s reflection and transmission spectrums to be measured as the laser was pulsed. The spectrum analyser was operated in power mode. A tuneable laser was set to continuously scan through a wavelength range at an output power of 0.9mW. The wavelength scan time was adjusted to equal the sweep time of
the spectrum analyser. The wavelength scan rate was set to 1 nm per second and the scan range was set from 1545 nm to 1555 nm. Spectra of the signal from the grating were captured on computer (IBM compatible) for later analysis.

**Preparation and Exposure of Fibre (Bragg grating)**

The fibres were prepared and exposed in the following manner:

- Obtain test piece of fibre ~30 cm in length.
- Cleave and clean both ends of the test fibre and mount ends in temporary connectors.
- Attach temporary connectors to bulkhead connectors mounted on testbed.
- Strip and clean a 2.5 cm length of the fibre.
• Mount fibre with magnetic strips in centre V-groove of stainless steel insert.

• Mount testbed in vacuum chamber and confirm alignment of the fibre with the beam.

• Attach fibre feedthroughs and confirm laser diode signal on spectrum analyser for both reflection and transmission signals - this can be a lengthy process.

• Remove testbed from chamber and mount phase mask, making sure the mask is initially positioned well away from the test fibre.

• Using binocular microscope (Cambridge Instruments, StereoZoom 6) and fibre optic illuminator (Dolan-Jenner, Heavy-Duty), carefully bring phase mask close to fibre - this is a painstaking endeavour.

• Mask is positioned correctly when the distance between the phase mask and the fibre is less than half the diameter of the fibre and the fibre/phase mask distance is equal on both sides of the phase mask.

• Reconnect fibre feedthroughs and carefully mount the testbed in the vacuum chamber

• Position lens for desired fluence (correcting for both the change in the focal plane due to the presence of the phase mask and the absorption of the phase mask - assume a 20% absorption loss of the 157nm energy in phase the mask).

• Pump vacuum assembly to at least 5x10⁻⁴ Torr.

• Turn on laser and confirm energy.

• Expose fibre recording peak reflection spectrum measurements (frequency of measurement will depend on fibre response).

• Monitor laser energy periodically throughout exposure.

• After grating has saturated record transmission spectrum.
The setup shown in Figure 14 required five temporary connectors and four bulkhead connections. Each bulkhead connection had a measured transmission efficiency of ~25%. Due to all these losses the power at the spectrum analyser was ~1/200th of the tuneable laser’s stated output power. Two hydrogen loaded fibres were tested with the in situ setup. The test fluences were 360mJ/cm² and 25mJ/cm².
Chapter 4

Results

4.1 Photosensitivity

Photosensitivity results, calculated from the measured output of the Michelson interferometer, for the four fibre conditions (two fibre types; hydrogen loaded versus not hydrogen loaded) are given in Figures 15-18. Figure 15 is the photosensitivity response for the non-hydrogen loaded Corning fibre. The response for the three fluences are shown in the figure. Figure 16 shows the same results for the hydrogen loaded Corning fibre. Figure 17 shows results for the non-hydrogen loaded high germanium fibre while Figure 18 shows the results for the hydrogen loaded high germanium fibre. Note different vertical scales. The normalized raw data used to generate the 100mJ/cm² curve of Figure 15 is shown in Figure 19. Also displayed in Figure 19 are the energy readings taken during the fibre exposure. The energy readings are normalized to the energy reading taken when the system was under vacuum.

A more comparative way to look at the fibre responses is to plot the four fibre types together for the same fluence. Figures 20, 21, and 22 show the responses of the four fibre types to laser fluences of 25, 100, and 450mJ/cm² respectively.

Figure 23 shows the reflection spectrum of a grating after 5000 pulses illuminated by a fluence of 360mJ/cm². Figure 24 shows the transmission spectrum for the same grating. The peak reflectance is ~70%. In Figures 23 and 24 the peak reflectance was measured at
1548.35nm. Figure 25 depicts the index change (as calculated from equation (2)) as a function of laser pulse for the grating of Figures 23 and 24. Also shown on Figure 25 is the photosensitivity response of the same fibre type illuminated by a fluence of 450mJ/cm² as measured by the Michelson interferometer. Figure 26 shows the 0.18nm FWHM reflection spectrum of a grating produced at 80mJ/cm² for 100 pulses. The transmission spectrum for this grating was not observed but the reflectivity was estimated to be 2-5%.
Figure 15: Plot of index change versus laser pulse for Corning SMF-28 fibre irradiated by 157nm radiation at three different fluences.

Figure 16: Plot of index change versus laser pulse for hydrogen loaded Corning SMF-28 fibre irradiated by 157nm radiation at three different fluences.
Figure 17: Plot of index change versus laser pulse for AT&T 8% Ge fibre irradiated by 157nm radiation at three different fluences.

Figure 18: Plot of index change versus laser pulse for hydrogen loaded AT&T 8% Ge fibre irradiated by 157nm radiation at three different fluences.
Figure 19: Normalized raw data for Corning SMF-28 fibre exposed to 100mJ/cm² laser pulses. Also shown are the normalized energy readings taken during the exposure.

Figure 20: Plot of index change versus laser pulse for all four fibre types irradiated by a fluence of 25mJ/cm².
Figure 21: Plot of index change versus laser pulse for all four fibre types irradiated by a fluence of 100mJ/cm².

Figure 22: Plot of index change versus laser pulse for all four fibre types irradiated by a fluence of 450mJ/cm².
Figure 23: Reflection Spectrum of grating after 5000 pulses of 157nm laser radiation. Writing fluence for this grating was 360mJ/cm². The periodic dips are due to a cavity effect in the setup and were visible in a baseline spectrum that was taken before the fibre was exposed.

Figure 24: Transmission spectrum of grating after 5000 pulses of 157nm laser radiation. Writing fluence for this grating was 360mJ/cm².
Figure 25: Calculated index change as a function of laser pulse for grating produced with a writing fluence of 360mJ/cm². Also shown is the index change versus laser pulse from the photosensitivity study of the same fibre irradiated at 450mJ/cm².

Figure 26: Reflection spectrum of a grating produced after 100 pulses of 157nm laser radiation at a fluence of 80mJ/cm².
Chapter 5

Discussion

This chapter will discuss the results presented in chapter 4 and relate their significance to the published literature described in Chapter 2.

5.1 General Observations

This work constitutes the first report on the photosensitivity response of optical fibres at a record short wavelength of 157nm. The efforts are noteworthy because of the special “vacuum” requirements for radiation absorbed by air, and the paucity of optical materials in the VUV region. A fibre Michelson interferometer was successfully adapted and stabilized for use inside a vacuum chamber, providing the most useful data for characterizing index-of-refraction changes induced in the fibre core. Lastly, the popular phase mask approach to writing Bragg gratings inside optical fibres was successfully extended to the 157nm wavelength in this research effort.

Some general observations can be made from the photosensitivity response curves presented in Figures 15-22. All fibres tested in this thesis demonstrated a photosensitivity response at 157nm. The responses followed a similar pattern for every fibre: an initial sharp response which levels off to a steady linear increase. This is clearly seen in the (typical) raw data plotted in Figure 19. The cosine squared response appears compressed for the first 500 pulses then takes on a more regular form as the linear response regime is entered. The reason underlying the initial rapid response and subsequent slower linear response remains unclear.
However it is typical of the photosensitivity responses at 193nm and 248nm. The only fibres to have reached saturation were the high germanium hydrogen loaded and non-loaded fibres exposed to the highest fluence. The saturation of these fibres was most likely caused by a damage mechanism (discussed below) which prevents the normal photosensitivity mechanism from occurring. The inability to saturate the remaining test fibres was due to the slow 1Hz repetition rate of the laser and overall thermal stability of the Michelson interferometer, limiting measurements to ~9,000 laser pulses per fibre sample.

Hydrogen loading of the fibres improved the photosensitivity response. Tenfold, fourfold and twofold increases in the photosensitivity response was found for the hydrogen-loaded low-germanium fibre when irradiated by low, medium, and high fluence, respectively.

Unsaturated index changes were order-of-magnitude comparable with those obtainable by 193nm and 248nm illumination. An unsaturated index change of $8.1 \times 10^{-4}$ was measured in a hydrogen-loaded low-germanium fibre after 9000 pulses at a fluence of 25mJ/cm$^2$ per pulse. Without hydrogen loading, the 3% Ge fibre provided an index change of $~8.0 \times 10^{-4}$ after 7500 pulses at 25mJ/cm$^2$. An unsaturated index change of $2.2 \times 10^{-4}$ was obtained in an untreated fibre exposed to 450mJ/cm$^2$ following 3000 pulses. This value is typical of the saturated index changes produced at 248nm and 193nm for this fibre (cf. Table 1). The low-germanium hydrogen-loaded fibres were more photosensitive than any of the other three fibre types at every laser fluence.

The 70% reflective grating shown in Figure 24 is typical of spectra seen for type II gratings at 193nm and 248nm. The peak wavelength was 1548.35nm and the bandwidth was $~0.5$nm (FWHM). The calculated index change per-pulse for the grating in Figure 25 differs
by a factor of two with the response curve of the hydrogen-loaded fibre at 450mJ/cm².

5.2 Per Pulse Index Changes

A more fundamental way to look at the photosensitivity responses of the four fibre types is to plot the index change per F₂ laser pulse. In Figure 27 the solid lines indicate a best fit to the linear region of the response curves of Figure 15. The slopes of these lines, for all four fibre types, are plotted in Figure 28 and represent the long-term linear response of the fibres in the form of index change per laser pulse. For comparison purposes the results of the 193nm work by Hill and co-workers [5] is plotted on the same figure. Slopes were unobtainable for both the loaded and unloaded high germanium fibres at the highest fluence due to the rapid, premature, saturation.

Three significant trends can be readily interpreted from Figure 28. The first trend points to a damage mechanism causing premature saturation of the index change for hydrogen loaded fibre at higher fluences (open squares and open circles on Figure 28). The second trend is the evidence for a one-photon absorption process (slope of curve ~1) for both non-hydrogen loaded fibre types (closed squares and closed circles on the Figure 28). The third trend is the relative insensitivity of the photosensitivity mechanism at 157nm to increased germanium core concentrations. Each trend will be discussed separately.

Fibre Damage at High Fluence

The decrease in the per-pulse index change at higher fluences in hydrogen loaded fibres (particularly the high germanium fibre) was a surprising result since hydrogen loading and
Figure 27: Plot of linear index change regions of Corning SMF-28 photosensitivity data. Solid lines are best-fit curves to data. The index change per pulse are calculated from the slope of the best-fit line.

Figure 28: Plot of index change per pulse versus irradiating laser fluence. All four fibre types are plotted. Open markers are for hydrogen loaded samples. Circle markers are for low germanium fibres. Square markers are for high germanium markers. 193nm data [8] are plotted for comparison purposes.
increased germanium are both techniques use to increase fibre photosensitivity to 193nm and 248nm radiation. At the intermediate and higher fluences, either a completely different photosensitivity mechanism is taking place for hydrogen-loaded fibres or the increased sensitivity is creating highly absorbing damage sites in the cladding and core which are, in effect, preventing any further photosensitivity response. Two techniques were used to investigate possible damage process in the fibres.

The first technique involved rotating a saturated fibre and exposing the other side. If a damage mechanism was preventing penetration of 157nm radiation into the core of the fibre, then the damages should be located preferentially on the laser-irradiated side of the fibre. To test this possibility, a high-germanium fibre was exposed until saturation (~200 pulses) and rotated 180 degrees. The same fibre was re-exposed to 157nm radiation until it was re-saturated. The second exposure is shown on Figure 17 as the open square data points. The premature saturation is evidenced by the increase in the index after the fibre has been rotated. The rotated fibre then saturated at a level less than twice the initial saturation level. This is to be expected since some of the initial pulses would have generated damage sites throughout the fibre. This observation is clear evidence that at higher fluences a damage mechanism creates absorption sites which caused premature saturation of the fibre photosensitivity. The increased sensitivity to damage by higher germanium levels (discussed further below) was a strong indicator that the damage was occurring in the core as well as cladding of the fibre.

The second technique used to investigate the damage was to view the 157nm exposed fibres under a microscope. Figures 29, 30, and 31 show photographs of fibre damage for fluences of 25mJ/cm² (~8000 pulses), 100mJ/cm² (~3000 pulses), and 450mJ/cm² (~800
pulses), respectively. The photographs all show an exposed and unexposed portion of the fibre. Fine radial striations are visible along the length of the exposed region of the fibre for all three fluences. The highest per-pulse fluence produced the most striations and the lowest fluence showed the least. Clearly, the damage mechanism is highly nonlinear given that each fibre in Figures 29-31 received approximately the same ~200J/cm² fluence dosage. The striations appeared to be throughout the fibre, and not localized in the core or in the cladding. Visual inspection of the surface of the exposed fibre shows it to be smooth within the resolution of the microscope. Figures 32 and 33 show the testbed and interferometer with 0.63μm light coupled into the exposed arm of the interferometer. Figure 33 is a closeup view of exposure region of Figure 32. In both figures a strong out-coupling of the light is noted in the exposed area of the fibre. A final indication of a damage mechanism was the high brittleness of the fibres exposed to 450mJ/cm². These fibres would easily break in the exposed region if not handled with utmost care.

The threshold for 157nm ablation of germanosilicate wafers was measured in this lab [6]. A threefold decrease in the ablation threshold (380mJ/cm³) was found for germanosilicate (3% Ge) wafers versus the threshold for fused silica (~1.1J/cm³). An irradiating fluence of 450mJ/cm² would then most likely create damage in the core which may propagate outward to the cladding region.

It is reasonable to conclude that at higher fluences a damage mechanism in the core and cladding of the fibre is preventing 157nm radiation from activating the normal type I photosensitivity mechanism. Further corroboration of this idea is the response of the fibres to the initial few laser pulses. In all fibre types (cf. Figures 15-18) at 450mJ/cm² the initial
Figure 29: Photograph of exposed and unexposed regions of test fibre. The exposed region (top) was irradiated with ~8000 pulses of 157nm radiation at a fluence of 25mJ/cm².

Figure 30: Photograph of exposed and unexposed regions of test fibre. The exposed region was irradiated with ~3000 pulses of 157nm radiation at a fluence of 100mJ/cm².
Figure 31: Photograph of exposed and unexposed regions of test fibre. The exposed region was irradiated with \(~800\) pulses of 157nm radiation at a fluence of $450\,\text{mJ/cm}^2$.

Figure 32: Photograph test bed with 0.63\,\mu\text{m} laser light coupled into the Michelson interferometer. Strong out-coupling of the light can be seen in the exposed region on the fibre. The aperture mask is folded back to reveal bare the fibre.
response of the fibre is a more rapid rise (~10 times) in index change compared with the lower fluence responses. After this rapid rise a damage mechanism then predominates and the measured index change quickly saturates.

**One-Photon Absorption Process**

The second significant trend discernable from Figure 28 is the fluence dependance of the photosensitivity response in non-hydrogen loaded fibres. Albert *et al.* [5] saw a two-photon process in low germanium fibres at 193nm, manifested by the slope of two in their data in Figure 27. This two-photon process stimulates electrons high into the conduction band.
where they efficiently produce colour centres. In order to have a two-photon process the absorption coefficient for a one-photon process must be low enough not to predominate. With low-germanium concentrations, the one-photon process at 193nm is sufficiently weak to allow an efficient two-photon process. It was not expected that a two-photon process would dominate at 157nm due to the strong (measured to be $-35\text{cm}^{-1}$) absorption of 157nm radiation in silica. The preponderance of silica defects in fibres and the reduction of the bandgap (to 7.1eV in 5% Ge glasses [6]) by the inclusion of a germanium dopant ensures a strong coupling of 157nm radiation into germanosilicate fibres. The slopes of the non-hydrogen loaded samples in Figure 28 were calculated using the relation:

$$\Delta n \propto F^b t$$

The derivative of $\Delta n$ versus time, $t$, yields the growth rate: $d(\Delta n)/dt = F^b$ ($F$ is the irradiating fluence). The slope of a log-log plot of index change per pulse versus fluence will yield the exponent $b$. Note that the index change per exposure time, $t$, and the index change per pulse are interchangeable since the pulse rate of the laser is constant. Albert et al. calculated a slope of $b=1.13$ for high-germanium doped fibres (indicative of a one-photon process) and $b=1.98$ for low germanium doped fibres (indicative of a two-photon process). Slopes calculated for our results are: $b=0.76$ for low germanium fibres and $b=0.93$ for the high germanium fibres. These values strongly point to a one-photon process photosensitivity process at 157nm. Premature saturation due to damage at higher fluences is the most likely cause of the deviation of both results to a value below a slope value of $b=1$. Most significant is the increase efficiency of the one-photon process at 157nm versus 193nm for low-doped fibres (same index
change per pulse at \(-1/10\) the fluence). This shows that the energetic 157nm photon is capable of exciting electrons into high conduction band states that can only be reached with two photons when using the 193nm ArF excimer laser source.

**Inn Sensitivity to Germanium Concentration**

The increase in germanium core concentration had little effect on the index change response of the fibres at the lowest fluence (25mJ/cm²). The relative independence of germanium concentration on index change is unsurprising in lieu of the decreased bandgap produced by the presence of germanium in the fibre. The 157nm photon carries enough energy to directly access above-bandgap states in germanium doped silica so that the absorption is linear and irrespective of germanium concentration.

At higher fluences the effect of increased germanium core concentration is an increase in the sensitivity of the fibre to damage. It is unclear at this time what specific role the germanium atoms play in the damage mechanism, although the strong linear absorption of 157nm radiation due to presence of germanium will tend to concentrate the laser energy in the fibre.

**5.3 Fibre Grating**

The fibre-grating transmission spectrum shown in Figure 24 shows a strong 70% reflection with lossy higher order modes at shorter wavelengths. The reflection spectrum of Figure 23 confirms the higher-mode losses since no reflections are seen at the corresponding wavelengths. The periodic dip in the reflection spectrum is due to a cavity effect created by
the couplers in the grating setup. The dips were of the same magnitude and spacing in a baseline spectrum before the fibre was exposed. The complex structure is thought to be due to a misalignment of the phase mask and the fibre. The phase mask used in this thesis was custom fabricated (Lasiris) on a circular optical MgF₂ flat. The circular nature of the mask made accurate vertical positioning difficult. An investigation of the effect of a misaligned phase mask by Dyer et al. [24] showed that the misalignment would create spikes in the grating’s spectral profile. Figure 26 shows a grating produced at low-fluences by an aligned phase mask. This grating has a 1-5% reflectance (based on input power and coupling loss estimates) and was characterized ex-situ four days after exposure. The low-writing fluence indicates that this grating was produced by a type I mechanism. Both gratings described above were confirmed by stretching the fibre and watching the peak wavelength shift. The fibre grating shown in Figure 24 had the same striations when viewed under the microscope as the striations produced in the Michelson interferometer photosensitivity study. The magnitude of the peak reflectance remained stable for two hours after exposure.

A comparison of the curves in Figure 25 shows that the calculated index change from the peak reflectance of the grating of Figure 24 is about 50% of the magnitude of the index change measured for the same fibre type by the Michelson interferometer. The factor-of-two magnitude difference can be explained in a number of ways. First, the fluence used for the photosensitivity measurement was 20% higher than the fluence used to write the grating. Second, the 11% zeroth order transmission of the phase mask may produce a DC index change in the fibre. This induced index change would have been on the order of the calculated Δn for the grating since 11% of the 380mJ/cm² writing fluence is ~41mJ/cm² - close to 25mJ/cm².
fluence which was found to produce the largest index changes. A third factor that reduced the peak reflectance was the misalignment of the fibre. These three factors indicate that gratings of much higher reflectancies are possible at 157nm. Damage to the phase mask was observed for the high fluence grating. However it is uncertain whether the damage was due to a material deposition or to a physical marring of the surface.

5.4 Repeatability and Error

Substantial efforts were put into stabilizing the Michelson interferometer in order to avoid sudden large shifts in phase. A drop in laser energy would lead to a false indication of saturation of the index response causing the experiment to be halted prematurely. The addition of the Faraday cage, instigation of long pre-exposure vacuum pumping, and careful wrapping of the interferometer arms greatly reduced the random spikes in the measurements. Each fibre type was exposed until a spike-free response was obtained. Reproducible results were obtained from each fibre type for at least two runs. Further, the Michelson interferometer was tuned such that thermal drifts opposed the index changes. Therefore, results are conservative estimates of index change.

Each laser pulse induced a large thermal index change in the fibre. Figure 34 shows the induced thermal index change per pulse at the three fluences. The induced index change was calculated by measuring the total phase change (mapped along the cosine squared response) immediately after the pulse until a steady state position was reached. Figure 34 shows that thermal index offsets as high as $-7 \times 10^{-3}$ (greater than a $\pi$ phase shift in the interferometer output) were created by a single 450mJ/cm$^2$ laser pulse. Since the fibre was
exposed in vacuum, recovery times were on the order of minutes as the heat of the laser pulse had to be dissipated along the length of the (insulating) fibre. The inclusion of one atmosphere of argon in the vacuum chamber greatly reduced the recovery time of the fibre to ~20 seconds (indicating that the large index shift was indeed caused by the thermooptic effect and not by a temporary stoichiometric effect) permitting the experiment to proceed more rapidly.

![Figure 34: Plot of induced thermal index change per single laser pulse. Data points for the three irradiating fluences are shown.](image)

The cylindrical lens and detector surface were inspected regularly to ensure that no debris was accumulating. The accumulation of debris would give a false energy reading. Incident fluences could also be affected by a variance in the lens position and the vertical and lateral position of the fibre in the beam. The lens was estimated to be positioned within 0.2mm of the desired location. The vertical and lateral fibre positioning was controlled by the X-Y translator and a set of vernier calipers. Fibre positioning was estimated to be within +/-
0.1 mm in the vertical and lateral direction. These fibre positioning tolerances ensured that the fibre received the desired laser fluence.

The largest variances in the irradiating fluence were due to the 20% pulse-to-pulse variance of the F2 laser and a permitted 20% drop in the illuminating fluence before the pump/argon refill procedure was initiated. The pulse-to-pulse variance was constant for all fibres tested so the relative responses should be equal as if there was no pulse-to-pulse variation (assuming a linear fibre response within the 20% variance). The magnitude of the effect of the permitted 20% degradation in the laser energy can best be judged from Figure 16. The low fluence curve shows ripples corresponding to the pump/argon refill cycle. The index change at 9000 pulses could be extrapolated to be 20% larger if the steeper sections of the ripples are taken as the true responses. Taking into account the laser pulse-to-pulse energy fluctuation, laser energy degradation over time, thermal drift, and fibre alignment it is estimated that the photosensitivity measurements are accurate to within 50% of the values presented in this thesis.

The repeatability of the fibre responses, the tight control of the exposure parameters, and the corroboration between the calculated index change of the grating and the measured photosensitivity change give confidence to the results presented in this thesis.

5.5 Significance of Work

This first study of photosensitivity at 157 nm has shown that this wavelength induces a strong photosensitivity response via an efficient one-photon process. Per-pulse index changes higher than have been produce with either the KrF or ArF laser sources were recorded.
The fast, linear, single-photon photosensitivity response observed in low-germanium doped fibres is an important result since such a response is very desirable for grating-based device manufacturing. The above bandgap electronic excitation produced by a single 157nm photon means that photosensitivity at this wavelength is not dependent on the germanium defects required by the KrF and ArF lasers. This also is an important result due to the potential of inducing index changes in fibres irrespective of dopants.

This work also has scientific merit since 157nm is the shortest wavelength ever studied in the fibre photosensitivity field. Index change measurements and Bragg grating fabrication in a vacuum environment are reported for the first time in this thesis.

In terms of commercial applications, the potential role of 157nm remains unclear. Offsetting the benefit of the large photosensitivity response at 157nm are a number of factors. The premature damage-induced saturation of the index change at high fluence requires working at lower fluences in order to avoid fibre damage. KrF and ArF laser sources are able to work at higher fluences thereby partly making up for their slower photosensitivity response. The requirement of VUV vacuum technologies when working with 157nm radiation dictate that clear (order-of-magnitude) advantages exist over a competing technology (in this case the KrF and ArF lasers) to justify the added difficulty of using vacuum systems. Such an order-of-magnitude advantage has not been shown in this thesis however the promise of a very large saturated index change remains.

Unfortunately, the inability to saturate the index change (due to the long experimental duration) leaves questions about the real promise of 157nm photosensitivity. Clearly, further work is required to assess the potential commercial prospects for 157nm photosensitivity.
Chapter 6

Conclusions and Future Work

6.1 Conclusions

This thesis sets a new short-wavelength boundary in the study of photosensitivity in optical fibres. A one-photon photosensitivity response was observed for non-hydrogen loaded high and low germanium core fibres. The largest per-pulse index change in a standard telecommunications fibre is reported for all the three irradiating fluences.

Photosensitivity was studied in a 3% germanium core dopant fibre and an 8% germanium core dopant fibre. Each fibre also was hydrogen loaded at ten atmospheres and the photosensitivity response was measured.

A Michelson interferometer setup was mounted in a vacuum chamber and used to measure the index change induced by 157nm laser pulses. A 5mm length of one of the arms of the interferometer was exposed to a near top hat 157nm beam. A cylindrical lens was used to focus fluences of 25mJ/cm², 100mJ/cm² and 450mJ/cm² in the test fibre. Index changes were calculated by measuring the phase shift of the interferometer due to the change in the optical path length of the exposed fibre.

A maximum unsaturated index change of $8.1 \times 10^{-4}$ was recorded for a hydrogen loaded fibre exposed at the lowest fluence for 9000 pulses. An unsaturated index change of $2 \times 10^{-4}$ was observed in an untreated fibre - comparable with the saturated index changes achievable with 248nm illumination. Hydrogen loading increased tenfold the index change rate at low
fluences. Saturated index values were not possible to measure due to the low repetition rate of the current F\textsubscript{2} laser.

Core germanium concentration had a marginal effect on the response of the fibres at low fluences. At high fluences a damage mechanism in the core and cladding prematurely saturates the index change. Higher germanium core concentrations amplify the damage mechanism at high fluences. The damage mechanism limits the usefulness of 157\textmu m-induced photosensitivity at high fluences.

Gratings were fabricated using a phase mask technique. This is the first reported fabrication of a grating at 157\textmu m. Fibre alignment proved to be critical to the successful writing of a grating. A type II grating with a reflectivity of \textapprox 70\% was written with 5000 pulses of the F\textsubscript{2} laser.

6.2 Future Work

Many avenues of future work can be envisioned coming from this preliminary study of 157\textmu m photosensitivity in optical fibres.

The foremost avenue is a measurement of the maximum, saturated index change producible by 157\textmu m radiation in all fibre types. To achieve this study a higher repetition rate laser will be required. At least a 10Hz repetition rate is required to bring the exposure time down from hours to minutes. In addition to a faster pulse rate the experimental setup could be improved to increase the accuracy of the measurements. Temporary fibre couplers should be avoided and replaced by permanent connectors on patch cables. A reduction in the number of argon purges could be achieved by reducing the leak rate of the vacuum chamber and
moving to a vacuum-compatible tape to secure the fibre to the testbed.

Due to the high response observed at 25mJ/cm² in a hydrogen loaded fibre, the low fluence region should be studied further. In particular the region between 10mJ/cm² and 100mJ/cm² should be explored to determine the fluence that maximizes the index change yet minimizes the fibre damage.

Non-germanosilicate and other germanosilicate fibres should be characterized since there seems to be a large photosensitivity dependence on the core and cladding composition of the fibre. A pure silica core fibre should be tested since photosensitivity has not been observed in this fibre at lower photon energies.

Photosensitivity of germanosilicate waveguides is a very attractive area of exploration since the lack of cladding means that high fluences can be used to induce large index changes. An *in-situ* measurement technique will have to be developed in order to properly characterize the waveguide response.

The writing of Bragg gratings is a rich area for future exploration. The dependance of a grating’s reflectivity on the fibre/phase mask distance, fluence, germanium concentration, hydrogen treatment and pulse count all need to be characterized. The alignment of the fibre and the phase mask needs to take place in the vacuum chamber so that correct positioning is ensured. Minor modifications to the X-Y translator and existing testbed will enable the setting and confirmation of the fibre alignment in the exposure position.

To facilitate a Bragg grating study a new phase mask should be acquired that has a substantially smaller zeroth order component (<2%). Calcium fluoride (CaF₂) might be a better choice for the mask material due to the inherent birefringence of MgF₂.
A more fundamental effort towards discerning the nature of the photosensitivity and damage mechanisms should be undertaken. VUV spectroscopy would enable the evolution of the short wavelength absorption spectrum to be monitored as the fibre was being irradiated.

Finally, a photosensitivity study at wavelengths slightly longer than 157nm (160nm-170nm) might yield interesting results. These longer wavelengths may still drive a one-photon photosensitivity mechanism but substantially reduce the damage incurred in the fibre.
References

37. Personal communication with C. Askins, Naval Research Lab.

determination of main fibre Bragg grating parameters using OLCR”, IEE Proc. Optoelectron,
141 (2), 141-144, (1994).

40. B. Malo, K.O. Hill, F. Bilodeau, D.C. Johnson, and J. Albert, “Point-by-point fabrication of
micro-Bragg gratings in photosensitive fibre using single excimer pulse refractive index


42. Q. Zhang, D.A. Brown, L. Reinhart, T.F. Morse, “Simple prism-based scheme for fabricating

monomode optical fiber by UV exposure through a phase mask”, Appl. Phys. Let., 62 (10),

44. D.Z. Anderson, V. Mizrahi, T. Erdogan, and A.E. White, “Production of in-fibre gratings

wavelength by writing gratings on prestrained fibers”, IEEE Phot. Tech. Let., 6 (7), 839-841,
(1994).

46. N.H. Rizvi, M.C. Gower, F.C. Goodall, G. Arthur, and P. Herman, “Excimer laser writing of
submicrometre period fibre Bragg gratings using phase-shifting mask projection”, Elec.

47. S.J. Mihailov, and M.G. Gower, “Recording of efficient high-order Bragg reflectors in optical
fibres by mask image projection and single pulse exposure with an excimer laser”, Elec. Let.,

fibre Bragg grating arrays fabricated in line on a draw tower”, Opt. Let., 19 (2), 147-149,
(1994).


wavelength-selective tap using an all-fiber mach-Zehnder interferometer and chirped photo-

51. P.C. Hill, P.R. Herman, and R. Sia, “Spectral Widths of an F2 (D'3Π_2→A' 3Π_{2u}) Laser”, J.

Appendix A:
Schematic Diagrams of Test Bed and Associated Photosensitivity Apparatus
Photosensitivity Experimental Setup

Back of Ablation Chamber

- Fiber
- 3dB Coupler
- Excess Fiber Coil
- 157nm Exposure Area
- Grooved Lines
- 2"x2" Steel Insert
- Excess Fiber Coil
- 1/4-20 holes for phase mask
FC/APC Connectors

To Feed-through

University Of Toronto  photonics Group

<table>
<thead>
<tr>
<th>Title</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Photosensitivity</td>
<td>Prof. Peter Herman</td>
</tr>
<tr>
<td>Ablation Chamber</td>
<td>Keith Beckley</td>
</tr>
<tr>
<td>Layout</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>July 8, 1996</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>#2</td>
</tr>
</tbody>
</table>

Note: All dimensions are in inches
Note: All dimensions are in inches
Both Sides Flat

0.105" (+/-0.002)

4 x 45 deg. corners

1"Ø hole drilled through

4 corner holes: counter sunk (csk) for 6-32 screw.

Fiber Groove - 3 groves x 3 grooves spaced by 1/8"

$R = 125$ microns

$D = 250$ microns

$H = 25\% \ D = 63$ microns

90 deg. groove depth = $(2.414 \cdot 125) - 63 = 239$ microns = 0.009"

6-32 clear

Note: All dimensions are in inches
Note: Piece B slides into piece A to form an O-ring groove.

O-ring: ref. #123
Width: 3/32 (0.103 +/- 0.003)
I.D.: 1 3/16" (1.174 +/- 0.012)
8 thru holes 1/4-20 tap

7 x 1/4-20 clearance holes with counter bore for head clearance; positioning +/-10 thou, non cumulative total

4 corners of recessed area 6-32 tap thru hole; position +/-10 thou

1" dia. thru hole

Base Piece is 1/2" thick stock aluminium then flycut (flattened) (-0.020"). Nickel plate after machining
Nickel plate after machining

1/4-20 clearance thru hole with counter sunk head

3 Pieces required

Note: All dimensions are in inches
Phase Mask Travel
Max: = 1.040"
Min: = 0.900"

Note: All dimensions are in inches
2 x 6-32 clearance thru holes with counter sunk heads

2 x 0.340" dia. thru holes

2 x 0.340" dia. thru holes

2 x 6-32 clearance thru holes

Note: All dimensions are in inches

<table>
<thead>
<tr>
<th>Title</th>
<th>Name</th>
<th>Material</th>
<th>Date</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Photosensitivity</td>
<td>Prof. Peter Herman</td>
<td>Aluminium</td>
<td>July 11, 1996</td>
<td>#1</td>
</tr>
<tr>
<td>Crystal Holder</td>
<td>Keith Beckley</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O-ring spreader</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale</td>
<td>1:1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Note: All dimensions are in inches
Fiber Feedthrough

Supplied Peice

Drill 1.5cm diameter hole through center

New Peice

Material: Al

Slot: 1mm x 9mm

- 5mm thick.
- To fit inside drilled hole of supplied peice.

Requested By: Keith Beckley (x86743)
Date: 96.06.03
Appendix B:
Amplifier Circuit for Semiconductor Diode
(Supplied by T. Alavie)
Detector Amplifier Circuit

15pF (Tantalum)

100k

10k

+12V

LT1055

-12V

PD/LD Detector

Resistors: Philips 1%
Appendix C:
Fibre Mirror Technique
(Adapted from notes supplied by T. Alavie)
Silver Mirror For Optical Fibres

Since a small volume of the solution is used in mirroring of the optical fibers, it is crucial to come as close as possible to the weight amounts required in making the solutions. Also, in order to ensure the quality of the mirror, the fiber must absolutely be clean. If a hand cleaver is used, gently touch the cleaved end of the fiber to a piece of tacky tape or isopropanol soaked tissue. This should rid the fiber of any debris which might have resulted from cleaving. Now dip the fiber end in distilled water and repeat a few times. The fiber should now be ready for silvering. Place the fiber aside and make sure that it does not come in contact with anything. Rinse pipettes well before changing solutions. A rubber stopper with slits cut into it is useful for holding the fibres in the test tube. 5ml test tubes work best.

Solution Preparation

Solution A: Dissolve 1.7 grams of Silver nitrate (AgNO₃) in distilled water and dilute to 100 ml.

Solution B: Dissolve 4.48 grams of Potassium hydroxide (KOH) in distilled water and dilute to 100 ml.

Solution C: Dissolve 4.5 grams of Dextrose (D-glucose C₆H₁₂O₆) in distilled water and dilute to 100 ml.

Solution A and B will stay in solution for a long period of time. Solution C has to be remade every month or so.

Procedure

1. Using a graduated 1 ml pipette, place 2 ml of Solution A in a clean test tube. Add one drop of 15M ammonia solution while swirling until the brown precipitate (hydrated Silver oxide) which initially forms just dissolves. It might take two drops!

2. Add 1 ml of Solution B to the content of the test tube. If a precipitate forms again, add 15M ammonia dropwise until it dissolves. It should not take more than two drops.

3. Suspend your already clean and cleaved fibers in the test tube so that they come in contact with the solution in the tube. You may Silver as many as six optical fibers at the same time. A piece of tacky tape or rubber stopper with slits come in handy when suspending the fibers in the test tube.

4. Add 0.17 ml of Solution C to the contents of the test tube.

5. Swirl the test tube so that the liquid comes in contact with the glass. Swirl until the Silver forms. The Silver should begin to form a few seconds after the final solution has been added.
Continue to swirl for two to three minutes. If solution C is old the silvering might take up to ten minutes. Silvering is finished when the test tube is completely silvered.

**Disposal of Solution**

The final solution must not be left to sit for an extended period of time as it might form an explosive precipitate. Dilute the solution to at least 100 ml of water in a beaker. The diluted solution may now be disposed of with large volumes of water or be poured in a container marked Silver Nitrate for proper disposal.
IMAGE EVALUATION
TEST TARGET (QA-3)

1.0
1.1
1.1
1.25
1.4
1.6
1.25
1.4
1.6
1.0
1.1
1.1
1.25
1.4
1.6

150mm
6"

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved