

Nano-Moulding of Integrated Optical Devices

A thesis submitted in fulfillment of the requirements for
the degree of Doctor of Philosophy



THE AUSTRALIAN NATIONAL UNIVERSITY

Ting Han

Research School of Physics and Engineering

Australian National University

August 2011

Declaration

The contents of this thesis are the result of original research and have not been submitted for a higher degree to any other university or institution. This thesis is entirely my own work, unless explicitly stated otherwise.

Ting Han  15/12/2011

Laser Physics Center
Research School of Physics and Engineering
Australian National University
August, 2011

Acknowledgement

First of all, my deepest gratitude goes to my thesis supervisor Steve Madden and Barry Luther-Davies. This thesis would not have been possible without their guidance and support. I am indebted to many of my colleagues in the Laser Physics Center who have been great sources of friendships as well as good advice and collaboration. I thank Sukanta Debremma and Douglas Bulla for their efforts in film deposition; I am also very grateful for the valuable advice given by Duk Yon Choi and Rong Ping Wang.

I want to thank RPO Ltd for supplying the Polysiloxane material through this project and putting together another Linkage grant. I thank Robbie Charters for initiating the original idea of designing insensitive couplers. I also want to acknowledge my colleagues in EME and ANFF for providing the fabrication facility. Special thanks to Fuaud, who has been an important advisor, both professional and personal.

It is an honor for me to acknowledge the technical staff in the school electronics units and mechanical workshops for their assistance in building equipments used in the lab. I thank Craig and John for training me in the mechanical workshop and giving me advice on car mechanics. My deep gratitude also goes to Maryla and Anita for their assistance in the chemical lab.

I am very grateful to have a group of snowboarding and motorcycle friends who have added a lot of flavors to the life in Canberra.

I would like to thank my beloved girlfriend Suan who has always been there cheering me up and standing around me through the good times and bad.

Last I would like to thank my parents for their tireless love and support over these years. 感谢父母这么多年来对我的关爱和栽培！

Abstract

Planar waveguide devices made by conventional semiconductor methods are typically very costly as a result of expensive tooling, high cost of raw materials, and many slow processing steps. To address the many mass market opportunities that exist today in fields such as consumer devices, sensing, medicine, etc, much lower cost methods are needed. Nanoimprint lithography was introduced to the semiconductor industry in recent years and was regarded as a serious candidate for next generation lithography. The reported resolution was down to molecular scale (2nm), and yet it offers high throughput and low cost. At this point, Nanoimprint lithography has been added to the International Technology Roadmap for Semiconductors (ITRS) for the 32 and 22nm nodes. In this thesis, Nanoimprint lithography was used for the fabrication of integrated optical devices on two types of material platforms.

Firstly, the fabrication of Polysiloxane waveguide devices using UV-Nanoimprint Lithography (UV-NIL) is demonstrated. With an innovative minimum displacement method, low loss channel waveguides were fabricated in a 4 step process that showed no excess loss from 750 to 1700nm. Using the same imprint technique, more complicated waveguide Bragg gratings were realized. For the first time, the transmission spectrum showed a polarization independent response and almost perfect agreement with the theoretically expected spectrum.

Next, the challenge was to extend this technique to directional couplers and multimode interference couplers. However it is well known that planar directional couplers are generally very sensitive to fabrication errors (waveguide dimension varies randomly in the lithography and etching processes), and true low excess loss multimode interference couplers remain to be demonstrated. Here we proposed a design mechanism to solve the problem of sensitivity to waveguide width and the full vector beam propagation modeling of the optimized directional coupler design showed superior fabrication tolerance to all other designs. For the first time it was identified that a single point in the design space

exists where the design is very tolerant to variations in the waveguide width for both TE and TM polarizations. By putting the theory into test, we demonstrated such optimized directional couplers could be fabricated using the same imprint process and the performance was indeed better than other random designs. It was also shown that MMIs can be designed with very low excess losses and good imbalance simultaneously. However, the practical realization of this was thwarted by issues in the imprint stage that require more sophisticated tools than available at the time to resolve the issue.

The other material system investigated was based on the chalcogenide glasses. Thermal Nanoimprint Lithography (T-NIL) is a technique which offers freedom from the constraints and process complexities imposed by lithographic/plasma etching processes in chalcogenide waveguides. It was used to directly mould single mode rib waveguides on chalcogenide thin films thermally evaporated on 4 inch silica wafers. Using a soft stamp made from PDMS, the moulding of $\text{As}_{24}\text{Se}_{36}\text{S}_{36}$ was accomplished at 190°C and cutback measurements revealed a loss down to 0.26dB/cm which was more than 10 times lower than previously published results and the first time a soft stamp has been used to perform hot embossing of chalcogenides. The moulding of the more robust glass composition As_2S_3 was also demonstrated and the measured waveguide nonlinearity was shown to be $13.5\text{W}^{-1}\text{m}^{-1}$ on a $\sim 2 \times 1\mu\text{m}$ waveguide.

Table of Contents

- CHAPTER 1 INTRODUCTION 1
- CHAPTER 2 NANOIMPRINT LITHOGRAPHY FOR PHOTONICS 5
 - 2.1 CONVENTIONAL NANOFABRICATION TECHNIQUES..... 7
 - 2.2 NANOIMPRINT LITHOGRAPHY..... 9
 - 2.2.1 UV-curable nanoimprint lithography 10
 - 2.2.2 Thermal Nanoimprint Lithography 13
 - 2.3 NIL APPLICATIONS AND LIMITATIONS..... 16
 - 2.4 CONCLUSION 18
- CHAPTER 3 NANOIMPRINTED POLYSILOXANE WAVEGUIDES 19
 - 3.1 OVERVIEW 19
 - 3.1.1 Key characteristics for integrated passive waveguide devices..... 19
 - 3.1.2 Common material systems for integrated optics..... 21
 - 3.1.3 Polymer optical waveguides 24
 - 3.2 IPG™ MATERIAL PROPERTIES 32
 - 3.3 UV-NANOIMPRINTED POLYSILOXANE WAVEGUIDES..... 35
 - 3.3.1 Stamp fabrication 35
 - 3.3.2 Waveguide design and minimum displacement approach 39
 - 3.3.3 Lithography and Etching process for SiO₂ master fabrication 41
 - 3.3.4 Imprint process..... 44
 - 3.3.5 Waveguide testing 50
 - 3.4 CONCLUSION 53
- CHAPTER 4 NANOIMPRINTED POLYSILOXANE WAVEGUIDE BRAGG GRATINGS 55
 - 4.1 GRATING SIMULATION AND DESIGN..... 57
 - 4.2 FABRICATION PROCESS 61
 - 4.2.1 Grating master fabrication 63
 - 4.2.2 UV-Nanoimprinted Polysiloxane Waveguide Bragg Gratings 69
 - 4.3 PERFORMANCE 70
 - 4.4 CONCLUSION 72

CHAPTER 5 OPTICAL COUPLER DESIGN AND OPTIMIZATION	73
5.1 MULTIMODE INTERFERENCE COUPLER OPTIMIZATION.....	73
5.1.1 <i>Taper optimization</i>	75
5.1.2 <i>MMI width optimization</i>	76
5.2 DIRECTIONAL COUPLER OPTIMIZATIONS	79
5.2.1 <i>Fabrication error insensitive design of 3-dB couplers</i>	80
5.2.2 <i>Fabrication Error Insensitive Design of 1310/1550nm WDM Couplers</i>	87
5.3 COUPLER FABRICATION	94
5.3.1 <i>Design parameters</i>	95
5.3.2 <i>CAD design and fabrication</i>	96
5.4 COUPLER DEVICE TESTING.....	98
5.4.1 <i>MMI coupler performance</i>	98
5.4.2 <i>3-dB coupler performance</i>	100
5.4.3 <i>WDM coupler performance</i>	104
5.5 CONCLUSION	107
CHAPTER 6 CHALCOGENIDE GLASS WAVEGUIDE TECHNOLOGIES.....	109
6.1 INTRODUCTION.....	109
6.2 MATERIAL PROPERTIES.....	110
6.2.1 <i>Linear optical losses</i>	111
6.2.2 <i>Refractive index and dispersion</i>	112
6.2.3 <i>Photosensitivity</i>	113
6.2.4 <i>Optical nonlinearity</i>	114
6.2.5 <i>Chalcogenide glasses for all optical processing</i>	116
6.3 CHALCOGENIDE GLASS THIN FILM PREPARATION	117
6.3.1 <i>Common film deposition methods</i>	117
6.3.2 <i>Thermal evaporation of chalcogenide thin films</i>	119
6.3.3 <i>Evaporated thin film versus Bulk</i>	120
6.4 CONCLUSION	126
CHAPTER 7 HOT EMBOSsing CHALCOGENIDE GLASS WAVEGUIDES	129
7.1 CHALCOGENIDE GLASS WAVEGUIDE FABRICATION APPROACHES.....	129
7.2 HOT EMBOSsing APPROACH	133
7.2.1 <i>Soft stamp for hot embossing</i>	134
7.2.2 <i>Tool design</i>	135
7.2.3 <i>Tool operation</i>	138

7.3	HOT EMBOSSING $As_{24}Se_{38}S_{38}$ WAVEGUIDES	141
7.3.1	<i>The Fabrication</i>	141
7.3.2	<i>Measurements and Results</i>	144
7.4	HOT EMBOSSING As_2S_3 WAVEGUIDES.....	148
7.4.1	<i>Thin Al_2O_3 layer via atomic layer deposition system</i>	149
7.4.2	<i>Ultra thin polymer resist</i>	151
7.4.3	<i>Double layer chalcogenide glass approach</i>	155
7.5	CONCLUSION	162
CHAPTER 8 CONCLUSIONS AND FUTURE WORKS		163
8.1	CONCLUSION	163
8.2	RECOMMENDED FUTURE WORKS	166
BIBLIOGRAPHY		169
APPENDIX		187
LIST OF JOURNAL PUBLICATIONS		193

Chapter 1

Introduction

In contrast to the earlier centuries, one of the most prominent traits during the 20th century was the drastic growth of technology. Telecommunication systems in particular have experienced paradigm shift in the underlying technology and applications in the last 50 years having only previously seen incremental evolution since the invention of the telephone in 1876 [1]. The development of worldwide telephone networks during the 20th century led to many advances in the design of electrical communication systems. It was realized in the 1950s and 1960s that there were fundamental limitations to the capacity that could be transported over national and intercontinental distances caused both by bandwidth limitations and the very short repeater spans required for high data rate communications over coaxial cables. The realization was made by a number of researchers that the capacity bottleneck could be overcome if information was encoded in light waves and transmitted over suitably low loss optical fibres which were theoretically proven possible [2]. The first generation light wave systems operating near 0.8 μ m were deployed in the late 1970s [3] providing a bit rate of ~ 100 Mb/s and repeater spacing of about 10km. Compared to coaxial systems, the larger repeater spacing provided a great deal of motivation for research on optical communication systems. In following years, inventions such as the InGaAsP semiconductor laser emitting at 1.3 μ m reduced the optical loss to below 1dB/km whilst operating at the zero dispersion point in silica fibre, and high bit rates became possible as a result of using single mode fibres. By 1987, second generation lightwave systems operating at bit rates of 1.7Gb/s with a repeater spacing of 50km were commercially available. In the third generation lightwave systems, fibre loss was minimized by operating at 1.55 μ m and the use of dispersion engineered silica fibres made it possible to achieve a bit rate in excess of 10Gb/s at repeater spacing of even 100km.

Since the late 1990s, the demand for enhanced information capacities increased dramatically, primarily as a result of the internet “explosion”. An economically viable solution for solving this problem was to introduce a wavelength division multiplexing (WDM) system. In a WDM system, instead of using a single carrier wavelength, multiple carriers at slightly different wavelengths are transmitted simultaneously along the optical fibre. The combination of the erbium doped fibre optical amplifier (EDFA) and WDM has unleashed the huge bandwidth potential of optical fibre for the first time. Modern systems now allow more than 200 such channels, each operating at between 10 and 40 gigabits per second, to be multiplexed together to provide an aggregate rate in excess of a terabit per second.

Looking ahead, it is becoming increasingly clear that adding more wavelength channels is not the complete solution to future capacity demand, as each channel results in increased equipment costs and added network complexity. Consequently, increasing the data rate of each individual channel via optical time division demultiplexing (OTDM) or more complex modulation formats might be the means by which the capacity of future transmission systems will be expanded. To operate at 160 gigabits per second and beyond with binary only data, optical communication systems will need to process signals entirely in the optical domain to overcome the speed limitations associated with opto-electronic conversion. As a result there is a growing interest in all-optical signal processing which involves the control of light by light in a nonlinear optical material.

Not only are optical telecommunication systems constantly improving in their performance and capacity, but also the deployment of optical systems is spreading deeper into the consumer market. Fibre-optic networks are in some countries now routed directly into households and even to the back of each computer. The limitations of copper interconnects are now also being reached at the circuit board level and even VLSI on chip interconnects are being targeted for optical transmission [4, 5]. As optical fibre gradually replaces copper cables, it will become necessary for many of the electronic network components to be replaced by equivalent optical components: splitters, filters, routers and switches etc. Furthermore, the emerging applications of integrated optics will make significant differences to a number of important aspects of the way we live and work today,

e.g. cheap spectrometers for inkjet printers, large-scale touch screen technology, disposable sensors, fast & cheap medical diagnostic devices available at GP clinics and methods for aligned tissue growth.

The desire to fabricate compact, manufacturable, low-cost and integrated optical components has stimulated lots of interest in planar integrated optics research. Over the past a few decades, various processing techniques, e.g. photolithography, etching, direct laser writing, electron beam lithography, were developed which demonstrated the capability of fabricating integrated optical devices with submicron precision. However few of them are really practical in terms of high volume production at low enough cost to reach the consumer market. Thus, the work in this thesis was motivated by the need to find means of making potentially nanoscale devices with short process times and low fixed and variable costs to enable penetration of optical technology down to the consumer level. Single step imprint and moulding technologies seemed like an obvious avenue for this given the demonstrated capabilities of micro-moulding technologies as embodied in the manufacture of compact discs or DVDs are routinely fabricated, where the manufacturing cost of the discs are a few cents yet $<200\text{nm}$ features are manufactured.

The goal of this thesis can be divided two fold. The first goal was to research means and device designs to fabricate high yield and high performance planar integrated optical devices using single step micro-moulding type methods in polymers that could be scaled at low cost high volume production. This goal was to realize devices such as throw away medical sensors and true consumer level products where the market just could not support the cost of solutions such as silicon photonics ($\$5\sim 16/\text{cm}^2$ depending on the processes and materials involved with typical optical applications pushing the higher end of this range due to the need for a transparent under-cladding [6]).

The second objective was to investigate similarly simple and low cost means for patterning chalcogenide glasses into integrated optics devices by a moulding technique. Chalcogenide glasses have a number of very attractive properties for a variety of important applications including MIR sensing for health and the environment, national security, defense, industrial and agricultural sensing, etc based on properties such as their huge non-linear optical coefficients, excellent mid-infrared transmission, good acousto-optical

properties [7]. Unfortunately, chalcogenide glasses are relatively difficult to process into high quality planar devices due to their chemical sensitivity, the difficulty of making bulk like thin films, low melting points etc. Thus a simple and fast method that used no chemicals and that even exploited the low melting points would be of considerable benefit to the future exploitation of the attractive optical properties of these glasses.

This thesis is separated into 6 chapters to describe the experiments and achievements towards meeting these two goals. Chapter 2 gives an introduction and review of Nanoimprint Lithography (NIL) which is subdivided into two categories: UV-NIL and T-NIL. In chapter 3, we describe the design, fabrication and performance of imprinted Polysiloxane waveguides. Following a similar imprint process, in chapter 4 we demonstrate the same Nanoimprint technique can be applied to more complex 3-dimensional nanoscale devices: waveguide Bragg gratings. Chapter 5 presents a novel technique for the design of optical couplers which is immune to practical fabrication errors and the modeling is compared to experimental results based on the Nanoimprint approach. In chapter 6, we review various properties and applications of chalcogenides. In chapter 7, we illustrate the first low loss chalcogenide waveguides fabricated by thermal Nanoimprint lithography.

Chapter 2

Nanoimprint Lithography for Photonics

The goal of photonic integrated circuits (PIC) is to develop miniaturized optical devices of high functionality on a common substrate. It is similar in its intent to electronic integrated circuits, but the-state-of-the-art development on PICs is far behind its electronic counterpart due mainly to the much richer range of effects which must be implemented. Unlike electronic integration where silicon is the dominant material, PICs are fabricated in a variety of material systems, including silica on silicon, silicon on insulator, various polymers and semiconductor materials (such as GaAs and InP). The different material systems are used because they each provide different advantages and allow tradeoffs of their different limitations depending on the functions to be integrated.

Common PIC devices are waveguides, grating filters/couplers, photonic crystals, switches/modulators, splitters/couplers, wavelength division multiplexers, add/drop filters, optical amplifiers, sources, detectors, etc. The desire is to integrate a subset of these elements together into functional “system on a chip” type devices such as a fully integrated phase diversity coherent receiver on a chip for example, something that would be expensive, bulky, and may not even work when assembled from discrete components. Most of those devices require submicron precision and the performance heavily relies on the fabrication processes.

The interaction between photonics and biology stimulated intensive research and applications in biophotonics. The potential application of PIC technology in disposable medical sensors has been widely discussed in recent years. Typical example of such device architecture is highlighted in Figure 2.1. This device is based on an optical interferometer, in which one arm is sensitized to whatever is to be sensed, e.g. human tissue, thereby changing the output intensity of the interferometer in proportion to the amount of sensed

material. This is long established technology, but what has prevented it from reaching widespread usage is the usual need to couple light in and out of the chip via precisely aligned optical fibres (i.e. a very expensive reader unit) and high cost sensor chips. The use of coupling of the interrogating light as beams (via grating couplers on the throw away sensor card) thereby avoiding the high-accuracy alignment requirement has greatly simplified the operation. However the requirement of ultra fine fabrication precision (10s of nano meters in the grating area) over large substrate area (a few centimetres) has been a major challenge.

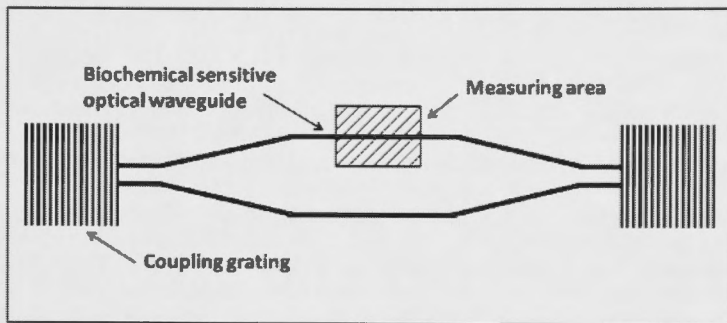


Figure 2.1: Schematic of a disposable sensing device based on grating in/out couplers and Mach-Zehnder interferometer

Over the last decades, there are many good demonstrations of high performance nano wire type devices so it is clearly possible to fabricate with the required accuracy and smoothness [8]. Demonstrations in the scientific literature typically use direct writing lithography methods, such as electron beam lithography or focused ion beam lithography. These methods, although excellent for scientific studies, are not really capable for low cost manufacturing. Optical lithography solutions developed for electronic integrated circuits based on reduction steppers or scanners can produce high resolution and high throughput but are rather expensive for photonics fabrication and it is highly questionable if the cost can be supported in applications where the device size is a few square centimeters but the cost must be down to a few cents, e.g. disposable medical sensors.

There exist many alternative lithography methods, but their scale-up to cost effective volume production is challenging. One promising candidate is Nanoimprint Lithography (NIL). NIL was first introduced in 1995 by Stephan Chou [9] and since then this technique

has attracted enormous interest for a wide range of applications. It is a cost effective method for nano-fabrication with the capability of delivering large volume production (particularly through roll to roll imprint technology). As early as in 2003 NIL had gained substantial support and was chosen as one of MIT's Technology Review's "10 Emerging Technologies That Will Change the World". At this point, NIL was added to the International Technology Roadmap for Semiconductors (ITRS 2003) for the 32 and 22nm nodes. The selection was justified by the fact that NIL could bridge the gap between nanotechnology research and low cost production level manufacturing.

In this chapter, the conventional methods for micro and nano fabrication are briefly reviewed. Then two types of NIL processes: UV Nanoimprint Lithography (UV-NIL) and Thermal Nanoimprint Lithography (T-NIL) are introduced and reviewed. Lastly comments are made on some of the applications and challenges for NIL.

2.1 Conventional nanofabrication techniques

The word lithography comes from the Greek *lithos*, meaning stones; and *graphia*, meaning to write. Today photolithography is the key technique used in the semiconductor industry for integrated circuit (IC) manufacturing and is the step that defines the maximum possible complexity of devices or alternatively the cost per device through the ability to reduce the device area. Photolithography utilizes templates (photomasks), most often having transparent and opaque areas. Light is shone through the photomask onto a substrate coated with a photosensitive thin film called photoresist, either by contact shadow masking or by projection through a lens system. Photoresist areas that are exposed will transform to either soluble (positive photoresist) or non-soluble (negative photoresist), depending on the chemistry of the photoresist. Light replicates patterns from the photomask to the photosensitive film and further steps are taken to transfer the copied patterns to the substrate. Commercially available IC parts are currently using linewidths as low as 32nm, and 22nm production is ramping for an availability date in the second half of 2011. To achieve these results, 193nm deep-UV exposure wavelengths, ultra-high NA water immersion lenses, and 4:1 reduction technology along with scanning exposures are used, and wafer throughputs of 175 (300mm) wafers per hour are achieved (ASML Twinscan

NXT:1950i [10]). Note that the maximum device size attainable without stitching together multiple exposure fields is about $33\times 27\text{mm}$. However these kinds of systems cost several tens of millions of dollars to purchase, have considerable operating costs ($>\$1\text{M}$ per annum), and have limited mask lifetimes, making acquisition and amortization of the instrument and its running costs impossible unless very high volumes can be marketed and average selling prices of the parts produced are sufficiently high (many tens of dollars).

Interference lithography (or holographic lithography) is a useful technique for patterning regular arrays of fine features (e.g. gratings) without the use of complex optical systems or photomasks. In this technique, coherent light source are divided into two or more beams and interfere on a substrate coated with photoresist; this interference pattern can then be transferred to the photoresist layer and subsequently to other layers on the substrates. With a 193nm ArF source, 42nm half-pitch has been demonstrated [11]; using an extreme UV light source emitting at 14.5nm, 12.5nm half-pitch was produced [12].

Direct laser writing (also known as multiphoton lithography) of polymer templates has been known for years. The working principles are similar to photolithography, the structures is accomplished by illuminating negative/positive tone photoresists via multiple photon absorption to induce a dramatic change in the solubility of the resist for appropriate developers. Direct laser writing has been very well known as its rapid, cheap and flexible capabilities to pattern photonic nanostructures [13, 14].

In electron beam lithography (EBL), a beam of electrons is focused to a small spot and the beam is deflected in a pre-designed fashion across a surface coated with electron beam sensitive resist. This resist is then selectively removed after exposure and developing where the exposed area has either been scissored or polymerized by the electron beam depending on the resist polarity. This technique can pattern very small structures in the resist layer that can be subsequently transferred to the substrate material. The primary advantage of EBL is that it is one of the ways to beat the diffraction limit of light and make features in the nanometer regime. For example even “budget” tools such as the Raith 150 can make features below 10nm. This form of maskless lithography has found wide usage in photomask fabrication for conventional photolithography, low-volume production of specialized semiconductor components, and research & development. On the other hand,

the key limitation of electron beam lithography is throughput, i.e. the very long time it takes to expose an entire silicon wafer or glass substrate. A long exposure time leaves the user vulnerable to beam drift or instability which may occur during the exposure. As the wavelength of the electron is very small, even a basic EBL system offers high resolution. Registration of the patterns in EBL is not necessarily nearly as good as the resolution of the system, because the substrate has to be moved over large distances during the exposure. This requires a fast and extremely accurate mechanical stage. Electron beam lithography systems based on the use of multiple beams are being developed at present to tackle the throughput problem. In 2009, reflective electron beam lithography (REBL) system equipped with approximately 1 million beams was demonstrated [15]. This system was targeted to produce five to seven densely patterned 300mm wafers and up to forty sparsely patterned wafers per hour for the 45nm node with extendibility to the 32nm node and beyond. Although multi-beam EBL system may produce unprecedented direct writing throughput, it is expected that it will take a long time before the technology is commercially realized.

2.2 Nanoimprint lithography

Nanoimprint lithography (NIL) is often classified as an unconventional lithographic technique; unlike traditional lithographic approaches, which achieve pattern definition through the use of photons or electrons to modify the chemical and physical properties of the resist, NIL relies on direct mechanical deformation of the resist. Although similar techniques have been applied to CD and DVD manufacturing since the early 1980s, the demonstrated capability of replicating nanometer features in a NIL process has stimulated an enormous amount of interest. NIL processes are low cost, high throughput methods for the parallel replication of structures at the micro and nano scale. With a single master or stamp, thousands of copies can be produced as required over large surfaces. Its unique capabilities are the key advantage over other fabrication techniques.

High resolution: Since the patterning mechanism of NIL is based on mechanical deformation of the resist, the resolution is not limited by optical diffraction, scattering, resist chemistry, etc. In fact, the resolution for NIL at present is not limited by the process,

but the ability in making small features on the mould. It was shown that 6nm resolution half-pitch features could be imprinted into the resist [16].

3D capability: Three dimensional features are often needed for various applications and usually involve several overlay processes to accomplish with conventional approaches. 3D patterning capability is a unique feature in NIL processes; an early demonstration utilizing this property was given by Li *et al* for moulding of T-gate structures [17].

Low cost and high throughput: NIL does not require the use of complicated and expensive optical systems; therefore NIL tools are much cheaper to purchase and run than projection reduction based photolithographic tools. The cost of ownership of NIL system is significantly lower than immersion and EUV lithography (predicted by Molecular Imprints Ltd). The-state-of-the-art throughput given by a NIL tool is about 4 wafers (8 inch diameter) per hour at sub-32nm half pitch resolution and 20 wafers per hour is under development [18].

Cheaper mask options: The creation of the original mask is expensive and complicated; however it is possible to create many replicas of this mask for the use as NIL moulds. This approach is similar to many well developed moulding technologies, e.g. CD/DVD and banknote, replicas of the expensive master are used for the imprint process. Therefore it is possible to reduce the cost even further by using the replicated mould.

In principle, there are two types of NIL of interest for waveguide fabrication. One is based on moulding UV-curable polymers pioneered by Haisma *et al* (UV-NIL) [19]; and the other one is based on thermally embossing materials with the first demonstration in 1995 [9]. In the following years, these two types of processes developed in different directions. In the first part of this section, UV-NIL is introduced and briefly reviewed, and in the second part, thermal-NIL is considered.

2.2.1 UV-curable nanoimprint lithography

The UV-NIL process is conceptually rather simple. A transparent template patterned with the desired features is used as the stamp and a layer of photo-curable polymer is applied on top of the substrate to be processed. During the imprint process, the stamp is pressed into

the photo-curable polymer layer and UV exposure is applied to cure this polymer. A residual layer is commonly left over after the stamp being released from the substrate and can be removed by an etching process. A typical process flow diagram is shown in Figure 2.2.

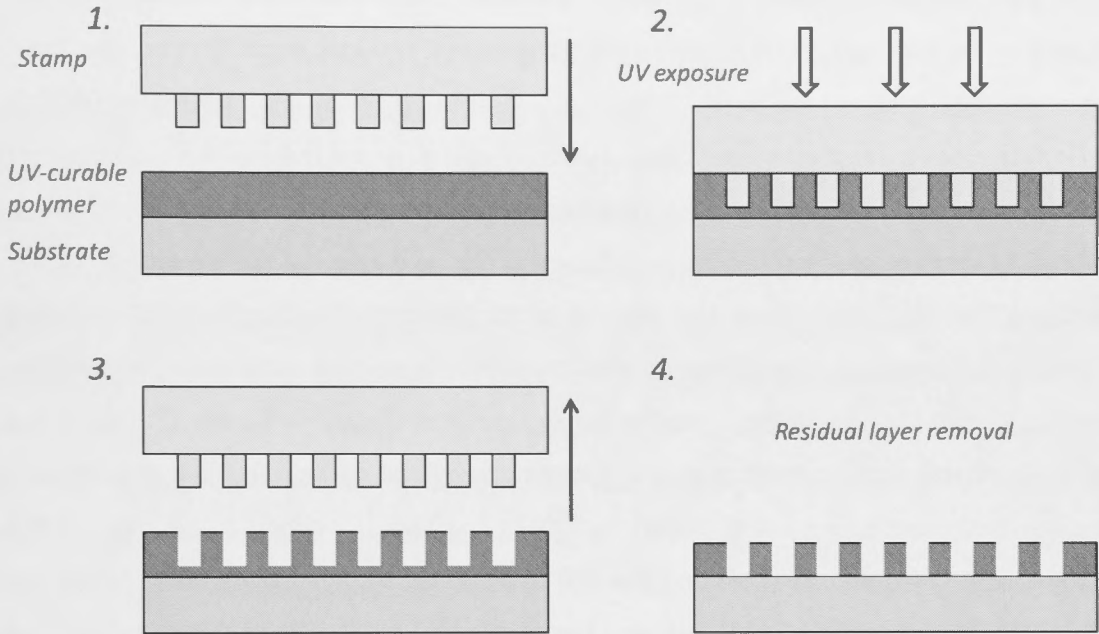


Figure 2.2: A typical UV-NIL process flow diagram

The mould in the UV-NIL process can be divided into two categories: hard stamp and soft stamp. Hard stamps made from materials such as rigid quartz offer high resolution and alignment accuracy as well as exact pattern fidelity. However the fundamental limitation of hard stamps lies in the imprint area. Surface waviness from the wafer/stamp hampers full contact between the mould and resist for large imprint areas (larger than about a square inch). Further the demand on homogeneous residual resist thickness underneath the recessed features becomes difficult. Most resists also adhere relatively well to materials like quartz, and so there is the need for a release coating on the mould. Lastly, due to the rigidity of the stamp, separation of the stamp and wafer is much more difficult than with soft stamps where some “peeling” can be applied and this is clearly more of a problem for full wafer sized devices. Hence full wafer patterning with rigid moulds is currently only performed with step and flash imprint lithography (SFIL), in which the imprint cycle is

performed over a small area in each die. The first demonstration of an imprint process with rigid moulds was published in 2000 [20] and since then major effort has been expanded into the development of SFIL by both academia and industry.

Soft stamps, on the other hand, are capable of offering full wafer patterning with a single step. The flexible nature of the mould is able to adapt to the wafer surface waviness at low imprint pressure while delivering homogeneous residual resist layers. The most commonly used material for soft stamps is elastomer (e.g. Polydimethylsiloxane) which can be fabricated by casting a liquid prepolymer against a master that has the desired relief structure coated on the surface. The replicated elastomeric stamp can then be used to perform the imprint process which minimizes the risk of damaging the expensive master template. The replicated stamp can also have advantageous mechanical and chemical properties. For example, it was demonstrated that the softness of the stamp can be tuned by the composition [21]; in addition, stamps made from Polydimethylsiloxane (PDMS) have very hydrophobic surfaces with very low surface energy and do therefore not require anti-adhesion treatment as very few materials adhere to them. In between the rather large hardness range of rigid quartz stamps and soft PDMS stamps, other material selection has enabled a wide spectrum of applications. For example, Lee *et al* have demonstrated that stamps made from amorphous fluoropolymers, such as Teflon AF2400 can be used without any surface treatment; its tensile modulus is almost a thousand times harder than PDMS which means such moulds have the capability of being rigid for patterning small features while being flexible for wafer scale patterning [22]. In addition, the combination of multiple layers of stamp material also opened up the possibility of engineering the both local and global stamp properties [23]. However the fundamental drawbacks of soft stamps come from the lower resolution and alignment accuracies. The resolution achieved with low viscosity resists is about 50nm using PDMS stamps, whilst using quartz stamps can improve this down to <10nm [24, 25]. With a three step alignment procedure based on diffractive gratings, overlay accuracies down to 50nm have been achieved using soft stamps [26].

Resists play a key role in successful application of UV-NIL where adhesion between the substrate & resist should be high and between resist & mould as low as possible.

Generally low viscosities are needed both for rapid dispensing & filling of mould cavities and minimized residual layer thicknesses. Thin resin layers on top of a thicker transfer layer are used to achieve a homogeneous final film thickness. Cross-linking and photopolymer conversion are adapted to achieve high curing speed and high etch resistance in the subsequent breakthrough plasma etching process.

Overall, there are two ways to coat the UV-NIL resist onto the substrate, one is by spin coating and the other is droplet dispensing. The advantage of spin coating strategy is that large areas can be covered with very high thickness homogeneity; furthermore, they can be prepared in advance. Spin coating is also used for patterning over topography, i.e. for the preparation of the thick solid planarization layers in multilayer resists. The droplet dispensing process is particularly suitable for step and repeat processes. An array of droplets of low viscosity UV-curable monomer are dispensed onto the substrate prior to imprint; by contact of the stamp with the droplet array, a continuous film is formed by capillary action. However the challenge for this technique lies in the difficulty of implementing vacuum and the inability to compress trapped air inclusions due to the low imprint pressure; also the pattern density variation can lead to non-uniform residual layer. The common solutions for those problems are demonstrated by the use of multinozzle inkjet droplets, “contact geometry modulation”, imprinting in He or CO₂ atmosphere etc [27-31].

2.2.2 Thermal Nanoimprint Lithography

Thermal Nanoimprint lithography (T-NIL, also called hot embossing) is very similar to a UV-NIL process. A typical T-NIL process flow diagram is illustrated in Figure 2.3. Here a layer of thermoplastic polymer or glass deposited on top of the substrate is used as the imprinting resist. Once the substrate has reached the imprinting temperature (greater than the glass transition temperature T_g), the stamp is pressed against the thermoplastic polymer layer with high pressure, followed by cooling. The temperature and pressure holding times depend on several factors and are typically a few minutes. Demoulding (separation of the stamp and substrate) takes place when both are just below the glass transition temperature. Subsequent etching or lift off processes are used to remove the residual layer and further

transfer the pattern to the substrate. The embossed pattern on the polymer layer can be used as: (a) an etch mask for transferring pattern to other substrates, (b) a step in a lift off process, or (c) depending the polymer properties, it can be used as optical or electronic devices.

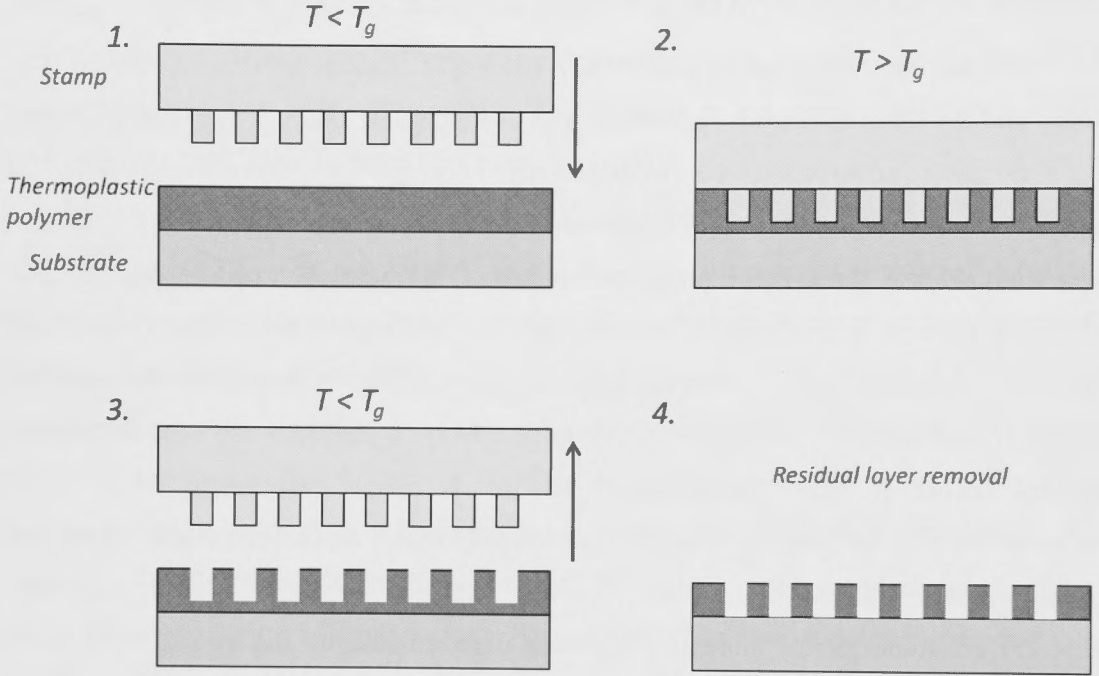


Figure 2.3: T-NIL process, T_g is the glass transition temperature of the thermoplastic polymer

The T-NIL stamp material includes essentially any type of solid material that can be precisely patterned and which exhibits sufficient strength and stability under embossing conditions. It is generally preferred that the stamp surface should be as hard as possible in a T-NIL process to avoid any distortion from the high stress induced during the vertical sinking of the stamp and lateral viscous flow of the polymer. The high imprint pressure enables the compensation for the lack of flatness of substrate and stamp by conformal bending over large areas. The most commonly used mould materials are silicon and quartz, which can retain their high strength over a wide temperature range and the patterning techniques are well developed from the microelectronics industry. Metal moulds are stronger than semiconductor materials, but patterning of metals on the nanometer scale is limited by their finite grain size. Recently amorphous metals (metallic glasses) were used for fabricating T-NIL moulds, feature sizes down to 13nm were demonstrated [32].

For many polymers and glasses, the glass transition temperature T_g can be taken as the point of reference to determine both the imprint temperature T_i and de-moulding temperature T_d . For instance, for some thermoplastic polymers, T_i is chosen to be 50-70°C higher and T_d 20°C lower than T_g . It is generally easy to switch from one thermoplastic material to another in a T-NIL process simply by using a sufficiently high temperature above T_g . Thermoplastic resists are commercially available from e.g. NanoNex, Microresist technologies GmbH, Sumitomo Ltd with a range of molecular weights and different polydispersities [33-35]. These resists can be easily prepared for a range of thicknesses from simple spin-coating process. In a moulding process, the thermo-mechanical properties of a polymer change significantly from glassy (below T_g) to rubbery glass (above T_g). Figure 2.4 shows this schematically for a polymer with a T_g around 100°C for normal process conditions; below T_g the thermo-mechanical properties between stamp and polymer become sufficiently different; at temperature beyond T_g , the viscosity drops to desirable values for moulding processes.

The first published T-NIL paper was in 1995 showing 25nm imprint resolution; later, Chou *et al* reported the imprint of 6nm diameter holes in PMMA and transferred these to a metal layer using a liftoff process [9, 36]. In 2004, Hua *et al* demonstrated linewidths as low as 2nm using a carbon nanotube-based template [37], approaching the size of a single molecule; this is the current record for NIL, but the patterns were not transferred to the underlying substrate. Commercially the best reported throughput values for T-NIL systems are from Molecular Imprints (Imprio 300) who demonstrated a throughput of 4 wafers per hour for 300mm wafers using an imprint field of 26×32mm. The alignment accuracy record for was also set by the Molecular Imprints Imprio 300 showing a 3σ alignment accuracy of 16nm using thick glass templates that have Moiré-alignment marks [18].

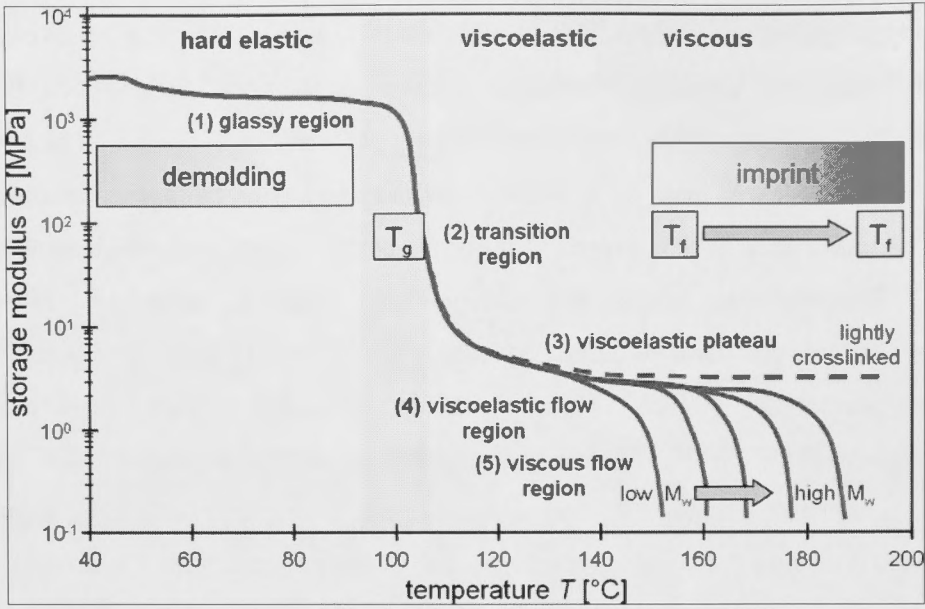


Figure 2.4: Mechanical properties of polymers dependent on temperature, molecular weight, and cross-linking. [38]

2.3 NIL applications and limitations

Because of its unmatched advantages over the existing nanopatterning technology, Nanoimprint technology, as soon as it was invented, was applied quickly and increasingly to a broad range of disciplines, including magnetic data storage, hybrid plastic electronics, organic TFTs and electronics, diffractive optical elements, waveguide polarizers, high resolution OLED pixels, NLO polymer nanostructures, high density quantized magnetic disks, patterned magnetic media, etc [39-45]. Initially, Nanoimprint technology was used in laboratory demonstrations; but in recent years, Nanoimprint technologies have been pushed by various industry sectors to become key candidates in industrial manufacturing.

In the semiconductor industry, the minimum dimension of integrated circuits (IC) has been shrinking at a rate of 30% every three years, following Moore's Law. Recently it was reported that Intel's next-generation, 22nm microprocessors will be in production by late 2011 [46]. In NIL processes, the high resolution and low cost potential of NIL processes is a key advantage for the next generation lithography (NGL) technique unmatched in cost terms by radiation-based patterning. So far, NIL has been put on the roadmaps of ITRS as

a next generation patterning method for manufacturing semiconductor ICs and the roadmap for manufacturing magnetic data storage disks.

Another important application of imprint technology is for the fabrication of micro- and nanophotonic devices such as lasers, waveguides, grating filters, couplers, photonic crystals etc. Previously there are many demonstrations of nanoscale photonic devices in the scientific literature, but very few of them are practical in a marketability sense simply due to the tradeoff between cost and resolution. Again the low cost, high resolution and high throughput Nanoimprint process is ideally suited for bridging the gap between the lab and commercial manufacturing. Furthermore, the imprinted polymer/glass layer can itself be used as a device layer which significantly simplifies the fabrication processes. Recently NIL has been applied to the fabrication of waveguides, distributed feedback lasers, Bragg gratings, resonators, modulators, photonic crystal LEDs and solar cells etc. [47-53].

NIL also plays a critical role in micro- and nano-fluidic devices for biological and lab-on-a-chip applications. Traditionally micro-fluidic devices are fabricated in a silica platform using conventional micro-fabrication techniques such as photolithography, EBL and RIE. Those techniques however are rather expensive and not readily accessible to researchers in the biology field. Furthermore, the demand for low cost and disposable bio-chips based on bio-compatible substrates has shown a dramatic increase over the last decade [54]. The polymer platform in combination with Nanoimprint lithography offers attractive solutions to these requirements.

Although NIL has been regarded as a key technology for various applications, it poses some challenges as well:

- The mechanical patterning process is analogous to contact lithography, facing issues with defects caused by resist sticking to the stamp; however this problem can be resolved by the use of anti-sticking layer coated on the stamp [55].
- For thermal NIL, a challenge lies in the diverse material thermal expansion ratio which increases the process complexity and limits the material selections.

- Mask damage is another issue in a contact printing. A variety of technologies have been devised for avoiding and reducing mask damage. For example, before imprinting a die on a wafer, the die can be previewed by a microscope and will be skipped from imprinting if significant particulates are observed, avoiding mould damage. A soft mould also can be used to reduce the mould damage. Further the cost of a soft mould is rather small so they can be considered consumable at a much higher rate than a photomask would be.
- The-state-of-the-art NIL tool offers 4 wafers per hour throughput which is quite slow compared to the modern photolithographic stepper (175 wafers per hour). This is receiving considerable attention in the industry but can also be offset by parallelism given the much lower cost of the tools.

2.4 Conclusion

In this chapter, the methods, achievements, and challenges of Nanoimprint lithography are reviewed. NIL offers high resolution, high throughput for fabrication of nano-scale features at low cost. It is clear that NIL holds the key for various cheap prototyping and manufacturing applications. Unlike photolithographic patterning, which has been well developed by the semiconductor industry; NIL has only been 15 years since its discovery with significantly less funding for research and development. Whether NIL will be able to replace other NGL for CMOS fabrication for one of the next nodes is still an open question. Within the near future, it is clear that a range of other non silicon chip based products will be fabricated based on NIL.

Chapter 3

Nanoimprinted Polysiloxane Waveguides

This chapter explores a novel technique leading to low cost and high throughput production of Polysiloxane waveguides. Here we demonstrate low loss and high index contrast Polysiloxane waveguides fabricated on a wafer scale via a simple four step imprint process. Section 3.1 gives an overview of the key characteristics for integrated optics platforms and the background of this project. Section 3.2 describes the material properties of Polysiloxanes which is the class of polymer being studied in this project. Section 3.3 describes the design, fabrication and testing of Polysiloxane channel waveguides fabricated by UV-Nanoimprint lithography.

3.1 Overview

There are a number of candidate material systems for building integrated optical waveguides, each with advantages and disadvantages. Waveguides are simple optical devices because they require only a high index material surrounded by low index cladding for classical devices. However in practice, there are many additional criteria to make a waveguide useful. In this section, a few of the key desirable properties and a few common integrated optics material platforms are discussed. Finally, various polymer fabrication processes for integrated optics are reviewed.

3.1.1 Key characteristics for integrated passive waveguide devices

Single mode operation: This means that there is only one electromagnetic mode supported by the waveguide for each of two orthogonal polarization states. In a multi-mode waveguide, each electromagnetic mode propagates with a different speed, which leads to undesirable signal distortion if the waveguide is used to transmit high speed data over

desirable distances. For this reason, most integrated waveguides of interest support only a single mode for each polarization state.

Low coupling loss: The deployment of single mode fibre has revolutionized the field of communications. Although many people envision futuristic integrated optical circuits consisting of complex interconnected devices, at present most integrated optical devices are single elements inserted between optical fibres. As such, low coupling loss into and out of an integrated waveguide device from a single mode fibre becomes an important selection criteria. Low coupling loss arises from two important waveguide properties:

- The optical mode of the integrated waveguide at the entry/exit facet must have a similar size and shape to that of the optical fibre at its end facet. Note that this can be accomplished by manipulating both the fibre and the waveguide.
- The effective refractive index of the integrated waveguide must be close to that of the optical fibre, or otherwise a special anti-reflective coating is required.

Low propagation loss: This property is very critical for integrated circuits. There are quite a few factors contributing to propagation losses:

- Intrinsic material loss arising from absorption overtones
- Scattering loss due to defects and inhomogeneities in the optical materials
- Scattering from sidewall roughness incurred during the fabrication process
- Radiation loss to high index substrates (e.g. silicon) or higher index cladding materials

Small bend radius: Bending loss refers to the leakage of light from the waveguide as it bends in a curved trajectory. There are many excellent models for calculating bending loss in optical waveguides [56-58]. Generally, the amount of bending loss decreases exponentially with increasing radius of curvature. Also, waveguides with high index contrast (core-clad index difference) exhibit lower bending loss than waveguides with low index contrast. Thus, the desire for low bending loss often competes with the desire for high coupling efficiency to an optical fibre.

Low birefringence: Birefringence and polarization-dependent loss (PDL) simply refer to the difference in propagation constant and loss between the fundamental TE and TM modes. Again, the desire for low polarization dependence stems from the prevalence of optical fibre as a transmission medium. Because the optical fibre has no preferred polarization axis, an integrated optical device should ideally provide polarization independent performance as well.

Robustness: For telecom devices to be marketed, it is vitally important to make sure the device functions stably at various extreme conditions and more importantly over a long period of time. Therefore, an important selection criteria is the material stability, e.g. the variation of birefringence, refractive index, loss, etc as functions of temperature, humidity and time.

3.1.2 Common material systems for integrated optics

There are several material groups commonly used in planar waveguide fabrication. The most widely used is silica on silicon. Other market proven and reliable potential materials for waveguide fabrication are systems such as other oxide glasses, Lithium Niobate (LiNbO_3), Silicon, Indium Phosphide (InP), and Polymers.

One of the earliest systems used for integrated optical devices is a combination of SiO_2 and Si_3N_4 . One advantage of such a material system is that it can be easily integrated on a silica substrate. The structure typically consists of a lower buffer (cladding) layer of SiO_2 , grown by high-pressure thermal oxidization, wet oxidization, or plasma enhanced chemical vapor deposition (PECVD). The core layer of Si_3N_4 is typically deposited using low-pressure chemical vapor deposition (LPCVD) or via nitridation of the oxide in an ammonia atmosphere [59, 60]. The core layer must be relatively thin (typically a few hundred nanometers) to ensure single mode operation due to the high refractive index contrast ($n \approx 2$ for Si_3N_4 and $n \approx 1.46$ for SiO_2). Waveguides based upon this geometry have been reported with propagation losses as low as 0.3dB/cm [60]. Waveguides with a box-shaped cross section consisting of a low index material (SiO_2) surrounded by a thin high index coating layer (Si_3N_4) was recently introduced producing optical losses down to 0.1dB/cm

[61]. However the small core thickness, high index contrast and significant polarization dependence characteristics are not appropriate to match to an optical fibre.

Silica on silicon has long been the benchmark material for integrated optics globally and can be considered the most mature integrated optics platform [62]. The propagation loss for silica optical fibre is about 0.15dB/km at 1550nm due to the low intrinsic absorption of silica and low scattering loss on the fibre core/cladding interface. Silica has excellent stability and environmental resistance; is photosensitive when appropriately doped; can exhibit optical gain when appropriately doped and pumped; and has low temperature dependence compared to most materials. In integrated circuits, the deposition of silica layers on silicon substrates is usually conducted via chemical vapor deposition (CVD) or flame hydrolysis [63]. Both growth processes are lengthy, and performed at high temperatures. The deposited layers typically have a high level of stress which can result in polarization dependence and stress-induced scattering loss. The polarization dependence can be reduced by etching grooves for stress release [64], designing a cross-sectional profile that cancels the polarization dependence in rib or strip-loaded waveguides, adding a thin birefringence-compensating layer that results in double core waveguides [65-67]. However, these approaches affect the fabrication complexity and eventually the cost of the device. Passive optical waveguide circuits fabricated from doped silica films deposited on planar substrate were pursued by many research groups, e.g. NTT, LETI and Bell labs. Researchers at NTT demonstrated channel waveguides with propagation loss reduced down to 0.01dB/cm and fibre coupling loss of only 0.05dB [68]. High index contrast (up to 5%) channel waveguides were reported by the research group in LETI; in their approach, the core layer was doped with phosphorus and the refractive index was controlled by the amount of phosphorus doping [69, 70]. Despite the high cost of the materials, the processing and the associated safety equipment, silica on silicon platform has been used to produce lasers, amplifiers, couplers, filters, switches and attenuators [71-75], and these are commercially available.

Silicon photonic devices may yet be of great importance for integrated optics and as on chip interconnects. Similar to silicon on insulator technology in microelectronics, silicon photonic devices can be made using existing semiconductor fabrication techniques with the

potential of creating hybrid devices in which optical and electronic components are integrated onto a single microchip. Silicon is a well known material in the semiconductor industry; it is transparent to infrared at wavelengths above $1.1\mu\text{m}$ and has high refractive index with high nonlinearity. Although the high index contrast between silicon and oxide/air seems to imply a small mode size (typically 220nm high and 400nm wide in channel waveguides), relatively large optical modes can be confined in silicon ridge waveguides without sacrificing single-mode operation [76] and based on this structure, propagation loss as low as 0.1dB/cm was reported [77] compared to an all time best of 0.8dB/cm for nanowires [78]. However polarization independent/birefringence free operation cannot be achieved in this mode of operation. Thermal oxidation can be used to reduce the roughness on the waveguide sidewall, and its effect on the sidewall has been extensively studied [79]. High coupling loss from a single mode fibre into a silicon waveguide can occur due to the high index contrast and small mode area. Using an inverse taper approach [80, 81], efficient fibre-waveguide coupling can be achieved. Coupling loss down to 0.2dB has been demonstrated based on this approach [81]. Another solution for efficient fibre to waveguide coupling is using surface gratings etched onto the silicon [82]. In recent years, silicon has been demonstrated for the fabrication of optical modulators, detectors, amplifiers, lasers, etc [83-86]. Silicon photonics takes advantage of the compatibility with CMOS process; it is still a great challenge to produce silicon photonic devices affordably. Efficient use of wafer real estate is what fuels the relentless scaling of CMOS to smaller feature sizes. For photonics to merge with VLSI electronics, it cannot significantly increase the chip area; otherwise, it will violate the economics of silicon manufacturing. The fabrication cost of CMOS process is $\$5\text{-}16/\text{cm}^2$ depending substrate material and processes [6]. At such cost, consumer devices (e.g. medical sensors) are hardly affordable.

Compound semiconductors are another well researched and proven material for integrated optical components. They can be conveniently integrated with active elements such as lasers and photodetectors. Indium Phosphide (InP) is one of the few semiconductor materials that can be used to produce both active and passive optical devices. However it is difficult and expensive to manufacture. Gallium arsenide is also commonly used for both active and passive optical devices. It is typically used to produce lasers in GaAs/GaAlAs

systems producing wavelength from 780-905nm and in InP/InGaAsP systems producing wavelength from 1-1.7 μ m [87].

Lithium Niobate is an attractive material for fabrication of optical waveguides because of its acousto-optic and electro-optic properties [88]. Whilst the fabrication of waveguides by processes such as Titanium indiffusion is an inherently low cost process, the material itself is not and matters are further complicated by the fragility and anisotropic nature of the material. Tight waveguide bends are also difficult, and as with glass substrates, hybrid integration of actives and self aligned pig tailing are difficult again meaning that Lithium Niobate is unlikely to be a realistic low cost device option.

Polymers have long been recognized as the leading candidates for the fabrication of low cost integrated optical components. The reasons behind this lie in the inherently low cost of the materials, the very large low cost substrates that can be processed, the potential processing speed possible, and options for low cost processing tools/methods. For example, waveguide devices can even be made by simple spin-coating and UV-Exposure with relatively simple exposure tools – certainly a fast and inexpensive fabrication route. The absorption loss of polymers can be less than 0.1dB/cm at all the key communication wavelengths (840, 1310, and 1550nm) [89]. Tunability of the refractive index difference between the core and cladding is easily achieved for large index contrasts which lead to compact waveguiding structures employing tight bend radii [87]. Most polymers possess large thermo-optic coefficients meaning that active devices (switches, variable optical attenuators, etc) with response times down to a few microseconds can be made. Low or high birefringence can be attained in polymeric films, optical gain, and electro-optic effects are possible and today there even exist some commercialized polymer modulator devices [90]. Using silicon as the substrate material also opens up the opportunities of processing large wafers, hybrid integration and self-aligned pigtailed to help with the back end costs.

3.1.3 Polymer optical waveguides

Polymers are one of the most important inventions of the 20th century. The robust characteristics that many polymeric materials display have not only created an enormous range of applications in our everyday life but also make them a good candidate for low cost

high performance integrated optics. The mechanical properties of a polymer are significantly affected by the molecular weight. Typically, single polymer molecules have molecular weights between 10,000 and 1,000,000g/mol. The polymer glass transition point and the melting point/decomposition temperature will determine which applications it is suitable for. As for crystallinity, polymers generally have a combination of crystalline and amorphous structures. Table 3.1 shows a comparison of various types of optical polymers commercially developed globally.

Table 3.1: Characteristics of optical polymers developed companies globally

Manufacturer	Polymer Type	Patterning Techniques	Propagation Loss, Single Mode waveguide, dB/cm (wavelength, nm)	Other Properties (wavelength, nm)
Amoco	Fluorinated polyimide (Ultadel™)	Photo exposure / wet etch	0.4 (1300) 1.0 (1550)	Birefringence: 0.025, Crosslinked, Thermally stable
Corning (formerly AlliedSignal)	Acrylate	Photo exposure / wet etch, RIE, laser ablation	0.02 (840) 0.3 (1300) 0.8 (1550)	Birefringence: 0.0002 (1550), Crosslinked, $T_g=25\text{ C}^\circ$, environmentally stable
	Halogenated acrylate	Photo exposure / wet etch, RIE, laser ablation	<0.01 (840) 0.06 (1300) 0.2 (1550)	Birefringence: 0.000001 (1550), Crosslinked, $T_g= -50\text{ C}^\circ$, environmentally stable
Dow Chemical	Benzocyclobutene (Cyclotene™)	RIE	0.8 (1300) 1.5 (1550)	$T_g > 350\text{ C}^\circ$
	Perfluorocyclobutene (XU35121)	Photo exposure / wet etch	0.25 (1300) 0.25 (1550)	$T_g = 400\text{ C}^\circ$
Gemfire	(Gemfire)	Photo exposure / wet etch	1.0 (1550)	Birefringence: 0.0002 (1550), Crosslinked
General Electric	Polyetherimide (Utem™)	RIE, laser ablation	0.24 (830)	Thermally stable
Hitachi	Fluorinated polyimide	Photo exposure / wet etch	TE: 0.5, TM :0.6 (1300)	Birefringence: 0.009 (1300), PDL: 0.1 dB/cm (1300), $T_g= 310\text{ C}^\circ$, Thermally stable
Hoechst Celanese	PMMA copolymer (P2ANS)	Photo bleaching	1.0 (1300)	NLO polymer

Chapter 3 Nanoimprinted Polysiloxane Waveguides

Ipitek	Poly(methylmethacrylate) with CLD-1 chromophore (PMMA-CLD-1)	RIE	5.0 (1300)	NLO polymer $r_{33}=60$ pm/V (1300) Pigtail loss= 3.5 dB/facet
JDS Uniphase (formerly Akzo Nobel)	Polycarbonate (BeamBox TM)	RIE	0.6 (1550)	Thermally stable
K-JIST	Fluorinated poly(arylene ether sulfide) (FPAESI)	RIE	TE: 0.42, TM: 0.4 (1550)	PDL : 0.02 dB/cm (1550), Birefringence: 0.0003 (1550), Crosslinked, Thermally stable
Lumera	Polyurethane with FTC chromophore	RIE	2.0 (1300)	NLO polymer $r_{33}=25$ pm/V (1310) Pigtail loss= 5 dB/facet
NTT	Halogenated acrylate	RIE	0.02(830) 0.07(1310) 1.7 (1550)	Birefringence: 0.000006 (1310) , $T_g=110$ C°
	Deuterated polysiloxane	RIE	0.17 (1310) 0.43 (1550)	Environmentally stable
	Fluorinated polyimide	RIE	TE: 0.3, TM: 0.7 (1310)	PDL: 0.4 dB/cm (1310) Environmentally stable
Optical Crosslinks	Acrylate (Polyguide TM)	Diffusion	0.18 (800) 0.2 (1300) 0.6 (1550)	Laminated sheets, excimer laser machinable
PacificWave	Polycarbonate with CLD-1 chromophore (PC-CLD-1)	RIE	1.8 (1550)	NLO polymer $r_{33}=70$ pm/V (1310) Pigtail loss= 1.5 dB/facet
Redfern (currently RPO)	Inorganic polymer glasses (IPGs TM)	Photo exposure / RIE	0.24 (1322) 0.52 (1548)	Environmentally stable
Telephotonics	(OASIC TM)	Photo exposure / wet etch, RIE, laser ablation	<0.01 (840) 0,03 (1300) 0.1 (1550)	Environmentally stable
Micro Resist Technology	Ormocer	Photo exposure / wet etch, RIE, laser ablation	0.05 (830) 0.02 (1310) 0.6 (1550)	Environmentally stable

3.1.3.1 *Refractive index*

There are several aspects of the refractive index that need to be considered. Firstly, the variation of index with wavelength (refractive index dispersion), is an important property of a waveguide material. In general, most polymers have significantly larger dispersion than silica, which can be both a problem and a benefit depending on the circumstances. This is clearly a property which has to be factored into device designs, but is not generally a limiting factor.

Secondly, refractive index is not only a function of wavelength, but also of temperature, humidity, light exposure, and ultimately time. Polymer-based waveguides have in the past been especially sensitive to the last two effects (yellowing and long term stability), especially at elevated temperatures [89]. Generally the refractive index of polymers vary more rapidly than other conventional optical materials with temperature. The refractive index of many polymers of interest for optical waveguides decreases at a rate of $\sim 10^{-4}/^{\circ}\text{C}$, which is one order of magnitude larger than that of inorganic glasses but usefully of opposite sign. This can be used to make active devices or to athermalise inorganic glass waveguides, where the small, positive thermo-optic effect in the core is canceled out using the negative thermo-optic coefficient of the polymer cladding. For all polymer devices, clearly the thermo-optic coefficient has to be allowed for the device design.

Humidity induced changes of the refractive index can be problematic in several types of devices. For polymers, the refractive index changes are ascribed to the counterbalance between moisture absorption and swelling. For example, the refractive index of deuterio-PMMA increases as the humidity increases at temperatures higher than 60°C . Although the humidity dependence of deuterio-PMMA is as large as $10^{-5}\%(\text{RH})^{-1}$, some hydrophobic polymers, such as silicone polymer, are affected by humidity to a much lesser and acceptable degree than acrylic polymers [91].

Refractive index tunability over a wide range is a unique feature offered by polymers and this is accomplished by varying the side groups that branch off the main polymer backbone. Alternatively the incorporation of fluorine atoms into polymers in place of hydrogen can affect the refractive index in three ways simultaneously. Firstly, the increase

in free volume which often accompanies fluorine substitution (attributed to the greater steric volume of fluorine relative to hydrogen interfering with efficient chain packing) may decrease the refractive index via the density. Secondly, the electronic polarizability is always lowered with fluorine substitution because of the smaller electronic polarization of the C-F bond relative to C-H bond. Lastly the blue-shifting of the short wavelength absorption from fluorine substitution also contributes to the lowering of the refractive index.

The birefringence ($n_{TE} - n_{TM}$, TE = transverse electric, TM = transverse magnetic) indicates the optical anisotropy of a material. In a normally isotropic material, birefringence is also related to the stress build-up within the material due to processing or thermal treatment. Unlike inorganic crystals or glasses, polymers can be molecularly engineered to achieve either low or high birefringence. Some aromatic polymers, such as polyimides, exhibit a very large birefringence (up to 0.24) that is attributed to the strong preference of aromatic moieties to align with their planes along the film surfaces [92]. However, the birefringence can be extremely low (10^{-5} to 10^{-6}) in polymers that undergo little molecular orientation during processing, as is common in three dimensionally cross linked polymers [93].

3.1.3.2 *Optical loss*

Attenuation or loss is an important characteristic of a waveguide. The loss is generally attributable to several different mechanisms: absorption, scattering, radiation loss, etc. For polymer materials, generally, there are large absorptions in the ultraviolet because of fundamental electronic transitions across the band gap. These absorptions tend to be in the deep ultraviolet (less than 200nm) for polymers with predominantly aliphatic hydrogen atoms, and in the near UV (200 to 400nm) for polymers with significant numbers of aromatic hydrogen atoms. Partially or fully fluorinated polymers tend to have their UV absorptions deeper in the UV also. In general, though these UV bands are important in determining the refractive index and dispersion of the material, electronic absorptions in polymers contribute minimally to optical loss in the major telecommunication windows near 1310nm and 1550nm. In the 1300 to 1600nm range, however, absorptions appear

from the overtones of fundamental molecular vibrations [94, 95]. Since the strength of the absorption tends to decrease by approximately an order of magnitude between each harmonic order, higher harmonics are generally too weak to be considered. Both C-H and O-H overtones are seen to be highly absorptive in the telecommunications windows, whereas C-F overtones, for example, show extremely low absorption throughout the range of interest, due to their higher harmonic order. Table 3.2 provides a comparison of the positions and intensities of these vibrational overtones.

Table 3.2: Wavelengths and intensities of some important vibrational overtones. [96]

Bond	Overtone order	Wavelength (nm)	Intensity (relative)
C-H	1	3390	1
C-H	2	1729	7.2×10^{-2}
C-H	3	1176	6.8×10^{-3}
C-F	5	1626	6.4×10^{-6}
C-F	6	1361	1.9×10^{-7}
C-F	7	1171	6.4×10^{-9}
O-H	2	1438	7.2×10^{-2}

There are numerous extrinsic contributions to scattering loss in optical materials. Primaries are large inclusions such as particles, voids, cracks, and bubbles. Generally, an inclusion is considered large if it is greater than the optical wavelength, in which case the scattering intensity is largely wavelength independent. Extrinsic scattering in polymers can result from unfiltered particles, dust, dissolved bubbles, and untreated monomer. Intrinsic scattering results from density fluctuations and compositional inhomogeneities, both of which occur on very short length scales (100nm or less) and usually are negligible in integrated optics scale devices.

Polarization dependent loss (PDL) reveals the maximum difference of optical insertion loss measured between any of the two polarization states. For planar waveguide devices, the measured TE loss can be higher than the TM loss due to the rougher sidewalls of the core than the horizontal boundaries. Another source of PDL is from the stress built in

during the fabrication process which may increase the loss alone either TE or TM directions. By having a minimal edge roughness, a well-confined material stack, and low-stress processing a well-optimized waveguide can have PDL values that are very small, provided that the waveguide material itself has a low birefringence [97].

3.1.3.3 *Environmental performance*

The environmental stability of optical polymers is crucial and most polymers do not have good enough stability for use in telecommunications devices where the Telcordia reliability tests [98] dictate long term stability in damp heat conditions and through 40~85°C temperature cycles. An important characteristic is the thermal stability of optical polymers, since polymeric materials subjected to thermal aging can “yellow”; change their refractive index; harden and become brittle; amongst other effects. Typically, such aging results from the formation of partially conjugated molecular groups characterized by broad ultraviolet absorption bands, which tail off in intensity through the visible region [97]. This yellowing is strongly dependent on the chemical structure of the original polymer. In fully halogenated materials, yellowing becomes almost negligible at any wavelength because the absence of hydrogen prohibits the formation of H-halogen products that will result in carbon double bonds. These unsaturated double bonds are the major cause of yellowing when they are slowly oxidized under long-term thermal aging.

3.1.3.4 *Fabrication techniques*

Spin coating is widely used for polymer film deposition which offers simple, fast and extremely uniform thin film deposition over large areas. A wide range of rigid or flexible substrates can be used, such as glass, quartz, thermally oxidized silicon, glass-filled epoxy printed circuit board and flexible polymers. The polymer film thickness can be tailored in the range of <0.1 to >100µm by controlling the viscosity (either through molecular weight or polymer/solvent ratio) and spin speed. Optical polymers are generally designed and synthesized by chemical modification of constituent molecules to have the desired characteristics, such as melt or solution processibility in the form of monomers or prepolymers, photo- or thermo-crosslinking enhanced mechanical properties, and matched refractive index. Furthermore, these properties are adjustable through formulation

variations [97]. There are several polymer waveguide patterning techniques including direct lithographic patterning, direct laser writing and moulding in addition to the conventional photoresist based patterning and etching.

Direct lithographic patterning can only be applied to photosensitive polymers. This technique requires either exposure through a photomask to create the pattern or a direct write system; the polymers in the exposed regions become crosslinked leading to insolubility in a developer in contrast to the unexposed regions. The pattern is then developed by conventional wet etch of the unreacted material with a standard organic solvent. This lithographic process offers very high contrast response allowing the definition of polymeric features with dimensions ranging from a few microns to a few millimeters with a high degree of accuracy and process latitude [89].

The difficulty, cost, and delay associated with designing and making the masks strongly limits the flexibility of masked lithography, especially when a limited number of wafers are to be fabricated. Maskless techniques like direct laser writing constitute a suitable alternative. Direct laser writing makes use of UV, nanosecond pulsed, excimer, and Nd:YAG lasers for curing the polymer. Picosecond and femtosecond lasers have more recently raised interest by enabling 3D structuring with higher precision in a single step based on two-photon polymerization [99]. This technique offers considerable latitude in power level, focusing and writing speed, permitting the creation of novel structures that are virtually impossible to make by mask-based lithography. Furthermore, laser writing can play a role in the regime of very large dimension devices where masks cannot be produced; for example several meter long polymer waveguides can be direct written on large substrates such as rolls of flexible plastics (super computer based optical backplane interconnect would be one application for this sort of device).

However, some polymers (such as some polyimides) are not photosensitive, therefore cannot be patterned by direct exposure or laser scanning. Photoresist based patterning is another useful technique which does not require material to be photosensitive; it uses standard semiconductor processing technology involving spin coating, baking, exposure, etching, etc. The biggest advantage of this approach is that the process and tools are all commercially available and well developed. However a challenge for polymer waveguide

processing is the low etching rate contrast between the waveguide material and photoresist. Additional material and processes are usually involved which increases the cost and complexity. Additionally this method requires the use of single wafer processing plasma etching tools massively increasing processing costs and reducing throughput.

Moulding is an unconventional fabrication method with its unique ability to replicate features with low cost and high throughput. It contains several types of patterning techniques including injection moulding (IM), reaction injection moulding (RIM), microcontact printing, micromoulding in capillaries, UV-nanoimprinting (UV-NIL), thermal-nanoimprinting (T-NIL) and casting. In chapter 2 we reviewed the development and status for UV-NIL and T-NIL [38, 100]. Overall, the combination of a polymer platform and moulding can offer high resolution, low cost optical devices. In this chapter, soft lithography is adapted to imprint Polysiloxane waveguide devices and more details will be presented in next section. In chapter 7, hot embossing will be demonstrated for the replication of chalcogenide glasses waveguide.

3.2 IPGTM material properties

Using polymer materials it is, for example, possible to fabricate waveguide devices very quickly using only spin coating and UV cure/solvent develop processes for patterning. However, despite this promise there has been no demonstration to date of high index contrast waveguides fabricated by this route in materials known to be capable of passing the Telcordia reliability test suite. One polymer system well established to meet this requirement is the Polysiloxane family. There have been demonstrations of low loss waveguide devices with up to 0.6% index contrast made by either plasma etching or the UV cure/develop process [91, 101-104] and commercial devices are on the market [105]. However the relatively low index contrast precludes bend radii below 1cm severely limiting the compactness of fabricated devices.

Inorganic polymer glasses (IPGTM) developed by RPO Pty Ltd are a family of highly stable, photo-curable Polysiloxanes which have passed the stringent Telcordia environmental reliability criteria. High index contrast (up to ~5%), low birefringence and low optical loss at telecommunication wavelengths are the important characteristics for

potential low cost integrated optical components. The backbone of IPG™ is based on Si-O and the molecular structure is shown in Figure 3.1.

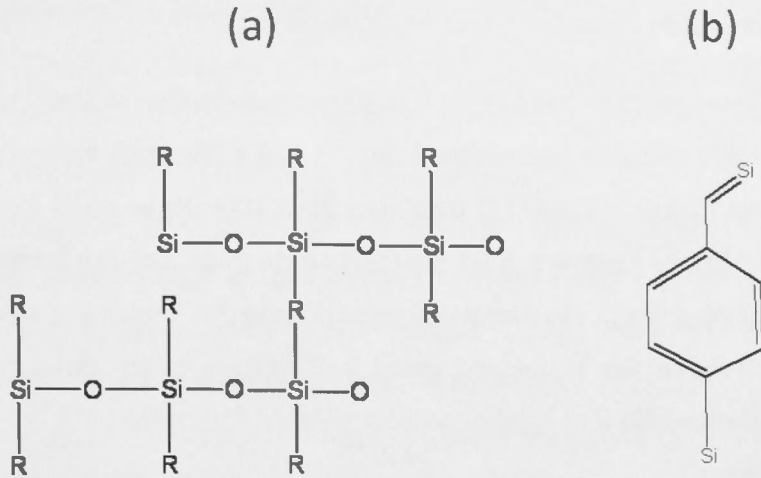


Figure 3.1: (a) Molecular structure of IPG, (b) chemical structure of R

Two types of IPGs were formulated in this project for waveguide applications: IPG B3 as the cladding material and IPG B11 as the core material; the refractive indices are 1.478 and 1.507 respectively at 1550nm. With the combination of photo initiator, B3 and B11 can be formulated as negative photoresist and therefore must be handled in UV-free environment. The thermo-optic coefficients for (dn/dT) are $-3 \times 10^{-4}/^{\circ}\text{C}$, coefficient of thermal expansion is about $600 \times 10^{-6}/^{\circ}\text{C}$, and the decomposition temperature is greater than 300°C , which is high enough for almost all optical applications.

IPGs are commonly formulated as negative photoresists for direct UV patterning; this method is simple and high throughput for relatively large features (greater than $5\mu\text{m}$), however, a fabrication bottle neck was encountered when small features were attempted due to photo initiator diffusion. This problem can be solved using conventional approaches: optical lithography and dry etching; this has been demonstrated by [106]. In this approach, a $10\mu\text{m}$ IPG cladding layer and $3\mu\text{m}$ core layer were spin coated on a 4 inch wafer and cured respectively. Using a deposited silica layer as the etch mask (due to small etch contrast between IPG and photoresist), the waveguide pattern was defined by lithography and dry etching processes. The etched waveguides demonstrated optical losses down to 0.73dB/cm for 1550nm and 0.40dB/cm for 1310nm. These losses are slightly higher than

the cured bulk material which was thought to be a result of optical damage of the material from the deep UV plasma emission [106]. The plasma etching route, whilst simpler and faster than that for a comparable silica waveguide structure, is capital, consumable, and time intensive compared to direct UV patterning method.

Liquid IPG is transparent to naked eye; it has strong absorption in the UV because of fundamental electronic transitions across the band gap and a few large absorption peaks in the near infrared due to the C-H and O-H overtones. Bulk IPG can be cured from the liquid phase by intense UV flood exposure in an oxygen-free environment. The intrinsic material losses were measured using a spectro-photometer. Figure 3.2 shows the measured IPG transmission spectrum of the liquid and cured bulk phases, slight differences can be observed comparing the two loss spectrum; most notably that cured bulk IPG has higher loss at around 1550nm.

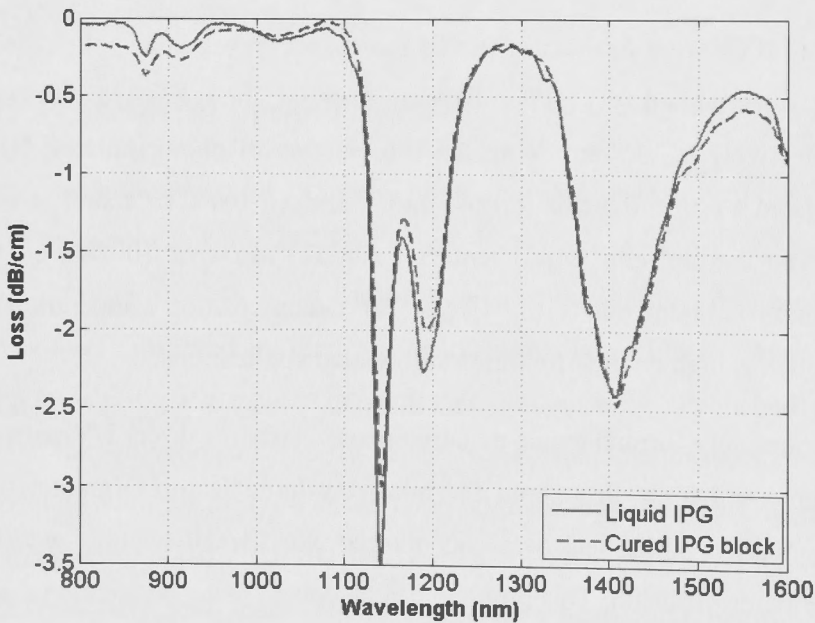


Figure 3.2: Measured loss spectrum for liquid IPG and cured bulk IPG

3.3 UV-Nanoimprinted Polysiloxane Waveguides

UV-Cured Nanoimprint Lithography (UV-NIL) is a non-photolithographic strategy based on replica moulding for micro-fabrication. The process and status of UV-NIL was reviewed in Chapter 2. Since the invention of UV-NIL, it has been applied to fabricate integrated optical devices, e.g. optical couplers, lasers, resonators and modulators [48-51] in acrylate or epoxy based materials. Such materials, whilst excellent for nanoimprinting, do not have the same level of demonstrated environmental stability as Polysiloxanes. Chang-Yen *et al* demonstrated an approach to imprint PDMS waveguide by curing PDMS at different temperatures (resulting in refractive index contrast), however this also introduced intrinsic temperature instabilities [107]. Kopetz *et al* used the groove-filling method to fabricate large core multimode (70×70µm) Polysiloxane and PDMS waveguides which could be applied in electrical-optical circuit boards; the measured loss was as low as 0.06dB/cm at 850nm [108, 109]. Kim *et al* demonstrated the use of UV-NIL and soft PDMS stamp to imprint large core (35×45µm) waveguides on Sol-gel siloxane based material; cutback measurements revealed an optical loss of 0.36dB/cm at 850nm [47]. The formation of a residual layer around the waveguide core after imprint was observed to be a problem; common solutions are reactive ion etching and “doctor blading” [110, 111]. Additionally, the large size of these waveguides masks the effects of surface roughness [112, 113] meaning that the viability of small telecommunication compatible waveguides fabricated by nanoimprint is still unproven. In this section, the UV-NIL process is used to replicate single mode Polysiloxane waveguides. The design, fabrication and testing of low loss, high index contrast waveguides are described.

3.3.1 Stamp fabrication

3.3.1.1 PDMS stamp

An elastomeric block with patterned relief structures on its surface is the key to soft lithography because it can make conformal contact with surfaces (even those that are non-planar on the submicron scale) over relatively large areas, and because they can be released easily from rigid masters or from complex, quasi-three-dimensional structures that are

being moulded. Polydimethylsiloxane (PDMS) is the most commonly used elastomer for this purpose. It belongs to a group of polymeric organosilicon compounds that are commonly referred to as silicones [114]. PDMS has a unique combination of properties resulting from the presence of an inorganic siloxane backbone and organic methyl groups attached to silicon. Uncured, they are fluids at room temperature; and these liquid materials can be readily converted into solid elastomers by cross-linking via a catalytic reaction. The formulation, fabrication, and applications of PDMS elastomers have been extensively studied and are well-documented in the literature [100]. In addition to its elasticity, the PDMS elastomer also has other properties that make it extremely useful in soft lithography:

- The surface of PDMS has low interfacial free energy ($\sim 21.6 \text{ dyn/cm}$) and good chemical stability; it does not react or adhere with most materials commonly used for moulding.
- PDMS is not hydroscopic; it does not swell with humidity.
- PDMS membranes are gas permeable; trapped air can escape through the membrane during the imprint process over time.
- PDMS has great thermal stability; the rated datasheet specified 200°C as the upper limit of material stability; experimentally we found PDMS is physically stable at least up to 300°C .
- PDMS is optically transparent down to $\sim 300 \text{ nm}$; pre-polymers being moulded can be cured by UV cross-linking.
- The PDMS elastomer is isotropic and homogeneous; stamps or moulds made from this material can be deformed mechanically to manipulate the patterns and relief structures in their surfaces.
- The interfacial properties of PDMS elastomer can be changed readily either by modifying the prepolymers or by treating the surface with plasma, followed by the formation of siloxane self-assembled monolayers (SAMs), to give appropriate

interfacial interactions with materials that themselves have a wide range of interfacial free energies.

However, PDMS also possesses some fundamental limitations:

- PDMS shrinks about 1% upon curing and it is readily swelled by a number of non-polar organic solvents such as toluene and hexane.
- Elasticity and thermal expansion of PDMS makes it difficult to produce high accuracy registration across a large area.
- The softness of an elastomer typically limits the aspect ratio of microstructures.

The type of PDMS used in the experiments described hereafter was Sylgard 184 from Dow Corning, which was prepared from a base material and a curing agent. It can be cured from room temperature to 150°C. It behaves as medium-viscosity liquid (medium viscosity is defined as 10,000 centipoise to 30,000 centipoise; the viscosity of water at 25°C is 0.8904 centipoise) in the uncured phase and becomes a flexible elastomer after curing. Experimentally, PDMS stamps can be made as shown in the following procedures:

1. A container (plastic cup or glass beaker) was used for mixing and filled with one part curing agent and ten parts of base agent by weight. For example, to cover the area of a 4 inch wafer, approximately 10g of mixed Sylgard 184 was needed; therefore, 1g curing agent plus 10g base agent will produce the right amount of mixture.
2. The base and the curing agent were manually mixed using a plastic spoon or equivalent tool for at least 5 minutes. Mixing incorporated a lot of air in the solution. Therefore the mixed materials were left to vent in clean air for half an hour to let the air bubbles settle.
3. Full removal of the air bubbles was carried out in a vacuum oven at room temperature. In practice, as the oven pressure goes down, the trapped air bubbles start to expand; overflow can occur when the pressure is low enough which is undesirable and pressure needed to be controlled manually. The degassing process

normally took half an hour and the mixture looked clear with no visible defects in it upon completion.

4. Pouring the Sylgard 184 mixture onto a sample was rather critical. It was essential to ensure that the substrate was perfectly horizontal inside the oven to prevent biased overflow and ensure thickness uniformity of the stamp. A home-built apparatus was built to provide a leveled surface and the leveling was tested by placing a large ball bearing on the top surface; a stationary ball bearing indicated the surface was in good leveling and the sample wafer could be placed on top of this surface. Then the PDMS mixture was poured onto the center of the wafer and allowed spreading out itself (spreading out a 4 inch wafer normally took less than 5 minutes). Surface tension stopped the flow and trapped the liquid at the edge of the wafer and a uniform stamp could be obtained.
5. PDMS was cured by an organometallic cross-linking reaction. In curing, the liquid mixture became solid via a hydrosilation reaction between vinyl groups and hydrosilane groups forming $\text{Si}-\text{CH}_2-\text{CH}_2-\text{Si}$ linkages. In this experiment curing was typically performed at 65°C under vacuum for 12 hours.
6. Once the stamp was fully cured, the remaining step was to peel it off from the master wafer. This was performed using a 4 inch vacuum chuck to hold the 4 inch wafer down using vacuum by its backside. A blade was used to peel up one edge of the stamp. Tweezers were then used to hold the peeled edge and slowly release the rest of the area via gentle pulling in a peeling type geometry.

3.3.1.2 *h*-PDMS stamp

h-PDMS was first formulated by Schmid and Michel as a higher resolution alternative to PDMS [21]. Its higher resolution is derived from the addition of vinyl and hydrosilane compounds which act to increase the Young's modulus of the elastomer. To date, the high resolution of *h*-PDMS has been demonstrated to improve the performance of elastomeric phase masks [115], contact printing, and replication down to the molecular scale [37].

The constituents of *h*-PDMS and their required quantities are specified in the literature [21], but they are reiterated here because of changes to product names. Preparation began by decanting 3.4g of vinyl PDMS prepolymer (VDT-731, Gelest Corp.), to which was added 18 μ L of the catalyst platinum divinyltetra-methyldisiloxane (SIP6831.2LC, Gelest Corp.), 0.1g of the modulator, 2,4,6,8-tetramethyltetravinyldicyclotetrasiloxane (87297, Sigma Aldrich) and 1g of hydrosilane component (HMS-301, Gelest Corp.). This solution was mixed thoroughly, producing a low viscosity liquid.

A thick layer ($\sim$ 1mm) of *h*-PDMS is rigid and a lot more difficult to release from the moulded substrate compared to PDMS stamps. It is more useful to apply *h*-PDMS as the printing layer in a multi-layer approach with the combination of different layers of material. One example is the combination of a thin layer of *h*-PDMS ($\sim$ 10 μ m) backed with a thick layer of PDMS ($\sim$ 1mm); such a combination provides local rigidity for defining high resolution features while being flexible globally.

The *h*-PDMS stamp in this thesis refers to the stamp fabricated in this double layer approach. Spin coating was used to deposit the thin *h*-PDMS layer and then it was cured at 110°C on a hot plate for 20 minutes. The production of a thick PDMS backing layer was identical to the process used for producing PDMS stamp which was discussed in the previous section.

3.3.2 Waveguide design and minimum displacement approach

Despite the low cost and high throughput advantages of the UV-NIL technique, there are some well-known problems associated with it. In an imprint process, the resist is displaced to create the desired features. Ideally features on the stamp need to be filled and the unwanted material has to flow away from the feature completely. This requires exactly the right film thickness (which must be less than the feature height so that the transported material has a volume equal to that of the feature) or else there will be excess material left. The residual layer is usually left after the imprint process anyway due to the large force and long times required to displace liquid as the film thickness becomes small and the required transport distances (several centimeters) are large compared to the film thickness. The time to halve the residual layer thickness goes as the fourth power of the transport

distance, and the inverse square of the film thickness, so to reduce a residual film from 100nm to 50nm with a 10^7 Pa applied pressure and a 1cm transport radius would take approximately 2 years with a typical imprint resist [116]. Further with the large viscosity of IPGTM of 2300 centipoises, it is very difficult to spin coat IPGTM films much below a thickness of 1~2 μ m; therefore it is difficult to just mould a rib for the core without a substantial residual layer. The common solutions for this residual layer are reactive ion etching and “doctor blading” the core into a pre-prepared trench [110, 111]. In this project, we propose an innovative “minimum displacement method” to minimize this residual layer without introducing extra steps as shown in Figure 3.3.

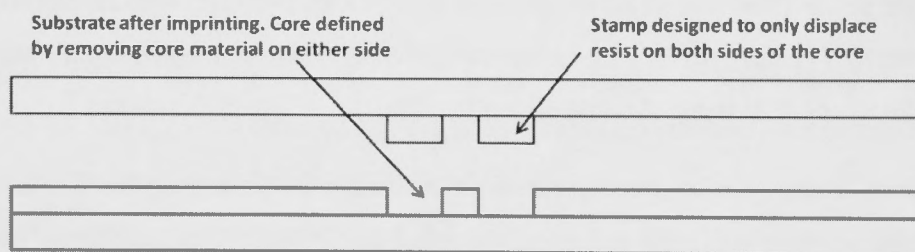


Figure 3.3: Schematic diagram of minimum displacement approach to minimize the residual layer

For each waveguide, only a limited cladding width on both sides of the core was imprinted thereby concentrating all the stamp force into the small “isolation ribs” and vastly reducing the transport distance. The goal was to find a design such that the displaced volume was small enough (<20%) to be easily taken up in the flexible mould areas either side of the waveguide cores. Some waveguide modeling was required to determine the required isolation rib width and suitable waveguide dimensions.

Waveguide modeling with the full vector complex generic Finite-Difference method (as embodied in the C2V Olympios software[117]) identified that the optimum core size for 2% index contrast was a waveguide core of 3 $\times$ 3 μ m. The resulting fundamental mode profile is shown in Figure 3.4(a). It was the best confined mode attainable with this index contrast and also provided the optimal mode match (loss <0.1dB) to available high numerical aperture fibres such as Nufern UHNA-3 fibre which could itself be spliced with low loss (<0.1dB under optimized conditions) to standard telecommunications fibres for

pigtailing. The 2% index contrast was also sufficient to bend this waveguide design with a minimum bend radius of $\sim 1\text{mm}$ meaning compact waveguide circuits could be realized [112]. Modeling of the radiation mode coupling loss into slab modes of the non-imprinted core layer region either side of the isolation trenches shown in Figure 3.4(b) suggested that the cladding/isolation trench needed to be at least $7\mu\text{m}$ wide [118]. The final width selected was $10\mu\text{m}$ to allow a safety margin.

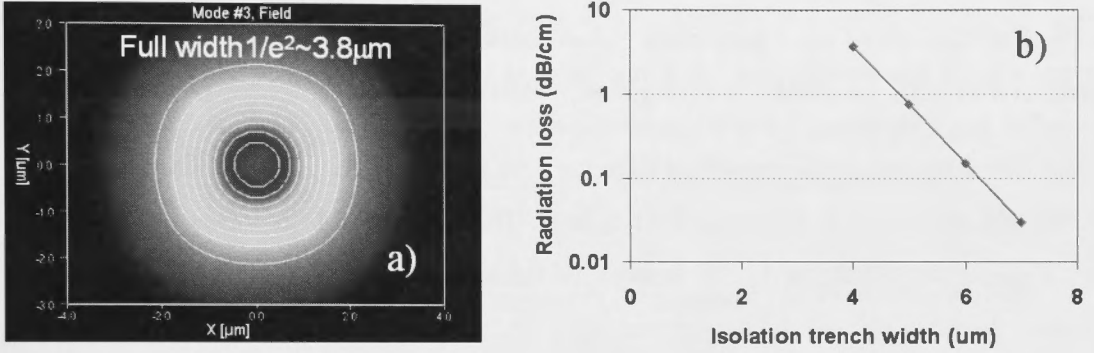


Figure 3.4: (a) Fundamental mode field profile for $3 \times 3\mu\text{m}$ waveguide with 2% index contrast, (b) Computed loss to radiation modes in unimprinted slab area versus isolation trench width.

To tolerate dimensional errors introduced during the fabrication process by factors such as photolithography and etch bias, and to allow for different thicknesses of anti-stick coatings on the master, waveguides with core widths of 2.20, 2.60, 2.80, 3.00, 3.20, 3.40, 3.80 and 4.00 microns were embedded on the imprint mask which was sent to Bandwidth Foundry Ltd [119] for fabrication.

3.3.3 Lithography and Etching process for SiO_2 master fabrication

Whilst many groups have shown SU-8 photoresist is a convenient method to make stamp masters, SiO_2 was chosen as the material for creating the master pattern in this work primarily due to its hardness and chemical inertness which allowed the master to be cleaned and reused many times. The fabrication process for the master is shown schematically in Figure 3.5 and was performed as follows:

First, bottom anti-reflection coating (BARC, XhiRC-16 from Brewer Science) was spin coated onto a thermally oxidized (5 μ m thick) 100mm diameter silicon wafer. With a thickness of $\sim$ 160nm, this BARC layer helped to improve the resist adhesion and to suppress the strong standing wave effects which degrade the resist profile when monochromatic 365nm radiation was used for resist exposure.

Then 1.5 μ m positive photo resist (Clariant AZ MiR 701) was spin-coated on top of the BARC layer followed by soft bake on hot plate at 90°C for 60 seconds. The lithography process was carried out on a Karl Suss MA-6 mask aligner; the exposure was set up for vacuum contact and a dose of $\sim$ 200mJ/cm² at 365nm exposure.

The wafer was then post exposure baked at 110°C for 1 minute before development in AZ MIF-300 developer in a puddle for 1 minute. The final step of the lithography process was a 1 minute hard bake at 110°C to improve the adhesion and harden the resist without degrading the profile. Next the pattern needed to be transferred into the silica layer.

Table 3.3: Etching recipe used in the ICP etching process for pattern SiO₂ layer

Purpose	Gas source and flow rate	RF Power	ICP Power	Chamber pressure
Remove BARC layer	O ₂ 30sccm	20W	200W	10 mTorr
Etch 3 μ m SiO ₂	Ar 50 sccm CHF ₃ 50 sccm	150W	0W	30 mTorr
Oxygen cleaning	O ₂	500W	200W	30 mTorr
Strip off remaining resist	O ₂ 30sccm	20W	200W	10 mTorr

All the etching processes were carried out in an Oxford Instruments ICP 100 system equipped with a laser interferometer for etch rate monitoring, a quartz plate mechanical wafer clamp and 4 types of gas (O₂, CHF₃, Ar and CF₄) for various etch recipes. To transfer the pattern from the photo resist layer to the SiO₂ layer, four etching steps were adopted. The etch recipe and system configuration is shown in Table 3.3. BARC layer removal normally took about 2 minutes and this process was monitored experimentally using the laser interferometer; once the BARC layer was removed, there was a significant

change in the etch rate and hence the process was terminated manually allowing 20 seconds of over etch to tolerate uniformity variations. 3 μ m deep silica etching then followed; again this process was monitored using the interferometer and the process was terminated automatically once the required depth was reached. With the standard recipe in Table 3.3, the silica etching rate was generally about 35nm/min and the selectivity ratio was 4:1 to photo resist. After silica etching, the ICP chamber needed to be cleaned (without the sample in it) using an oxygen plasma due to polymer formation on the chamber surfaces from CHF₃. The final step was to remove the remaining photo resist; here an oxygen plasma was used again and the end point was determined by monitoring the etch rate of an area with photo resist on it. An abrupt change in the etch rate indicated all the photo resist had been removed and the process was terminated manually.

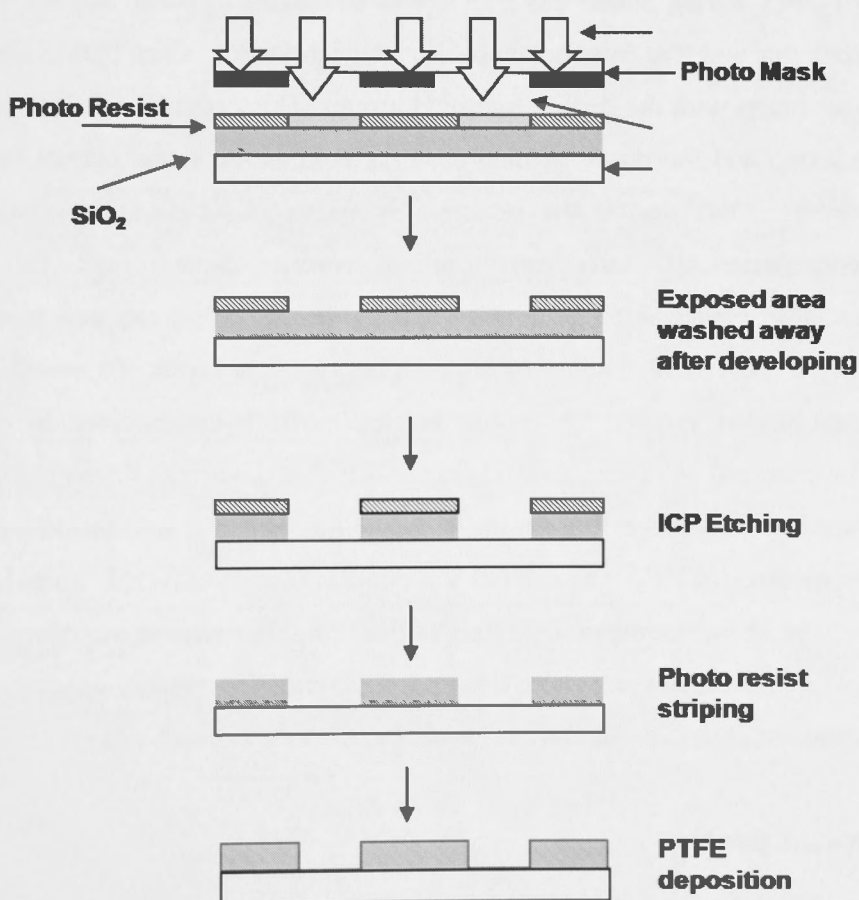


Figure 3.5: Process flow diagram for creating Master stamp on SiO₂ for UN-NIL process

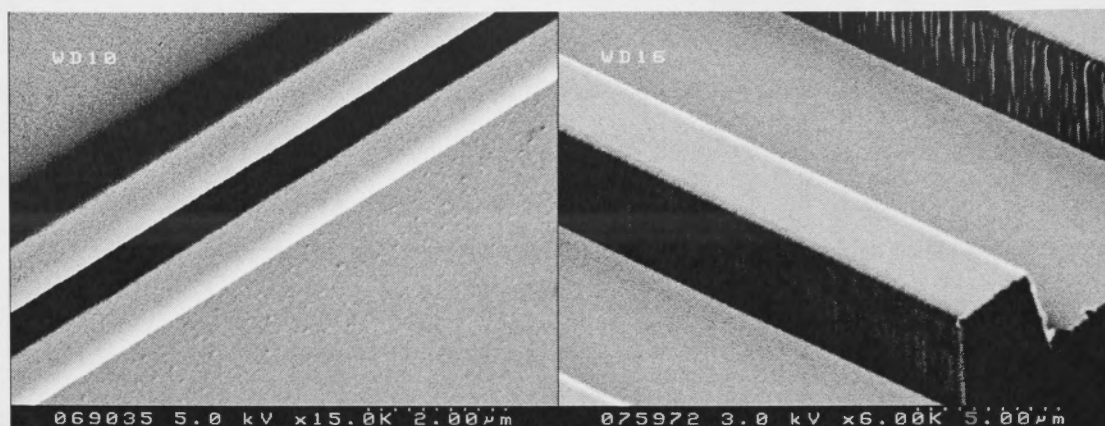


Figure 3.6: SEM image of photo resist (left) and etched silica (right) [118]

Experimentally we observed that plasma etched silica always resulted in non-releasable adhesion to PDMS during stamp casting. It was important to make the SiO_2 master's surface hydrophobic and free from polar species after fabrication, since PDMS (believed to be hydrophilic) reacts with the surface hydroxyl groups. This causes a covalent connection between the stamp and the master, which destroys both as the stamp cannot be released when this occurs. Moreover, if the substrate is hydrophilic before curing the stamp, capillary condensation of water can occur in narrow contact gaps, even in dry environments. The condensation generates capillary pressure that can pull surfaces into contact causing extremely high adhesion strength between two layers. To avoid destroying the stamp and master mould, the mould needed to be hydrophobized by gas-phase deposition, or chemical or physical treatments. An ICP process was developed by Zhang [118] to deposit a Teflon-like film on the etched silica wafer as an anti-adhesion layer. Here trifluoromethane (CHF_3) was used as a monomer source; only 150 watts ICP power was used and the chamber pressure was set to 30mTorr. For release treatment, a 100nm PTFE layer was considered thick enough to ensure no pinholes and this was achieved with a deposition time of about 10 minutes.

3.3.4 Imprint process

One of the most attractive advantages of UV-NIL is the simplicity of the process. Spin coating offers a uniform IPG thin film at the desired thickness. In contrast to normal solvent spin coating, IPG does not dry off over time and the final film thickness depends

on both spin speed and time. Due to the high viscosity (2300 centipoises), it was very difficult to spin an IPG film with a thickness below $3\mu\text{m}$. For the cladding layer, a $15\mu\text{m}$ IPG B3 film was obtained by spinning at 3000rpm for 90 seconds and the $3\mu\text{m}$ IPG B11 core layer was obtained at 9000rpm for 180s. The fabrication process (graphically shown in Figure 3.7) for the imprinted waveguides involves just four short process steps:

1. Spin coating & curing the $15\mu\text{m}$ bottom cladding
2. Spin coating the $3\mu\text{m}$ IPGTM B11 core layer
3. Imprinting the core material
4. Spin coating and curing a $15\mu\text{m}$ top cladding

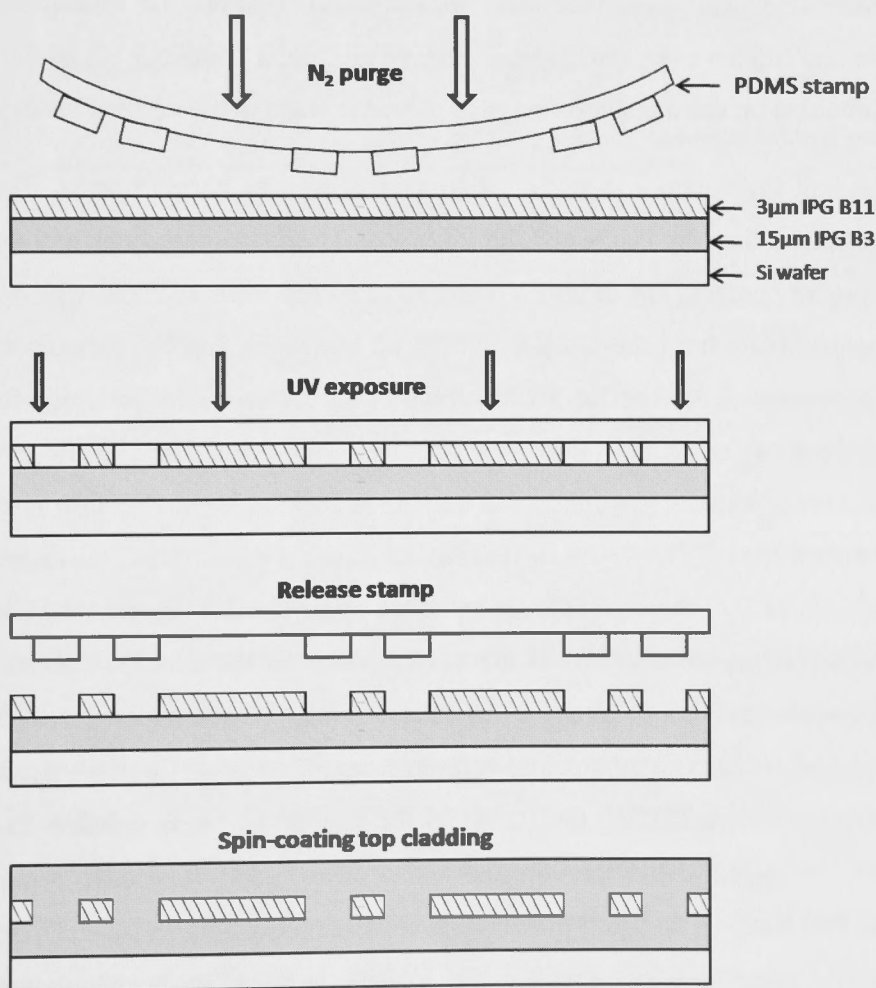


Figure 3.7: UV-NIL process flow diagram

The imprint step was carried out using a home built apparatus in an open (clean room) atmosphere. Normally air bubbles trapped during the process would be a major limitation necessitating operation in vacuum. Therefore, a different approach was adopted as illustrated in Figure 3.8. The goal here was to bow the stamp a little and ensure contacting at the wafer centre first with a concentric spreading of the contact patch as the wafer was raised to expel air. A cylinder (thickness of 10mm and a diameter of 95mm) with a circular vacuum groove embedded at the bottom surface was used as a stamp holder. A transparent 6 inch quartz plate clamped on top of the stamp holder was used to form a sealed chamber inside the cylinder while UV light can still be transmitted to illuminate the stamp and substrate. A 100mm vacuum chuck built from stainless steel mounted on top of a rotation stage and an X-Y-Z translation stage was used to hold the 100mm substrate which gave fine 3-dimensional control over the wafer location and rotation. To minimize human contamination and improve the smoothness of stage motion, a computer-controlled “pico-motor” was mounted on the translation stage to drive the stage in the vertical direction.

Before loading the stamp and wafer, alignment needed to be performed. The wafer chuck was pushed all the way inside and the stage was raised until the chuck and the stamp holder were just in contact. The X and Y translation stages were adjusted whilst looking through the quartz plate until the circular pattern on the chuck and the cylindrical stamp holder were concentric. Then the X&Y tilts on top of the stamp holder were adjusted until the bottom surface of the stamp holder was parallel to the top surface of the chuck. To check the centration, a dummy wafer could be loaded and the stage raised to ensure that the initial contact was at the wafer centre and that the contact patch spread uniformly as the wafer was raised. Finally rotational adjustment of the wafer chuck was performed to ensure the stamp pattern was aligned to one of the $\langle 100 \rangle$ planes of the silicon substrate. A bad rotational alignment of the pattern on the wafer leads to non-square cleaves when performing optical test (extra losses and uncertainties). It was difficult to ensure good rotational alignment when loading the stamp on the holder due to its softness and it was relatively easy to place the wafer on the chuck with good rotational accuracy by implementing two metallic locating pins on the chuck and pushing the wafer flat against the two pins. To align the wafer chuck to the loaded stamp, a linear groove was milled through the center of wafer chuck parallel to the line joining the two wafer location pins.

Once the stamp was loaded, the rotation of the wafer stage was adjusted until the linear groove was parallel to the linear features (a series of waveguide features and die separation marks visible to the naked eye) on the stamp.

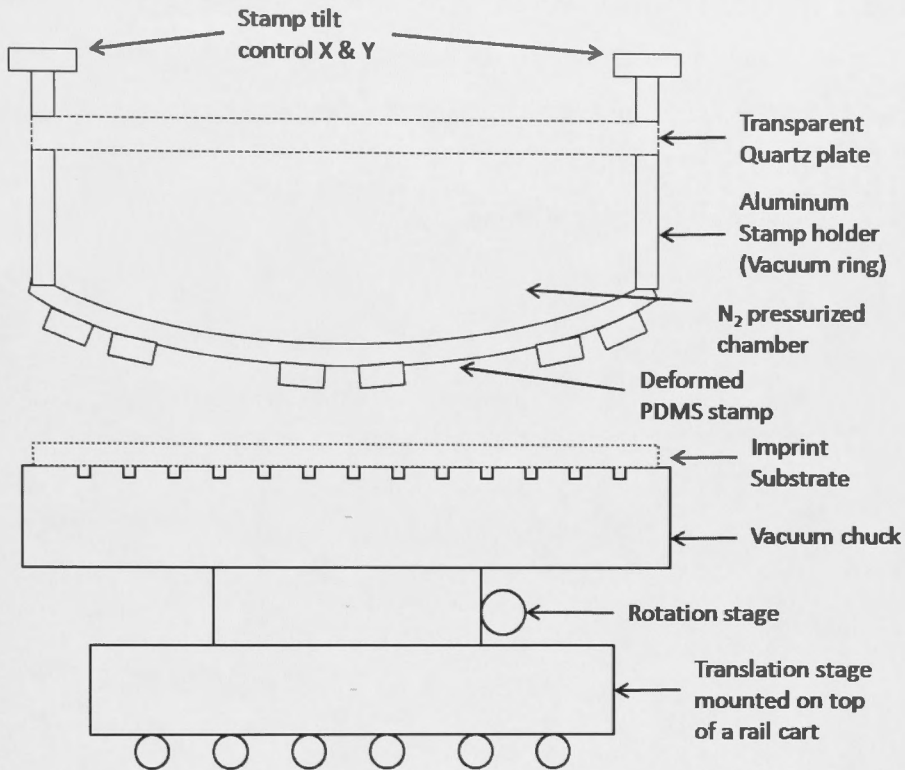


Figure 3.8: Schematic diagram of UV-NIL apparatus

After pre-alignment and loading the stamp onto the holder, the imprint process could be performed. As mentioned in the four step imprint process, the first step requires spin coating of 15 μ m IPG B3 material for bottom cladding which was performed on a SVG 8600 automated coating and development track; the film was then cured under a 500W Hg-Xe UV flood exposure source that illuminated a 150mm diameter region for 2 minutes in a nitrogen environment. On top of this bottom cladding, another 3 μ m IPG B11 material was spin coated and the “wet” wafer was loaded onto the wafer chuck before imprint. The degree of bowing on the stamp could be controlled by pressurizing the stamp holder chamber with nitrogen and tuning the pressure manually. The Z-stage was then slowly raised via a PC to power the “pico-motor” [120] which was mounted on the translation stage. With a good pre-alignment, the stamp and imprint substrate would contact from the

center and spread out uniformly in an expanding circular motion (this could be observed through the quartz plate).

After the stamp and wafer were in full contact, the “pico-motor” was stopped, and the chamber pressure released followed by waiting for at least 5 minutes. This was rather a critical stage in obtaining a good imprint as the stamp underwent elastic deformation during the contacting process; a short waiting time was found to be able to minimize this deformation. In addition, air trapped between the stamp and substrate in closed features (primarily the identification numbers on the mask) could escape through the stamp because the PDMS was gas permeable. After curing under the UV flood exposure source for 3 minutes, the stage was lowered by driving the pico-motor in opposite direction for automatic releasing. Finally a 15 μ m IPG B3 layer was spin coated on top of the imprinted core layer and cured under UV for 3 minutes.

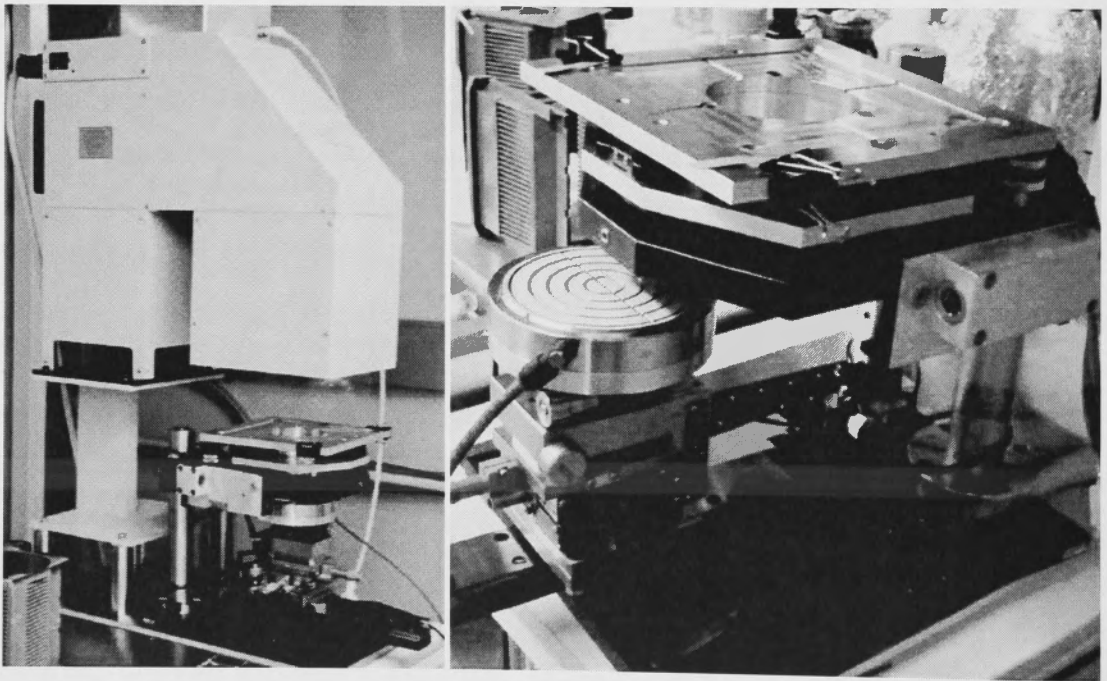


Figure 3.9: Image of UV-NIL apparatus

The entire fabrication process from bare silicon to completed waveguide wafer took under an hour. Excellent surface morphologies and no clearly observable residual layers were obtained in the imprinted waveguides as shown in Figure 3.10 when inspected in an

optical microscope. Under SEM observation, a thin residual layer was measured to be around 90nm at high magnification as illustrated in Figure 3.10 and Figure 3.11. Such a thin layer has no effect on the propagation on light in these structures and so no further attempts were made to eliminate it though there were measures available to do so.

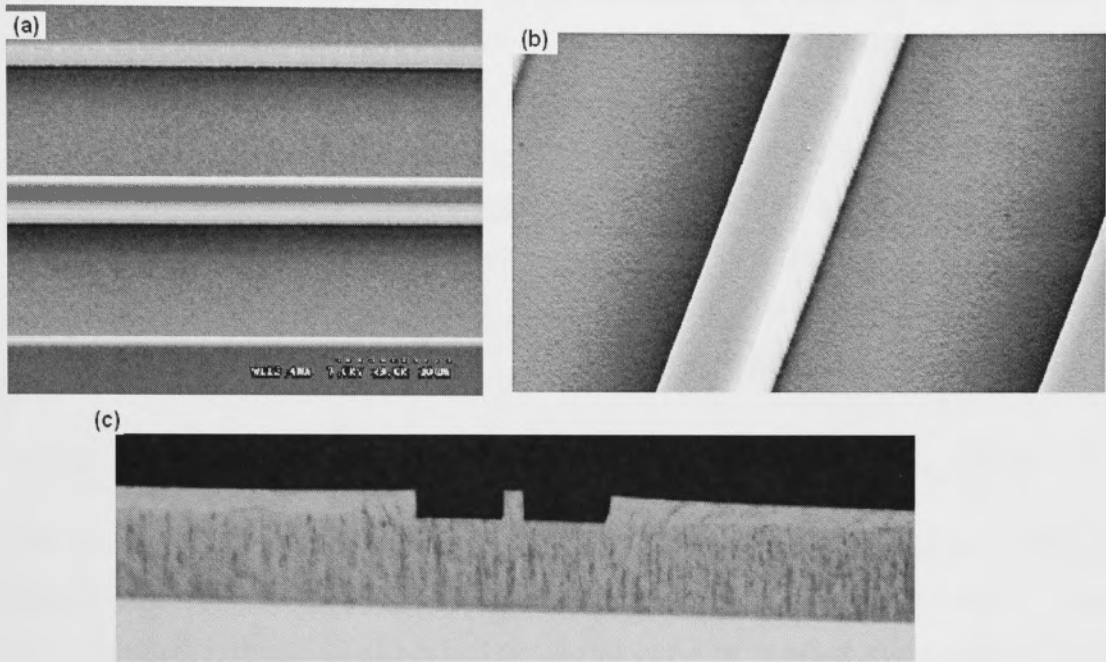


Figure 3.10: (a) & (b) SEM images of imprinted waveguides. (c) Cross sectional view of the imprinted waveguides under optical microscope

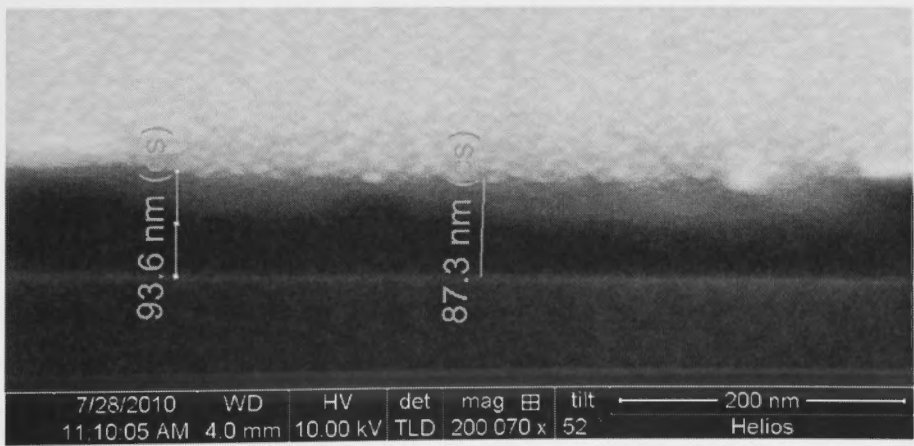


Figure 3.11: SEM image showing the residual layer with a thickness of approx. 90 nm in the imprinted waveguide

The whole imprint process was also relatively insensitive to the spun thickness of the core material. Experimentally, we imprinted various wet film thicknesses from 2.7 μm to 3.8 μm , and there was no observable change in waveguide quality except the appearance of a slightly thicker residual layer as the film thickness rises above $\sim 3.5\mu\text{m}$ (300nm residual at 3.8 μm wet film thickness). Though it was not confirmed, it was possible that even this could be eliminated by appropriate process adjustment (longer wait time, thicker stamp, etc). However the reproducibility of the wet spun layer thickness is far better than 0.2 μm so the degree of process latitude is certainly sufficient. The reproducibility of this process is critical in terms of mass production and was demonstrated by successive imprinting of 10 wafers using the same PDMS mould under the same imprint conditions. Comparing the 10th imprint to the 1st imprint, no noticeable changes for the waveguide dimensions or quality were visible under SEM observation.

3.3.5 Waveguide testing

The cutback technique is a widely used technique to test optical waveguides. Firstly, the wafer was hand cleaved to form a rectangular shape such that all the waveguides were located parallel along the chip with end facets exposed for light coupling; then this chip was placed on a vacuum chuck located between two fibre stages on the optical testing bench. Coupling to the waveguides was accomplished using piezo controlled three axis stages at each end of the waveguide chip and Nufern UHNA-3 fibre. To index match the waveguides, drops of core IPG material without photo-initiator were used on the fibre ends to suppress the effects of reflections and facet imperfections, leaving misalignment or mode overlap as the only sources of coupling loss. As noted above, the expected mode overlap losses are very small and the piezo stages and index matching made finding optimum alignment relatively simple and highly repeatable. Light was injected from either a JDS/FITEL SWS 1501 tunable source, an ASE fibre amplifier source (980nm pumping), or a white light source consisting of a fibre coupled Hg arc lamp. The laser source was followed by a scanning polarization controller (Agilent 11896) to determine the polarization dependent loss (PDL), and signal detection was accomplished using a 150 μm diameter SC-receptacled InGaAs detector with low PDL feeding a high accuracy six decade logarithmic amplifier (Analog Devices AD 757) or an optical spectrum analyzer

(Agilent 86142B). The output from the logarithmic amplifier was digitized with a 16-bit ADC card to make measurements. Figure 3.12 shows the results for cut back loss measurements using the ASE source (predominantly 1532nm), averaged over 5 waveguides of each width.

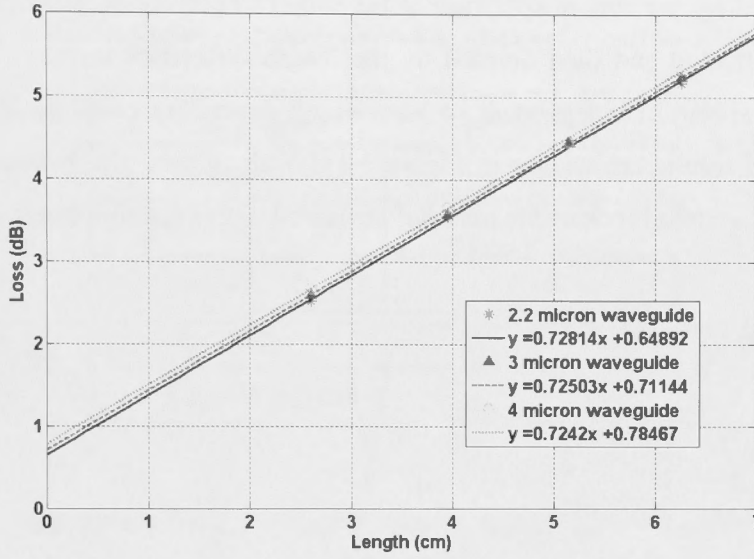


Figure 3.12: Cutback results at 1532nm for various waveguide widths

The results showed excellent linearity demonstrating the cut back measurement was valid, and for all waveguide dimensions show essentially the same loss (approximately 0.72dB/cm with a standard deviation on the loss for each width below 0.02dB/cm). The insensitivity to waveguide width suggested scattering loss was not a contributor to the overall losses at 1532nm. The PDL of the waveguides was also measured using the laser source and polarization scanner, and found to be essentially indistinguishable from the measurement system background (0.13dB arising principally from the angled connector feeding the photodiode). Note that the somewhat higher than expected coupling loss (~0.7dB measured versus ~0.1dB predicted) was caused by an angle on the cleaved facets preventing the coupling fibres getting right up to the waveguide core. This resulted from difficulties in aligning the silicon wafer crystal plane to the waveguide stamp in the homebuilt imprint tool and is not a fundamental limitation.

The optical loss spectrum was obtained using the mercury arc lamp source and optical spectrum analyzer. The measured chip spectrum was normalized using a measurement with no chip between the coupling fibres to correct for the coupled light source spectrum and variations in between different length measurements. Waveguide dimensions at $2.2\mu\text{m}$, $3\mu\text{m}$ and $4\mu\text{m}$ were tested at 6.25cm and 2.6cm waveguide lengths respectively; the loss spectra normalized by the source spectrum at the time of each measurement at these two lengths were subtracted and then divided by the length difference to provide the actual propagation loss spectrum independent of wavelength dependent coupling losses, source drift, etc. Typical results are shown in Figure 3.13(a) along with the measured intrinsic material losses in a cured block of the material measured with a spectrophotometer.

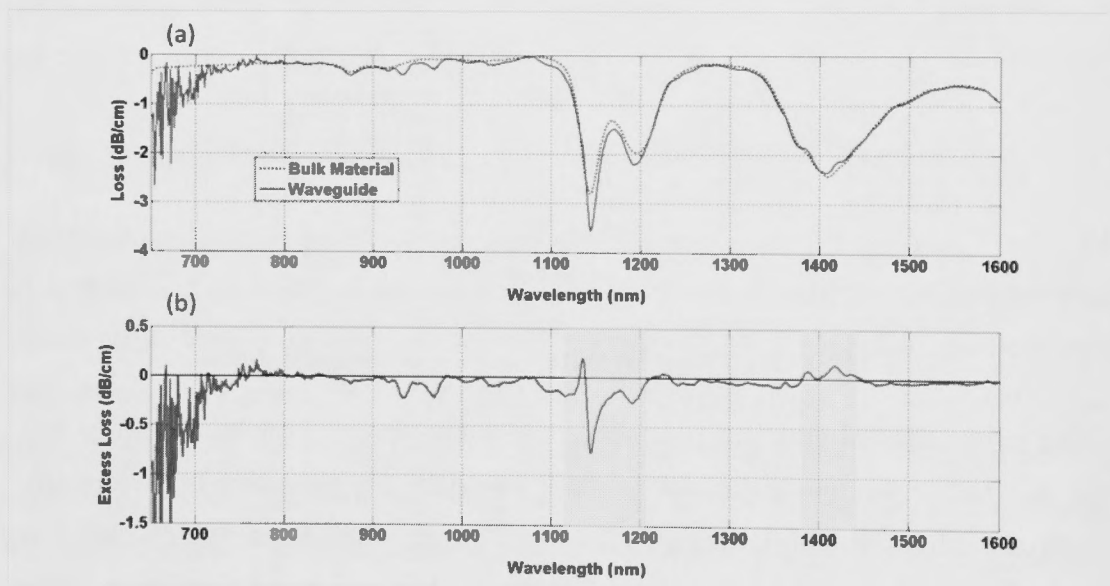


Figure 3.13: (a) Optical loss spectrum of imprinted waveguide compared to the cured bulk material. (b) Excess loss introduced by waveguide (measurement regions highlighted by yellow boxes have reduced reliability due to differences in the resolutions and dynamic ranges of the measurement instruments for the fibre and bulk results)

The white light results gave the losses in the major transmission windows shown in Table 3.4. These results are essentially identical to the bulk material, with the exception of the 650nm figure (intrinsic loss here $\sim 0.4\text{dB/cm}$). The discrepancy at 650nm may be due to a combination of modal effects between the waveguides and launch fibres and to waveguide sidewall scattering losses. These losses are certainly low enough for cost

sensitive applications and can be further improved if necessary at higher material cost by fluorination or deuteration of the polymer materials [91]. Assuming the losses at wavelengths below 700nm are scattering related; these could also be further improved by depositing a thicker anti-stick coating on the master as this has the effect of smoothing the sidewalls.

Table 3.4: Insertion losses at major transmission windows for imprinted waveguides

Wavelength (nm)	Loss (dB/cm)
650	2.0
850	0.22
1050	<0.1
1310	0.23
1550	0.58

Figure 3.13(b) shows the excess loss of the waveguide after subtracting off the measured intrinsic material losses and shows essentially zero excess loss from 750nm to 1600nm. There is no observable wavelength dependent loss in the transmission windows of interest indicating very low scattering loss and the high quality of the imprinting process.

3.4 Conclusion

The fabrication of high quality Polysiloxane waveguides using UV-cured Nano-imprint Lithography is demonstrated. A home-built nano-imprint apparatus was assembled and a fabrication process was successfully developed. Low loss buried channel waveguides with core cross sections of 2~4 microns width and 3 microns height and a 2% refractive index contrast were fabricated on bare silicon wafers with a simple and fast four step process using a 100mm diameter PDMS stamp. The waveguides were patterned using an innovative "minimum fluid displacement" method which eliminated the residual films often seen either side of rib like features such as the waveguide cores, and which also produced very good dimensional control of the core itself regardless of the uncured spun

core layer thickness. Thus this process also offered good manufacturing process tolerances. The imprinted waveguides showed essentially no excess loss or PDL over a bandwidth spanning 750~1600nm. It has been demonstrated that this fabrication process is highly repeatable with excellent quality. Further, the technology holds the promise of patterning complete passive devices including waveguide gratings for example to yield low cost wavelength division multiplexing devices with no increase in production complexity and cost. Potentially the process can be scaled to a roll to roll implementation to generate very low cost devices.

Chapter 4

Nanoimprinted Polysiloxane Waveguide

Bragg Gratings

Waveguide Bragg gratings (WBG) are a type of distributed Bragg reflector constructed in a short segment of an optical waveguide which reflects particular wavelength bands and transmits all others. This is accomplished by periodic modulation of the effective refractive index of the waveguide which generates a dielectric mirror at a specific wavelength. WBGs are important photonic devices which are commonly used for various purposes, including wavelength filtering, sensing, wavelength measurement/locking, spectral narrowing/locking of laser diode output, and for input/output coupling of fibres to waveguides, etc. Devices based on Bragg gratings written into the core of an optical fibre are important in telecommunications and sensing in particular due to their sharp frequency response that can be readily tailored for specific applications. However, the mass production of gratings in “traditional” glass planar waveguide technology has proven taxing since large numbers of gratings need to be fabricated quickly and with very high accuracy (sub-nanometer accuracy of the pitch is required on features with line/space periods of $<500\text{nm}$) and preferably in parallel. The cost of a process failure on a wafer scale process is high compared to that in single fibre devices due to the large number of devices affected and the inherent materials and process costs. Polymer platforms offer a potential opportunity to overcome these problems by enabling faster, parallel processes using much lower cost materials and processes, particularly by employing UV-NIL.

Aside from their spectral properties, one of the key requirements for many applications are that grating devices must be single mode and have low polarization dependence (i.e. use low birefringence materials and a low form birefringence design). Various methods

have been investigated to pattern gratings into polymers e.g. [121-123]. However, none have delivered high fidelity, low cost and high throughput simultaneously. This has motivated interest in UV-NIL, where there have recently been several key demonstrations.

Kim *et al.* [49] described a two-step process to make inverted rib type polymer wavelength filters in low viscosity acrylate materials using a hard quartz stamp and UV-NIL. Here a 3 μ m deep, 6 μ m wide trench with a 0.8 μ m deep grating in the bottom was first formed in a 20 μ m thick polymer layer by UV-NIL. A 3 μ m thick core layer was then spun onto this and cured to form an inverted rib waveguide which was completed with a further 5 μ m thick cladding layer. This 15mm long grating waveguide had a transmission dip of $\sim$ 15dB centered at $\sim$ 1560nm and a 3dB bandwidth of 0.8nm, and it exhibited relatively linear thermo-optic tunability. The shape of the transmission dip was far from the uniform grating response that would be expected, and although data was reported for TE mode, there was no mention of the TM mode resonance wavelength or spectral properties.

Kocabas *et al* [124] used a different 2 step process, firstly using PDMS stamps to make a sheet grating in low viscosity epoxy material and then forming a BCB rib waveguide over it by photolithography & RIE. In a 15mm long grating, a 20dB transmission dip with a 3dB bandwidth of 1.5nm was achieved, but the spectrum was shown to be fairly noisy and far from the theoretically expected response which was due to positioning errors in the grating grooves (displacement error occurred between write fields during e-beam writing). The grating response was also highly polarization dependent which was to be expected given the asymmetric rib waveguide and the use of BCB which has significant birefringence.

Chuang *et al.* [125] formed true channel waveguides by capillary moulding using thinned low viscosity epoxy into an inverted rib type substrate similar to [49] but made with a soft PDMS stamp. This 5mm long grating demonstrated $\sim$ 18dB transmission dip with a 3dB bandwidth of $\sim$ 8nm. However the fabrication process was rather complicated (14 steps involved) and the spectra performance of this grating was far from theory.

None of these demonstrations however, whilst important in their own rights, made a birefringence free, zero excess loss, matching theoretical spectral response, single mode

device in a single step in proven high reliability polymer as is desirable for real world devices.

In this section, the fabrication of single mode, polarization insensitive, Polysiloxane channel waveguide Bragg gratings by a four-step process based on UV-NIL with a PDMS stamp is described. The imprinted 2mm long grating exhibited a 10dB dip at the 1st order resonant wavelength and no excess loss compared to a waveguide alone (off resonant wavelength). The normalized spectral response showed very close agreement to theory. Furthermore, features down to ~100nm were replicated using the soft stamp offering further opportunities for apodisation of the gratings via duty cycle variation.

4.1 Grating simulation and design

The theory and modeling of physically structured gratings have been explored in detail by many authors [126] and here we will only highlight the important equations. The Bragg grating may be considered as a one dimensional diffraction grating which diffracts light from the forward traveling mode into the backward traveling mode. The condition for diffraction into the reverse traveling mode is called the Bragg condition. In order for light to be efficiently diffracted in the opposite direction, the reflection from subsequent periods of the grating must interfere constructively. This means that the Bragg period Λ must be related to the free space Bragg wavelength λ_0 by:

$$\Lambda = \frac{\lambda_0}{2n_{eff}} \quad (4.1)$$

where n_{eff} is the effective index of refraction of the waveguide mode which depends upon the materials comprising the waveguide and grating geometry. Equation 4.1 assumes that the phase accumulation between reflections from adjacent grating teeth is precisely one wavelength. This is the condition for a first-order Bragg grating. It is also possible to utilize higher-order diffraction to couple to the forward and backward modes. The more general condition for constructive interference is that the phase accumulation between subsequent reflections must be an integral number of wavelengths. Therefore, the Bragg condition for an m^{th} -order Bragg grating is given as:

$$\Lambda = \frac{m\lambda_0}{2n_{eff}} \quad (4.2)$$

In this work, only the first order Bragg gratings ($m = 1$) is considered, because the diffraction efficiency is the strongest. The most common way of analyzing Bragg gratings is to use a coupled mode formulation [127, 128]. In this approach, the grating is modeled as a small perturbation which produces a coupling between the forward and backward modes of an unperturbed waveguide. Consider a waveguide having a corrugated section with length L , etch depth a , core thickness t and 50% duty cycle as shown in Figure 4.1, an analytical solution [129] can be obtained to describe the amplitudes of the forward and backward waves, $B(z)$ and $A(z)$ respectively as:

$$A(z)e^{i\beta z} = B(0) \frac{i\kappa e^{i\beta_0 z}}{-\Delta\beta \sinh SL + iS \cosh SL} \sinh[S(z-L)] \quad (4.3)$$

$$B(z)e^{-i\beta z} = B(0) \frac{e^{-i\beta_0 z}}{-\Delta\beta \sinh SL + iS \cosh SL} \{\Delta\beta \sinh[S(z-L)] + iS \cosh[S(z-L)]\} \quad (4.4)$$

Here the κ is the coupling coefficient and grating strength can be expressed as: $S = \sqrt{k^2 - \Delta\beta^2}$. At the phase matching condition where $\Delta\beta = 0$, Equation 4.3 and 4.4 can be simplified as:

$$A(z) = B(0) \frac{\sinh[\kappa(z-L)]}{\cosh \kappa L} \quad (4.5)$$

$$B(z) = B(0) \frac{\cosh[\kappa(z-L)]}{\cosh \kappa L} \quad (4.6)$$

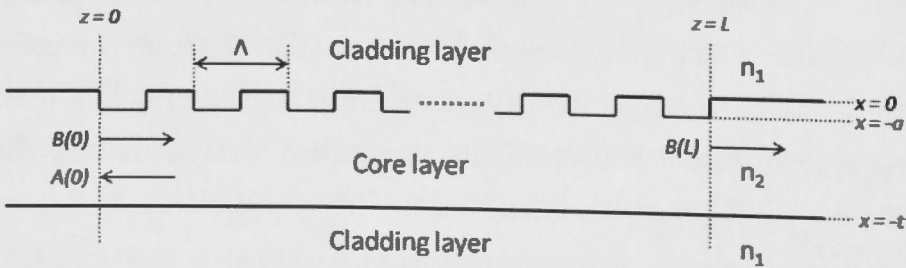


Figure 4.1: Schematic diagram of a corrugated periodic waveguide

A short section of a corrugated waveguide thus acts as a high reflectivity mirror for frequencies near the Bragg wavelength. The transmission and reflection of such filter can be further calculated as:

$$T = \left| \frac{B(L)}{B(0)} \right|^2 \text{ \& } R = \left| \frac{A(0)}{B(0)} \right|^2 \quad (4.7)$$

We refer to gratings with $\kappa L < 1$ as weak Bragg gratings because they only reflect a small fraction of the incident light and this is demonstrated in the 1st plot ($\kappa L = 0.5$) in Figure 4.2. A weak Bragg grating does not make a suitable add/drop filter since it only partially reflects the input signal. However there are cases where the “*sinc*”-shaped spectral response of a weak grating is desirable. In many binary communication systems, the encoded signal has precisely the same “*sinc*”-shaped spectral response. Thus the weak Bragg grating provides a convenient implementation of an all-optical matched filter, which should provide the optimal signal to noise ratio (SNR) for detecting the signal in the presence of white background noise. Gratings where the strength $\kappa L > 1$ are classified as strong gratings and the spectral response is demonstrated in the 3rd and 4th plots in Figure 4.2. Within this regime, the grating has a very high reflectivity within a band of frequencies called the stopband. Outside of this stopband, the spectral response shows a series of ripples or sidelobes. The sidelobes quickly decay as the wavelength move away from the Bragg condition until the structure is effectively transparent. If the grating is made longer without changing the value of κ , the bandwidth remains unchanged but the peak reflectivity rises closer to 100%; the spectrum becomes more square-shaped and the sidelobes get closer together and grow in size.

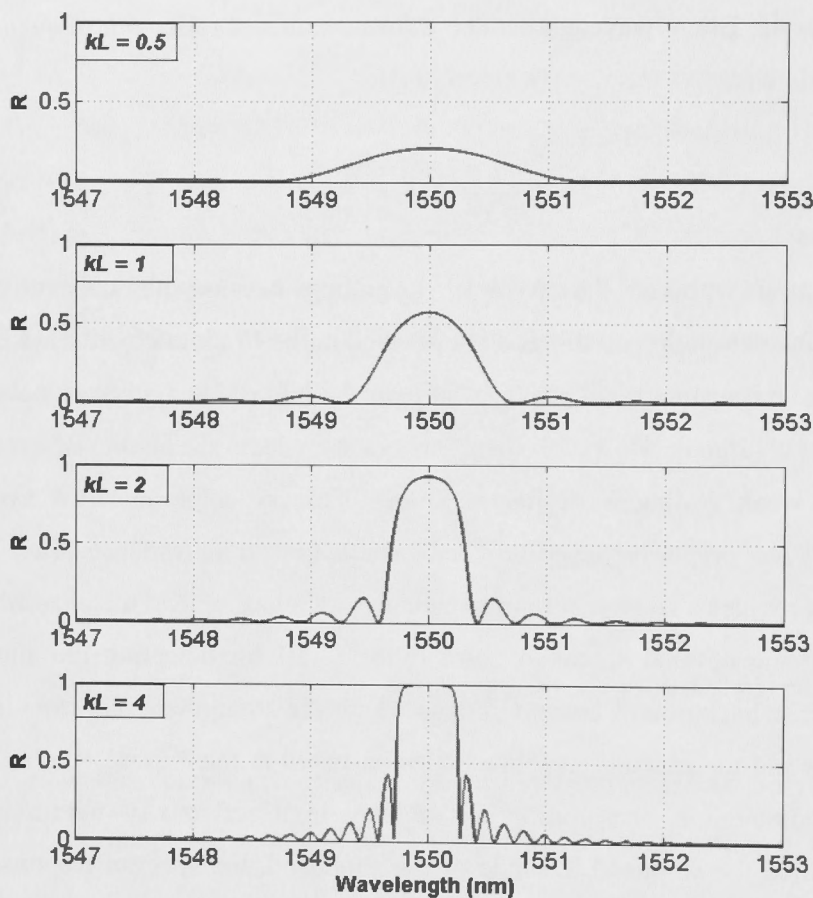


Figure 4.2: Calculated reflection spectral response at different grating strength (κL) by varying the length

The grating strength κ is a function of effective index, etch depth and grating duty cycle. A simplified model describing κ is shown in Equation 4.8 [126]. In this equation, $k=2\pi/\lambda$, β is the wave propagation constant, D is the grating duty cycle (the fraction of the grating period which is occupied by a tooth of core material) and the quantity Γ is a dimensionless number less than 1 which describes the extent to which the electromagnetic mode overlaps with the grating region. Therefore for a strong grating it is desirable to have a grating duty cycle close to 50%.

$$\kappa = \frac{k^2}{2\pi\beta} (n_{core}^2 - n_{clad}^2) \sin(\pi D) \Gamma \quad (4.8)$$

If the pitch of the Bragg grating changes slowly along the length of the grating, we say that there is a chirp. More generally, even when the grating is perfectly periodic, if the waveguide itself has some slow variation in its propagation constant across the length of the device, the structure will exhibit chirp-like properties. When the amplitude of the grating constant κ changes with position, we say that the grating is apodized (An example demonstrated in Figure 4.3). Grating apodization has been widely used in fibre Bragg gratings. The envelope of the periodic refractive index change is tailored in such a way to reduce the grating sidelobes to acceptable levels.

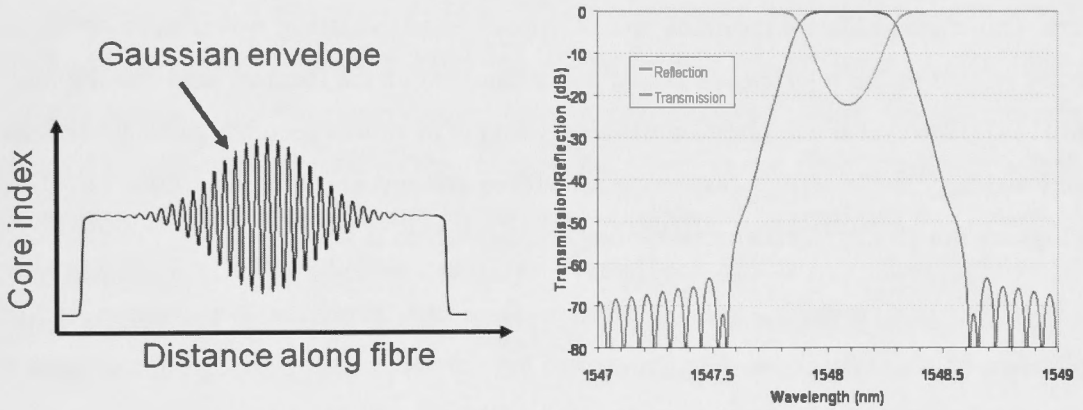


Figure 4.3: A typical apodized grating design with Gaussian envelope and its spectra performance

4.2 Fabrication process

There are many ways to produce a periodic modulation in an integrated waveguide. In some cases, it is possible to directly modulate the refractive index of the guiding layer, by illuminating the waveguide with UV exposure, or by acousto optical or electro-optical effects [130-133]. However, these techniques are limited to materials which possess photorefractive, acousto-optic or electro-optic properties. A rather flexible way of introducing a grating structure is to physically corrugate the waveguide using lithographic techniques and pattern transfer. However the grating fabrication challenge comes from the high precision requirements on critical dimensions and registrations. Depending on the

material and operating wavelength, a typical grating period is around 500nm (for silica at $\sim 1550\text{nm}$) over a length of 1-10mm. Photolithography using deep UV step and scan tools is more than capable of reaching this goal, but the acquisition and running costs of the exposure tools and masks are large.

Interference lithography as we described in Chapter 2 is specifically useful to pattern grating structures with high precision. Here the UV laser is split into two beams which interfere with each other creating a periodic intensity distribution along the interference pattern. This technique has been widely used for fabricating fibre Bragg gratings; in this process, the refractive index of the photosensitive fibre changes according to the intensity of light that it is exposed to. It can also be used for patterning photoresist coated on a planar substrate, followed by developing and etching to transfer the grating pattern to other layers. This method allows for quick and easy changes to the Bragg wavelength, which is directly related to the interference period and a function of the incident angle of the laser light [134]. However the application of this technique to wafers requires either large laser beams and very stable set ups (assuming all written gratings are to be identical), or (if the gratings are not all identical) a serial writing strategy which is slow.

A major step toward easier inscription from the interference technique is the application of phase masks as a component of the interferometer. The significant features of the phase masks are the grooves etched into a UV-transmitting silica mask plate, with a carefully controlled mark-space ratio as well as etch depth. The principle of operation is based on the diffraction of an incident UV beam into several orders and producing interference fringes on the photosensitive fibre/substrate forming grating patterns [135, 136]. In phase mask lithography, the phase mask is rigidly held against the substrate (e.g. by vacuum), and therefore it is typically more stable than interference lithography. Furthermore, phase mask lithography does not require narrowband coherent illumination for the exposure and the mask can be partially scanned for exposure in desired areas only. For these reasons, phase mask lithography is the method of choice for patterning fibre Bragg gratings. However, this technique is not tunable which means the period of the exposed grating cannot be changed without replacing the mask itself. Further, wafer sized

phase masks are expensive and not reconfigurable, and with a contact process there is considerable risk of damage to the mask.

Electron beam lithography (EBL) can also be used to pattern grating structures on electron-sensitive resists. It offers flexibility for rapid prototyping by simply changing the CAD design. However, the resist is limited to only a few electron sensitive materials such as PMMA, ZEP and Hydrogen Silsesquioxane (HSQ). Although very high resolution is achievable from EBL, stitching field accuracy between adjacent write fields can be a problem for gratings (a complete grating typically consists of 100 or more write fields). It is also a relatively slow and expensive process.

In this chapter, single step imprint of the waveguide gratings will be described using a master patterned by a combined EBL & contact lithography process. EBL was used to pattern the master grating on a 5 micron thermal oxide silicon wafer. Using optical lithography and various etching processes, a single mode waveguide was then overlay patterned on top of the grating pattern. Stamps were then casted from the master and the nanoimprint process developed in Chapter 3 was employed to replicate the waveguide Bragg gratings in a Polysiloxane core layer. Again one of the key advantages of the imprint technology is that the master pattern only has to be produced once, and so it is affordable to use a slow and relatively expensive method to fabricate the master.

4.2.1 Grating master fabrication

Electron beam lithography has historically been an important complementary technique for high resolution/precision lithography. The primary advantages of electron beam lithography are that it is a very flexible technique (patterns can be changed at will) and that it can beat the diffraction limit of light and make features in the nanometer regime. However, the key limitation of electron beam lithography is throughput, i.e. the very long time it takes to expose an entire silicon wafer or glass substrate which is not very practical for high volume production. Another drawback of long exposure times is that it leaves the system vulnerable to beam drift or instability which may occur during the exposure. However, the high resolution and availability of a tool locally made it the method of choice for the work described here.

The EBL system available to us was a Raith 150 at the Australian National Fabrication Facility (ANFF). The Raith 150 is equipped with a Zeiss GEMINI SEM column which was reported to have imaging resolution down to 4nm over its acceleration voltage range using an edge-sharpness method [137]. Unlike most EBL systems, the Raith 150 offers flexibility in beam-acceleration voltage from 200V to 30KV and working distance from <1mm to 20mm. A laser interferometer controlled stage gives registration accuracy down to 10nm under ideal conditions; a fast pattern generator with up to 10MHz writing speed yields minimum dwell time increments approaching 2ns. Additionally, the FBMS (Fixed Beam Moving Stage) approach offers some possibilities for eliminating stitch field errors commonly seen in EBL (for large structures, e.g. waveguides).

At 20KV electron acceleration voltage and using a 7.5 μ m aperture, the measured beam current was 0.0165nA; various exposure trials were performed to find the optimal exposure dosage (dwell time). PMMA (polymethyl methacrylate) from MicroChem was used as the EBL resist for patterning the grating structures. 120nm thick 950K molecular weight PMMA was spin coated on a 5 micron thermal oxide silicon wafer and then hard baked on a hotplate at 180°C for 2 minutes. For a conductive coating, a thin layer of ESPACER [138] was deposited by spin coating on top of the PMMA layer at 1500rpm for 90s.

The fabrication of waveguide Bragg gratings in this project was based on the IPG platform with a refractive index of 1.478 for the cladding and 1.507 for the core at 1550nm. For a 3x3 μ m waveguide dimension, the effective index calculated was 1.4900 using commercial simulation software (RSoft FemSIMTM [139]). Substituting this value into Equation 4.1 with operating wavelength at 1580nm returns the desired grating period to be 530nm. In practice, the grating period should be an exact multiple of the writing grid, and the well characterized recommended write field size of 100x100 μ m imposed a 4nm writing grid in the EBL system which meant the grating period has to be exact multiples of the writing grid. Therefore a 532nm grating period was used and the targeting wavelength then moved to 1585nm.

4.2.1.1 *Shot-shifting method for minimizing stitching field errors*

Stitch field errors in EBL occur when the length of the feature exceeds the size of the write field of the electron beam system, as multiple fields then have to be stitched together to fabricate the feature. Imprecise write field calibration, mechanical errors, thermal drift, and stage inaccuracy produce a small positional error when moving to a different write field. An example is demonstrated in Figure 4.4, using 100 μm write field, a 200 μm long grating was written, and an obvious phase change could be observed at the write-field boundary. As a result of these phase errors, the spectral response of Bragg gratings is degraded by the appearance of periodically located spurious sidelobes and the appearance of transmission peaks in the main grating dip. Small field sizes in the stitching process can reduce this effect and this can be further enhanced by using variable field sizes [140]. Multiple-write techniques have been used previously to reduce stitch errors. By moving the stage every 1/5 of the total exposure, the stitch field error was absorbed into every grating tooth to form a uniform grating but with altered duty cycle [141].

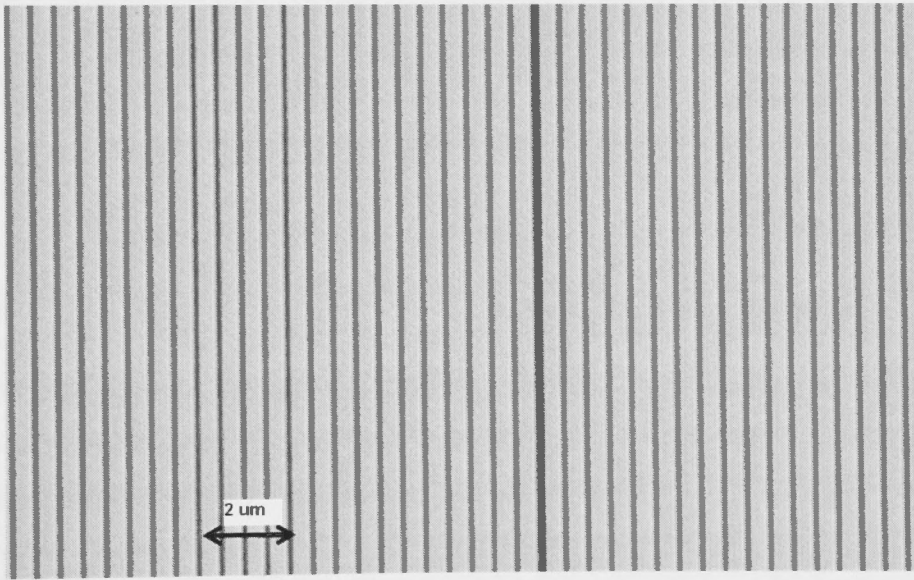


Figure 4.4: Demonstration of stitch field error created in the grating using conventional method (at 100 μm write field)

In this project, we adapted this shot-shifting method for grating exposure. With 100 μm write field, 185 grating periods were allocated as one group which could be filled in a write

field. Each time the stage moved by $19.684\mu\text{m}$ (37 grating periods), the designed pattern was exposed by $1/5$ of the total dose. This process is shown in Figure 4.5. In this approach, basically every grating unit was exposed at 20% of the required dosage for 5 times in a different write field. As a result, the stitching error is smeared at the cost of duty cycle mismatch which can be compensated by varying the grating width.

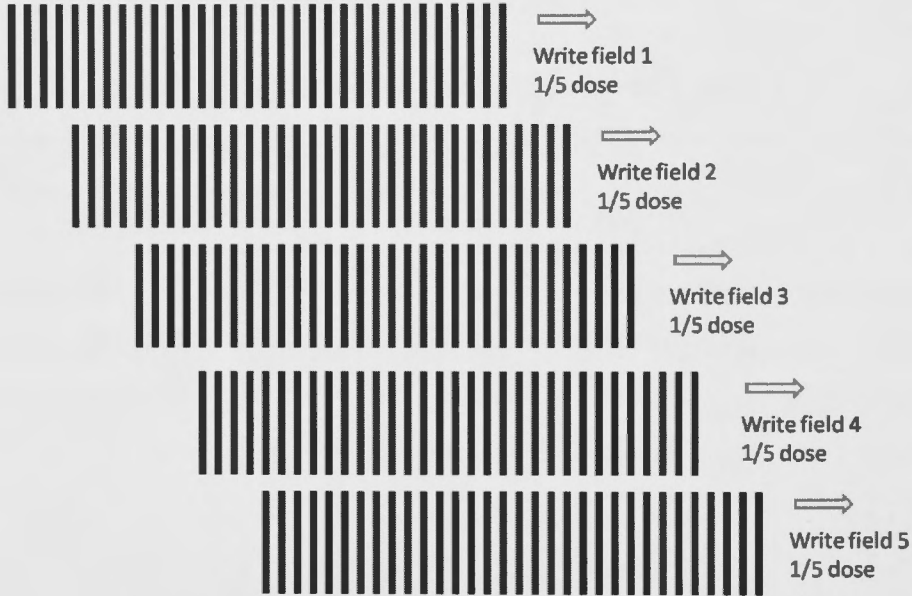


Figure 4.5: 5 pass shot-shifting method for grating exposure diagram

4.2.1.2 Charging in EBL system

A major challenge in the EBL process is the potential charges accumulated on insulating materials, in this case the thick oxide layer on the silicon substrate. Since electrons are charged particles, they tend to charge the substrate negatively unless they can quickly gain access to a path to ground. For a high-energy beam incident on a silicon wafer, virtually all the electrons stop in the wafer where they can follow a path to ground. However, for a quartz substrate such as a photomask, the embedded electrons will take a much longer time to move to ground. The type of substrate used in this project was $5\mu\text{m}$ thermally oxidized silicon wafer; this silica layer behaves just as an insulator which was disastrous for previous calibration based on a silicon wafer. The typical solution to this problem is to

deposit a thin conductive layer above or below the resist. Here we spin-coated a thin layer of ESPACER-300 (a spin on conducting polymer) on top of the PMMA. The effect was dramatic on small chip (typically a few square centimeters) written in the universal chuck; no charging was observed despite the use of oxidized silicon wafer.

However, when the same recipe was tried on a 4 inch wafer scale (4-inch chuck used), the process experienced severe charging problems even with the use of a conductive layer. The universal chuck on the Raith 150 generally handled small chips and could easily displace electron charge with the help of a “finger” (a metal pin connected to the ground which can penetrate into the substrate); unfortunately a 4 inch wafer was too large for this chuck to handle and the 4 inch wafer chuck had to be used instead. The 4 inch chuck however did not have the “finger” and relied on 4 metal studs to contact the edge of the wafer for charge displacement. This was a major difficulty in patterning a 5 micron thermal oxide wafer because the wafer itself was completely covered by an insulator: SiO_2 . A typical charging problem is shown in Figure 4.6; even with a conductive layer, severe distortion still ruined the grating features. This posed a fundamental limit for the Raith 150 system and the easiest solution was implemented by adding a conductive “finger” on the 4 inch chuck. In addition, the edge of the wafer was ground at the stud locations (polished by a diamond file to expose the silicon layer).

Applying the multi-pass approach and expose the grating pattern at $300\mu\text{A}/\text{cm}^2$ for the total dosage, a group of 2mm long gratings were created on the PMMA layer and Figure 4.7 shows a typical SEM image of the grating pattern. A dry etching process described in Chapter 3 was applied to etch into silica by approximately 100nm using PMMA as the etch mask. Then the remaining PMMA layer was removed by Oxygen plasma etching leaving the grating pattern engraved on top of the silica layer.

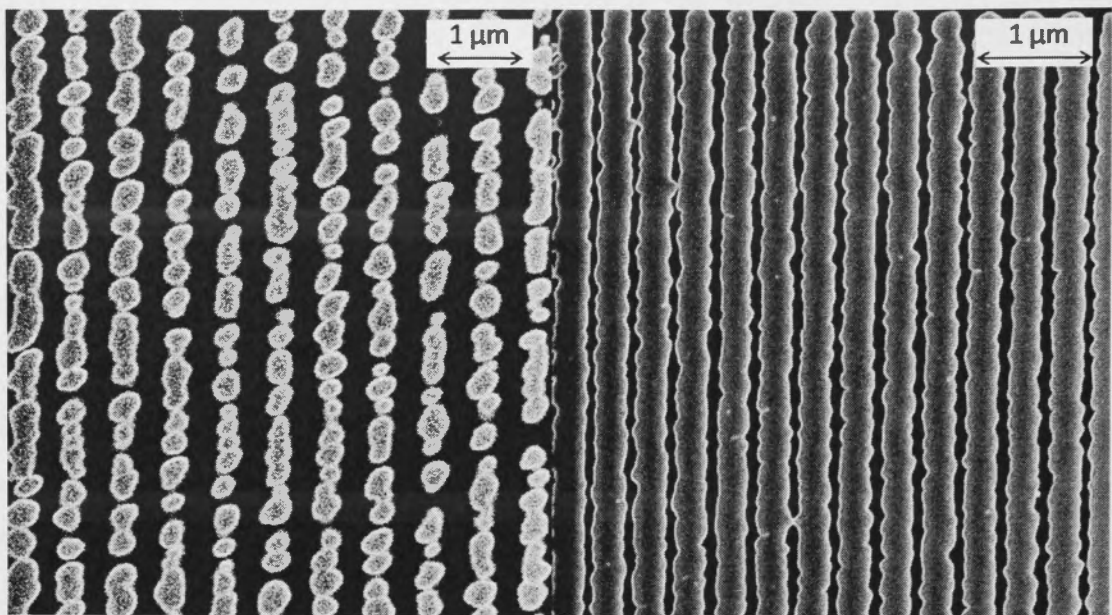


Figure 4.6: SEM image of grating patterned on PMMA at $250 \mu\text{A}/\text{cm}^2$ dose (left) and $350 \mu\text{A}/\text{cm}^2$ dose (right) experiencing charging problem

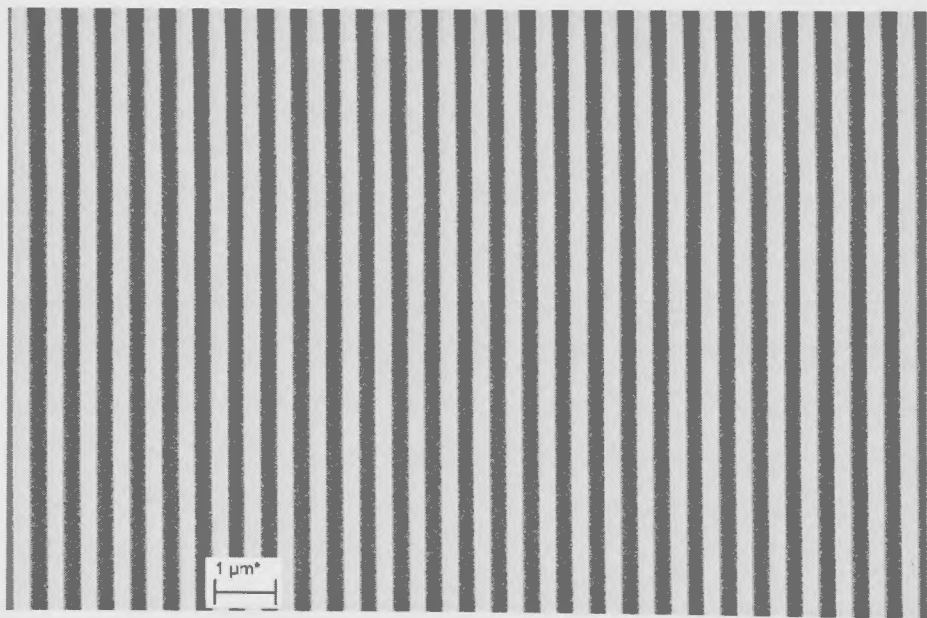


Figure 4.7: Grating patterned on PMMA

4.2.1.3 *Overlay patterned waveguide*

After the successful implementation of the grating pattern, the next challenge was to overlay pattern a waveguide through the grating as shown in Figure 4.8. Here we used positive photo resist processing techniques as described in Chapter 3 to create a channel waveguide in the resist and a precise overlay alignment was done on the Karl Suss MA-6 contact aligner. Initially a coarse alignment was done by matching two alignment marks on both sides of the wafer (simply $50 \times 50 \mu\text{m}$ boxes etched into the silica matching the boxes on the photo mask). Fine alignment was then performed by looking through the mask at high microscope magnification (50x) to match the grating on the substrate and waveguide on the photomask. UV-exposure was then performed once the mask and substrate were in alignment. After developing, the Ar and CHF_3 etching recipe (previously described in Table 3.3) was used again to remove the side cladding to a depth of $3 \mu\text{m}$, leaving the core channel engraved with the grating pattern. Finally, 50nm PTFE deposition was applied for surface release treatment. A stamp was then fabricated by casting PDMS onto this master wafer as described in Chapter 3.

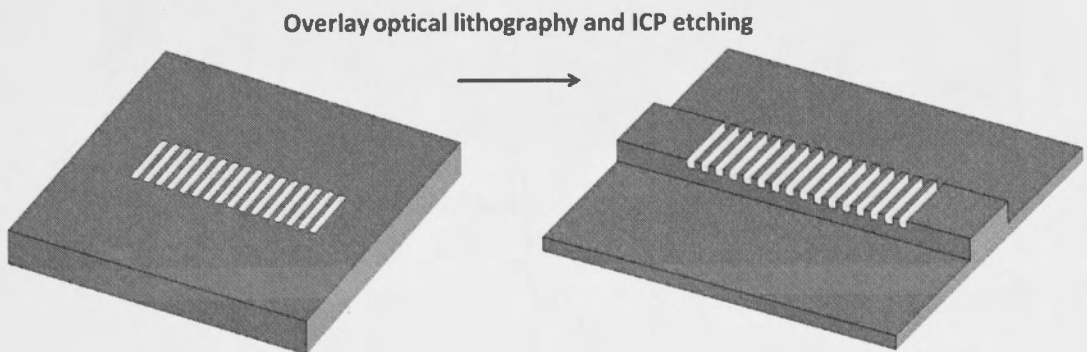


Figure 4.8: Overlay patterning a waveguide on top of a Bragg grating

4.2.2 UV-Nanoimprinted Polysiloxane Waveguide Bragg Gratings

Although it was fairly complicated to fabricate the master waveguide grating, the replication process was rather simple. The same nanoimprint process that we discussed in Chapter 3 was used to create the PDMS stamp and imprint onto the Polysiloxane layer. Figure 4.9 shows a SEM image of a waveguide Bragg grating obtained by this process.

Duty cycle shrinkage occurred during fabrication of the master to <20% (due to charging in the electron beam system reducing the effective dose and the application of a ~50nm thick Teflon anti-stick coating on the master which partially filled the etched gaps). Most interestingly it is clear that features of ~100nm were accurately reproduced despite the use of a soft stamp. This is because the grating was moulded into a free liquid film thereby eliminating stamp distortion that often limits UV-NIL.

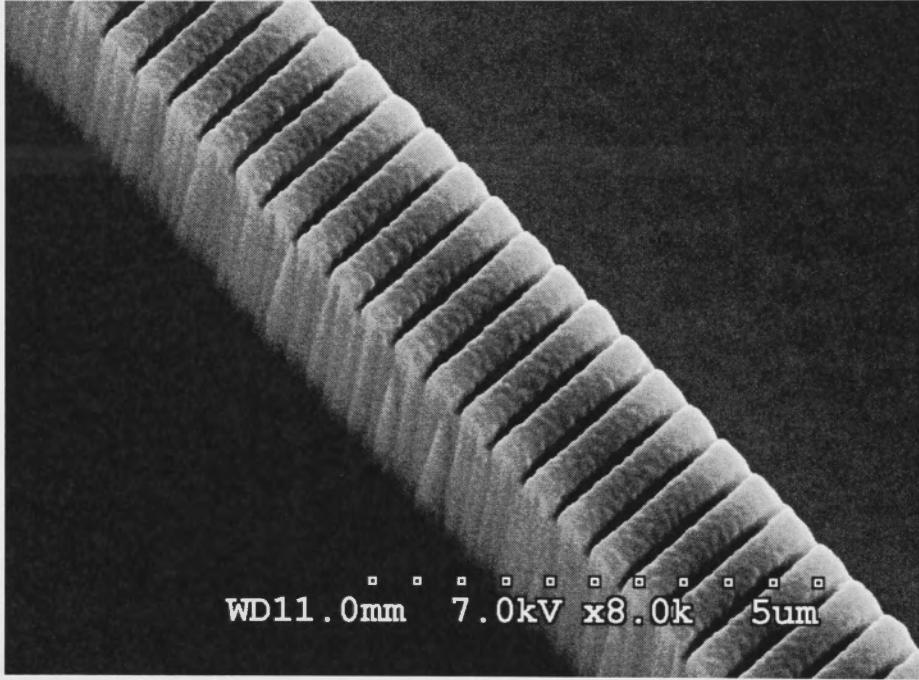


Figure 4.9: SEM image of imprinted Polysiloxane WBGs

4.3 Performance

Testing of this WBG was again accomplished using a fibre coupled mercury arc lamp with chip coupling through Nufern UHNA-3 fibre and acquiring the spectrum using a spectrum analyzer (Agilent 11896 or Ando AQ6317). A tunable laser source (JDS Uniphase SWS16101), scanning polarization controller, and PD/log amplifier combination as described in Chapter 3 were also used to scan over a range of wavelength. The measured waveguide Bragg grating transmission spectrum was normalized by subtracting the spectrum obtained from an adjacent waveguide and a 10dB deep dip in transmission was observed at ~1569nm. The reduced grating strength was due to the duty cycle shrinkage to

less than 20%. The shape of the grating transmission function shows excellent symmetry and agrees, essentially perfectly, with the shape predicted theoretically by coupled mode theory [126] for a 2mm long uniform grating with $\kappa L=1.76$, co-plotted in Figure 4.10. The actual grating duty cycle was estimated at about 14% from the SEM images and the etch depth at $\sim 100\text{nm}$, which together with the 2mm length result in a calculated $\kappa L=1.82$, a close match to the fitted result. The good agreement with theory means that simply extending the grating length to 5mm would result in a $\sim 30\text{dB}$ rejection whilst attaining 50% duty cycle would provide a transmission dip in excess of 50dB for the same 2mm long grating. The polarization dependence of both the grating strength and centre wavelength was tested using a swept wavelength laser test system and polarization controller set to probe transverse electric (TE) and then transverse magnetic (TM) polarizations, and no measurable dependence of either of these parameters was observed. The fibre-to-fibre (Nufern UHNA-3) insertion loss of the 5.5cm long waveguide containing the 2mm long grating was 3.1dB at 1550nm : equal to the sum of the intrinsic material loss measured from Chapter 3 and the coupling loss calculated earlier.

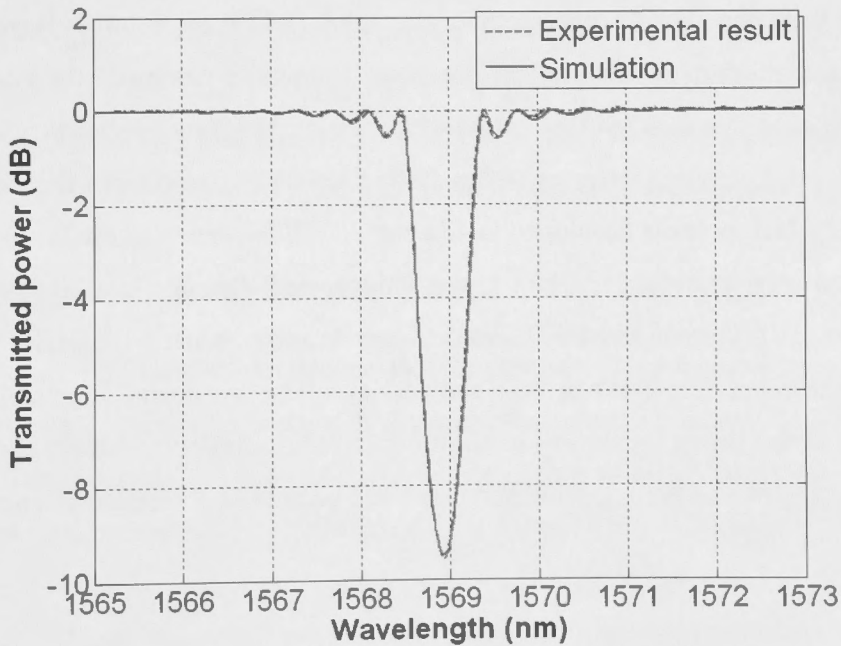


Figure 4.10: Transmission spectra of the imprinted Polysiloxane WBG in comparison with simulated result ($\kappa L = 1.76$)

The center wavelength of the spectral dip however was shifted to 1568.7nm compared to the design of 1585nm. There are several factors that may have contributed to this spectral shift in the Bragg condition. The presence of a residual layer (~100nm) and non-vertical sidewall on the waveguide could change the effective index, hence leading to a shift in the Bragg wavelength. In addition, it was possible that PDMS stamp could shrink/swell due to temperature change, mechanical forces during application of the stamp, and UV-exposure which could result in a change in the actual imprinted grating having a different period from that designed. This is an effect which can clearly be compensated for however so is not a fundamental limitation. The reproducibility of the grating was limited by the e-beam writing step; the charging problem posed random variations in the effective dose applied on the resist.

4.4 Conclusion

In this section, we demonstrated the creation of complicated three dimensional waveguide Bragg gratings as a master stamp on thermally oxidized silicon wafer with various processing technologies. The grating pattern was firstly created on the PMMA layer by an EBL process. With the shot-shifting method, the stitch field error commonly seen in an EBL process was minimized. Dry etching was used to transfer pattern to the silica layer. The waveguide core was then overlay patterned on top of the grating pattern using optical lithography and dry etching processes. After casting a PDMS stamp from the master and applying the UV-NIL process developed in Chapter 3, WBGs were successfully replicated in Polysiloxane in four simple imprint steps. Unexpected duty cycle shrinkage due to charging in the EBL system and PTFE coating significantly reduced the performance of the gratings; however the gratings still showed excellent symmetry and up to 10dB rejection ratio at the Bragg condition. In addition, the transmission spectrum agreed with the expected shape of a uniform grating and it showed no sign of polarization sensitivity.

Chapter 5

Optical Coupler Design and Optimization

Optical couplers are key components in photonic integrated circuits for power splitting, signal routing and processing. Two types of couplers are commonly used in integrated optics: Multimode interference couplers (MMI) and directional couplers. In this chapter, we investigate the possibility of optimizing the design of MMI and directional couplers to achieve better precision of the power splitting (important in integrated interferometers for a range of applications), lower excess losses and immunity to real world fabrication errors that occur in integrated devices.

In section 1, we numerically simulate the optimization process for the design of multimode interference couplers. Section 2 focuses on creating a fabrication error insensitive design for 3-dB directional couplers and based on this design concept, similar designs for 1310/1550 WDM couplers are also presented. In section 3, we apply the previously developed UV-NIL approach to fabricate these optimized couplers. And lastly the performance of the imprinted optical couplers is compared with simulation.

5.1 Multimode Interference Coupler Optimization

In recent years multimode interference (MMI) couplers have become one of the most important types of power splitters used in integrated optics, particularly for high index contrast waveguides, due to the lack of need for high resolution lithography inherent in their design. The operation of the MMI coupler is based on the self-imaging properties of a multimode waveguide, as suggested by Bryngdahl [142] and described in more detail by Ulrich [143]. MMI couplers are gaining wide applications in power splitting and combining [144], polarization-independent switching [145, 146], in phase-diversity optical receivers and in ring semiconductor lasers [147].

The most widely used MMI coupler is the 2×2 3-dB coupler, where power launched into the input is split equally between the two outputs. Excess loss and the imbalance between the two outputs are often the two most important parameters for a 3-dB coupler. Generally low excess loss is preferred from optical device point of view. It is rather critical for 3-dB couplers to have low power imbalance between the two output ports, particularly so when they are used in Mach-Zehnder Interferometers (MZI), as the imbalance translates directly to an extinction ratio degradation. In this section, the imbalance and excess loss characteristics in MMI couplers are examined with fabrication error taken into account. It is shown that there exists a margin of improvement on the published designs to achieve better performance.

The simulations of MMI couplers were carried out using a commercial simulation software package: RSoft BeamProp in the full vector 3-D calculation mode. The modeled material platform was based on IPG B3 for the cladding and IPG B11 for the core material with refractive indices of 1.478 and 1.507 respectively at 1550nm. All BPM modeling was performed in a full vector 3-D geometry. Taper structures were used in the input/output ports of the coupler as shown in Figure 5.1. $3 \times 3 \mu\text{m}$ waveguides were implemented for all the waveguide input/output ports of the coupler due to the small mode area and low insertion loss to available high numerical aperture fibres such as Nufern UHNA-3 fibre as mentioned in Chapter 3. Here we particularly investigate the MMI performance with variations in the taper width and MMI width.

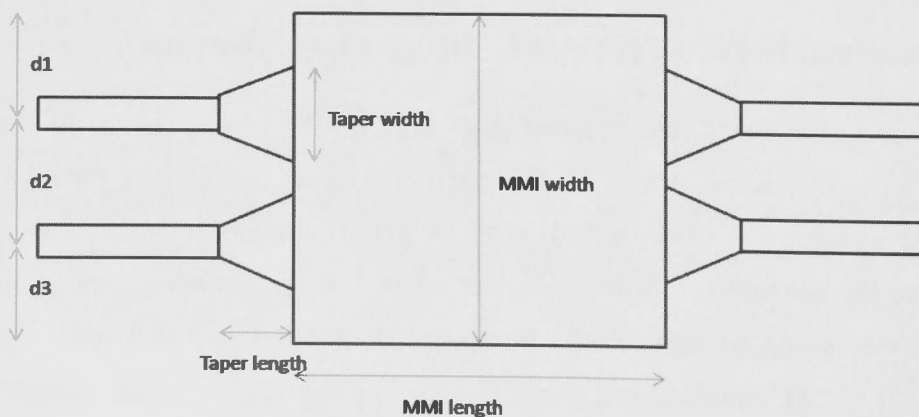


Figure 5.1: Schematic diagram of an MMI

5.1.1 Taper optimization

Based on the quasi-analytical results published by Hill *et al* [148] for high index contrast devices, it was shown that paired interference couplers described therein have better imbalance performance than general interference couplers. The imbalance and excess loss in MMI couplers is primarily determined by the way the input power is partitioned into the MMI section. This partitioning is in turn determined by the normalized access waveguide width (ratio of access waveguide width to MMI section width) and position. For paired interference couplers, choosing a normalized access waveguide width near 0.3 delivers minimum imbalance, with low excess loss. To match this optimized access waveguide to the desired input/output waveguide, a taper is required.

Linear taper structures generally have to be fabricated with a certain minimum length to satisfy the adiabaticity criterion to minimize the radiation loss. A simple simulation using RSoft BeamProp showed low radiation loss was achieved if the angle of the taper (taper edge relative to beam propagation direction) was less than 3 degrees. The taper width optimization was performed with a BPM model which had an MMI section width of $60\mu\text{m}$ and length of $2416\mu\text{m}$. In this model, the taper width connecting to the multimode section was the variable, and the total transmitted power and imbalance were measured at the two outputs. It was found that the minimum power imbalance could occur with several taper widths (relative to MMI section width): 0.15, 0.18, 0.27 and 0.33 whilst the insertion loss approached zero with the increase in the taper width as shown in Figure 5.2. Therefore it was desirable to have the taper width designed at 0.33 relative to the MMI section width. This result shows good agreement with the results published by Hill [148] in which a simplified analytic model was used where the modes were approximated by sine waves and had zero field outside the core – certainly not the case for an IPG waveguide.

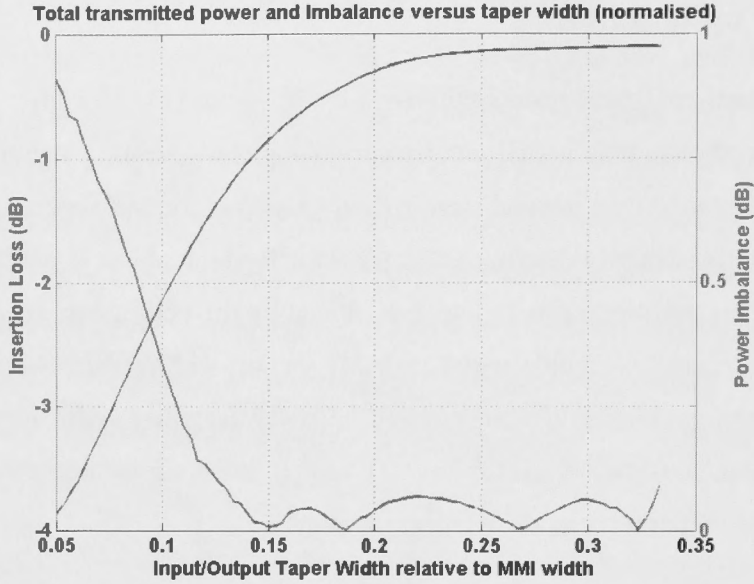


Figure 5.2: Total transmitted power and imbalance as a function of relative taper width (MMI width = $60\mu\text{m}$, MMI length = $2416\mu\text{m}$)

5.1.2 MMI width optimization

With the optimized taper design (0.33 as the relative taper width), the same BPM model was used to simulate the performance variation with changes in the MMI section width. In the modeling, the MMI section width was varied from 30 to $60\mu\text{m}$ and the MMI length was also optimized to attain the minimum power imbalance and/or insertion loss. At small MMI section widths, it was not possible to have minimum power imbalance and insertion loss simultaneously. A typical example is shown in Figure 5.3; the two curves in this graph represent the required MMI length to achieve minimum insertion loss and power imbalance respectively (More plots at different MMI section widths are shown in Appendix). As the MMI section width increases, this deviation length imbalance decreases and reaches zero at about $57\mu\text{m}$. This trend is plotted in Figure 5.4. With an increase in the MMI width, the gap between the two curves (optimal MMI length determined by minimum imbalance and minimum insertion loss) becomes smaller. This indicates that as long as the MMI width is greater than $57\mu\text{m}$, minimum insertion loss and power imbalance can be achieved simultaneously.

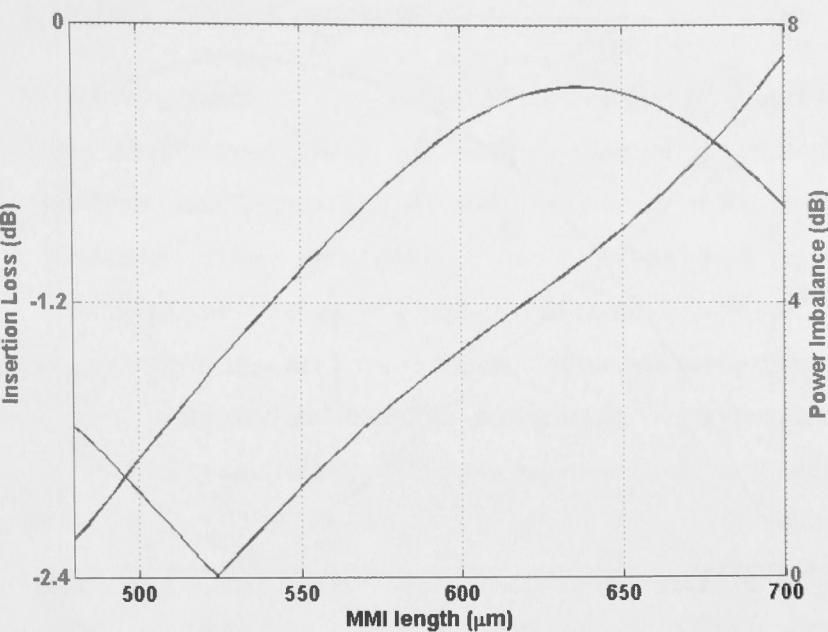


Figure 5.3: MMI insertion loss and power imbalance –vs- MMI length (MMI width = $30\mu\text{m}$); the location for minimum imbalance and minimum insertion loss deviate dramatically

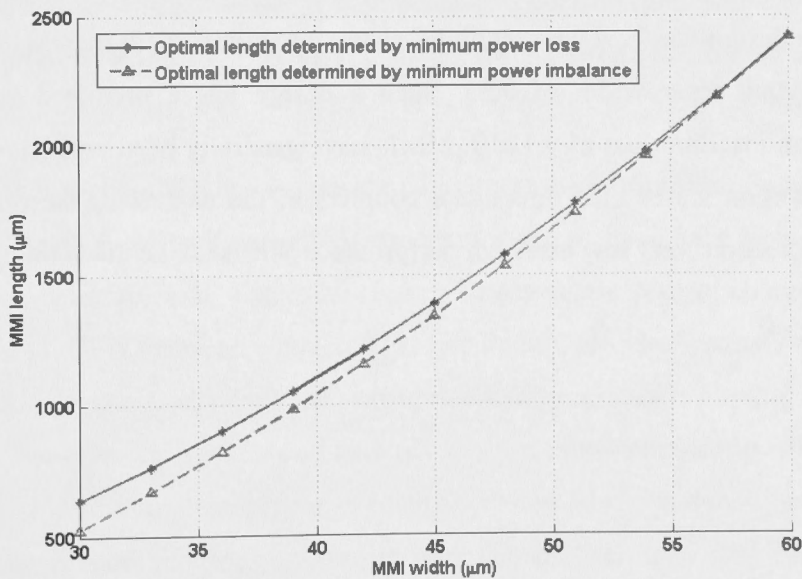


Figure 5.4: Optimal MMI lengths required to achieve minimum insertion loss and power imbalance for a range of MMI widths and other parameters optimized

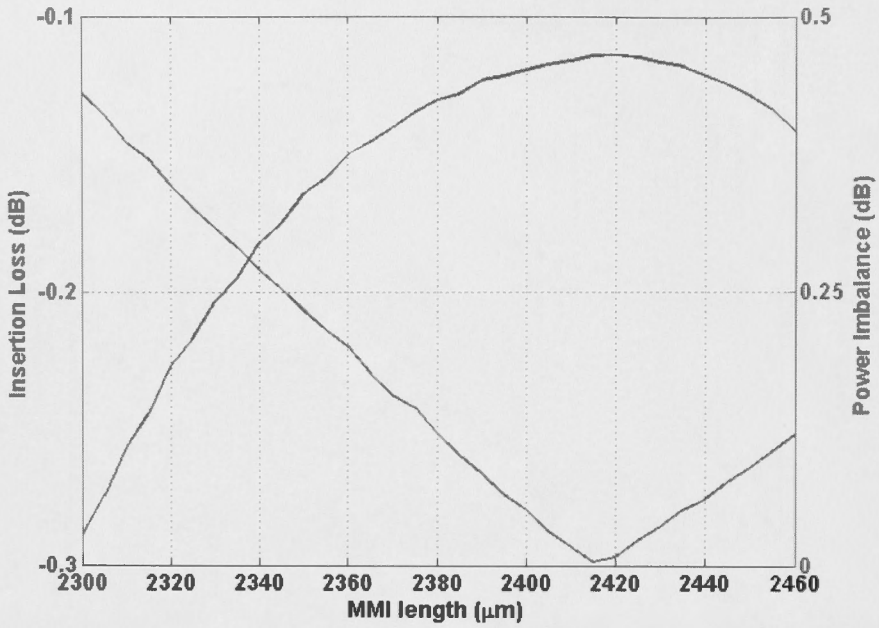


Figure 5.5: MMI coupler insertion loss and power imbalance versus MMI length (MMI width = $60\mu\text{m}$)

With the optimized design for MMI taper width and section width, remarkable performance was achieved for both power imbalance and insertion loss as illustrated in Figure 5.5. This design was based on $60\mu\text{m}$ MMI section width, $2417\mu\text{m}$ MMI length and relative input/output taper width of 0.33. Such a design has a predicted zero power imbalance and an insertion loss of 0.12dB. MMIs have generally been considered to have much larger insertion losses than directional couplers in the past, with the optimization proposed in this section, very low loss high performance MMIs are achievable.

5.2 Directional coupler optimizations

Directional couplers are perhaps the best established technologies for power splitting and coarse filtering in single mode fibres and integrated optics at telecommunication wavelengths. The fibre based approach offers real time control of the coupling profile during device fabrication and so great accuracy can be achieved in the final device characteristics and this has been extensively exploited in commercially available devices. In the planar integrated case, there are however a range of random process variables which affect the final device geometry and therefore performance. The typically exponential dependence of the coupling coefficient on the gap separating the waveguides serves to vastly magnify the effects of these variations. Commonly they are lithographic critical dimension variation for the etch mask defining the waveguides, and the final etch bias relative to the actual etch mask size, both of which would also typically vary across the surface of a wafer. These effects result in the waveguide core widths typically shrinking randomly relative to the photolithography mask design values, and therefore the gap between the waveguide edges increasing with a random variation which cannot be compensated by design bias alone. It is important to note that the actual waveguide core separation defined on the mask is very accurately transferred into the final device as the error is usually symmetric.

This issue is well known and is considered to make the fabrication of planar directional couplers sufficiently difficult in some instances that alternatives have been sought which are more fabrication tolerant. The usual choices of device are vertical couplers [149], zero gap couplers [150], Y-junction couplers [151] or multimode interference devices (MMIs) [152]. Vertical couplers exchange the waveguide width variations for that of a deposited spacer layer between waveguides and take advantage of the accuracies possible in modern deposition and monitoring equipment to ensure accurate fabrication though at the expense of a multilayer process requiring good overlay alignment. Zero gap couplers exchange the control of the gap width for that of the coupling region and typically win about a factor of 2x in fabrication tolerance relative to a specified case, but suffer extreme lithographic demands in making the zero width taper required at the entrance and exit of the device required for very low loss. Y-junction couplers function essentially by symmetry but have

essentially the same demands on the lithography at the tip of the “Y” where any rounding produces excess loss. MMIs relax the lithography constraint but unless carefully designed can suffer significant excess loss [153], and even in the best cases demonstrated to date (excepting the discussion above) have performance somewhat less than can be achieved with a directional coupler.

Thus there existed an opportunity for a design to achieve high optical performance (low loss, accurate coupling ratios), whilst being tolerant to the process variables discussed above. The basis for the work expounded in this thesis comes from the realization that the core separation of the waveguides is accurately transferred to the wafer despite the process variations and is set purely by the lithographic mask. Therefore if a means can be found to “automatically” compensate the change in coupling strength resulting from gap changes (as a result of waveguide width variations), a much more fabrication tolerant design would result. It is shown here that by operating the waveguides in an appropriate regime, such compensation can be achieved with considerable consequent improvements to the fabrication tolerances for a desired level of coupler performance.

5.2.1 Fabrication error insensitive design of 3-dB couplers

The waveguide system selected for study is based on the IPG materials with core index of 1.509 and cladding index of 1.478 at 1550nm. Modeling and design was carried out to develop the desired devices using R-Soft FEMSim and BeamPROP in the full vector 3-D calculation mode. FEMSim was used to model parallel waveguide structures to quickly extract the mode propagation constants to calculate the coupling length so that the model space could be mapped quickly and efficiently. From the results of the FEMSim analysis, full vector BeamPROP models incorporating the bent input and output waveguides were constructed and optimized to counter the effects of coupling in the bent sections, this being particularly important for the WDM devices.

Figure 5.6 shows the calculated mode area for a square IPG waveguide versus size, and it displays the classic minimum mode volume behaviour as expected, but it is the area to the left of the minimum (shaded in Figure 5.6) that is of interest to compensate fabrication tolerance. The behaviour in the shaded region can be conceptually exploited in a simple

manner. For example, if the waveguide width shrinks (i.e. wider gap from edge to edge and therefore a lower coupling strength) then in the shaded region the optical field expands, thereby increasing the coupling strength to compensate the change. The reverse case is also true. Notably the variation in the effective area has an exponential like shape which might be expected to provide a good match to the exponential dependence on coupling gap. The question is how exact can this compensation be for fixed ratio and WDM couplers? For rectangular waveguide geometry with a fixed height of $3\mu\text{m}$, the calculated effective mode area as a function of waveguide width reveals the minimum mode area occurs at $2.1\mu\text{m}$ for 1310nm and $2.5\mu\text{m}$ for 1550nm as shown in Figure 5.7.

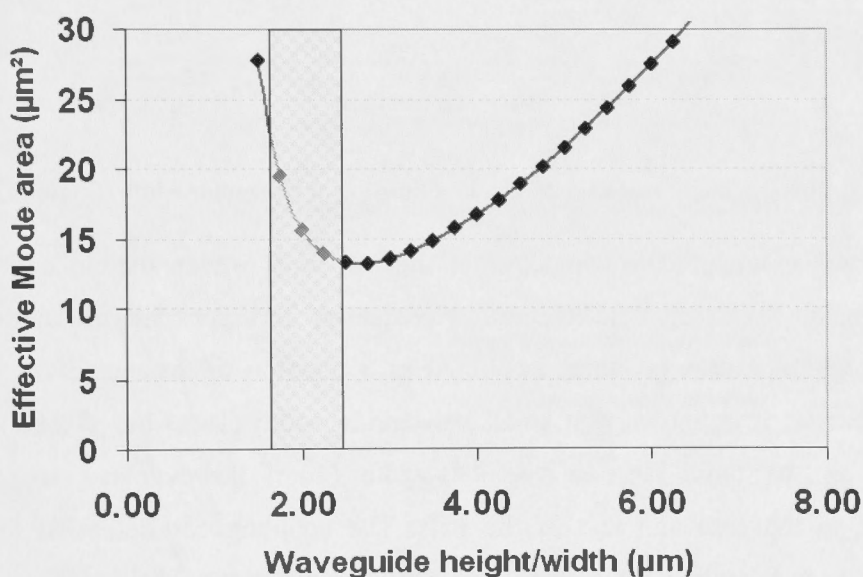


Figure 5.6: Mode area versus width/height for square core IPG waveguide. Operation in shaded region is expected to result in lower tolerances on the coupler.

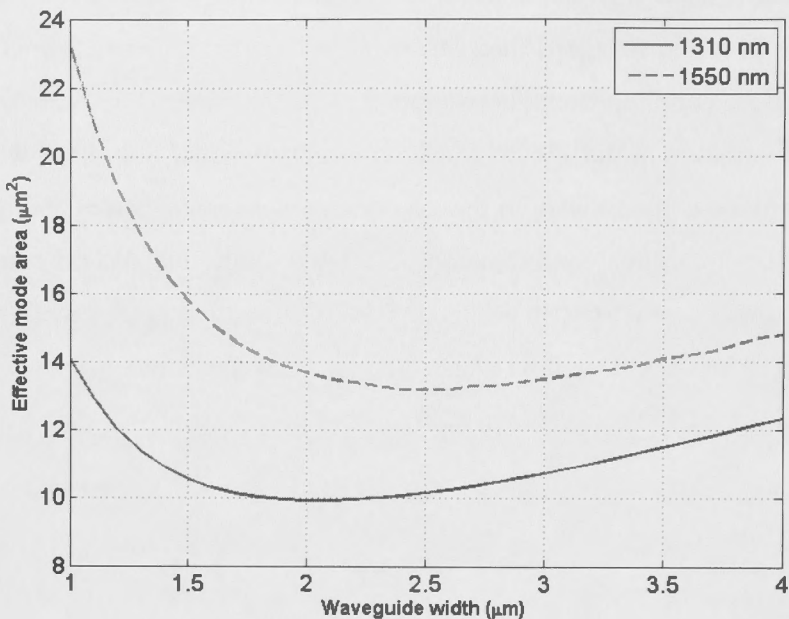


Figure 5.7: Effective mode area distribution as a function of waveguide width (height of 3μm)

Another way to analyze this compensation mechanism is to view the mode distribution in one dimension (by doing field integration vertically). In Figure 5.8, the mode field at various waveguide widths (1~4μm) is plotted as a function of distance away from the waveguide center; it is shown that small waveguide width (1μm) has a lot more field spread out on the tails; large waveguide width (4μm) however has more energy concentrated in the core and less in the tails. The coupling coefficient of directional couplers depends heavily on the overlapping of the evanescent field with the second waveguide. The overlap integral [154] of the paired parallel waveguide model can be evaluated numerically by integrating the field imposed on the core area of the second waveguide. With the core separation set constant, comparing the overlap integral as a function of the core widths, as shown in Figure 5.9; there exists a minimum overlap integral (and therefore a region of improved tolerance) when the core width varies in a sensible range. Another interesting phenomenon is that the corresponding width at minimum overlap integral shifts to larger width as the core separation increases and the shape of the curve changes markedly.

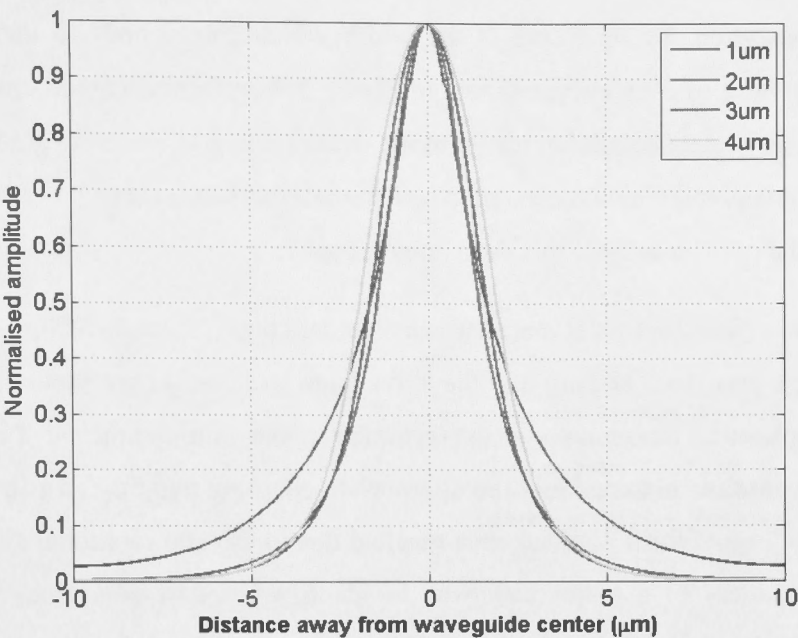


Figure 5.8: 1-D mode field distribution for various waveguide widths

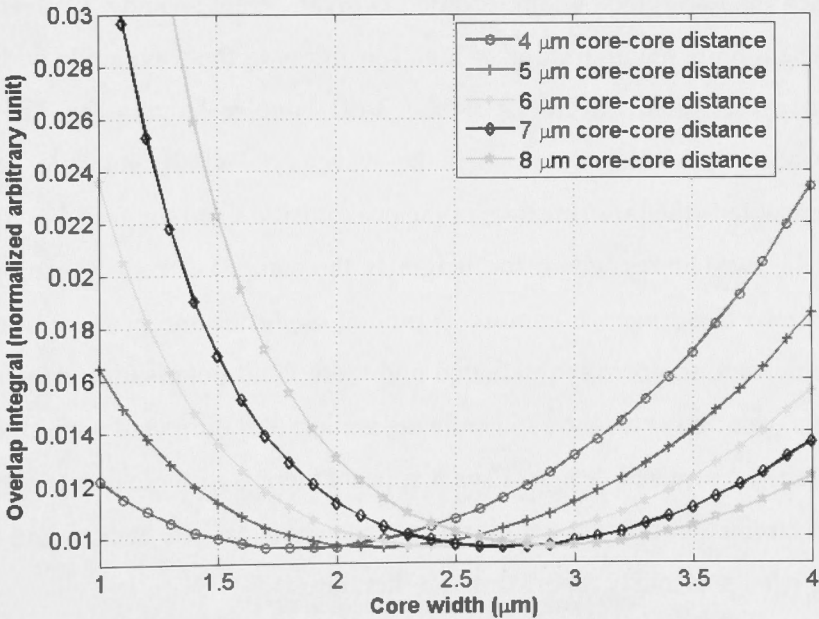


Figure 5.9: Evaluation of normalized overlap integral for paired waveguide model as a function of core width for various waveguide core separations (TE mode)

This is a very significant result for fabrication error tolerant 3-dB coupler design. With a given core separation, by operating at the width which corresponds to the minimum overlap integral (floor of each curve) shown in Figure 5.9, in theory a small change in the core width will introduce negligible change in the overlap integral since the gradient of the curve is zero at this point, which means practically small fabrication error in the core width does not affect the performance of this directional coupler.

The next step was to model parallel waveguide couplers in FEMSim where the waveguide height was fixed at $3\mu\text{m}$ and the waveguide width and core separation varied. The modal propagation constants for the symmetric and anti-symmetric TE and TM “supermodes” were thus obtained and the appropriate coupling lengths for a first order 3-dB coupler. A degree of form birefringence resulted due to the non rotational symmetry of a pair of waveguides, so a major task was to identify a set of conditions where the birefringence went to zero yet the coupling length was insensitive to the waveguide width. Figure 5.10 shows the 1st order 3-dB coupler length versus waveguide width at several core separations. As expected, there exist peaks in the 3-dB coupler lengths for both TE and TM launch fields when the waveguide width is varied at given center spacing. Conversely it is also clear that the coupling length has rather high sensitivity to the waveguide width on the shoulders of the peak. Small deviations in the 3-dB coupler lengths for TE and TM polarization are observed which vary when the waveguide width and core separation change. Equally visible is the birefringence in the peak position and the fact that there is an intersection for the two curves where the length is the same, i.e. zero birefringence. In Figure 5.11, the zero birefringence contour is plotted alongside the peak position locus. Where the two intersect, the peaks are aligned and there is no polarisation dependence in the coupling. This occurred at a centre to centre separation of $8.6\mu\text{m}$, and a width of $3.3\mu\text{m}$ which is therefore the optimized design. Thus it appears there is a single point in the design space where this fabrication tolerant zero birefringence characteristic occurs, and this does not seem to have been previously reported in the literature.

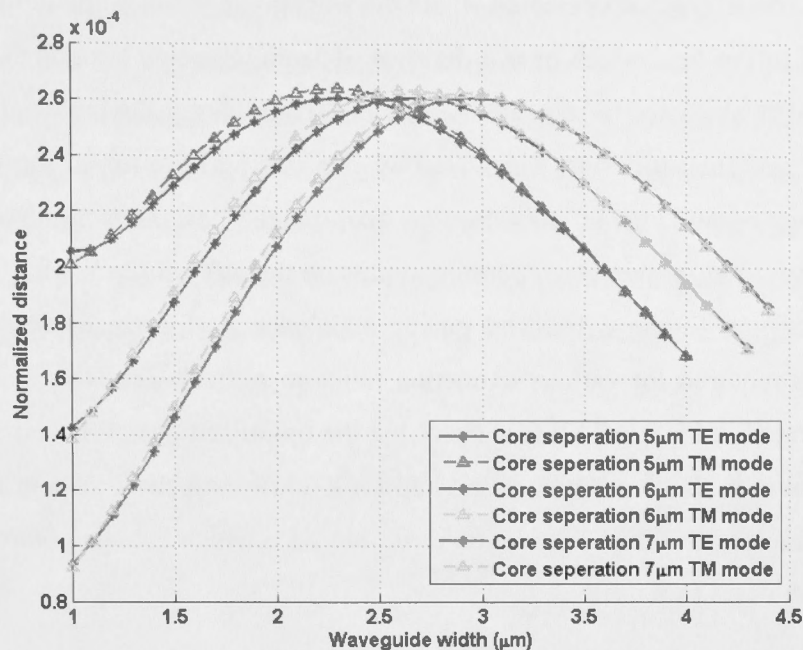


Figure 5.10: Normalized 1st order 3-dB length as a function of waveguide width

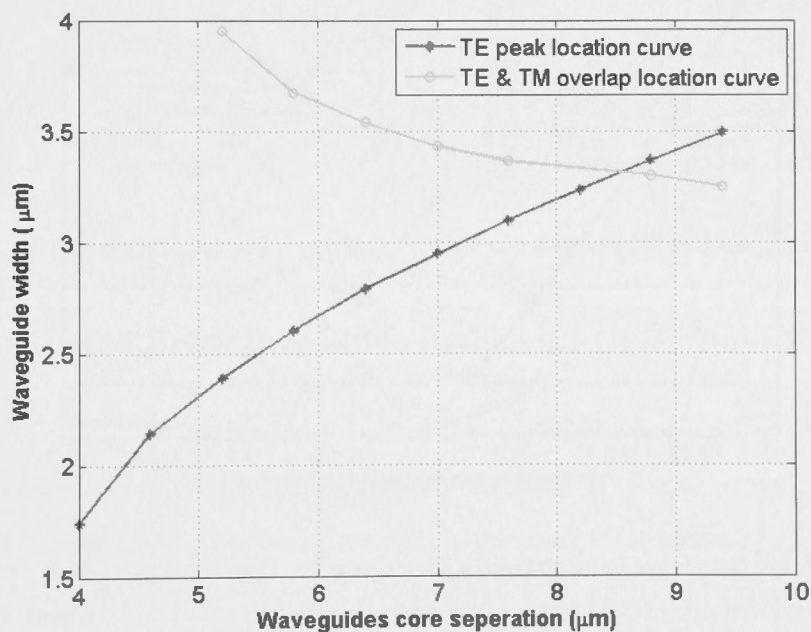


Figure 5.11: Peak (from Figure 5.10) at waveguide width and core separation combinations and the zero birefringence curve (where the two curves intersect, zero birefringence and fabrication error insensitive couplers can result)

Next a BPM model was implemented where the waveguide width at the input was $3\mu\text{m}$ and was tapered to the final width over a distance of 1mm . Bending structures with bend radius of 8mm were also used to separate the pair of waveguides at the inputs and outputs. The performance of such a design was tested by introducing an error in the waveguide width in the range of $\pm 0.2\mu\text{m}$. In addition, two unoptimized designs were also randomly selected for comparison; in this case operating points on the left tail ($2\mu\text{m}$ width) and right tail ($4.5\mu\text{m}$ width) in Figure 5.10. The power imbalance performance along with the imbalance levels required for various extinction ratios in a Mach-Zehnder interferometer (MZI) are illustrated in Figure 5.12; it is clear that the optimized design is less responsive to fabrication errors in the waveguide width and for a 40dB extinction ratio in a MZI, the optimized design offers $>300\text{nm}$ fabrication error tolerance which is huge compared to the other two random cases ($<50\text{nm}$).

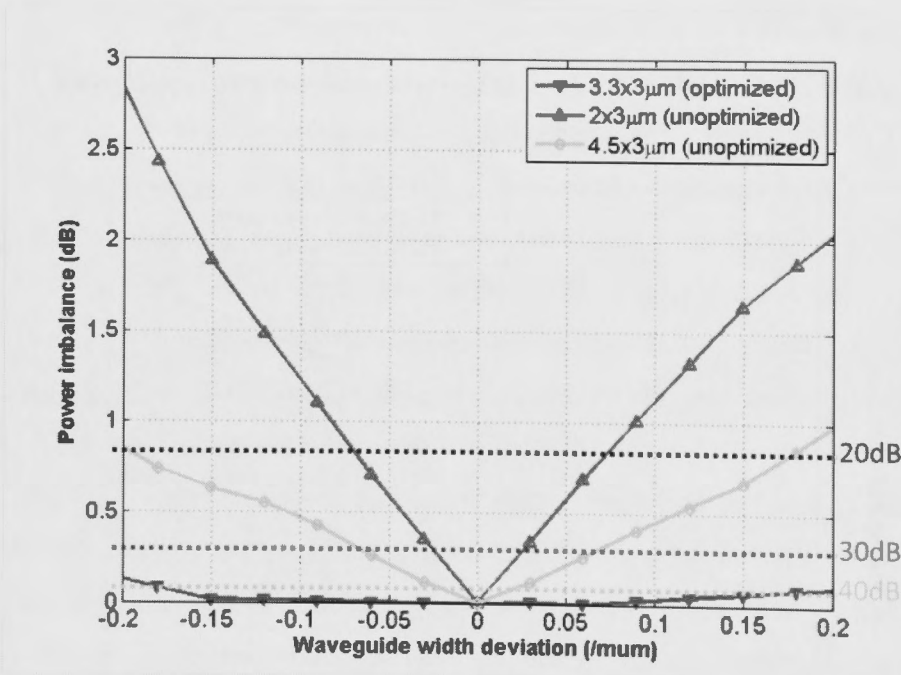


Figure 5.12: Power imbalance induced from a deviation in the fabricated waveguide width with comparison of optimized design ($3.3\times 3\mu\text{m}$) and un-optimized designs (2×3 and $4.5\times 3\mu\text{m}$). The colored horizontal lines show Mach-Zehnder Interferometer extinction ratio achievable at selected imbalances.

A comparison of spectral performance of the 3-dB directional and MMI couplers is shown in Figure 5.13. The MMI coupler shows higher excess loss and it goes up quite

rapidly as the wavelength tuned away from the design. The directional coupler shows remarkably low excess loss across the entire spectrum, however when the power imbalance is concerned, the directional coupler is a lot more wavelength sensitive. There are ways to achieve wavelength insensitive performance for directional couplers such as using tapered waveguide couplers [155], asymmetric waveguide couplers [156], and cascading of two similar couplers in a Mach-Zehnder configuration [157, 158]. Future work could examine if the technique developed here could be applied to such designs to achieve wavelength and fabrication error insensitivity.

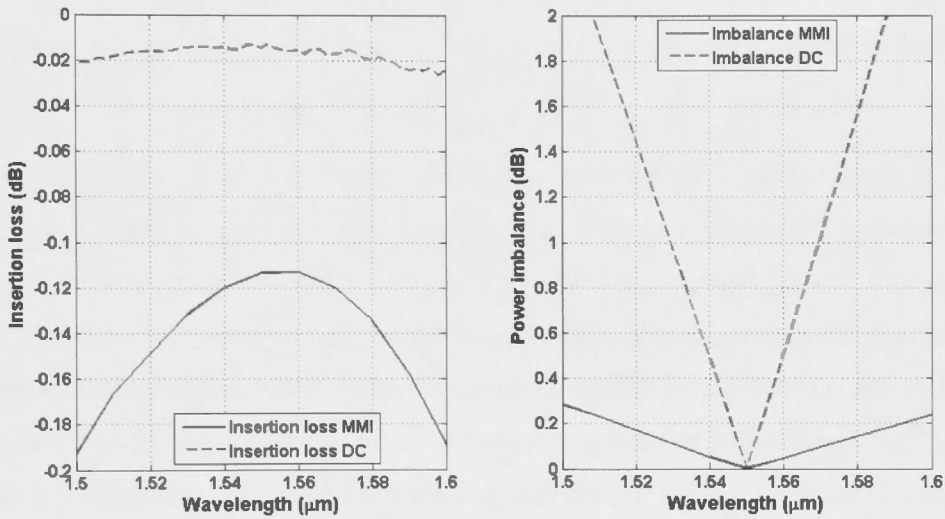


Figure 5.13: Spectral comparison of MMI and 3-dB directional couplers

5.2.2 Fabrication Error Insensitive Design of 1310/1550nm WDM Couplers

Another important application for directional couplers is coarse wavelength division multiplexing in telecommunications, for example pumping multiplexing in fibre amplifiers (980 or 1480nm multiplexed with 1550nm) or 1310/1550nm multiplexing. This device is commonly seen in fibre optics devices, where the core of two adjacent fibres are brought close enough for evanescent coupling, and at a certain distance, light at 1550nm exits from the straight through port corresponding to the input having coupled over and back to the input fibre and light at 1310nm exits from the port having coupled over entirely to the

other output fibre. In planar form the interest is in integrating such components with other functionality to yield devices such as 1310/1550nm transceivers or complete amplifiers on a chip. Fabrication tolerance is however also a concern here as it was for the 3-dB couplers.

Similar to the optimization process for 3-dB couplers, there exist margins to improve the design of WDM couplers by investigating the effect from core separation and waveguide width. Generally, longer wavelengths have larger mode areas for the same single mode waveguide which yield a higher coupling coefficient. Therefore for the same coupler, light at 1550nm has a higher coupling coefficient than at 1310nm. Here we define **The Characteristic Ratio Γ** to be the ratio of coupling coefficients at 1550nm and 1310nm shown in Equation 5.1.

$$\Gamma = \frac{L_{\pi 1550}}{L_{\pi 1310}} \quad (5.1)$$

$$\Gamma = \left(\frac{2n}{2n-i} \right) \text{ or } \left(\frac{2n+i}{2n} \right) \quad (5.2)$$

Without considering the bending structures, for a parallel waveguide 1310/1550nm WDM coupler, it is desired for 1550nm to couple exactly $i*\pi$ (i is odd number) more than 1310nm. There are infinite solutions, e.g. 2π & π , 3π & 2π , 4π & 3π combinations. Therefore the condition for Γ is shown in Equation 5.2, where n is integer and i is odd number, and $i < 2n$. From a design perspective, it is desirable for the device to be simple and possess a high fabrication tolerance. Large value of n and i generally leads to long and complicated devices which are more vulnerable to fabrication errors. Selecting the minimum values of n and i is the simplest and best design which leads to $\Gamma = 2$.

5.2.2.1 Optimization Mechanism

Again in this section, FEMSim was employed initially to find the modal propagation constants for the symmetric and anti-symmetric TE and TM “supermodes” to compute the coupling coefficient in a parallel waveguide model. By varying in the core width and core separation independently, a matrix of coupling coefficients at 1550nm and 1310nm was obtained, hence the contour of the characteristic ratio Γ was computed as shown in Figure 5.14. Each contour line in the plot represents a particular characteristic ratio. Hence for the

case of pure parallel waveguides (without bending structures), the simplest design is achievable by operating at any width and separation combinations on the contour curve $\Gamma = 2$.

In real world of device fabrication, attaining accurate feature size is a great challenge. A fabrication error tolerant design requires the characteristic coupling ratio which has the least change with respect to the waveguide core width variations. Fortunately this optimal criteria can be easily identified from the contour curve ($\Gamma = 2$); by operating at $5.18\mu\text{m}$ core separation and $2\mu\text{m}$ core width, this contour curve hits a zero gradient point where small changes in the waveguide core width induces minimum effect on the characteristic ratio. Hence this operating point is more fabrication error tolerant than any other point on the curve.

The performance of this optimized design was verified by the BPM approach for the parallel waveguide model. For the same core separation ($5.18\mu\text{m}$), the output power extinction ratio is measured over a wide range of core widths and the result is plotted in Figure 5.15. The plot shows very high immunity to waveguide width variation for both 1310nm and 1550nm (almost flat between 1.8 and $2.5\mu\text{m}$), but the overall power extinction ratio is not high. This is because when the waveguide cores were close, the evanescent field of the 1310nm mode overlaps strongly with the out coupling for the 1550nm field crosstalk. This can be eliminated by adding bend structures to separate those parallel waveguides and more details will be discussed in next section.

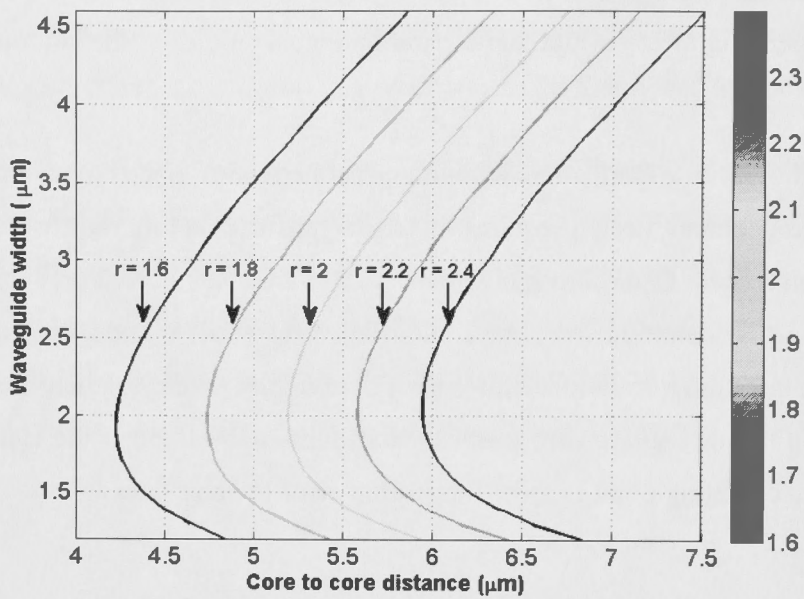


Figure 5.14: Contour plot of coupling coefficient ratio between 1550nm and 1310nm at various waveguide width and core separation combinations

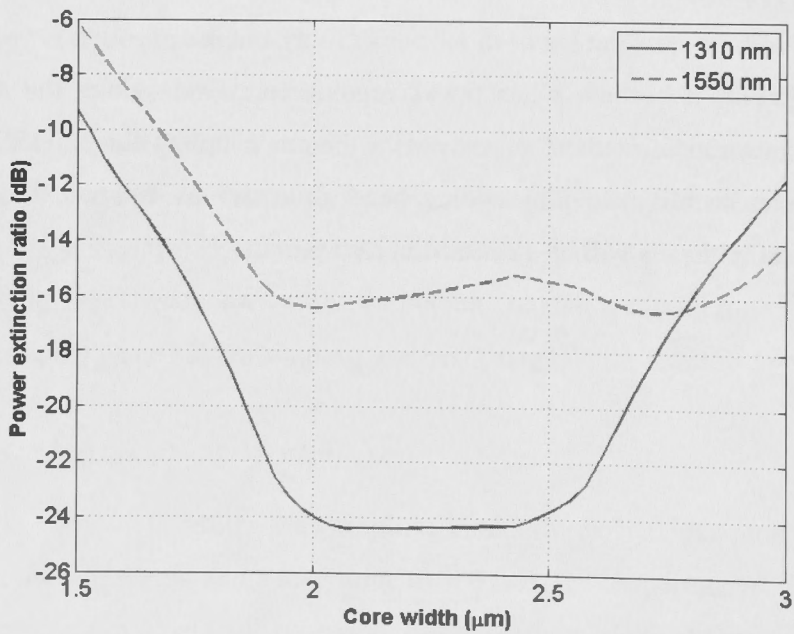


Figure 5.15: BeamProp simulation result showing the power extinction ratio at the two output of WDM coupler based on pure parallel waveguide model (without S-bend)

5.2.2.2 Bending compensation

Simple parallel waveguide devices as modeled in the previous section are not realizable in practice because bending structures are required to bring 2 waveguides close enough for coupling and then separate them apart far enough for no further interaction outside the coupling zone. To minimize effects from coupling inside the bending structures, tight bending is preferred; however tight bending can result in high radiation loss. For IPG waveguides with 2% index contrast, minimum bending radius can be as small as 1.5mm without suffering significant loss [112]. However the less tightly confined mode at 1550nm always leads to more coupling in the arm structures than for the 1310nm case. This can just be seen in Figure 5.16 where light at both wavelengths enters the upper port from the left and light can clearly be seen in the 1550 crossover waveguide within the bends. Compensation of this effect is clearly required to attain high isolation.

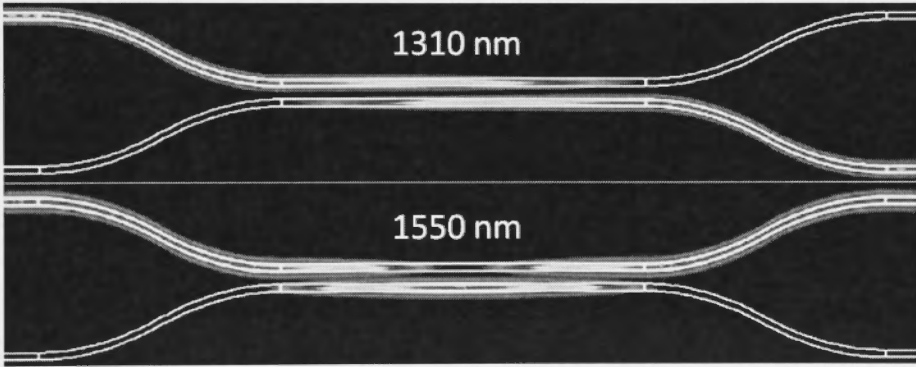


Figure 5.16: Illustration of WDM coupling mechanism at 1310 and 1550nm

Previously Equation 5.2 for the characteristic ratio was derived based on the pure parallel waveguide model. The addition of bending structures in this situation can be considered to be an additional coupling length compared to the 2π phase shift; here we define this effective coupling length to be ζ , and effective phase θ .

$$\theta = \frac{\zeta}{L_{2\pi}} \quad (5.3)$$

Physically $L_{2\pi}$ represent the length required for a particular wavelength to couple 1 complete period (The power as a function of waveguide length is a sinusoidal wave) and θ

represent the equivalent fraction of period. Therefore the new characteristic equation with bending is shown in Equation 5.4.

$$\Gamma = \left(\frac{2n - 2\theta_{1550}}{2n - i - 2\theta_{1310}} \right) \text{ or } \left(\frac{2n + i - 2\theta_{1550}}{2n - 2\theta_{1310}} \right) \quad (5.4)$$

A numerical computation using Rsoft BeamProp was used to simulate this undesired coupling from the S-bend structures. In the design file, a directional coupler was drawn with S-bends (4.35mm bend radius and 3.6° bend angle) and the coupler length set to zero. In this case, the amount of coupling at the output was purely from the bending structures. Figure 5.17 shows the numerical simulation result; overall as expected, 1550nm (graph on the right) has a lot more undesired coupling compared to the launch field at 1310nm (graph on the left); the undesired coupling drops exponentially as the core separation increases.

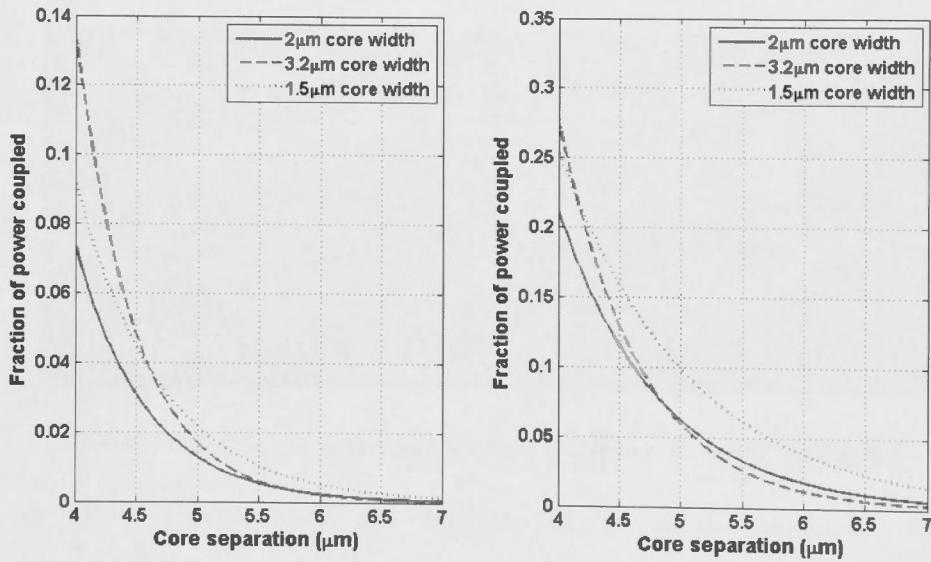


Figure 5.17: Numerical computation of the undesired coupling from S-bend with launch field at 1310nm (left) and 1550nm (right)

Knowing the effective coupling length at a particular width and core separation for 1310nm and 1550nm, and substituting into Equation 5.4, the desired characteristic ratio can be obtained. In practice, it is a lot easier to determine the optimized parameters numerically. A matrix of power extinction ratio as a function of core width (e.g. 1–4 μm) and core separation (5.1–5.3 μm) were computed and plotted parametrically as in Figure

5.18. Comparing the performance at both 1310 and 1550nm, the optimal core separation can be determined graphically. The performance of such design is fairly sensitive to changes in the core separation (a mask fabrication task where ultrahigh performance tools can be employed as only a limited number of masks are made), but highly error tolerant to changes in the waveguide widths. Yet it is possible to achieve 30dB power extinction ratios for both 1310 and 1550nm having a waveguide width tolerance of $\pm 100\text{nm}$. As a comparison, two other random designs were also selected from the same contour curve ($\Gamma = 2$); one focused at $1.5\mu\text{m}$ waveguide width and the other at $3.2\mu\text{m}$. The performances are co-plotted as shown in Figure 5.19. As expected, sharp dips at the design widths were obtained and the extinction ratios fell very rapidly when tuning away from the design widths.

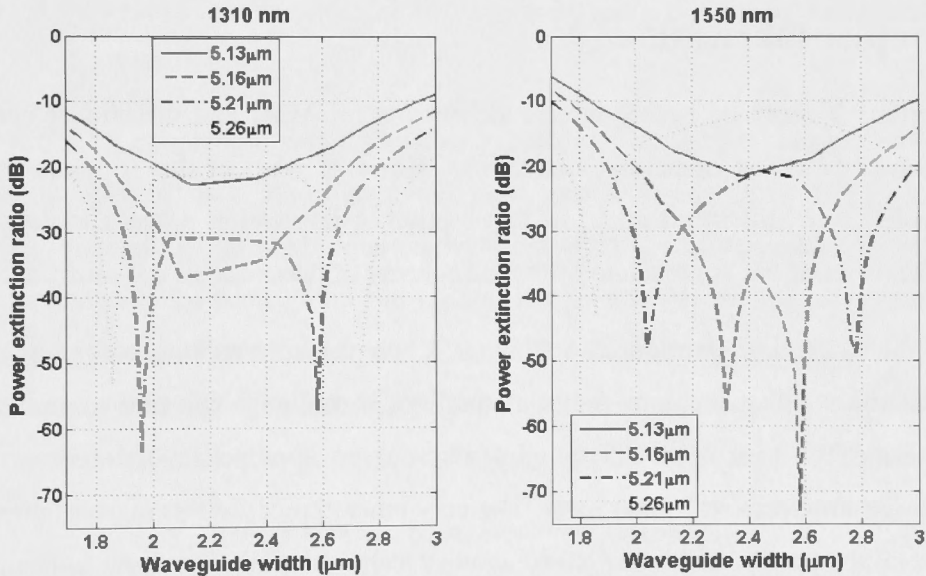


Figure 5.18: Power extinction ratio at the two output ports for 1310nm and 1550nm over a range of waveguide widths at various core separations (TE)

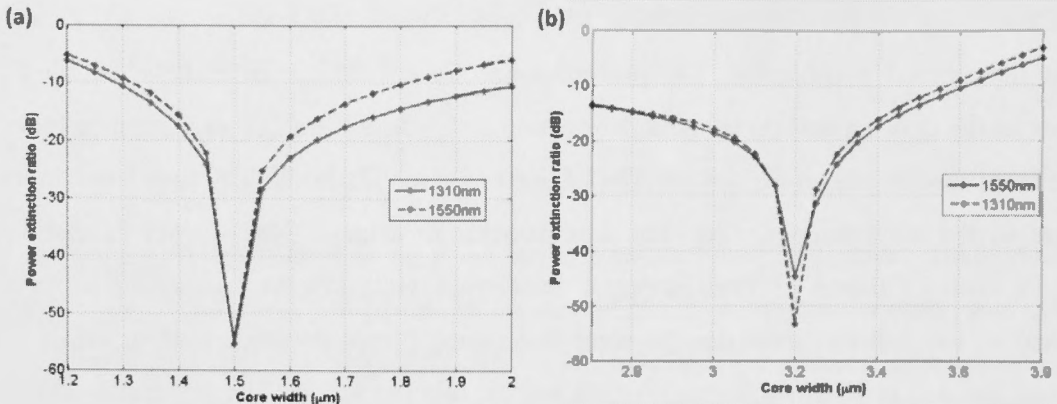


Figure 5.19: Power extinction ratio at the two output ports for 1310nm and 1550nm over a range of waveguide widths for two unoptimized cases (a) designed core width at 1.5μm (b) designed core width at 3.2μm (TE)

5.3 Coupler fabrication

In the previous 2 sections, optimization mechanisms for MMI and directional couplers were developed based on numerical simulations. However whether this technique would work in reality was still in question. In this section, a fabrication process is developed based on the nanoimprint approach to prove the concept of these design optimization.

The UV-NIL process developed in Chapter 3 is a versatile technique for replicating features including optical couplers. As usual, the biggest challenge was how to produce the original master. Electron beam lithography was not an appropriate option due to the relatively large structures and wafer scale. The only other choice for this master fabrication was by photolithography. Then this led to another technical challenge: how to design the photomask? It was necessary to engineer the structures based on minimum displacement during imprint as previously described to avoid thick residual layers which meant the design task was to draw a band of cladding around the coupler. There was no commercial software available which could draw such customized devices parametrically.

In addition, the quality of this mask needed to be guaranteed; for the experiment it was desirable to have a range of waveguide core separations which varied by a known and guaranteed amount between sets (say 25nm increment in centre to centre spacing between sets). Most commercial mask writers use scanning methods to write and registration errors

can easily account for more than this in even high end tools. Thus extreme attention also had to be paid to the mask writing strategy to minimize such errors and enable a systematic investigation of the effects of waveguide width and centre to centre separation.

5.3.1 Design parameters

Before commencing the mask design, one question that needed to be answered was: what are the design parameters? The goal of this mask was two-fold; firstly to demonstrate that the UV-NIL process was capable of imprinting high performance optical couplers and the other was to prove the concept of optimized design mechanism for optical couplers. Therefore the couplers designed on this photomask should not only include the optimized design, but also other un-optimized designs for comparison. In addition, the device on the mask must be able to handle practical errors which were not seen in the modeling, e.g. refractive index variations.

For the MMI couplers, it was discovered in Section 5.1 that the coupler section width needs to be greater than $57\mu\text{m}$ to avoid high excess loss at zero power imbalance conditions. Four groups of MMI couplers were designed at section widths 30, 39, 51 and $60\mu\text{m}$ respectively; for each group the section length was varied in seven segments for compensating potential errors as shown in Table 5.1. In addition, the taper width plays a fairly important role and the optimal design was to have input/output taper width of $1/3$ relative to the MMI section width (e.g. for a $30\mu\text{m}$ wide MMI, the taper width is $10\mu\text{m}$).

Table 5.1: Design parameters for MMI couplers

MMI section width (μm)	MMI Section length (μm)						
	L_{-3}	L_{-2}	L_{-1}	L_0	L_{+1}	L_{+2}	L_{+3}
30	494	504	514	524	534	544	554
39	922	942	962	982	1002	1022	1042
51	1635	1670	1705	1740	1775	1810	1845
60	2267	2317	2367	2417	2467	2517	2567

For 3-dB directional couplers, the best design was a waveguide width of $3.3\mu\text{m}$, a length of $4652\mu\text{m}$, and core separation of $8.6\mu\text{m}$; the S-bend radius was chosen to be $8005\mu\text{m}$ for 2.86° . Couplers with width variation from $2.9\sim 3.7\mu\text{m}$ were designed to investigate the width error tolerance. The design parameters are shown in Table 5.2; for comparison, similar approach was implemented for the un-optimized designs at width of $2\mu\text{m}$ and $4.5\mu\text{m}$. To compensate possible systematic error, coupler lengths were varied by $\pm 5\%$ and $\pm 10\%$.

Table 5.2: Design parameters for 3-dB directional couplers

	Coupler length(μm)	Coupler waveguide width (μm)								
Optimized design	4652	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Unoptimized design (1)	2743	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4
Unoptimized design (2)	3681	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9

The design strategy for WDM couplers was similar to the 3-dB couplers. The optimized design was: $5.11\mu\text{m}$ core separation, $2\mu\text{m}$ waveguide width and $897\mu\text{m}$ coupler length. The coupler width was varied between 1.5 and $3\mu\text{m}$ with an increment of $0.1\mu\text{m}$ and the core separation was varied between 5.06 and $5.16\mu\text{m}$ with $0.025\mu\text{m}$ increment. Two other un-optimized designs were also included for comparison.

5.3.2 CAD design and fabrication

Unfortunately there was no commercial software available which could easily handle the drawing of these devices and the only option left was to write a program to generate such design files. The idea was to transform all the devices into polygons and specify all the corner coordinates in ASCII format to be further processed into a GDS file by importing them into the Raith design software. This program was written in LabVIEW. With the input design parameters for MMI or directional couplers, an entire group of couplers with all the variations contained within could be generated easily and quickly. Then all the

polygon groups were combined onto a single mask layer using the Raith graphics editor. Figure 5.20 and 5.21 shows typical exported polygons based on MMI and 3-dB couplers.

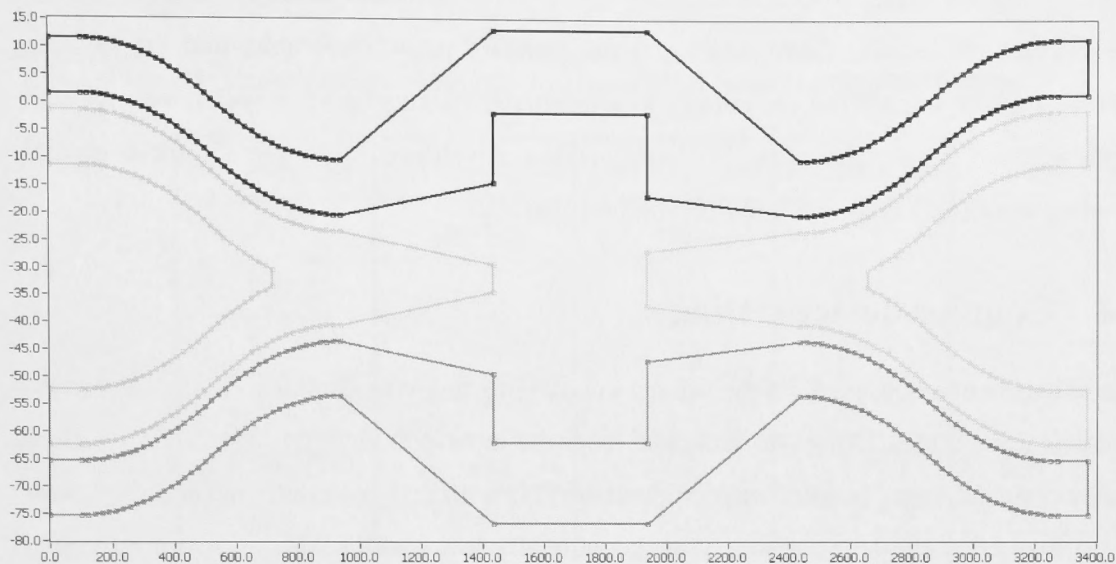


Figure 5.20: A drawing of polygons generated representing a typical MMI coupler

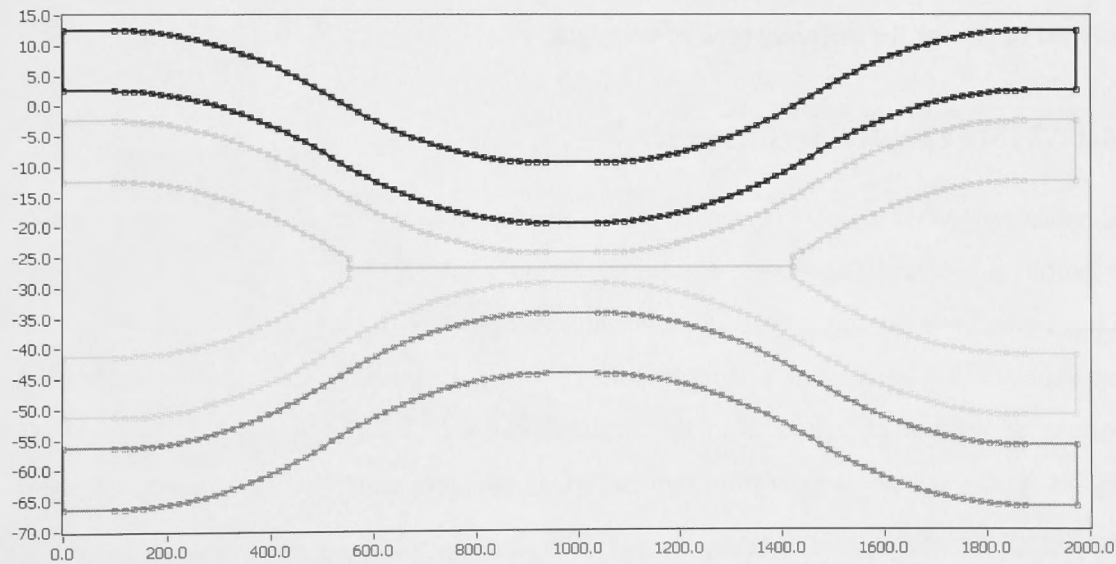


Figure 5.21: A drawing of polygons generated representing a typical 3-dB/WDM coupler

The photomask was fabricated by Taiwan Mask Corporation with a 244nm laser mask writer using a 0.0083 μ m writing grid size, 0.1 μ m critical dimension and 0.1 μ m registration accuracy, and using a quadruple pass scan in the same way as described during the grating EBL approach to minimize stitching errors. This strategy was considered by the vendors to

be capable of delivering $\sim 10\text{nm}$ accurate spacing variations in the waveguide centre to centre dimension. Note that with the use of even a low end reduction stepper (5x reduction) that ensuring the centre to centre accuracy on the mask therefore becomes relatively easy. The imprint master was fabricated using the standard photolithography and dry etching approach which transferred the pattern to a thermally oxidized silicon wafer with an etch depth of $3\mu\text{m}$. Using the same UV-NIL process developed in chapter 3, these optical couplers were replicated onto the Polysiloxane material.

5.4 Coupler device testing

The experiment setup used for the optical couplers testing was similar to that used for the standard waveguides. Light was launched from the input port using Nufern UHNA-3 fibre (index matched to the coupler waveguide using IPG with no photo-initiator) and the power was measured at the output ports. The exceptionally low standard deviations of measured insertion loss evident on the straight waveguides shown in Chapter 3 means we can reliably use the measured data to calculate power imbalance accurately. The results were analyzed in groups for different type of couplers.

5.4.1 MMI coupler performance

For measuring MMI coupler performance, we used a tunable laser emitting at 1550nm and the output power imbalance was compared within a single group of devices. The group selected was based on the $60\mu\text{m}$ section width design; with a variation in MMI length, it was expected to hit a zero power imbalance design. However the data revealed that majority of the power exited from the straight port and this was true for most of MMI lengths. It was considered possible that the MMI couplers experienced imprint distortion instead of a design failure.

To further investigate the possible imprint distortion, we used an optical profiler (Veeco Wyko NT9100) to scan the surface profile of one of the imprinted MMI couplers. The measured profile image is shown in Figure 5.22(a). Examining the cross section of this MMI coupler, it is shown in Figure 5.22(b) that the top surface is not horizontal. In fact the dip at the center of the MMI was measured to be 400nm which was believed to be the

major contributor to the poor imbalances measured as the distortion was a significant percentage of the core height and would lead to a systematic de-phasing of the MMI modes along the length of the device.

Table 5.3: Measured output power for a group of MMI couplers (60μm MMI width)

MMI length (μm)	port 1 power (dB)	port 2 power (dB)	Imbalance (dB)
2267	8.98	4.84	4.14
2317	4.77	11.27	6.5
2367	4.2	10.64	6.44
2417	3.96	10.33	6.37
2467	3.48	10.39	6.91
2517	3	10.4	7.4
2567	3.49	9.91	6.42

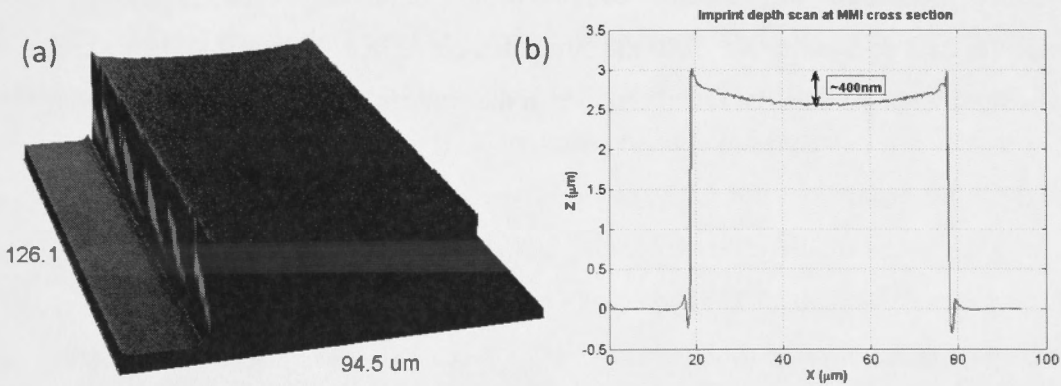


Figure 5.22: (a) MMI coupler section image measured from an optical profiler, (b) measured height for the cross section of this MMI coupler.

Fundamentally this distortion comes from the sag of the soft stamp. Normally it was not a problem for small devices, e.g. waveguides, however it clearly became significant when dealing with large features. One solution would be to use a hard stamp, but a hard stamp would have required commercial imprint equipment which was unavailable to us at

the time and a lot more effort for developing a recipe. Another approach could be to use the double layer stamp made from thin layer of *h*-PDMS backed with thick layer of PDMS which was discussed in Chapter 3. However insufficient time was available to trial this route.

5.4.2 3-dB coupler performance

Testing of the imprinted 3-dB couplers also used a tunable laser as the light source; the laser was programmed to scan over a range of wavelengths from 1535 to 1580nm and the transmission spectrum at the each output was acquired for each coupler. The power imbalance was then analyzed among a group of couplers. Overall the measurements at 1550nm showed the optimized couplers were less sensitive to variations in the coupler waveguide width than other designs. However the devices did not appear to be optimized for 1550nm and the desired coupler lengths were significantly shorter than expected. Instead it appeared that by reducing the wavelength to ~1540nm and using the shortest coupler design (10% less than the ideal expected coupler length), the overall performance appeared to be consistent with the modeling. Figure 5.23 shows the imbalance performance measured at 1540nm compared to simulated result. Although the experimental data does not quite fit to the simulated curve, it is shown that the optimized design is significantly less sensitive to changes in the waveguide width than other designs.

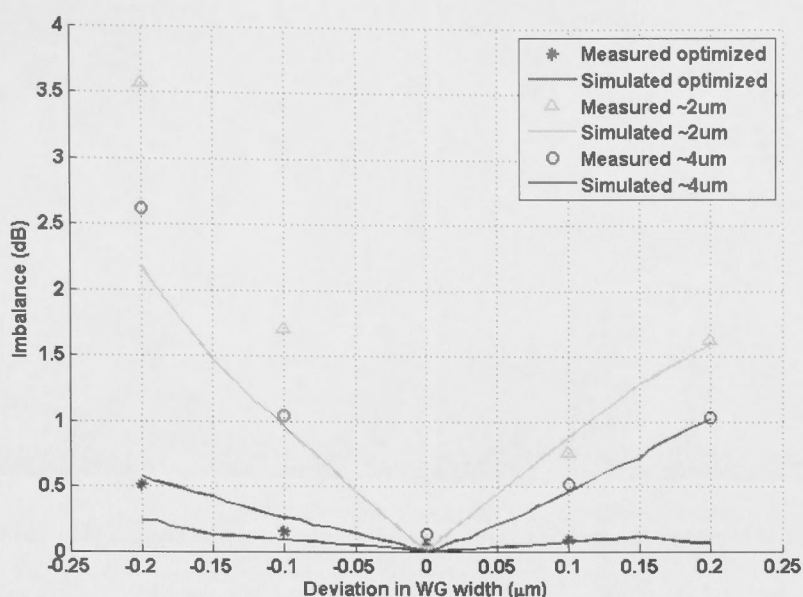


Figure 5.23: Imbalance performance of optimized 3-dB coupler compared to other designs.

The result has shown that the fabrication error tolerant design mechanism is indeed functioning; but it also leaves quite a few questions to be answered. Firstly, there is slight disagreement between simulation and measurements at the best matching wavelength. Secondly, the real device functions at a shorter wavelength and shorter coupler length than expected. To answer those questions, the exact fabricated coupler geometry had to be known. A SEM image revealed that the coupler waveguide sidewall was not vertical as had previously been achieved; an estimate over the angle of the sidewall was about 82° (shown in Figure 5.24). This was not as good as had previously been attained (Figure 3.10) and after much work it transpired that something had changed in the etch system after its preventative maintenance service. A lack of time prevented the recipe being re-optimized to attain $>87^\circ$ sidewalls as previously obtained. A residual layer measured at around 80nm was also present and the impact of this had to be ascertained.

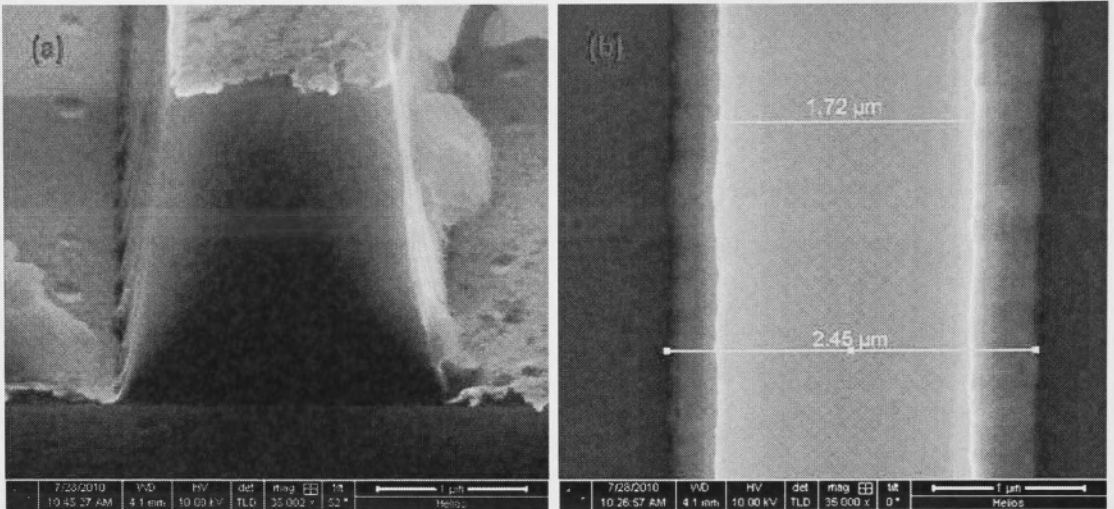


Figure 5.24: SEM image of the imprinted directional coupler (a) cross section view (b) top view

The previous modeling assumed pure channel waveguide structures with perfectly vertical sidewalls. Generally a non-vertical sidewall tends to spread out the mode; similarly a residual layer can be considered a leaky channel for the optical field to escape. Therefore both mechanisms can lead to larger mode area and larger coupling coefficient, and therefore shorter device lengths. That is why the real device actually functions at $\sim 1540\text{nm}$ (shorter wavelength has smaller mode area) and shorter device length. To model the real fabricated device, sidewall angle and residual layer had to be accounted for. Using FEMSim, the effective index of waveguides with $3\mu\text{m}$ height was computed at various widths and it was also possible to include the sidewall angle and residual layer. The result is shown in Figure 5.25; 100nm residual layer very slightly modifies the effective index; however the major impact is given by the sidewall angle which significantly shifted the effective index.

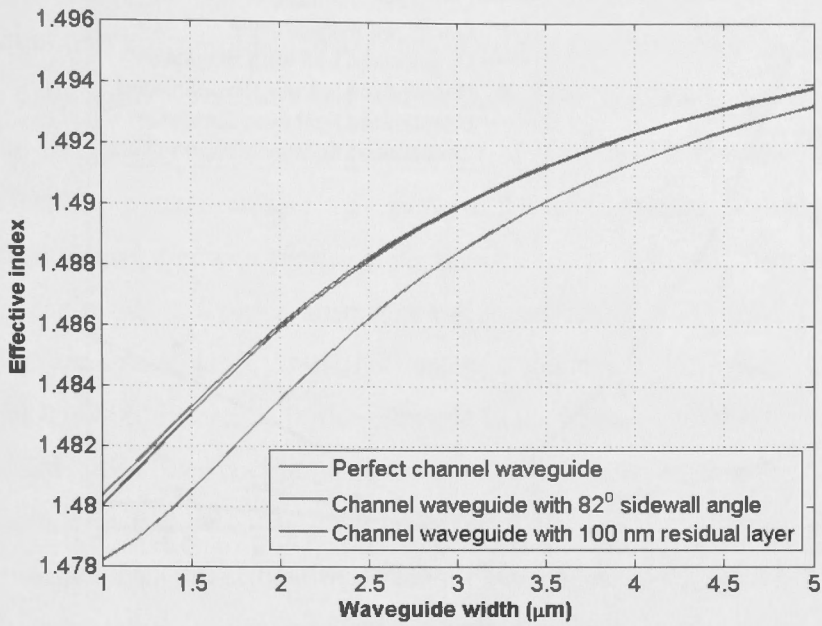


Figure 5.25: Effective index as a function of waveguide width

Therefore the disagreement between measurement and simulation is a result of the non-vertical sidewall. Taking the 82° sidewall angle and a 100nm residual layer into account, the performance of the designed 3-dB couplers was simulated again and further compared to the experimental result as shown in Figure 5.26. Compared to a pure channel waveguide model, the non-vertical sidewall makes 3-dB couplers more sensitive to width variation. It was also shown in the simulation that by improving the sidewall angle to $>87^\circ$, the distortion could be significantly reduced and the overall performance was equivalent to pure channel waveguides which is achievable by improving the lithography and etching processes.

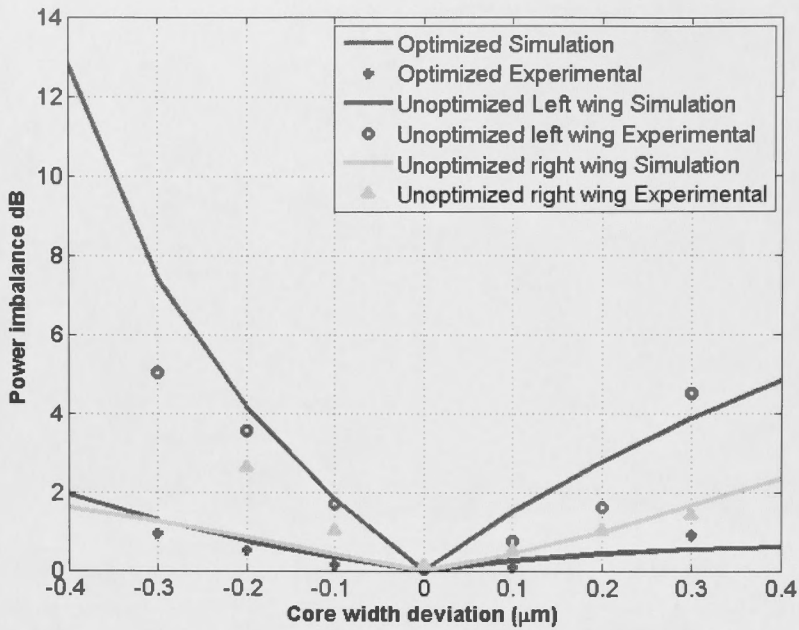


Figure 5.26: Comparing performance of optical couplers to simulation (including the 82° sidewall angle and 100nm residual layer)

5.4.3 WDM coupler performance

For the testing of 1310/1550nm WDM couplers, two laser sources were used to measure the power extinction ratios with 1550nm exiting through the straight port corresponding to exactly one coupling period and 1310nm exiting through the cross port corresponding to half a coupling period. The simulated WDM coupling mechanism is shown in Figure 5.16. The performance of such WDM couplers was assessed from the power extinction ratio comparing the two output ports at both 1310 and 1550nm. The measured results are plotted in Figure 5.27 and 5.28 showing the performance of the optimized WDM coupler design comparing to other un-optimized designs. It is shown that at 1550nm, the performance is fairly similar to the modeling result as shown in Figure 5.18 and 5.19; the optimized design offers waveguide widths error tolerance up to 600nm for beyond 30dB power extinction ratio which is far superior to other designs. On the other hand, the data for 1310nm are rather noisy and low in power extinction ratio especially towards smaller waveguide widths. To investigate the possible reasons behind this phenomenon, a white light source was launched into the coupler and the spectra at both ports were acquired for comparison

(shown in Figure 5.29). As expected, there is a ~26dB dip at around 1550nm shown in the straight output port and a ~15dB dip at around 1310nm shown in the cross output port. The low power extinction ratio at the cross port indicating this is not a design problem, rather it is related to the quality of the mask. This kind of issue was discovered decades ago to attain “perfect” coupling from one waveguide to the other, the two waveguides needed to have identical propagation constants, i.e. be almost exactly identical. Tiny variations in the dimensions can result in a phase mismatch and imperfect coupling with power remaining in the input waveguide [159, 160]. As such we conducted a simple simulation which showed that 0.00005 difference in the effective index between the two waveguides could result in a low cross over coupling similar to what is shown in Figure 5.29. Such small difference could in fact be easily produced from a core width difference of 20nm which was well smaller than the critical dimension given by the mask specifications. Clearly attaining high isolation will require either better masks or the use of reduction steppers which essentially reduces the difference error by 5x thereby making it tolerable.

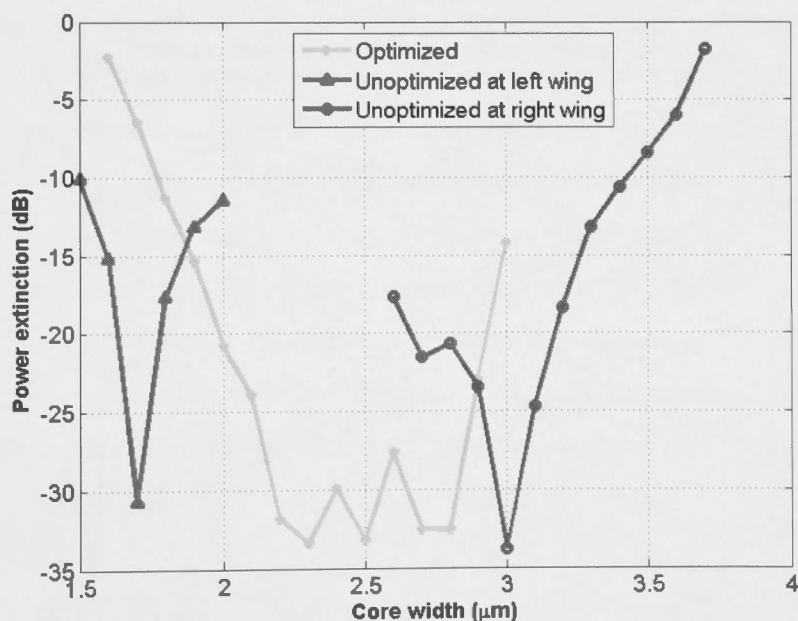


Figure 5.27: Measured power extinction ratio at 1550nm for the nano-imprinted WDM couplers (measurement uncertainty: +/-1dB)

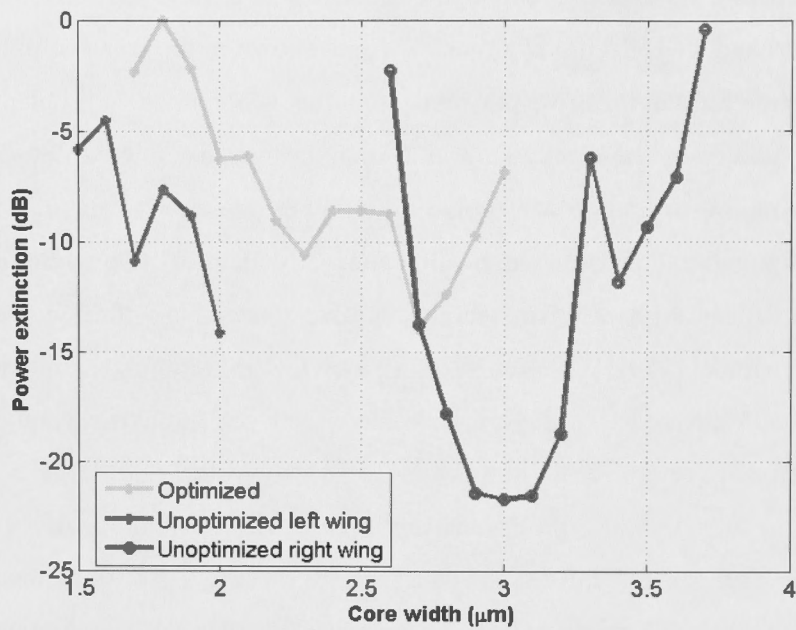


Figure 5.28: Measured power extinction ratio at 1310nm for the nano-imprinted WDM couplers (measurement uncertainty: +/-1dB)

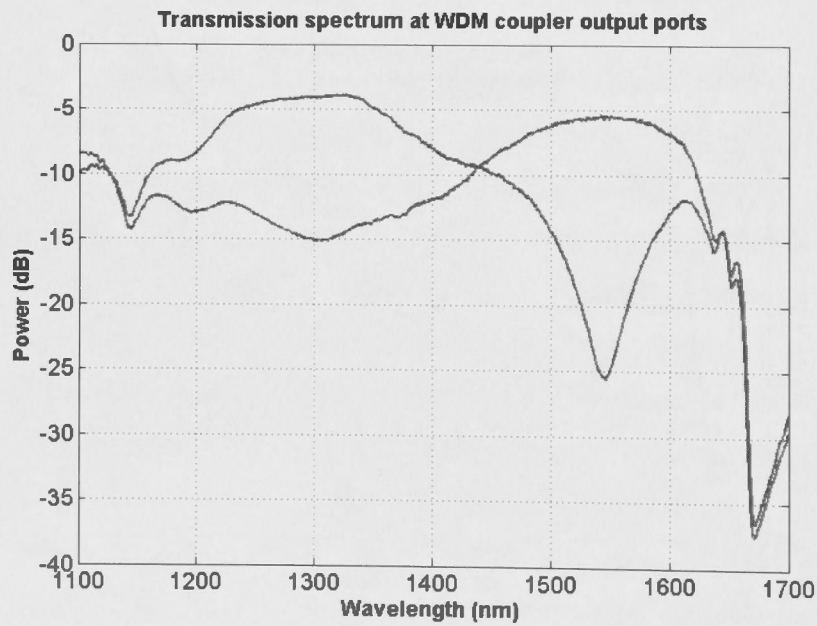


Figure 5.29: White light transmission spectrum of the fabricated WDM coupler at both output ports

5.5 Conclusion

In this Chapter, we described the design, optimization and fabrication processes for planar optical couplers. Multimode interference and directional coupling are the most widely used approaches for power splitting and coarse filtering. The performance of MMIs are highly dependent on the section width and taper width; it was shown that a wider MMI section width could avoid high radiation loss and the optimized input and output taper widths were $1/3$ relative to the MMI section width. A very low excess loss design with excellent splitting uniformity was demonstrated for the first time. The fabricated MMI couplers using UV-NIL process, however experienced problems with stamp deformation which is a fatal distortion to the performance of these couplers. Further work on the imprint technology using either a stiffer stamp or a backplane, preferably on a commercial tool are expected to be able to resolve this issue.

The design optimization of directional couplers has proven that fabrication error tolerant designs are achievable at specific of waveguide dimensions. It was shown for the first time that a single point in the design space exists where the device is basically insensitive to the waveguide width for both polarizations. Using the UV-NIL process, we proved this concept was possible. The fabricated 3-dB couplers showed significantly less sensitivity to errors in the waveguide width than other designs. The 1310/1550nm WDM coupler has demonstrated the capability of reaching high extinction ratio ($>30\text{dB}$) at 1550nm over a fairly wide range width tolerance (600nm); however the output at 1310nm port suffered from low extinction ratio and we believe this problem comes from the error produced in the mask design (the two waveguides having a very small difference in the effective index) which result in the cross port being unable to couple 100%.

Chapter 6

Chalcogenide Glass Waveguide Technologies

6.1 Introduction

Chalcogenide glasses (ChG) are remarkable materials with wide applications and have attracted enormous interest for infrared optics since the 1950's [161]. Chalcogenides have also found widespread application as phase change materials for optical data storage media (DVDs) and non-volatile random access memories (PRAM), as lens materials for thermal infrared imaging, as photovoltaic cells, and due to their large non-resonant non-linearity and low linear and non-linear losses, as materials for nonlinear optics [162-164]. Aside from passive optical components, ChG based optical devices have found a number of applications, particularly in fibre form [165] including: infrared laser power transmission; remote sensing and scanning near-field infrared microscopy. The extraordinarily wide transmission of ChGs (out to 20 μ m in some cases) has also sparked a lot of interests in using them for mid-infrared integrated optical processing for defense, medical, industrial, chemical and bio-sensing, as most chemicals and biological materials/toxins have their spectral fingerprints in this region.

ChGs have a number of unique properties that make them attractive for fabricating planar optical waveguides. Their high linear refractive index and broad infrared transparency suggest that compact optical circuits made from sub-wavelength, single mode waveguides can be fabricated for telecommunications, optical sensing and mid-IR science. Their low phonon energy make them attractive hosts for rare earth doping which will lead to waveguide lasers operating on long wavelength infrared transitions [166]. Their large ultra-fast third order optical nonlinearity has already been successfully used for all-optical signal processing of telecommunications signals [167], and in the future should lead to the generation of broad-band super-continuum further into the mid-IR than achievable with

other materials leading to bright sources for spectroscopy and sensing [168]. Finally there exists a wide range of glass-forming systems and compositions and this allows material properties to be fine-tuned for specific applications. Motivated by such possibilities over the last decade, interest has increased in the fabrication and use of high performance planar waveguides made from ChGs.

6.2 Material properties

Chalcogenide glasses contain one or more of the Chalcogen elements from group 16 of the periodic table (S, Se, Te but excluding O) covalently bonded to networks formers such as As, Sb, Ge, Si, etc. They are, therefore, composed of relatively weakly bonded heavy elements and this leads to many of their most important optical and physical properties. Relatively low bond energies result in optical gaps in the visible or near IR as well as low to moderate glass transition temperatures ($T_g \approx 100\sim 400^\circ\text{C}$).

A picture of how the properties of ChGs depend on composition is emerging from the literatures. The previous work has substantially improved understanding of the network topology at least of ternary chalcogenides such as the Ge-As-Se system [169-172]. Thorpe showed the existence of a phase transition from a “floppy (or spongy)” to “rigid” phase at $\text{MCN} \approx 2.4$ whilst Tanaka identified a second transition from “rigid” to “stressed rigid” phase at $\text{MCN} \approx 2.67$ ($\text{MCN} = \text{Mean Coordination Number}$ which equals the sum of the products of valency times atomic abundance of the constituent atoms). Using temperature modulated differential scanning calorimetry, Boolchand [172] claimed a so-called “intermediate” phase existed in Ge-As-Se glasses for MCN in the range 2.28~2.44 and that this corresponded to a self-organizing network characterized by zero non-reversing heat flow which means the glass composition in this phase are configurationally close to their liquid counterparts. Recent studies comparing the properties of Ge-As-Se films with those of bulk glass suggest that for some compositions, films formed by thermal evaporation also self organize such that they form with chemical bonds indistinguishable from those of the bulk glass [173]. This is in fact quite unusual for chalcogenides since creating a film by physical vapor deposition onto a cold substrate is a highly non-equilibrium process which results in the film containing large numbers of defect bonds or molecular clusters. As a

result it is usual for evaporated chalcogenide films to have different physical properties (band-gap, refractive index, density, etc) from the bulk glass. Thus the self-organizing nature of networks is important for film forming and creates films that have been shown to be thermally stable.

For integrated optics and all optical signal processing, chalcogenide glasses offer several important properties: large refractive index, low absorption, photosensitivity, high optical nonlinearity, fast response time, low two photon absorption, wide transparency, low phonon energy, high acousto-optic figure of merit, flexibility of glass composition, etc. For the rest of this section, some of the important characteristics are highlighted.

6.2.1 Linear optical losses

For chalcogenide glasses the long wavelength cut-off lies in the mid infrared due to large atomic masses and relatively weak bond strengths resulting in low phonon energies [174]. Figure 6.1 compares the infrared transmission for several glasses, the last three being chalcogenide glasses [165]. As a rule of thumb, the transparency edge is $12\mu\text{m}$ for sulfide based glasses, $15\mu\text{m}$ for selenide glasses and $20\mu\text{m}$ for telluride glasses [175]. In reality impurities often exist in bulk glasses or films which significantly limit long wavelength transmission. For example “high purity” chemical elements used for glass fabrication often contain significant quantities of C, O and H and these lead to absorption bands between 1.4 and $15\mu\text{m}$ [176]. As a consequence approaches for purifying the starting materials have been developed that can reduce impurity levels to 10^{-5} wt% and this is adequate particularly for waveguide applications where path lengths can be short (10s cm) [177].

Low loss ChG fibres were demonstrated in the early 1980s [178], showing losses down to 35dB/km at $2.44\mu\text{m}$ for $\text{As}_{40}\text{S}_{60}$ unclad fibre. Generally the ChG fibres are obtained by heating preforms fabricated via rod-in-tube type processes or by double crucible processes [178-180]. Depending the glass composition, the sulfide, selenide and telluride based fibres transmit between about $0.8\sim 7\mu\text{m}$, $1\sim 10\mu\text{m}$, and $2\sim 12\mu\text{m}$ respectively. The As-S fibres are the most widely used to-date and losses down to 0.1dB/m is routinely achievable [165].

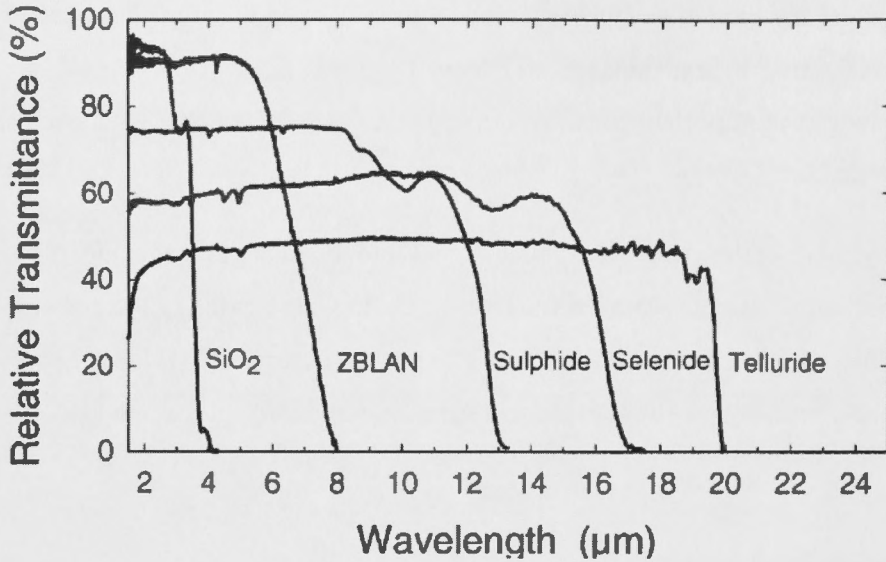


Figure 6.1: Infrared transmission for bulk glass samples [165]

6.2.2 Refractive index and dispersion

The refractive indices for chalcogenide glasses are generally between 2 and 3 [181]. The high refractive index is advantageous for strong optical field confinement and hence small waveguide bend radii and enhanced optical intensities which are critical characteristics for application in integrated optics and efficient nonlinear interactions. In addition, the large index contrast to air provides a complete band-gap for photonic crystals. The zero dispersion wavelengths for ChGs lie well in the mid IR. They exhibit strong normal dispersion at telecommunication wavelengths (1550nm); however waveguide dispersion can be engineered to zero the chromatic dispersion [182]. Figure 6.2 shows the refractive index and dispersion curve for a common chalcogenide glass: As_2S_3 . The refractive index increases as sulfur is replaced by the more polarisable selenium and tellurium.

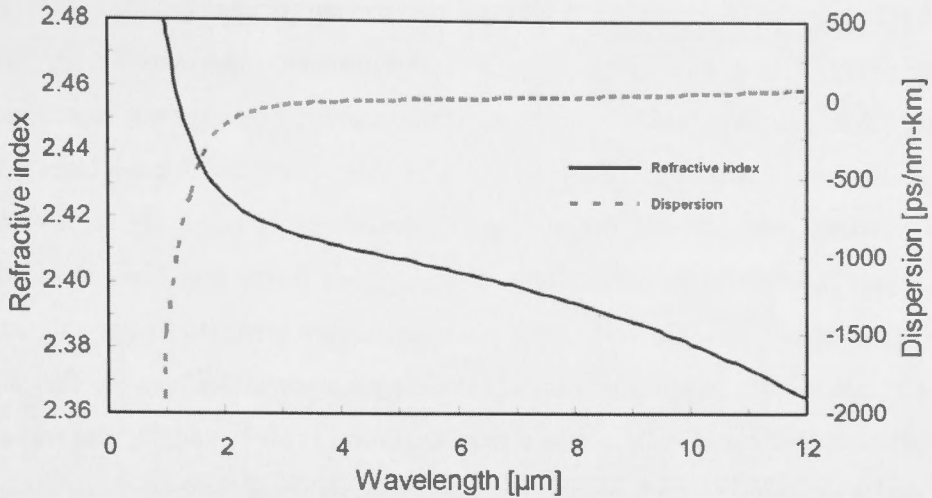


Figure 6.2: Refractive index and Dispersion curve of As_2S_3 [183]

6.2.3 Photosensitivity

One of the most widely studied and technologically important properties of ChGs is their photosensitivity [184, 185]. There are a rich range of phenomena associated with optically-induced changes in ChGs, for example photo-diffusion, photo-fluidity, photo-crystallization and photo-induced birefringence, some of which have also been useful for device fabrication. The “classic” photodarkening and photobleaching effect displayed by ChGs is associated with local changes in the chemical bonds induced by light via the formation of self-trapped excitons which change the valency of neighboring atoms and hence the bonding. When these photo-induced excitons annihilate either the original bonds are restored or, because of the inherent steric flexibility of chalcogenides, different bond configurations are created which can change the macroscopic properties of the glass, such as its band gap or refractive index. The phenomenon of photo-darkening and the associated change in refractive index can be used for direct writing of waveguides and Bragg gratings into chalcogenide films. It is worth noting that bond switching can also be induced by energy in the form of x-rays, electron or ion beams or heat and leading to applications as x-ray or electron beam resists [186].

Based on the photosensitive characteristics, gratings embedded in chalcogenide glass waveguides were first demonstrated by Tanaka et al. using a Hill grating geometry [187];

followed by using the side-writing technique to pattern Bragg gratings into planar waveguides [188]. Using a modified Sagnac interferometer, apodised Bragg gratings written into As_2S_3 rib waveguides have been demonstrated showing 5nm rejection band and up to 30dB transmission rejection [189]. Whilst these phenomena have been a fertile ground for research over several decades, photo-sensitivity is generally undesirable in optical waveguides, e.g. the photosensitivity at 1550nm of As_2S_3 thin films induced self-written waveguides in slabs. However such photosensitivity seems to occur only in thin-film form and not in bulk samples or fibres [190]. Its presence underlines the fact that the glass network is unstable, not bulk-like, and may therefore, evolve changing the waveguide properties under exposure to high optical fluences, such as those necessary for all-optical signal processing. In this context it is worth noting that a photo-stable glass in the Ge-As-Se system has been reported which indicates that this is indeed a valid question [191]. Also decades of work exploring the “annealing” of the As_2S_3 thin films (the workhorse glass for nonlinear optical processing) to make them have the properties of the bulk have yet to find a means of doing so and a photosensitivity threshold of a few GW/cm^2 at 1550nm is commonly encountered.

6.2.4 Optical nonlinearity

Another important property of chalcogenide glasses is their large third order nonlinearity. Miller’s rule provides a simple method to estimate the third order nonlinearity. The equation is given by Vogel *et al* [192]:

$$\chi^{(3)} \approx [\chi^{(1)}]^4 10^{-10} (\text{esu}) \quad (6.1)$$

From the large linear refractive indices for the chalcogenide glasses (2 to >3), the nonlinear coefficients can be predicted approximately two orders of magnitude larger than fused silica. Other semi-empirical models given by [181, 192] also show a similar correlation between refractive index and nonlinearity. Figure 6.3 shows a plot of the relationships between linear refractive index and third order optical susceptibilities for various glasses [193].

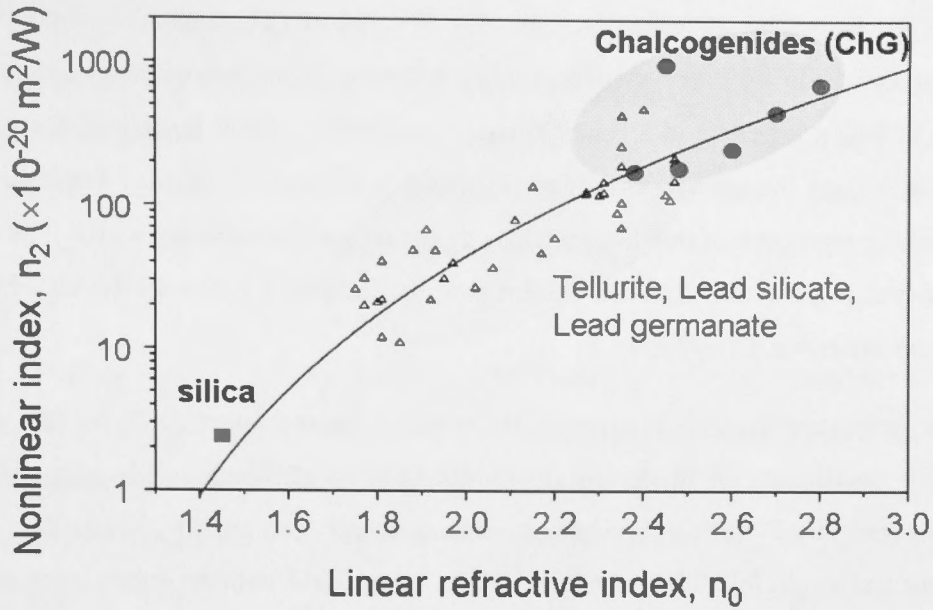


Figure 6.3: Relationship between linear refractive index and third order optical susceptibilities [193]

The Kerr nonlinearity of bulk glasses is commonly measured by Z-Scan technique developed by Shiek Bahae *et al* in 1990 [194]. This technique is particularly useful when the nonlinear refraction is coupled with optical absorption. Alternatively the nonlinearity of waveguides can be measured based on optical nonlinear effects, such as self phase modulation and four wave mixing [195]. The measured nonlinear index of refraction of various compositions of chalcogenide glasses was published by various authors in the past and nonlinear refractive indices for As_2S_3 and As_2Se_3 are 2.92×10^{-18} and $1.2 \times 10^{-17} \text{ m}^2/\text{W}$, which are approximately 130 and 540 times of silica value ($2.2 \times 10^{-20} \text{ m}^2/\text{W}$) respectively [196, 197].

Most of the Kerr nonlinear effect in ChGs is associated with ultra-fast electronic processes with time scales on the order of 50fs [198]. Measurements have shown that the nuclear contribution to the nonlinear effect for Sulfide based glasses is between 12~13% [181]. The measured nuclear time scale, for selenide glasses, is on the order of 500fs. As the nuclear contribution ratio is similar to that of silica, the Raman gain coefficient is also several orders of magnitude larger than silica [195].

Multi-photon absorption is a nonlinear process that occurs at harmonics of the electronic band absorption frequency causing two or more photons to be simultaneously

absorbed. The lowest order effect, two-photon absorption (TPA), is described by the imaginary part of the third order susceptibility resulting in an intensity dependent loss. Generally TPA is a nuisance in all optical signal processing which leads to a decrease in transmission and an increase in switching threshold [199] and which may fundamentally prevent realistic operation of the device. ChGs generally have a band gap which falls in the visible spectral region; they tend to exhibit low (occasionally moderate levels) TPA at telecommunication wavelengths.

Another important measure is given by the material figure of merit, $FOM=n_2/\beta\lambda$, where β is the TPA coefficient, parameterizes the nonlinear phase shift achievable over one TPA length. Devices used for all optical processing ideally require $FOM>1$. The large nonlinearity and negligible TPA of ChGs lead to large FOM with no free carrier effects, making them an ideal platform for signal processing at ultrahigh bit rates.

6.2.5 Chalcogenide glasses for all optical processing

Large refractive indices, a high nonlinearity and moderate to low two-photon absorption make ChGs ideal for demonstrating integrated devices for all-optical signal processing. The first report of nonlinear ChG devices were given by Asobe *et al* in 1992 [200] and used a loop mirror based on an As_2S_3 fibre for all optical switching. Lenz *et al* demonstrated strong Kerr nonlinearity in Se-based ChGs [197]; Spalter *et al* [201] showed strong self-phase modulation in single mode ChG planar waveguides; Thielen *et al* [202] demonstrated 20dB of Raman gain in a 1.1m long As-Se fibre and Slusher *et al* [198] measured Kerr nonlinearities nearly 1000 times higher than silica fibres and Raman gains nearly 800 times that of silica. Recently, following the development of nanowires engineered to have anomalous dispersion, ChG waveguides have proven themselves to be efficient broadband generators of super-continuum light [203]. The broad infrared transparency of chalcogenides should also allow the super-continuum to be extended well into the mid-infrared, and this is now the subject of active research [168].

An interesting application of chalcogenide glass in all optical signal processing is for signal regeneration. A demonstration given by [204] showed the use of As_2Se_3 fibre for all optical signal regeneration based on SPM followed by spectral filtering. Apart from optical

regeneration, the strong normal dispersion of chalcogenide glass combined with the high optical nonlinearity can also be applied in compact low power optical pulse compression schemes. In this regime, the high optical nonlinearity and dispersive properties are used to generate a SPM broadened pulse with a linear frequency chirp at low peak powers. The chirped pulses can then be efficiently compressed using a precisely tailored fibre Bragg grating [205].

The SPM regenerator concept can easily be extended to other important all optical functions such as wavelength conversion. In this regime, sideband wavelengths can be generated based on XPM or FWM. A recent demonstration shows the use of a 7cm long As_2S_3 dispersion engineered waveguide for signal demultiplexing in the Tera-bit per second regime [206].

6.3 Chalcogenide glass thin film preparation

The production and patterning of thin films on metals, semiconductors and dielectrics are major preoccupations of the high-tech industry with a huge range of applications particularly in microelectronics and optics. To unleash the potential of chalcogenide planar waveguide devices, the primary step is to develop techniques for thin film deposition. In this section, first we briefly review the common techniques developed for ChG thin film deposition; then in section 2 we describe the method employed in this thesis for creating ChG films via thermal evaporation. In section 3, the annealing properties of as-deposited As_2S_3 films are analyzed and a novel technique is present to create bulk-like films.

6.3.1 Common film deposition methods

There are quite a few well-established processes for thin film deposition, including chemical vapor deposition (CVD), thermal evaporation, electron-beam evaporation, sputtering and Pulsed Laser Deposition (PLD). Depending on the particular preparation method, the deposited film can have dramatically different structure and properties compared to the bulk glass. The particular choice of technique depends on the materials to be deposited and the quality of the film that is required. Films deposited for waveguide applications pose a big challenge since they need to have the same composition and optical

properties as the bulk glasses, have good surface quality and be free from particulates and defects so as to minimize losses.

Recently Plasma Enhanced Chemical Vapor Deposition (PECVD) techniques similar to those widely used for silicon-based film deposition have been used to prepare chalcogenide films [207, 208]. Compared to films deposited by thermal evaporation, the As-S films deposited by PECVD had bonding closer to that expected for the As_2S_3 structure. By carefully controlling the volume ratio of precursor gases, the PECVD deposited As_2S_3 had fewer As_4S_4 molecular clusters and higher density leading to a larger refractive index compared fresh thermally evaporated films. However, PECVD-deposited chalcogenide films were proved to be more absorbing than their thermally evaporated counterparts. Furthermore, gas-phase chemistry is necessary for PECVD, limiting the range of materials that can be produced.

Pulsed Laser Deposition (PLD) is a relatively quick, simple and highly versatile technique for depositing thin films of a wide variety of materials. Interest in the technique has experienced an explosive growth since it was firstly used to deposit thin films of high- T_c superconductors in 1987 [209]. A team at the University of Southampton was the first to use PLD to deposit chalcogenide Ga-La-S films, although the stoichiometry was slightly sulphur deficient compared to the expected composition [210]. A well-known advantage of the PLD technique is that it should accurately transfer the stoichiometry of a multi-component target to a film deposited on a substrate. This is particularly important in materials containing weakly bonded volatile components such as sulphur, where thermal evaporation often results in marked changes in stoichiometry [211]. Whilst there has been an increasing interest in investigating other chalcogenide films deposited by PLD such as glasses from the As-S-Se system and Ge-As-Se system, relatively little work has been carried out under optimized conditions (namely the Ultra-fast PLD technique ideally operated in the single pulse ablation regime with above bang gap light).

Sputtering is also a commonly used technique for ChG film deposition. With the use of rapid thermal annealing on sputtered $\text{Ge}_{10}\text{As}_{40}\text{S}_{25}\text{Se}_{25}$ films, it was possible to attain low loss photoinduced channel waveguides ($<0.3\text{dB/cm}$) [212]. Tan *et al* reported the

fabrication of As_2S_3 films through magnetron sputtering and a measured propagation loss of 0.2dB/cm on as-deposited As_2S_3 waveguides on Ti:LiNbO_3 at $1.5\mu\text{m}$ [213].

The method of hot dip-spin coating was first applied to fluoride glasses as a means of obtaining waveguiding films [214]. Recently, it was demonstrated that thick chalcogenide films could be deposited by spin coating of molten chalcogenide glass [215]; however film uniformity and coating thin films remains as an ongoing challenge. One great advantage of this approach, despite its real world complexity, is that by definition it results in a bulk like glass film.

The simplest and most commonly used method for fabricating thin ChG films is by thermal evaporation due to the relatively low cost and ease of processing (low melting temperatures). For multi-component systems, like ChGs, the differing evaporation rates of each elements result in a change in the film stoichiometry poorly matched to the bulk material [216]. However, a recent study showed that the composition of thermally evaporated AMTIR-1 ($\text{Ge}_{33}\text{As}_{12}\text{Se}_{55}$) films was closely reverted to the bulk material and the films showed no significant differences in the optical properties [217].

6.3.2 Thermal evaporation of chalcogenide thin films

In this thesis, the thermal evaporation technique is adapted for the fabrication of chalcogenide glass films. Two types of chalcogenide glass are investigated in this Chapter: $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ and As_2S_3 . The former was investigated due to its very low glass transition temperature ($\sim 115^\circ\text{C}$) which made it a good candidate for easy initial experiments on hot embossing. The bulk $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ was prepared by combining these three elements in an ampoule and then mixing in a rocking furnace. Bulk As_2S_3 was commercially sourced from Amorphous Materials Garland, Texas, USA. Small pellets of the bulk glass were placed in a baffled Molybdenum boat in a vacuum chamber pumped to a base pressure of 2×10^{-7} Torr. The substrates used were 100mm diameter $1.5\mu\text{m}$ silica (SiO_2) on silicon wafers and these were rotated in planetary motion above the source using a carousel. The substrates were unheated prior to deposition but were irradiated with a beam from an ion gun (Ar^+ , 50eV) immediately prior to deposition to improve adhesion of the chalcogenide material to the substrate. The film thickness and deposition rate were measured in situ by a

crystal monitor (INFICON quartz crystal) placed close to the substrate. The film thickness was controlled through a manual shutter (start/stop) and boat temperature (deposition rate). The evaporation temperature was approximately 10°C above the glass melting temperature as measured using a thermal couple in contact with the boat. The evaporation rate was highly dependent on the process temperature, and for this work, As_2S_3 was evaporated at 315°C and this corresponded to a deposition rate of 0.1~0.3nm/s for a source to substrate distance of ~40cm which was known to result in stoichiometric As_2S_3 films from prior work.

6.3.3 Evaporated thin film versus Bulk

It is well known that thermally evaporated chalcogenide films usually have substantially different properties from the original glass. These differences can include changes in stoichiometry due to preferential evaporation of more volatile phases; substantially different bond structures due to the highly non-equilibrium nature of the film forming process; and the appearance of particulates, most likely due to condensation of sub-phases in the vapor plume or ejection of particles from the source. These physical differences lead to changes in important optical parameters such as refractive index, band-gap, absorption, etc. For instance freshly evaporated amorphous films of the As-S system contain some As_4S_4 and other fragments which were formed during the evaporation of As_2S_3 , due to dissociation [218, 219]. Illumination with light around the band gap energies and thermal annealing are known to decrease the content of the As_4S_4 molecules and S-S bonds, and therefore increase refractive index and reduce band-gap energies of As-S. Such effects are shown in the measured Raman spectrum with comparison of as-deposited with light annealed As_2S_3 films (plotted in Figure 6.4). AMTIR-1 films have also been deposited using thermal evaporation; however these films are usually non-stoichiometric and crack upon processing. They are also highly photosensitive and have a relatively low damage threshold [217].

A recent publication has shown that thermal annealing of As_2S_3 fresh deposited film can not only stabilize the physical properties, but also reduce the sources of light attenuation [220]. Without heat treatment, As-As or S-S containing phases dispersed in the

backbone network can cause enhanced Rayleigh scattering and elevated levels of absorption due to the presence of exponential absorption tails extending from the band edge. Annealing also allows the film to have consistent optical properties (refractive index, optical band-gap, absorption, etc) and thus improves device stability. Improved resistance to photo-oxidation ($\text{As}_2\text{S}_3 + \text{O}_2 \rightarrow \text{As}_2\text{O}_3 + \text{S}_2$) of the film is another benefit of thermal treatment. The refractive index of the film rises with annealing due to thermal densification and increased hetero-polar bond density. The surface roughness and thermal stress of the film, however, limits the applicable annealing temperature to $\sim 130^\circ\text{C}$. A lot of literature (e.g. [220]) has dealt with the effect of thermal annealing on as-deposited As_2S_3 films and concluded that it can accelerate the relaxation of a film into its equilibrium state and, thus, phase separation can be reduced.

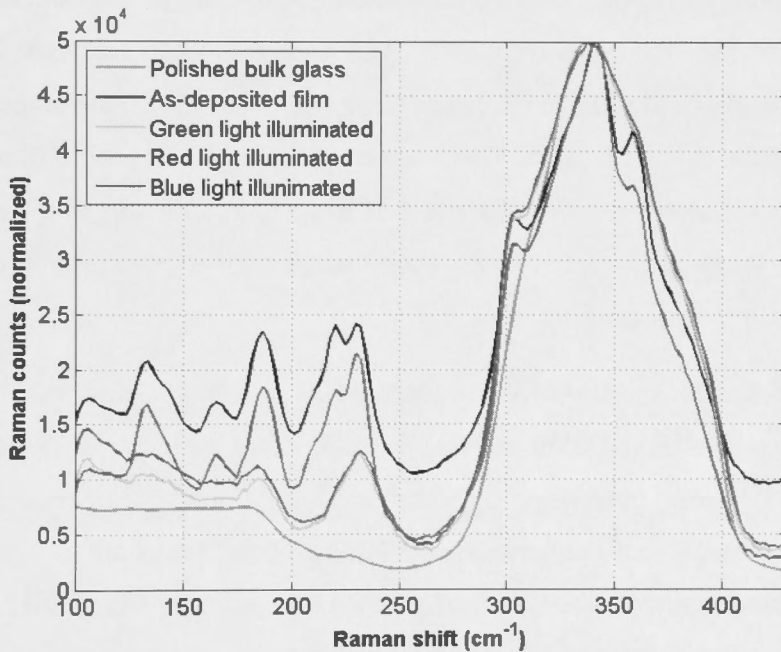


Figure 6.4: Raman spectra of comparison for bulk As_2S_3 compared to as-deposited film and light illuminated films using green, red and blue light

6.3.3.1 High Temperature annealing of As_2S_3

Clearly it is possible to bring the as-deposited As_2S_3 thin films to a more stable state via thermal annealing, however a question remained regarding whether annealing the sample

at very high temperature (beyond the glass melting temperature) would further improve matters and results in a bulk-like film. The technical challenge to realize this experiment was the loss of material due to evaporation at such high temperature. In this section, we describe a technique implemented to realize high temperature annealing.

Film annealing at high temperatures were conducted in a furnace and the furnace tube was purged with argon flow to avoid oxygen contamination. To retain the melted glass, we used two CaF_2 substrates with a diameter of 15mm; one substrate was coated with As_2S_3 film and the other one was deposited with 20 μm thick SiO_2 ring structure via PECVD on the edge (shown in Figure 6.5(a)). The two substrates were then brought into contact with a weight on top for applying pressure and then loaded into the furnace tube (shown in Figure 6.5(b)). The two CaF_2 substrates with the Silica ring form a sealed chamber for maintaining the As_2S_3 partial pressure. Three annealing temperatures were attempted: 280, 350 and 450°C for approximately 30 minutes and then the substrates were left in the furnace tube to cool down to room temperature. With 280°C annealing, the process showed no sign of film evaporation and a clean film was obtained; at 350°C, yellow film started to deposit on the surface of the furnace tube which is a signature of sulfur evaporation. This process became a lot more violent at 450°C such that all the film was evaporated despite the effort to maintain partial pressure.

The measured Raman spectrum for the annealed As_2S_3 films is shown in Figure 6.6. Considering the spectra of the films versus the bulk, there are clear differences in the 222/232 cm^{-1} and 190 cm^{-1} regions, and in the case of the lower temperature annealed samples, also the 130~140 cm^{-1} regions. The 190/222/232 cm^{-1} peaks are all considered to be markers for the concentration of Realgar (As_4S_4) type clusters where it is the As-As bond that is giving rise to the resonance. The 130/140 cm^{-1} complex is less certain in its origin. The As_6S_9 cluster found to be stable as an entity has resonances in this region, as does Orpiment (crystalline As_2S_3) [221]. Examining the film spectra, it can be seen that the 140/150 and 190 cm^{-1} complexes decrease in size up to 280°C, and then starts to increase slightly again (perhaps due to the observed evaporation of sulfur rich material). The behavior of the 222/232 cm^{-1} peak complex is less clear, perhaps obtaining the lowest values at 180°C before changing shape at higher temperatures. Of all the spectra, the one at

280°C seems to be closest in resemblance to the bulk, though as noted the evaporation of material in the 350°C sample may have distorted its spectrum. However, even the 280°C spectrum is still some way away from the almost indiscernible $<200\text{cm}^{-1}$ features of the bulk and in the height of the $222/232\text{cm}^{-1}$ complex. Despite the assertion that higher temperatures should take the material ever closer to the bulk [222], here even melting it has not delivered this. This may be due to the discovery that even liquid As_2S_3 is a molecular liquid until $\sim 650^\circ\text{C}$ [223] where it switches to a liquid of radical species. There is also evidence that the best structure in As_2S_3 glasses (i.e. lowest 232cm^{-1} peak and least homopolar bonds) is obtained when the quenching temperature is below 780°C [224]. So it may be concluded that to remove the homopolar bonds requires annealing above 650°C but below 780°C . Annealing at such a temperature would be tremendously difficult as it would require a large overpressure of an inert gas to prevent the liquid boiling [225].

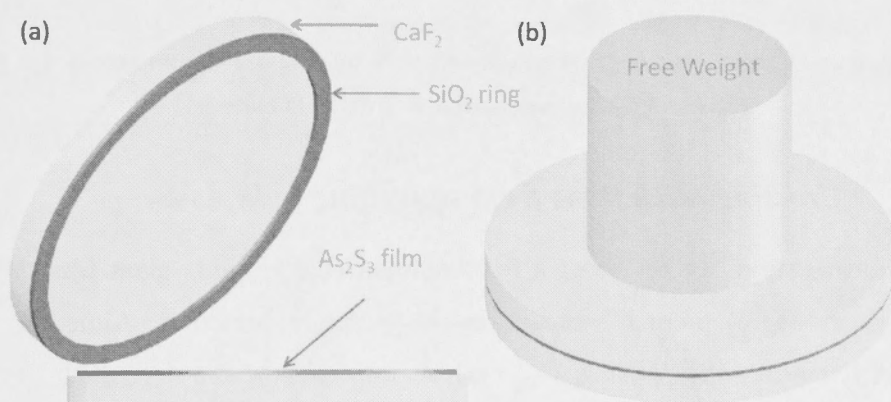


Figure 6.5: As_2S_3 film high temperature annealing process demonstration. (a) Substrates before contact (b) Substrates after contact

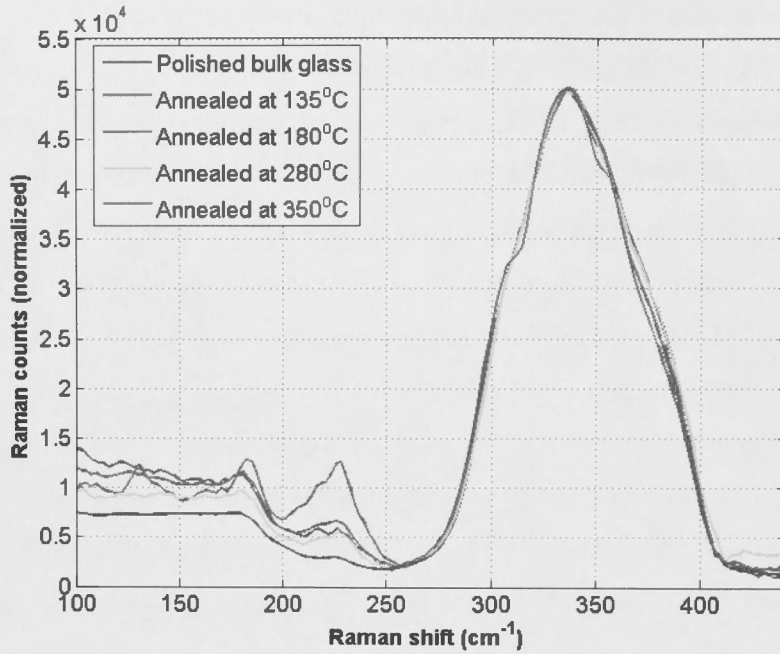


Figure 6.6: Raman spectra measured from evaporated As_2S_3 thick films ($\sim 10\mu\text{m}$) annealed at 135, 180, 280 and 350°C in comparison with the bulk material

6.3.3.2 *Creating thick films from squashing bulk As_2S_3*

In the previous section, we reviewed a few common chalcogenide glass film deposition methods; among them, thermal evaporation is generally preferred. Although thermal annealing can improve the physical and optical properties of the deposited As_2S_3 film, fabricated thin film waveguides still suffer photosensitive effects at high power densities which is not present in the bulk material. Raman spectroscopy shows differences from the bulk glass indicating that the film is still not in a bulk-like state even after high temperature annealing and melting of the glass.

In this section, a new approach was developed for thick As_2S_3 film formation. A home built apparatus as shown in Figure 6.7 was used for the fabrication. Initially a small piece (a few milligrams) of bulk material was placed between the polished Sapphire substrate and glassy carbon plate with no pressure; then the rig was heated to 250°C to soften the glass. After the temperature stabilized at 250°C , pressure was applied by hanging a free weight on top of the glassy carbon plate to squash the glass into a film. Finally the As_2S_3

film deposited on Sapphire substrate was removed after slowly cooling down the system to room temperature. The pressing procedure was performed under an inert nitrogen atmosphere to prevent contamination of the bulk glass. The squashed film thickness was in the order of a few tens of microns and could be varied by changing the squashing temperature and pressure. At 250°C and 500g weight, 40μm As_2S_3 film was deposited on the sapphire substrate.

It is obvious from the measured Raman spectrum in Figure 6.8 that the squashed bulk glass film has very similar properties compared to the bulk glass, as would be hoped for. For the first time, a bulk-like As_2S_3 film was created by squashing bulk glass into a film at high temperature. The film produced via the method used here is small in area, non-uniform and relatively thick which is not applicable for integrated optics. However using tools such as a precision hot embosser/wafer bonder, and an optimized process using a bowed substrate and a stamp with built in spacers should be capable of producing uniform controlled thickness films of the required dimensions. Time and equipment was however not available to explore this route.

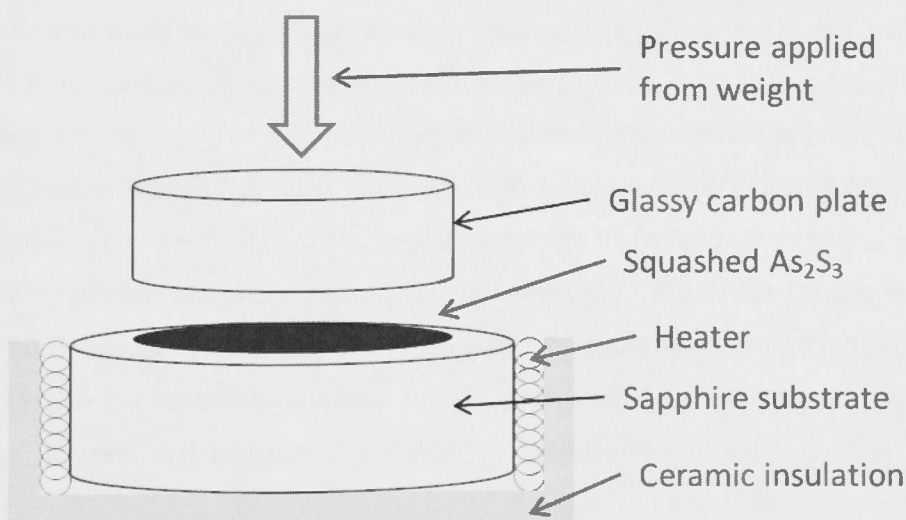


Figure 6.7: Experimental setup for squashing As_2S_3 thick film

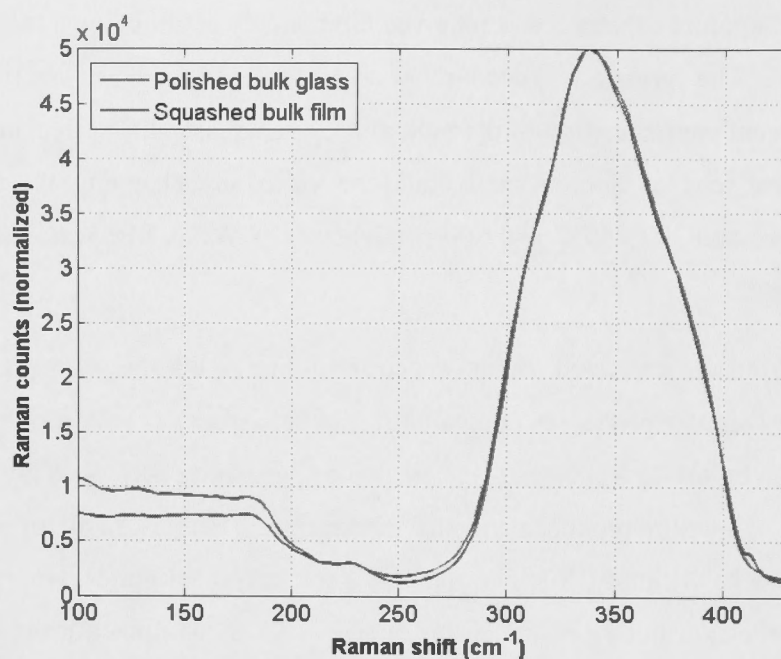


Figure 6.8: Raman spectrum of As_2S_3 film created from squashing bulk glass compared to polished bulk glass

6.4 Conclusion

In this chapter, the properties and applications of chalcogenide glasses are reviewed. ChGs have found widespread application in phase change materials for optical data storage media (DVDs) and non-volatile random access memories (PRAM), as lens materials for thermal infrared imaging, as photovoltaic cells. They are also good candidate materials for mid infrared sensing and ultrafast all optical signal processing. However on the other hand, chalcogenide glasses also suffer from some potential issues relating to stability and aging. It is mechanically weaker than silica based glasses. The optical damage mechanisms in thin film waveguide are still not well understood. These issues, however are not present in the bulk glass, and therefore the fabrication of bulk-like thin films has been an actively researched topic over the last a few decades.

Thermal annealing indeed improves the glass properties compared to the as-evaporated films. This improvement saturates between 135 and 180°C, and higher annealing temperature (even beyond the glass melting temperature) does not seem to deliver a better

result. The squashing of bulk As_2S_3 glass into a thick film at high temperature was pioneered to deliver bulk-like films. More efforts are required to engineer this process to produce uniform thin films for the application in integrated optical devices.

Chapter 7

Hot Embossing Chalcogenide Glass

Waveguides

7.1 Chalcogenide glass waveguide fabrication approaches

The first reports of waveguides made from chalcogenide glasses (ChGs) appeared in the 1970s from researchers in Russia [226] and Japan [227, 228]. Ohmachi demonstrated the acousto-optic effect in 1-D slab waveguides made from As_2S_3 deposited on a Lithium Niobate crystal. Towards the end of the 1970s photo-darkening was applied to make 3-D waveguides (2-D waveguides with bends) in As-S-Se-Ge glasses [228]. By irradiating the films with a focused Ar ion laser operating at 514nm, photo-induced index changes as high as 0.03 were achieved at 1064nm and the lowest losses were reported to be 0.4dB/cm at 1064nm.

Following these initial reports, there was little progress in the field until the late 1990s when new research on waveguide fabrication appeared. Meneghini *et al* [229] reported the use of ion implantation both for waveguide writing and also to achieve doping of the chalcogenide waveguide with Nd ions. Photo-darkening using light at the band edge was again applied to write waveguides in films of As-S(-Se) [230], Ga-La-S [231] and AsSeTe/AsSe [232] whilst Efimov *et al* [233] showed that femto second pulses at 850nm, well away from the band edge were equally effective. Photo-darkening was also shown to be a useful route for fabricating Bragg gratings into planar ChG films [234]. Waveguide gratings were first produced reported with a reflectivity of 86% at 1550nm in As-S-Se/As-S channel waveguides by exposure to near bandgap light at 514nm [235]. More recently ultra-strong apodized gratings with in-band rejection of >27dB (measurement limited) with low chirp and low side-lobe levels were written into As_2S_3 rib waveguides [236] and

used for experiments on all-optical regeneration [237]. Similarly high performance sampled gratings have also been demonstrated [238, 239].

In-diffusion of silver into ChG films can be used for waveguide fabrication due to the increase in the refractive index associated with silver doping. Fick *et al* [240] reported the use of a thermal process to in-diffuse a pre-patterned silver layer into a 500nm thick As_2S_3 film to produce a channel waveguides. Photo-diffusion has also been applied to produce waveguides in As_2Se_3 [241, 242] and GeS_2 [243]. The high index contrast (0.3~0.4) available by this method makes the production of compact waveguides feasible, however the reported losses were generally beyond 1dB/cm, and continued light exposure also leads to further diffusion of the silver.

Whilst photo-darkening or silver in-diffusion are relatively simple processes for locally changing the refractive index of ChG thin films, they are not necessarily desirable methods for producing waveguides which must be stable when exposed to high intensity light or operate at elevated temperatures. Further, in some applications small mode areas and zero dispersion is required which cannot be achieved with the low index contrasts available from these methods [203]. As a result it is preferable to create waveguides by physically structuring chalcogenide films for technologically-important applications such as sensing, all-optical processing and mid-IR science.

In 1999 Viens *et al* [244] reported the use of wet chemical etching to create structured waveguides in As-S(-Se) glasses. This appears to be the first attempt to use a photolithographic process although in this case the use of an NH_4OH -based developer resulted in isotropic etching and relative poor waveguide profiles with appreciable sidewall roughness. Nevertheless, losses around 1dB/cm at 1300nm were reported for 5 μm wide waveguides made from 1.25 μm thick $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ films etched to create a 0.4 μm high rib and over-coated with an As_2S_3 cladding.

Subsequently two methods have become popular: lift-off techniques and those based on dry (plasma) etching. A problem, illustrated by the wet etching approach described above, is that many chalcogenides are very soluble in alkaline photoresist developers. As a

consequence care must be taken to prevent chemical attack of the ChG films that results in roughening of the film surfaces and enhanced optical losses.

The lift-off techniques circumvent this problem and involve the deposition of the ChG film onto a pre-patterned resist [245]. However side-wall roughness remains an issue and both graded index coatings and reflow methods have been used to reduce the waveguide losses [246, 247]. Typically it is possible to reduce losses by around a factor of two using either of these methods, for example, the losses in $800\text{nm} \times 400\text{nm}$ As_2S_3 nanowires were reduced from $\approx 6\text{dB/cm}$ to $\approx 3.2\text{dB/cm}$ at 1550nm by the reflow approach. Waveguides and ring resonators produced using the lift-off method has been successfully used as platforms for optical sensing [248, 249].

For dry etched waveguides there were two fundamental problems that had to be solved. Firstly a suitable dry etch chemistry had to be found that offered high anisotropy, good selectivity to the mask, and that etched smoothly. Secondly, to use dry-etching thin protective coatings must be applied to the ChG film beneath the photo-resist to protect the surface of the ChG film from chemical attack by the photo-resist developer. Both CF_4/O_2 and CHF_3 provide good anisotropy during dry etching resulting in near vertical waveguide sidewalls. However, the CF_4/O_2 route has much lower selectivity to photoresist and also results in rougher etched surfaces. This latter effect arises from the fact that most ChG films deposited by thermal evaporation or pulsed laser deposition are composed of molecular clusters of different phases which may etch at different rates resulting in the production of a roughened, grainy etched surface [250]. Whilst this could be reduced by thermal annealing of the films prior to etching which reduces phase separation in the films, careful choice of plasma chemistry and process conditions with CHF_3 as an etch gas can almost completely eliminate phase decoration [251, 252].

As to the protective coating, then it must meet several requirements for the fabrication of rib waveguides, namely:

- Reasonable etch resistance to the chalcogenide etch
- Good dry etch selectivity to the chalcogenide, i.e. it can be etched without etching the ChG (especially important for rib waveguides)

- Either highly transparent at all wavelengths of interest, or removable without damaging the chalcogenide

Requirement 1 is relatively easy to attain. Requirement 2 is problematic due to the fact that chalcogenides such as As_2S_3 are either etched or damaged by practically all known gas etch chemistries. Even an Oxygen plasma in its own right destroys As_2S_3 , although some other chalcogenides such as the Ge-As-Se class of materials have proven to be more robust in Oxygen plasmas. Requirement 3 is also hard to meet as few non-chalcogenide materials are transparent across the MIR, and these are often not suitable for protective coats themselves anyway. This leaves the other option as removal, and this too is difficult as most available chemical strippers are based on alkaline materials or Amine type chemistry which can itself dissolve chalcogenides. Dry etching too is difficult for some classes of materials as noted above, and even for the Ge-As-Se glasses a layer of surface oxide is generated which has to be removed for MIR devices. However for non-MIR devices there has been much success with the protective coat/dry etch method.

Madden *et al* [253] attained waveguide losses of 0.05dB/cm at 1550nm in a $4 \times 2.5 \mu\text{m}$ rib waveguides fabricated by dry etching As_2S_3 in CHF_3 gas and using Brewer Science Bottom Anti-Reflective Coating (BARC) as a protective layer. It was found that an optimized Oxygen plasma with just a little CHF_3 and Argon resulted in an etch that would remove BARC relatively quickly with only slow attack of the As_2S_3 and little surface roughening so that the BARC could be etched prior to the patterning of the As_2S_3 itself. The BARC was however highly absorbing at 1550nm and had to be removed, and the only way to do this was to only partially crosslink it by baking it at much lower temperatures than normal such that it could be stripped by prolonged soaking at room temperature in AZ Quikstrip. Whilst this produced outstanding results in the larger core waveguides, it was found that thinning the waveguide to the dimensions required to attain zero dispersion (850nm height) resulted in higher losses than desirable as the Quikstrip did attack the chalcogenide surface a little, and the enhanced electric field at the top surface of the waveguide resulted in more loss for the zero dispersion TM mode.

Substituting a very thin ($\sim 150\text{nm}$) layer of SU-8 for the BARC meant that the protective coat did not have to be removed as it was relatively transparent at 1550nm, and

this resulted in dispersion-engineered rib waveguides $2\mu\text{m}\times 850\text{nm}$ in As_2S_3 with losses as low as 0.2dB/cm in TM mode. These have been successfully used for a wide variety of experiments on nonlinear optics and all-optical signal processing [203, 254, 255]. Dry etching with CF_4/O_2 plasma has also been applied to the production of waveguides for the MIR around $10.6\mu\text{m}$ in $\text{Te}_2\text{As}_3\text{Se}_5$ glass [256].

Despite these successes, the process to produce such waveguide devices is relatively complex, sensitive, and long. Further for MIR applications there will certainly be materials where there are no viable removal options for the established protective coats. Thus a strong motivation existed for a process which was simple, fast, used no aggressive chemicals, and required no protective coat. Thermal nanoimprint (or hot embossing) was one process that offered this possibility but was not yet proven to be capable of low loss small core size devices. Thus application of this technology for ChGs is explored in this chapter and low loss waveguide results are presented.

7.2 Hot Embossing approach

The fabrication of chalcogenide glass waveguides directly from Thermal Nanoimprint Lithography (T-NIL) can potentially offer a lot of advantages over conventional methods. The speed and simplicity of wafer scale direct replication can significantly reduce the cost of production; its high resolution offers an ideal platform for precision optical devices, and the high temperature processing can potentially anneal the chalcogenide glass to a more stable state which may improve the power damage threshold. However in reality, this technique also introduces a few problems. The presence of a residual layer is a well known issue which makes it difficult to accurately control waveguide height and high temperature processes can cause films to crack and crystallize [220, 257]. Further conventional hard stamp methods have size limitations (typically $\sim 25\text{mm}$ square) due to the difficulty of releasing the mould, and stamp damage is a real possibility due to the “hard” contact, and the stamps can be very expensive.

Early in 2003, moulding was applied to the fabrication of bulk ChG optical components for thermal imaging [258]. In 2006, Seddon *et al* [259] produced thin film waveguides using hot embossing approach with a hard stamp; despite film cracking and

crystallization after the process, hot embossing had been proven to be a promising route to fabricate low cost ChG waveguides. Followed by this success, there are several other demonstrations showing the possibility of moulding ChG waveguides [260, 261]. To date the best waveguides produced 2.9dB/cm propagation loss at 1550nm on embossed $\text{As}_{40}\text{Se}_{60}$ sputtered thin film [257]. However, this high propagation loss is far from real world application and all the hard stamp issues remain.

7.2.1 Soft stamp for hot embossing

Commercial hot embossing equipment is generally designed for hard stamps. When embossing over a larger substrate, e.g. wafers, the requirements for the external environment are stringent. Tiny particles trapped in between the stamp and imprint substrate can significantly degrade the quality of the imprint or damage the stamp. Another technical challenge for using hard stamps lies in the difficulty of de-embossing since the both the stamp and substrate are not flexible. Therefore it is crucial for the stamp surface to be anti-adhesive to the embossed substrate. Additionally, the cost of a hard stamp is generally quite high since it is usually created with conventional fabrication techniques, such as photolithography; hence stamp life time (number of imprints) must be considered in practice.

Due to the relative low glass transition temperatures of ChGs, PDMS was considered to be a good candidate material for the embossing stamp which solved the above problems. As mentioned in Chapter 3, the flexible nature of cured PDMS means it can accommodate particles trapped in between the stamp and substrate, and its low interfacial free energy and flexibility means it can easily be released. The fabrication cost for a PDMS stamp is fairly low; the expensive master stamp only needs to be fabricated once and replicas in PDMS can be made cheaply and quickly by simple casting and thermal curing.

The material thermal stability of PDMS is stated in the material datasheet as 200°C [262]. Experimentally, we found PDMS to be stable to at least 300°C with no visible degradation. Should even higher temperatures be necessary, there are Polysiloxane materials which are stable up to ~475°C [263]. One major question surrounding the use of PDMS arises from its soft nature which might limit the resolution and applicable pressure.

These were the issue that had to be investigated to determine if PDMS or a derivative could be rendered suitable for hot embossing.

Initially, the concept of using a soft PDMS stamp for hot embossing was tested with a simple experiment. A piece of bulk $\text{As}_{24}\text{Se}_{36}\text{S}_{36}$ glass was squashed into a film (on top of a Si substrate) using the technique described in Chapter 6 and the final film was measured to be $\sim 50\mu\text{m}$. Then a PDMS stamp patterned with waveguide structures with a height of $3\mu\text{m}$ was brought into contact with the squashed film and then placed on top of a hot plate. A free weight (equivalent pressure of approx. 0.5 psi) was placed on top of the stamp acting as a source of pressure and the hot plate was then heated to 180°C for 20 minutes followed by natural cooling. The pattern was fully transferred onto the glass layer with great fidelity as shown in Figure 7.1.

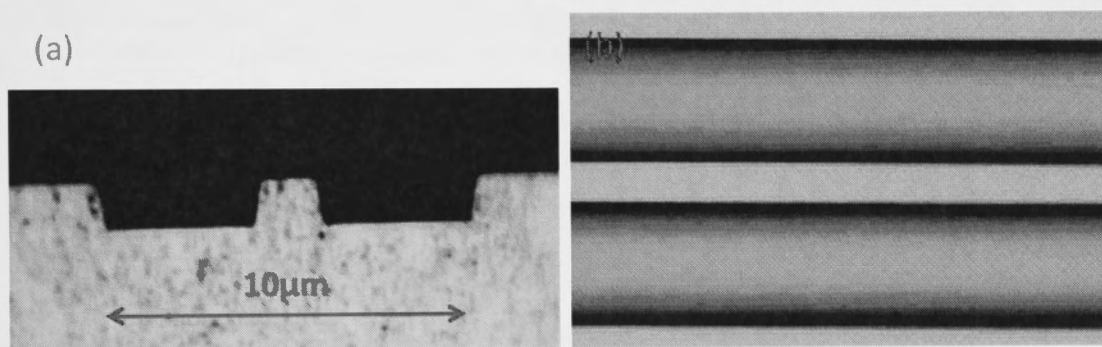


Figure 7.1: Hot embossing performed on squashed bulk As-Se-S glass using PDMS stamp (a) microscope cross section view and (b) microscope 100× top view

7.2.2 Tool design

Following the success in demonstrating that a soft PDMS stamp could be used for hot embossing, the next challenge was to scale up from a small chip to 4 inch wafers. Commercial embossing apparatus is available from several companies, e.g. EV Group, MII, SÜSS and Obducat. The concept of operation basically stems from anodic bonders in semiconductor processing. In a bonding machine, two hard substrates are pressed together without any movement; in an embossing machine, the pressing mechanism has to compensate for the vertical movement of the stamp due to the squeeze flow of the resist. Commercial embossing machines generally use a stiff compression mechanism based on

hydraulic, air, or screw driven hard plates, and the introduction of an elastic compliance layer, (e.g. flexible graphite, rubber or Teflon) in the buildup of the whole stack can compensate the vertical movement of the embossing substrates both globally and locally. Other concepts use an air-pressurized membrane as a soft cushion, which equilibrates local pressure variation due to the sinking of the stamp in a more controlled way. At the beginning of this project, a commercial embossing machine was not available at the ANU and therefore a home-built apparatus was required. It was reasonably trivial to build a hot press tool, but the fundamental challenge was to achieve uniform pressure and temperature over a large surface area (e.g. surface of a 4 inch wafer).

Good temperature uniformity at high temperature can be achieved using highly thermally conductive materials, good distribution of heater elements and good thermal insulation from the environment. Table 7.1 lists the thermal properties of some commonly available and more exotic materials. Pure silver is the most heat conductive metal, but too expensive to make a hot plate with. Pure copper is almost as good as pure silver with a reasonably affordable price. Aluminum has slightly worse performance, but it is rather cheap and easy to machine and suffers also from a relatively low melting/softening temperature. Stainless steel is one of the worst metals in terms of heat conduction and can be used as low thermal leakage structural supporting parts. Therefore, copper was used as the hot plate material and stainless steel was used for the supporting posts separating the hotplate and bottom plate.

Table 7.1: List of thermal conductivity of some metals at 68°F

Metal	Thermal conductivity (Btu/(hr °F ft))
Aluminum	118
Carbon steel (max 0.5%C)	31
Cartridge brass	69.4
Copper	223
Silver	235
Stainless steel	7~26

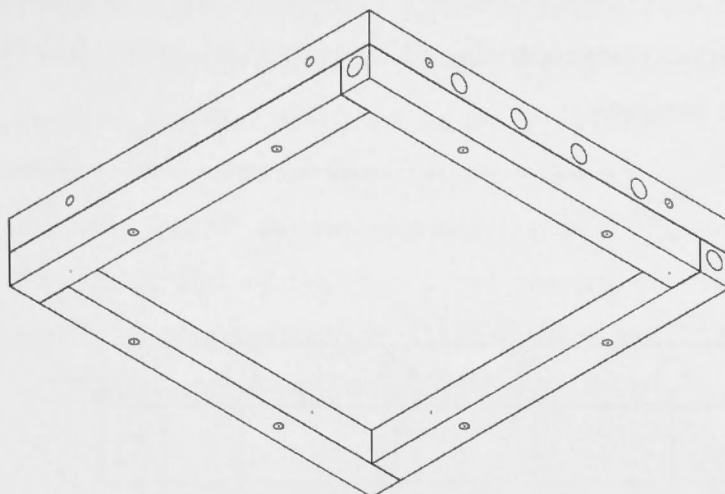


Figure 7.2: Schematic diagram for the hot plate design

Ideally large piece of copper is necessary to achieve high thermal inertia and hence better temperature stability; in practice, this was limited by the stock availability from the manufacturer. The only option available was copper plate with half inch thickness and 6 inch width which limited the design flexibility. The solution implemented was to silver solder several additional small copper plates to a central 150mm square plate with quarter inch holes drilled though to accommodate 8 cartridge heaters as shown in Figure 7.2. Two independent servo temperature controls were used to drive the heaters in the centre of the main plate and the four around the periphery in the added copper plates as shown in Figure 7.3, the objective being to compensate the edge losses from the hotplate. Here the two temperature controllers (Eurotherm 3216) took their inputs from two RTD temperature sensors (PT100) located at the center and the edge of the hot plate; the current signal from the two temperature controllers were then used to drive the two thyristors (Eurotherm TE10A) respectively. Four regulated AC power outputs from one thyristor were used to power the cartridge heaters embedded at the center of the hotplate; and similarly four outputs from the other thyristor were used to drive those heaters on the edge.

There are two major advantages in this design. Firstly introducing dual loop temperature control on the center and edge independently improved the temperature uniformity across the entire surface. Conventionally the edge on a hot plate losses heat faster than the centre; conventional single loop designs experience difficulties in keeping

the centre and edge at the same temperature. Furthermore, the large concentration of high power ($8 \times 2\text{kW}$) cartridge heaters driving a reasonably small copper block ($\sim 1\text{kg}$) makes it possible to achieve fast heating.

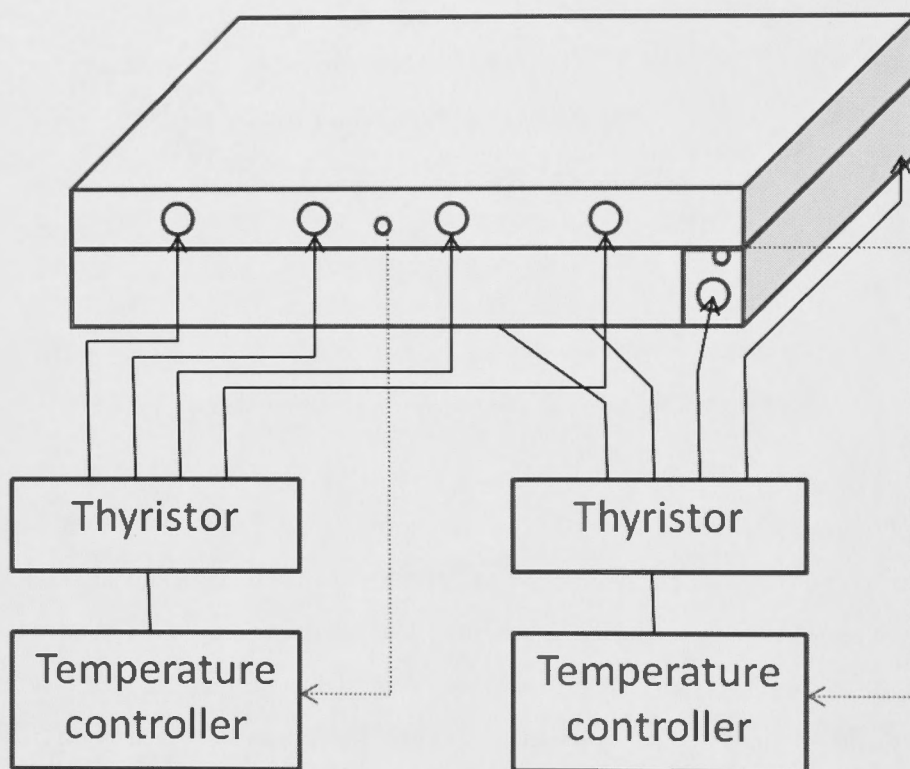


Figure 7.3: Temperature control diagram

Two concentric grooves with diameters slightly greater than 100mm were cut on the top surface of the hotplate and connected to two copper tubes respectively for the choice of supplying vacuum and nitrogen. A heat exchanging coil wound from quarter inch copper tube was silver soldered at the bottom of the hotplate to enable fast cooling by purging cold fluid or air through the tube. 3mm thick silicone rubber sheets were used to insulate the edges and other exposed surfaces of the hot assembly.

7.2.3 Tool operation

Figure 7.3 shows the cross sectional view of the pneumatic pressure control diagram for the embossing apparatus. An elastic silicone rubber membrane with a thickness of 1mm was placed between the hot plate and an aluminum cylinder to create two sealed chambers;

the silicone sheet had considerable elasticity and would deform if a pressure difference existed between the two divided chambers. By pressurizing the upper chamber with compressed air, the sheet would deform to deliver uniform pressure as required for the embossing experiment. The top chamber was externally connected to a pneumatic switch which could be manually toggled between vacuum pump and compressed air; soldered copper tubes on the hotplate were used to connect the bottom chamber to another vacuum pump and a pressure regulated nitrogen supply. The heat exchange stage was implemented by purging cold air through the wound copper tube soldered at the bottom of the hotplate.

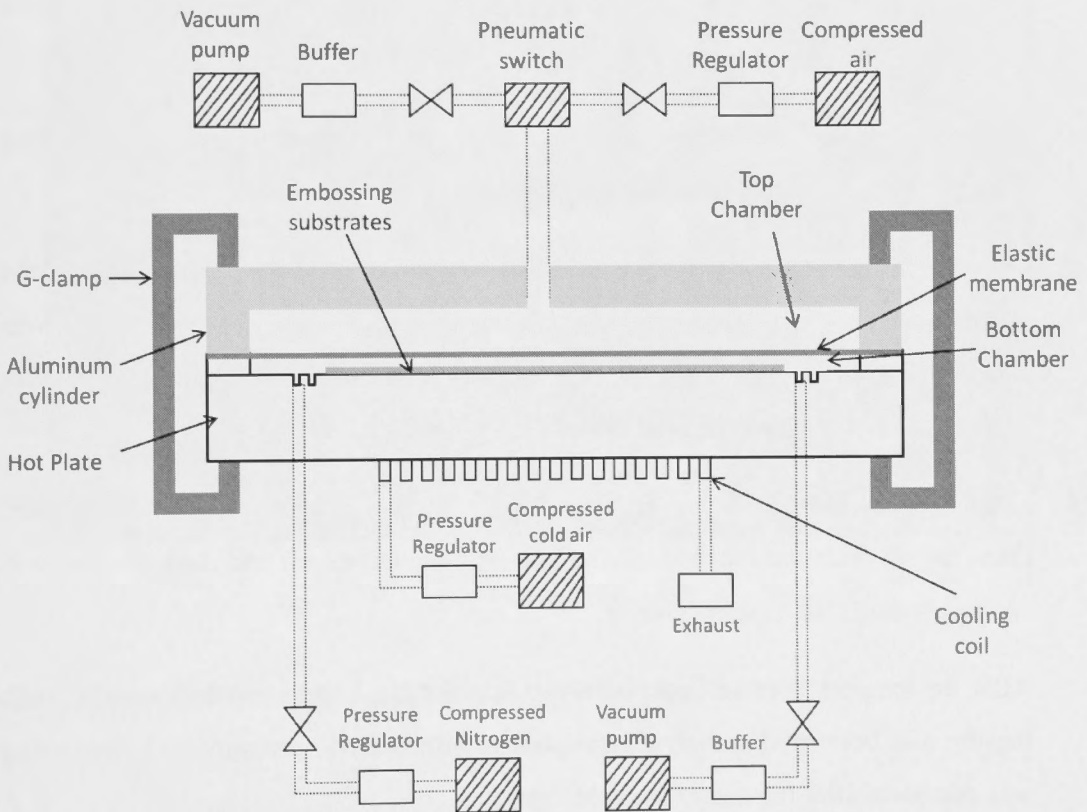


Figure 7.4: Pneumatic control diagram of the embossing configuration

The operation protocol for a typical 4 inch wafer embossing experiment was as follows:

1. The stamp and substrate wafer were brought into contact in a clean room environment. In practice, the rig built for UV-NIL (discussed in Chapter 3) was

used here to align the PDMS stamp and the wafer; a bowing surface from the stamp helped to minimize the air trapped between the two surfaces.

2. The contacted substrates were then loaded on the hotplate and the embossing chamber was then sealed using 4 G-clamps with the silicone rubber sheet in between the aluminum cylinder and the hot plate.
3. The two chambers were then evacuated simultaneously for removing the trapped air between the stamp and substrate while maintain the membrane unbent. In practice, due to the conformal characteristics of PDMS stamp, it was helpful to vary the top chamber pressure a few times (i.e., pump - purge – pump - purge...) such that the flexing of the silicon sheet squeezed out the remaining air trapped between the stamp and substrate.
4. The temperature controllers were then set to a predetermined embossing temperature to heat up the hot plate while keeping both chambers evacuated.
5. Once the temperature was stabilized at the set point, the top chamber was vented and manually switched to the regulated compressed air source. 1bar pressure was considered to be enough for most experiments, meaning that total applied pressure was ~2bar on the embossing substrates.
6. Typically the embossing time required was between a few minutes to half an hour. Once the set time was reached, all the heaters were turned off and flash cooling was applied through the heat exchanger.
7. After the temperature had cooled down below the glass transition temperature, both the top and bottom chamber were vented to atmospheric pressure and embossing was complete after removing the substrates.

In summary, this home built apparatus was built to deliver good temperature and pressure uniformity during a hot embossing process. The measured temperature distribution at 300°C showed a temperature uniformity of $\pm 0.5^{\circ}\text{C}$ across the entire hot plate. A pressure test done at 5bar using pressure sensitive indicator revealed a pressure uniformity equivalent to the result obtained from a commercial equipment (EVG 520). The

16-kw heater capability could ramp up the hot plate temperature to 350°C in less than 5 minutes and the flash cooling capability could cool the hot plate at ~30°C/min with just ~2bar compressed air making it possible to have fast heating and cooling. The maximum pressure difference tested on the thin silicon sheet was 5bar and this was limited by safety considerations (equivalent to ~1.5 tones of force on the chamber cap). Figure 7.5 shows a photo of the embossing apparatus.

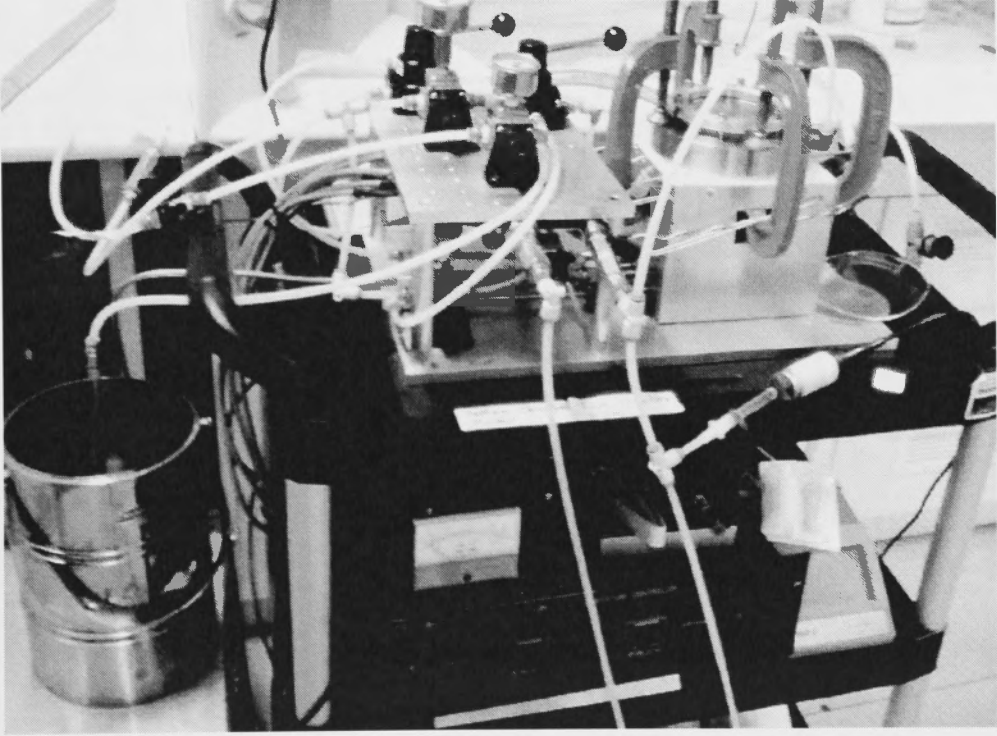


Figure 7.5: Image of the hot embossing apparatus

7.3 Hot embossing $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ waveguides

7.3.1 The Fabrication

The relatively low glass transition temperature of $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ ($T_g \sim 120^\circ\text{C}$) makes hot embossing an easy approach for waveguide fabrication and for this reason this was the first glass tested. Despite the high optical nonlinearity and low loss in the MIR, there are very few papers reporting waveguides in this glass composition. In this experiment, 1 μm $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ films were thermally evaporated onto 4 inch 1.5 μm thermally oxidized silicon

wafers and these deposited films were then annealed at 100°C for 24 hours in a vacuum oven.

The master stamp was made using standard optical lithography and dry etching which was detailed described in Chapter 3. Waveguides with nominal width from 2.2 to 4µm were patterned on the Silica layer and etched 450nm deep. The soft stamp was then made by casting uncured PDMS on top of the master stamp with curing at 100°C as also previously described.

Applying the procedure described in the previous section, the best embossing conditions were experimentally determined to be at 190°C with an applied pressure of 2bar for 30 minutes. The embossed wafer showed good uniformity visually, however some crystallization occurred on the surface across the entire wafer as shown in an optical microscope image (Figure 7.6). These defects were generally a few microns in diameter and randomly distributed in the area between adjacent waveguides. Fortunately, and for a reason that was not understood, these defects did not appear on the waveguide core or cladding and hence did not affect the waveguide optical performance. Inspection of the imprinted films showed no cracking despite the high thermal expansion coefficient of chalcogenide glasses in general and the contrasting low coefficient of the silica under cladding.

In Figure 7.7, two SEM images are captured showing the embossed waveguide pattern. It is evident that very smooth sidewalls have been obtained. Compared to the UV imprinted waveguides made with stamps fabricated by the same process (Chapter 3), the sidewalls are much smoother. It is likely that this resulted from pressure based smoothing of “high points” in the stamp coupled with softening of the stamp at the high process temperatures, the high surface tension of the glass, and the “hydrophobic” style of wetting of the glass to the stamp.

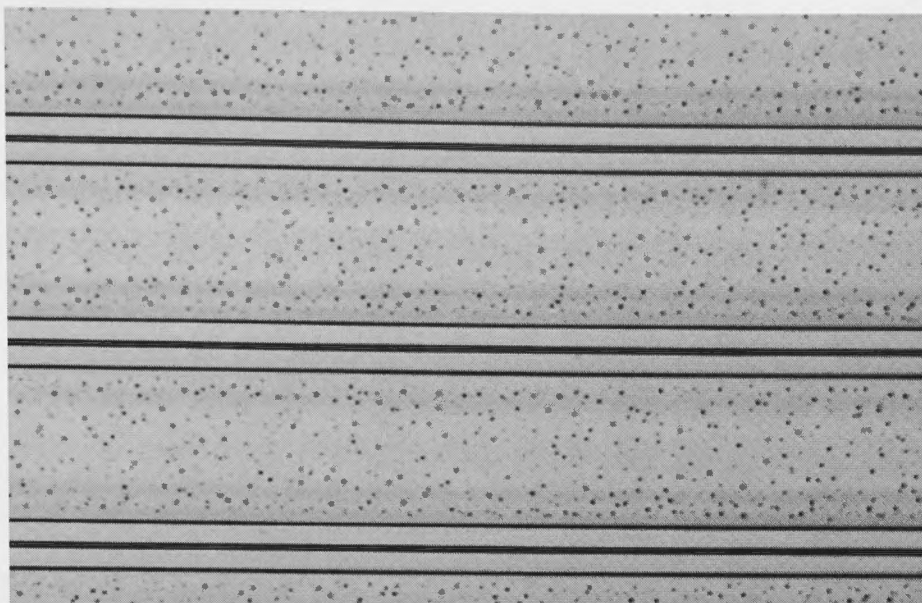


Figure 7.6: Optical microscopic (10× objective) view of the embossed waveguide

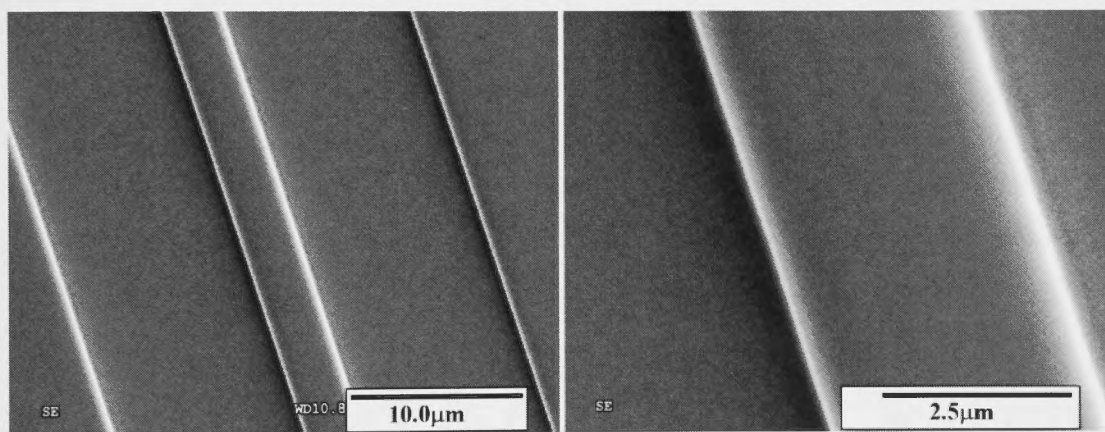


Figure 7.7: SEM image of embossed $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ chalcogenide glass

A 10μm IPG B11 upper cladding was then spin coated on the embossed wafer and UV-cured, and end facets hand cleaved on the chip with a diamond scribe leaving a finished waveguide with the profile shown in Figure 7.8. However the cross section profile shown here has a non-vertical sidewall angle which differs from the original master stamp. This was likely due to the soft nature of the PDMS stamp and insufficiently low glass viscosity at the embossing temperature.



Figure 7.8: Cross sectional optical microscope view of the finished imprinted rib waveguide

7.3.2 Measurements and Results

Measurements of the losses of the imprinted waveguides were performed using the cut back technique at 1550nm and with a fibre coupled mercury arc lamp and optical spectrum analyser. Light was launched from an external cavity tunable laser with frequency dithering (to average out chip Fabry-Perot resonances) and coupled into the waveguide using a lensed fibre pigtail with a $2.5\mu\text{m}$ $1/e^2$ mode field diameter. The output was then collected by another lensed fibre pigtail and measured by an InGaAs photodetector and logarithmic amplifier as previously described. Optical losses were measured for TE and TM modes of each waveguide at various chip lengths. Firstly the losses were recorded for the long chip (6.2cm), white light spectra collected, and then the chip was hand cleaved giving approximately 1/3 and 2/3 of the original length. By repeating the measurements for the “1/3 chip” and “2/3 chip”, three data points were acquired for each waveguide. Figure 7.9 shows the cut back results for launched TE and TM modes in 5 waveguides of $3.3\mu\text{m}$ width based on the tunable laser/power meter measurement. Measurement uncertainty was verified at $\pm 0.1\text{dB}$ via repeated measurements. The waveguides displayed considerable amounts of mode coupling/beating that manifested itself as a strong random (from waveguide to waveguide) wavelength dependence of the insertion loss. The laser-based measurements were therefore taken by sweeping the laser over $\sim 100\text{nm}$ and reading the minimum loss. Losses for $1\mu\text{m}$ high by $3.3\mu\text{m}$ wide $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ waveguides were 0.26dB/cm for TM polarization and 0.27dB/cm for TE polarization.

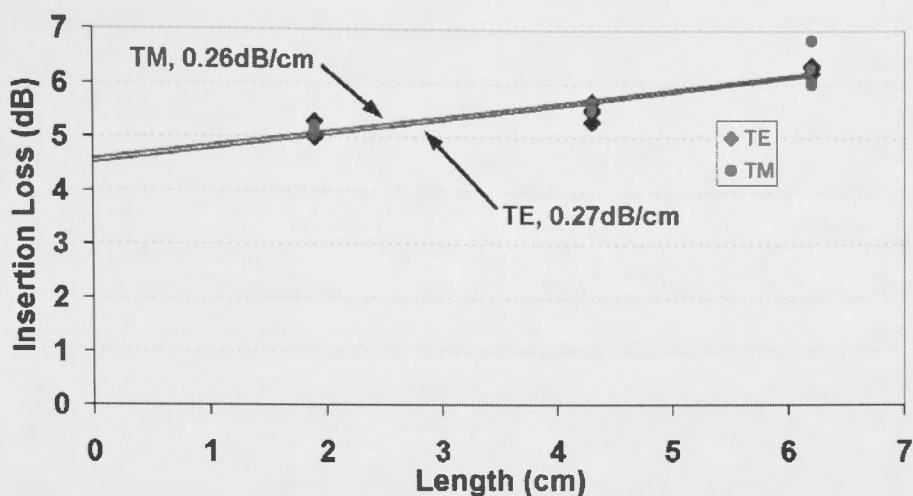


Figure 7.9: Insertion loss of 3.3 μ m wide waveguides measured using cutback method

The wavelength dependent propagation loss at each length was obtained with the fibre coupled mercury arc lamp and Agilent 86142B optical spectrum analyzer. The OSA data was taken with a 10nm resolution bandwidth to average out the mode coupling/beating problem observed with the tunable laser. The propagation loss was obtained by subtracting the measured spectrum (after normalization) at 1.9cm from that at 6.7cm, which removes all other wavelength dependent effects (e.g. lamp spectrum, coupling, etc). The cut back data of Figure 7.9 indicated that this was a valid measure of the propagation losses. Figure 7.10 shows a typical spectrum showing the wavelength dependent loss for a 3.3 μ m waveguide. Also shown in the same figure are two curves following $1/\lambda^2$ and $1/\lambda^4$ dependence fitted by pinning the loss at the 1550nm point to the measured cut back loss value. The propagation loss does not follow the $1/\lambda^2$ dependence expected for sidewall scattering induced losses [113], but rather the $1/\lambda^4$ Rayleigh scattering dependence exhibited by scattering off nanoscale inhomogeneities. Note that the input fibre goes multimode below 1100nm causing additional loss in the measured results below that wavelength. The observed wavelength dependence also agrees with the smooth sidewall roughness shown in the SEM images in Figure 7.7 and the lack of any polarization dependence in the measured losses. The question then arises whether the losses resulted from the film itself or were induced in the film by the high temperature processing, e.g. [222].

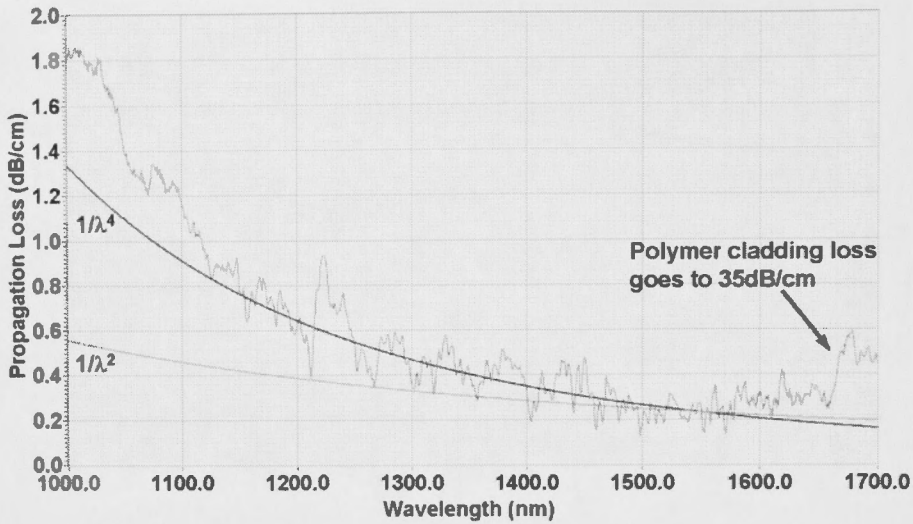


Figure 7.10: Measured optical propagation loss spectrum of a 3.3μm waveguide

To investigate the raw film losses, light was coupled into a chalcogenide glass film before the thermal imprinting process using a Metricon prism coupler and the film loss measured by imaging the top surface scattering at various wavelengths with a Xenics cooled InGaAs camera. The loss was determined using a custom LabVIEW software to process the captured waveguide scattering streak. The results are shown in Figure 7.11. The as-deposited thin film has a similar wavelength dependence of loss to the imprinted waveguide. This suggests that Rayleigh scattering, most likely due to phase separated clusters (known to occur in chalcogenide glasses) in the as-deposited films, was the source of the $1/\lambda^4$ dependence. The losses at 1550nm are ~0.1dB/cm lower in the films than the waveguides, and this could be a result of increased phase separation after high temperature treatment [222]. This implies that much lower losses should be possible in imprinted waveguides by using compositions that lead to more homogeneous films.

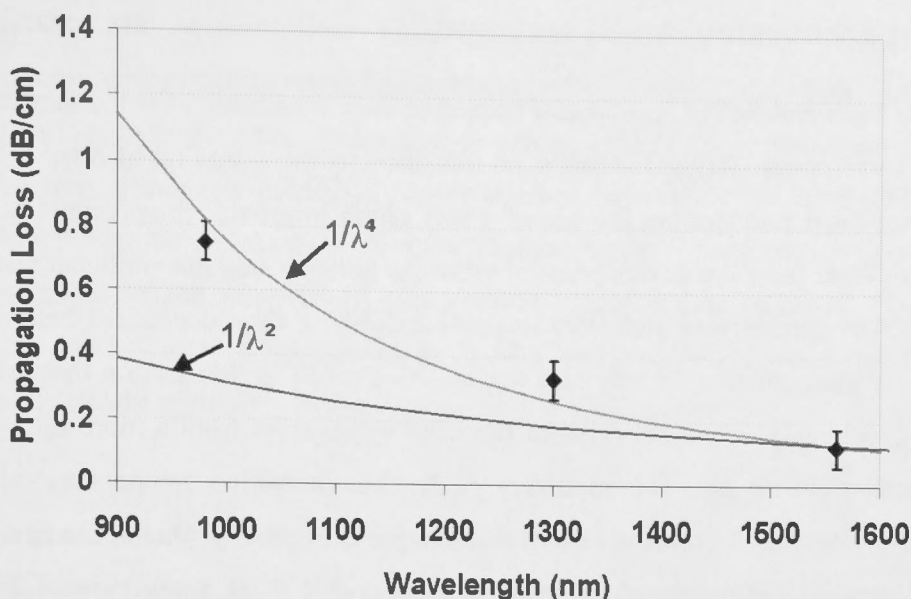


Figure 7.11: Measured wavelength dependence of film propagation loss

A nonlinear optics experiment was also performed using a pulsed laser source into one of the waveguide and observing the nonlinear phenomenon on an OSA. Significant self phase modulation (SPM) was generated (up to nine peaks in the output spectrum were observed), but the SPM spectrum varied significantly over a period of 10 minutes. This is likely resulting from self-written gratings or micro-channels inside of the waveguide. Standing wave formed between the two waveguide facets and the high peak power of the pulsed laser periodically modulated the waveguide refractive index in the z-axis due to the photosensitivity of this glass. Super-continuum was occasionally generated as the waveguide showed slightly anomalous dispersion at 1550nm, but this came and went of its own accord due to the photosensitive effects. Thus although the waveguide was low loss and highly nonlinear, the optical stability of the device was too poor to make it useful for any practical application. Thus attention was switched to a material known to have more stable performance, As_2S_3 .

7.4 Hot embossing As_2S_3 waveguides

The success from embossing $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ opened up new possibilities for the fabrication of other ChG waveguides. Whilst the low glass transition temperature (T_g) of $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ was an advantage for demonstrating the use of a soft stamp to mould rib waveguides, such a low T_g is not ideal from the device point of view. As noted during the nonlinear testing the $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ waveguides was also very unstable exhibiting time dependent behavior and this is clearly unacceptable for any real device. As a result in this section the embossing technique developed will be extended to fabricate waveguides from a more robust, work horse composition: As_2S_3 . The relatively high glass transition temperature of As_2S_3 ($\sim 160^\circ\text{C}$) indicates that a high embossing temperature is necessary. One of the first reports of experiments on embossing As_2S_3 was carried at 225°C at a pressure of $5 \times 10^6 \text{Pa}$; although submicron structures were successfully demonstrated, significant problems were reported due to the appearance of crystals on the embossed surfaces [261]. Lian *et al* [257] demonstrated the embossing of single mode waveguide on thermally evaporated As_2S_3 films with $\text{Ge}_{17}\text{As}_{18}\text{Se}_{65}$ as substrate, the measured propagation loss was 2.9dB/cm which was far from device application. Experiments have shown that the surface roughness (measured by AFM) remains constant up to 130°C annealing temperature, but started to increase at 150°C and became 10 times that of as-deposited film at 170°C [220]. The behavior beyond the glass transition temperature has not been studied but intuitively roughness might be expected to improve again due to flow effects. During the high temperature annealing experiments discussed in the prior chapter, it was clear that at temperatures somewhere in the vicinity of 250°C that sulfur (at the minimum) tended to evaporate from the film, and so there was initial concern about this becoming an issue for hot embossing.

Despite this, attempts were made to directly emboss As_2S_3 as per the method used with $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$. Typical embossing conditions were ($260\sim 280^\circ\text{C}$) with the temperature being chosen higher than the prior demonstration due to the need for lower viscosity to enable the soft stamp to operate. Initial experiments were made using “scrap” wafers that were cracked after annealing for 3 weeks at 130°C and several years of storage. Embossing was performed at 260°C and conditions found where reasonable looking imprints were obtained.

However, when the move to fresh substrates was made to fabricate a device for characterization, severe surface degradation was observed and yellowish film deposited on the stamp surface indicating the evaporation of sulfur. This phenomenon agreed with the observation from previously published papers and was believed to be the limiting bottle neck for low loss embossed As_2S_3 waveguide. Despite harder thermal and even additional optical annealing of the fresh films, this problem could not be resolved. This again indicates the subtlety of film structure in As_2S_3 films and the difficulty of obtaining bulk-like material; clearly multiple years of storage and 3 week anneals are not candidates for practical processes.

The proposed solution to the film degradation was to introduce a thin protective layer on top of the as-deposited As_2S_3 film to mechanically stop the surface degradation at high temperature. Ideally, this protective layer needs to be just thin enough to stop the glass evaporation and soft enough to be deformed and optically transparent at 1550nm (ideally in the MIR). The choice of material and deposition method was therefore limited.

7.4.1 Thin Al_2O_3 layer via atomic layer deposition system

One candidate material for this thin coating was alumina which could be deposited through the existing Atomic Layer Deposition (ALD) system. ALD is a coating technique based on Chemical Vapor Deposition (CVD). The main difference is that in an ALD process, a binary reaction is split into two half-reactions in order to achieve a precise control over the film thickness. Atomic layer deposition provides a unique method for depositing ultrathin, pinhole free and fully conformal films on surfaces.

To find out the minimum thickness of alumina necessary to stop the As_2S_3 film surface degradation, a series of embossing experiments (270°C) was carried out over a range of alumina thicknesses. A 10nm alumina layer successfully stopped the surface degradation while delivering the embossing profile as shown in Figure 7.12. Amazingly with a reduction in the protective layer thickness down to only 0.5nm, there was no sign of surface degradation in non-embossed areas despite the high temperature treatment. However a new problem arose due to the strong mechanical nature of alumina. At the edge of the embossed waveguide, the alumina layer seemed to be torn by the high pressure

applied from the stamp edge and as shown in Figure 7.13(a); in some circumstances, the As_2S_3 layer was exposed at the broken areas and surface crystallization and evaporation start to occur as shown in Figure 7.13(b). This was much more of an issue for the thin alumina layers, but even with the 10nm thickness, there were tears in the alumina sheet every a few millimeters.

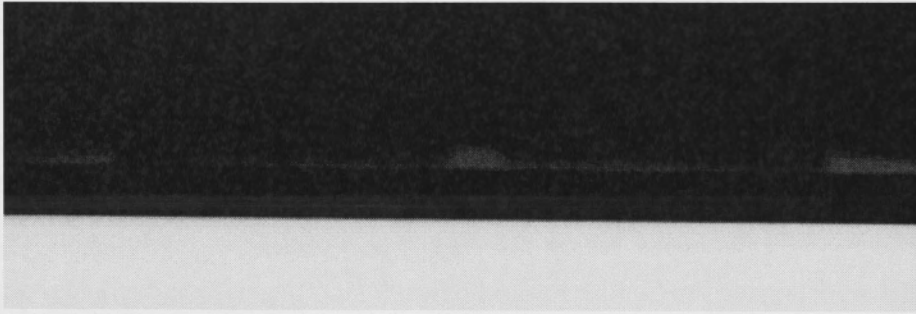


Figure 7.12: Embossed As_2S_3 waveguide using 10nm alumina protective layer cross section view

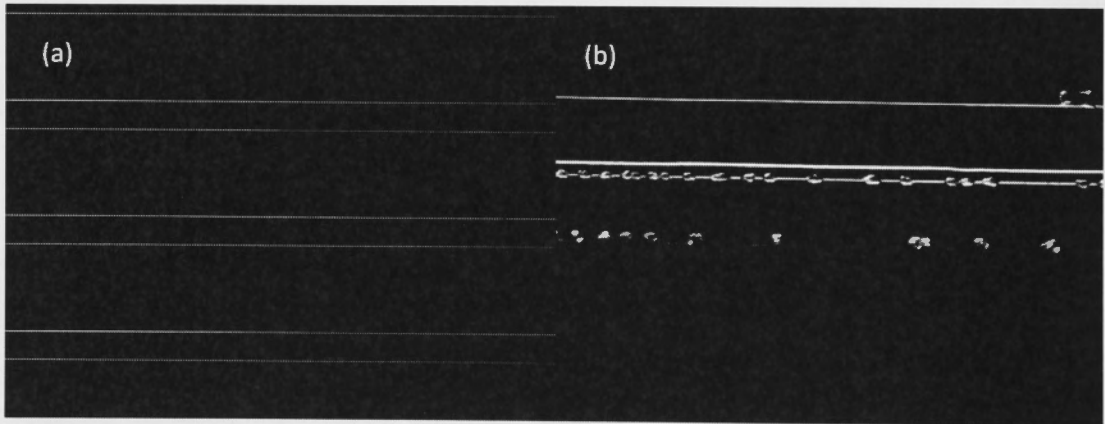


Figure 7.13: Embossed As_2S_3 waveguide captured from optical microscope darkfield with 0.5nm alumina coating

Although the ALD process could deliver sub nanometer thin films which was sufficient enough to protect the As_2S_3 film, the high tensile strength (low elasticity) characteristics of aluminum oxide led to non-ideal embossing profiles and tearing. The defects created during this process eliminated the possibility of achieving low loss waveguides.

7.4.2 Ultra thin polymer resist

Spin coating is the most straight forward technique for polymer thin film deposition. Thanks to the microelectronic industry, a wide variety of spin on polymers are commercially available and thin films from a few millimeters down to 100nm can be easily achieved. Another option for a surface protective layer was to apply a thin spin on polymer on top of the As_2S_3 layer. One of the best candidate materials was SU-8 due to its relatively high mechanical strength, good thermal properties, and good adhesion characteristics. The glass transition temperature for crosslinked SU-8 is slightly higher than As_2S_3 approximately 230°C which can be beneficial in a hot embossing process (capable to provide surface protection while being deformable). For the application in this experiment, a very thin layer (less than 50nm) was necessary in order to maintain the embossed waveguide profile and was fairly difficult to obtain. In theory, the SU-8 can be diluted with a large proportion of developer to obtain this kind of ultra thin film; in practice, this was limited by the spin quality, e.g. pin holes started to appear for films less than 50nm thick.

In the experiment, SU8-2 was diluted with developer at 1:20 in volume and a 45nm thick film was obtained by spin coating at 4000rpm. The sample was then soft baked at 90°C for 1 minute before UV flood exposure. The final SU-8 film thickness shrank to 40nm after a 2 minutes hard bake at 110°C was applied to enhance the strength and adhesion. Finally, the same embossing process was implemented at 260°C with 2 atmospheres of pressure for 20 minutes. The embossed surface showed no sign of degradation/crystallization indicating the thin SU-8 layer had performed the required function. An experimental comparison is shown in Figure 7.14, here the uncoated and thin SU-8 coated As_2S_3 films were both embossed under the same conditions and the dark field image reveals the dramatic surface improvement after adding this protective layer. It is apparent that some distortion of the profile occurred after adding the protective layer as shown in figure 7.14(c and d); the SU-8 coated waveguide sidewall angle is not as vertical as the uncoated sample and the waveguide edge is not defined as sharply. Figure 7.15 shows an SEM image of one of the embossed trench edges in high resolution which

confirms the distortion. In addition, the waveguide height has been increased from 850nm to $\sim 1\mu\text{m}$ which is due to the displaced glass flow to the surrounding areas.

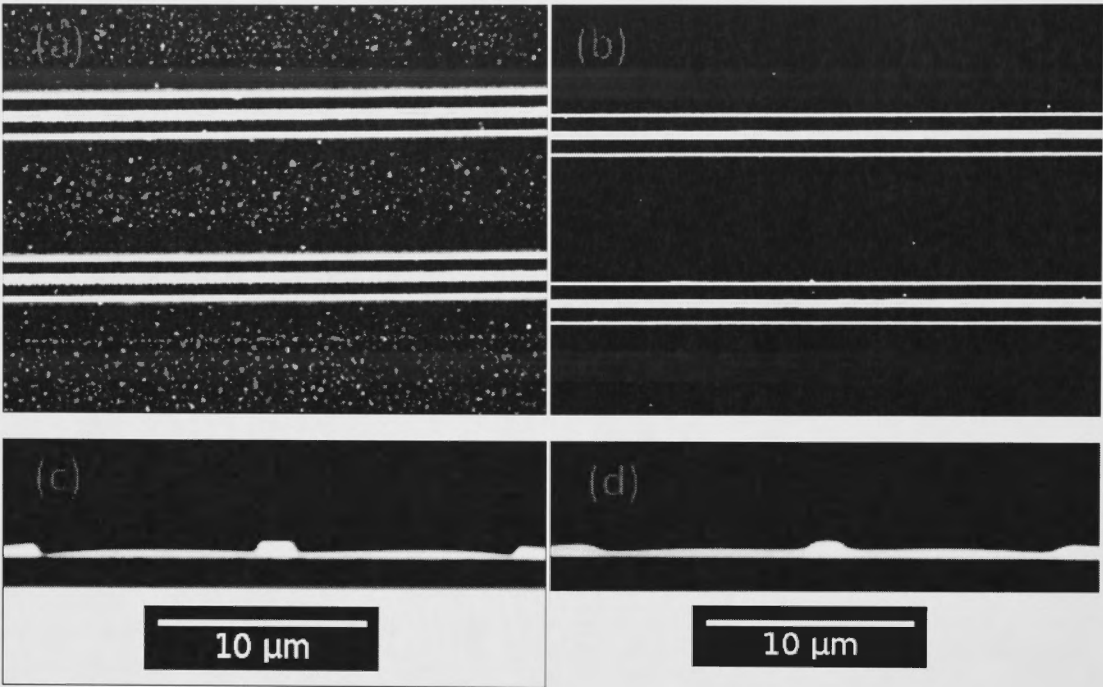


Figure 7.14: Optical microscope view of embossed As_2S_3 waveguide at 260°C . (a) Dark field view of surface without protective coating (b) Dark field view of surface with 38nm SU-8 coating (c) Bright field view of cross section without protective coating (d) Bright field view of cross section with 40nm SU-8 coating

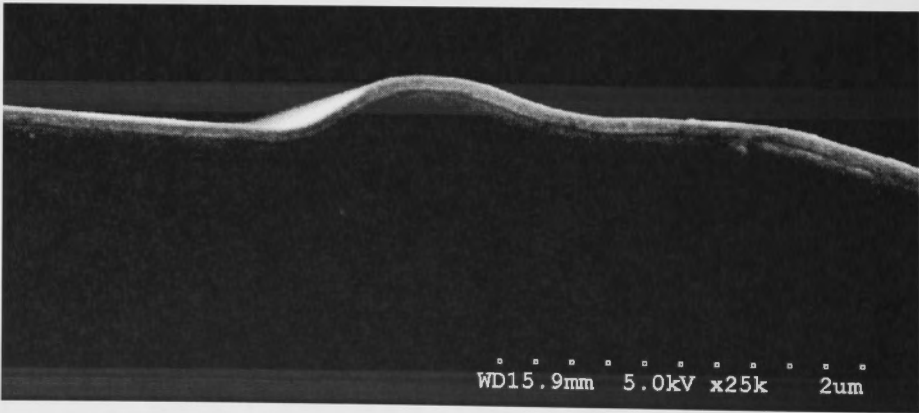


Figure 7.15: SEM image showing the cross section of a typical embossed edge (SU-8 coated embossed at 260°C)

The profile distortion in the SU-8 coated As_2S_3 waveguide was due to the viscosity difference at 260°C between SU-8 and As_2S_3 ; given the glass softening temperature of SU-8 is $\sim 230^\circ\text{C}$ compared to $\sim 160^\circ\text{C}$ for As_2S_3 , the SU-8 layer was likely a lot more difficult to deform at 260°C . To eliminate the distortion, one possible solution was to emboss at a higher temperature such that both layers become softer. An experimental investigation on the waveguide cross section profile in relation to different embossing temperatures was performed with both PDMS and *h*-PDMS stamps. Figure 7.16 shows optical microscope images of the waveguide cross section over a range of embossing temperatures from 275°C to 320°C with PDMS stamps (images on left) and *h*-PDMS stamps (images on the right). Clearly neither the embossing temperature nor the stamp hardness has had much effect on the profile, the embossed waveguide profile showing $\sim 45^\circ$ sidewall angle. This suggests that the SU-8 layer is not getting soft enough to deform sharply, as the *h*-PDMS is much harder and as at 320°C the As_2S_3 layer is unquestionably molten as evidenced by the very thin residual layer in the rib cladding region.

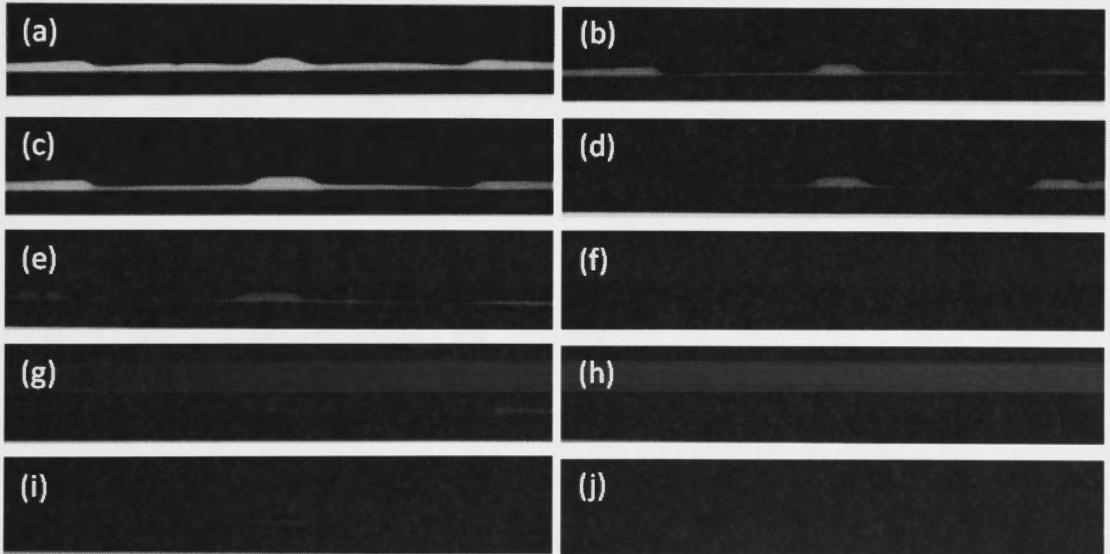


Figure 7.16: Comparison of embossed waveguide cross section profile at different temperature between PDMS and *h*-PDMS stamps. (a) 275°C PDMS (b) 275°C *h*-PDMS (c) 293°C PDMS (d) 293°C *h*-PDMS (e) 300°C PDMS (f) 300°C *h*-PDMS (g) 310°C PDMS (h) 310°C *h*-PDMS (i) 320°C PDMS (j) 320°C *h*-PDMS

Similar to the fabricated $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ waveguides, a cut back measurement was performed to measure the propagation loss of an embossed As_2S_3 waveguide (embossed at

280°C with 2bar pressure for 5 minutes). For TE polarization, 0.55dB/cm was recorded at 1550nm with a nominal waveguide width of 2.6µm and height of 0.85µm (shown in Figure 7.17). The normalized propagation loss spectrum had too much rapid oscillation and strong features (likely from mode coupling) to be able to cleanly discern the exact wavelength dependence of the loss, but clearly there is a decreasing loss trend with increasing wavelength. The “smoothed” loss appeared to decrease from about 1.1dB/cm at 1200nm to about 0.6dB/cm at 1650nm. The fractional ratio of these wavelengths squared was 0.53, which suggested that the loss dependence was in fact sidewall scattering dominated in contrast to the earlier results on the $\text{As}_{24}\text{Se}_{36}\text{S}_{36}$ glass. Further investigation into the use of SU-8 was halted at this point due to the non-ideal profiles obtained.

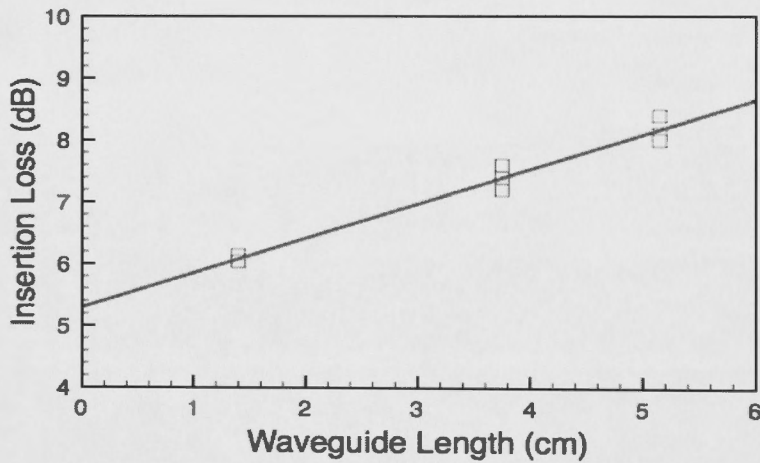


Figure 7.17: Insertion loss measured from the embossed As_2S_3 waveguide (Nominal dimension: 2.6µm × 0.85µm) with 40nm SU-8 coating

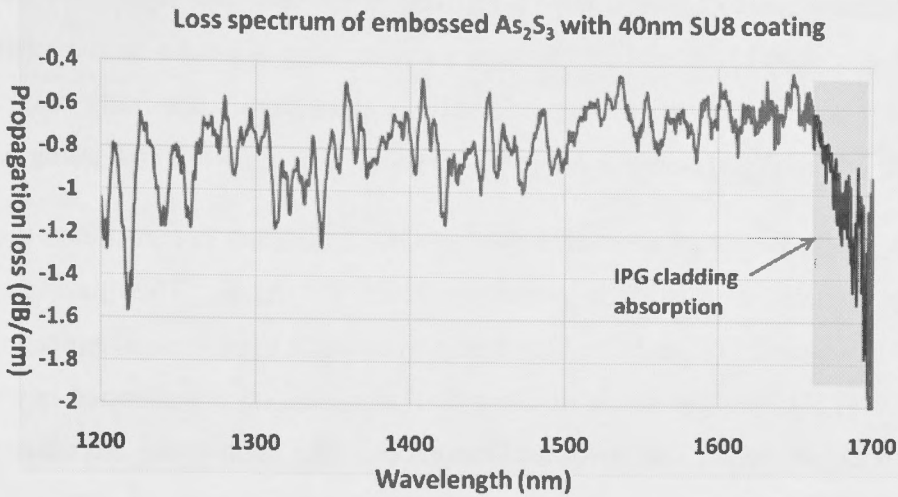


Figure 7.18: Normalized transmission spectrum of the embossed As₂S₃ (SU-8 coated)

In this section, it was shown that an ultra thin layer of SU-8 spin coated onto the As₂S₃ film could protect the film from surface degradation/crystallization and evaporation in a hot embossing process. The fabricated waveguide exhibited a propagation loss of 0.55dB/cm at 1550nm and wavelength dependent loss trend indicated sidewall wall scattering was dominating. The embossed waveguide cross section encountered distortion from the addition of the protective layer, and higher embossing temperatures did not really help. A thinner protective coating would be desirable, but it would be very difficult to reduce the SU-8 layer even further. Thus other alternatives were sought.

7.4.3 Double layer chalcogenide glass approach

Instead of using a spin on polymer, the third solution implemented was to coat with an appropriately stable glass with comparable viscosity to As₂S₃ at the embossing temperature. Using a more stable ChG as the protective coating is relatively easy and similar optical performance is a great advantage, especially in the MIR. In the last a few decades the Ge-As-Se composition has generated a large degree of interest in part because this ternary system has an exceptionally large glass forming region [264]. When compared with the As-S or As-Se system, the more complex Ge-As-Se system has GeS tetrahedral units that are connected together with Se-Se, Ge-Ge and Ge-Se bonds to form a 3-D network. This type of composition has a high linear refractive index (2.3-3 at 1550nm), high nonlinearity,

wide transparency range (between 0.8-16 microns in the IR), and high glass transition temperatures (between 150°C and 390°C). Since a wide range of Ge-As-Se compositions is possible, the physical and optical properties of this glass family are fairly tunable thus providing the possibility of acting as a matched protective layer for hot embossing As_2S_3 .

$\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ is one of a small family of Ge-As-Se glass compositions that have favorable properties as a surface protective layer for As_2S_3 . The glass transition temperature is around 250°C and thin films had proven stable upon thermal annealing up to around 250°C [173]. The deposition of 50nm $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ was performed in a similar manner to that of As_2S_3 via thermal evaporation. The embossing experiment was performed at 280°C with applied pressure of 2bar for 5 minutes using an *h*-PDMS stamp. The waveguides surface showed no sign of surface degradation/crystallization after the embossing and the cross section view of a typical waveguide is shown in Figure 7.19 indicating a good profile is defined in this process.

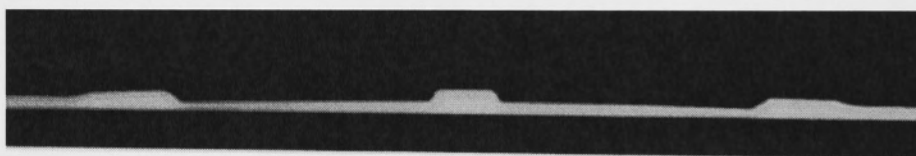


Figure 7.19: Microscope cross section view of an embossed As_2S_3 waveguide with 50nm $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ coating

The waveguide loss was measured based on a cut back method as before. Firstly the insertion losses were measured for the 8.3cm long chip; then the waveguide chip was hand cleaved leading to approx. 1/3 and 2/3 of the original length and same loss measurements were repeated. For different waveguide widths, the losses are plotted as a function of waveguide length as shown in Figure 7.20. The minimum loss recorded was 0.41dB/cm given by a 3.8 μm waveguide at TM polarization and overall small waveguide widths led to higher propagation losses.

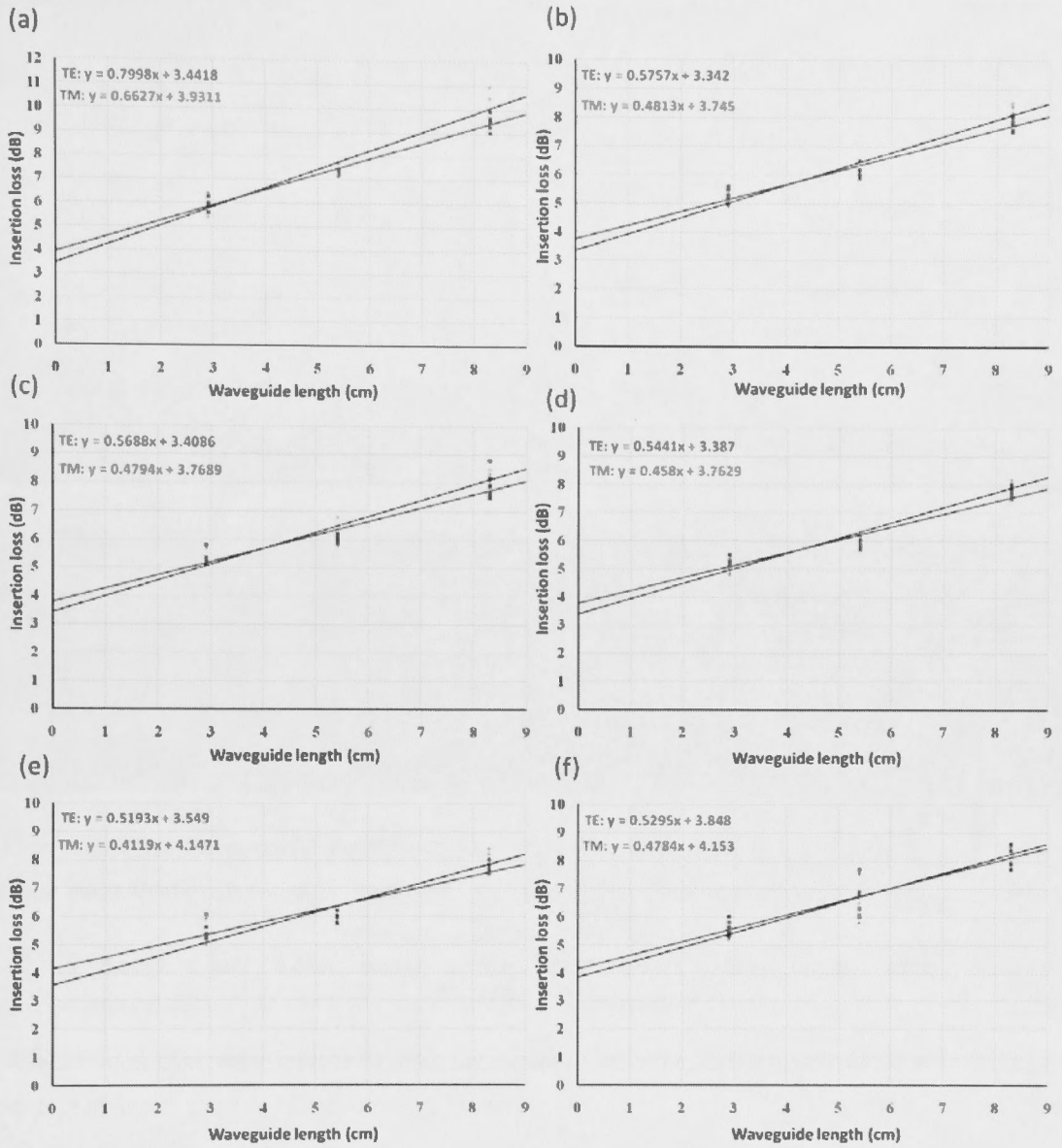


Figure 7.20: Optical losses measured based on cut back technique for waveguide widths of (a) 2.2 μm , (b) 3.0 μm , (c) 3.2 μm , (d) 3.4 μm , (e) 3.8 μm and (f) 4.0 μm

The measured propagation losses are much higher than the intrinsic material loss for As_2S_3 bulk material and were also above that of similar etched waveguides at 0.2~0.3dB/cm. To further analyze the propagation loss, the spectral performance of these embossed waveguides was investigated. Light from a super continuum source was coupled into the embossed waveguide and the output spectrum was acquired from an OSA at two

different lengths to yield a cut back propagation loss spectrum. Figure 7.21 shows a typical propagation loss spectrum from a 3.8 μm -wide waveguide.

Fitted trend lines indicate the wavelength dependent loss closely follows “ $1/\lambda^2$ ” relation which coupled with the observed width dependence means sidewall scattering is most likely responsible. SEM images taken at high magnification show the sidewall is very smooth locally (shown in Figure 7.22(a)); however at low magnification, the waveguide sidewall experiences a long period variation ($\sim 10\mu\text{m}$ shown in Figure 7.22(b)). It is believed this long period sidewall variation is responsible for the wavelength dependent loss which is likely due to bending of the soft stamp under stress during the imprint.

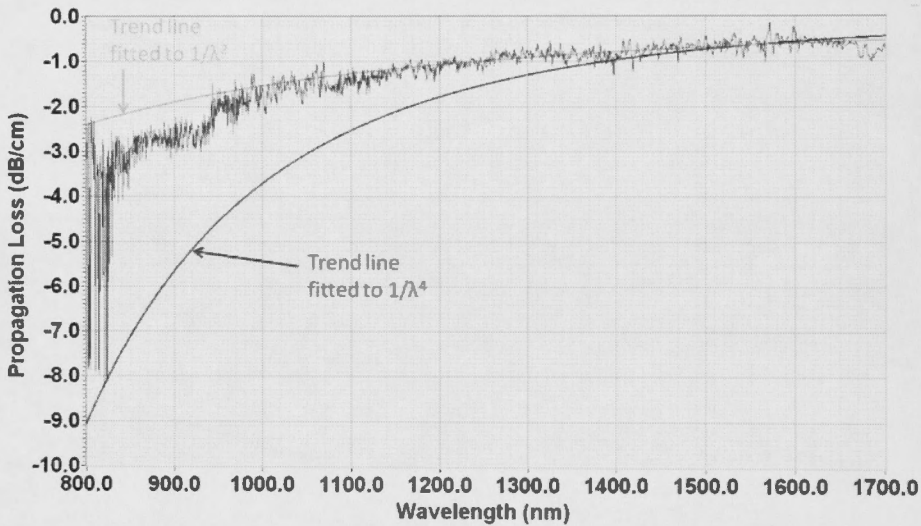


Figure 7.21: Loss spectrum measured from a 3.8 μm -wide As_2S_3 waveguide with fitted trend lines

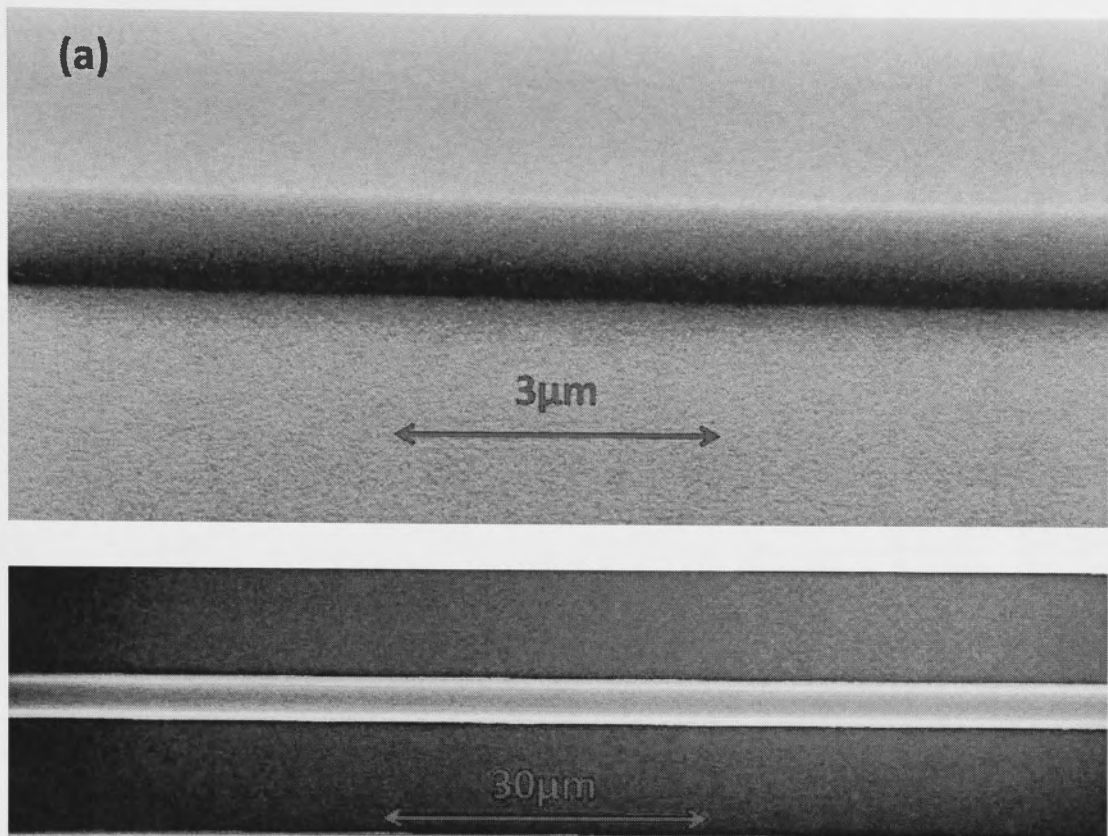


Figure 7.22: SEM images of the embossed As_2S_3 waveguide with 50nm $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ coating, (a) at high magnification, waveguide sidewall is very smooth (b) at low magnification, long period width variation on the waveguide is shown

The nonlinearity of this waveguide was measured based on a four wave mixing configuration. In order to eliminate any effect of dispersion on the measurement, the pump and signal were chosen close to each other at 1550.8nm and 1552.4nm, respectively. The pump and signal were then combined in a wavelength division multiplexer (WDM) with additional filtering used to eliminate the amplified spontaneous emission produced by the erbium-doped fibre amplifiers (EDFA) at the wavelength (1549.3nm) generated by FWM between the two inputs. Polarization controllers (PC) were used to adjust both pump and signal to either the TM or TE mode which could be determined by imaging the output of the waveguide onto an InGaAs camera through a Wollaston prism which created a split image for monitoring the powers in the TE and TM polarizations. The schematic drawing of the experimental setup is shown in Figure 7.23 and a typical image acquired from the optical spectrum analyzer is shown in Figure 7.24.

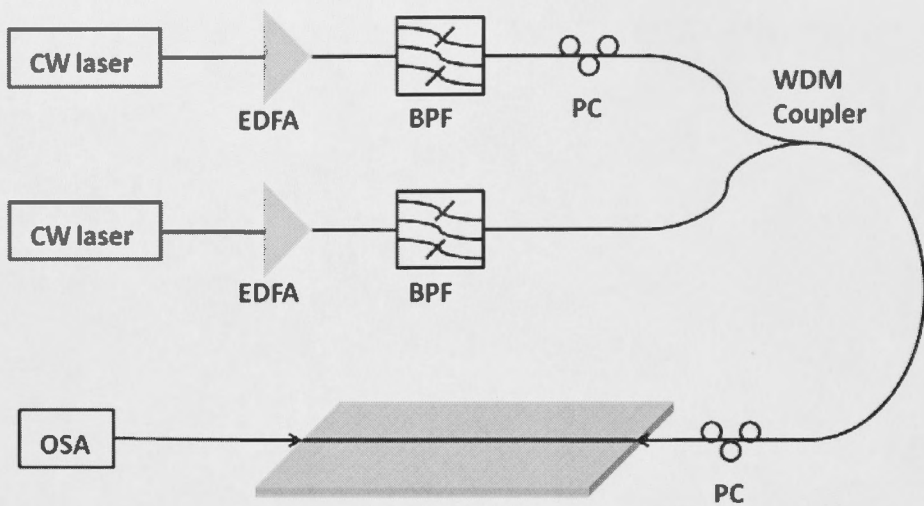


Figure 7.23: Experimental configuration for four wave mixing experiment

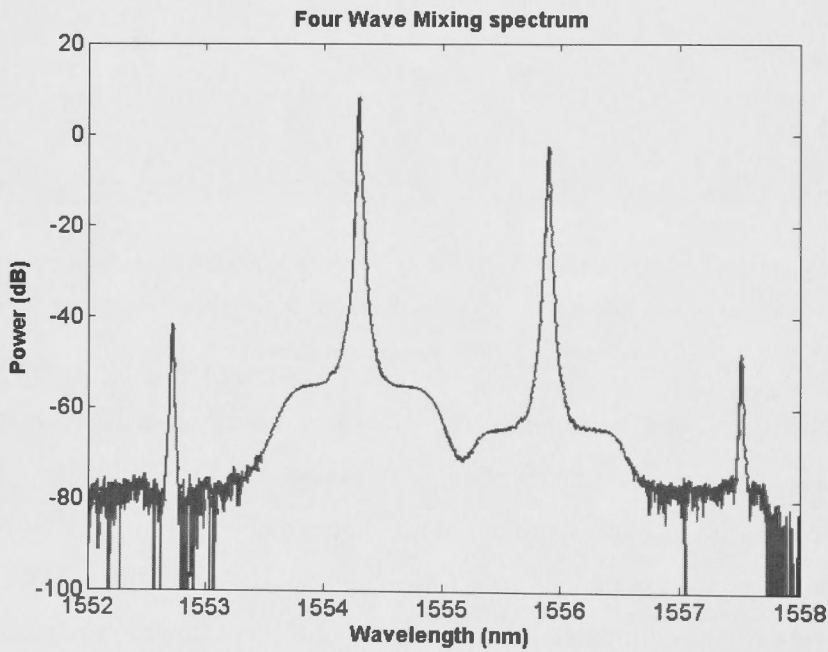


Figure 7.24: A typical four wave mixing spectrum acquired from the OSA

The measurement of the idler conversion efficiency used two cascaded narrow bandpass filters at 1549.3 nm to suppress all wavelengths except the generated signal power at 1549.3nm. The power was then measured using a power meter. A plot of the idler conversion efficiency as a function of the pump power is shown in Figure 7.25; a fitting to a power function shows the measured conversion efficiency exhibited a very close

quadratic relation towards increase in the pump power which agrees with the theoretically expected result.

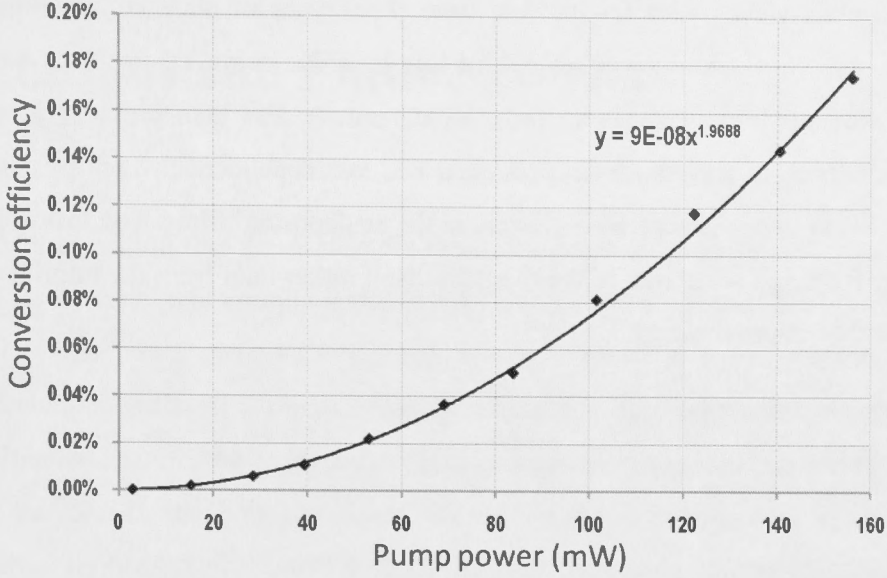


Figure 7.25: Four wave mixing idler conversion efficiency versus pump power

The nonlinear coefficient was calculated through the idler conversion efficiency according to equation:

$$\eta = \exp(-\alpha L)(\gamma P_p L_{eff})^2 \quad (7.1)$$

where P_p is the input power, α is the linear propagation loss and η is the efficiency of conversion from signal to idler at the output. The effective length L_{eff} accounts for group velocity dispersion and is given by:

$$L_{eff} = \sqrt{1 + \exp(-2\alpha L) - 2\exp(-\alpha L)\cos(\Delta\beta L)} / \sqrt{\alpha^2 + \Delta\beta^2} \quad (7.2)$$

where $\Delta\beta$ is the phase mismatch term due to second order dispersion β_2 . In the experiment, the idler conversion efficiency was measured using the OSA at the output of a $2.2\mu\text{m} \times 1\mu\text{m}$ waveguide with a length of 8.3cm. By measuring the power at the lensed fibre; the coupling losses; the propagation losses and relative output powers, nonlinear coefficient were to be $13.5\text{W}^{-1}\text{m}^{-1}$.

7.5 Conclusion

In this chapter, we successfully applied hot embossing for the fabrication of low loss chalcogenide glass waveguides for the first time. Two types of glass compositions were investigated: $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ and As_2S_3 . A record low loss was achieved from the embossed $\text{As}_{24}\text{Se}_{38}\text{S}_{38}$ waveguide which was an order of magnitude less than previously reported. However the fabricated waveguides experienced $1/\lambda^4$ loss dependence which was shown to be due most likely to phase separated clusters in the as-deposited films. The loss appears to be limited by Rayleigh scattering in the thin film itself rather than from the imprint process, promising further improvements.

Applying the same approach for As_2S_3 revealed issues with film degradation and evaporation at higher embossing temperatures. However this problem was solved with an introduction of a thin protective layer. The best solution found was the use of another appropriate chalcogenide glass on top of As_2S_3 . 50nm $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ thermally evaporated on top of As_2S_3 demonstrated the flexibility to produce good waveguide profiles while stopping the surface degradation. The fabricated waveguide, whilst showing very smooth sidewalls locally, however exhibited a $1/\lambda^2$ wavelength dependent propagation loss, most likely resulting from the long pitch sidewall variations which require further investigation.

Chapter 8

Conclusions and Future Works

The motivation behind this thesis was the rapid development in integrated optics and the need for low cost fabrication technologies necessary to reach the mass market. Traditionally integrated optical components are too expensive to be used in the cheap consumer/medical/sensing devices. The application of Nanoimprint Lithography to integrated optics has created an opportunity to make low cost and high resolution devices to satisfy the market needs. In this thesis, Nanoimprint Lithography was used to explore the fabrication of Polysiloxane and chalcogenide glass waveguide devices. The achievements are summarized in Section 8.1 and the recommended future work is proposed in Section 8.2

8.1 Conclusion

This thesis begins with an introduction of the Nanoimprint technology in Chapter 2 and the applications in photonics are thoroughly reviewed. The two material platforms divide this thesis into two independent projects: UV-Nanoimprint Polysiloxane (IPG) waveguide devices and hot embossing chalcogenide waveguides.

In Chapter 3, we developed an innovative minimum displacement approach in the pattern design such that very small amount of IPG core material was displaced during the imprint process. This led to “zero” residual layer ($<100\text{nm}$ compared to $3\mu\text{m}$ waveguide height) after imprint. The device fabrication consisted of four simple processes leading to the final finished devices on a 100mm wafer scale in less than half an hour. The imprinted waveguides showed essentially no excess loss or PDL over a bandwidth spanning $750\sim 1600\text{nm}$ compared to the bulk material. Furthermore, 10 imprints were reproduced by the same PDMS stamp and no observable difference between each imprint was made by

viewing under an optical microscope. Importantly the imprint process was shown to have high latitude to the spun film thickness making it a robust process.

The same four step imprint process is applicable to more complicated 3 dimensional devices. In Chapter 4, we demonstrated the fabrication of waveguide Bragg gratings (WBGs). The replication process was rather simple, but the real challenge lay in creating the original master. Electron beam lithography (EBL) was used as the method to pattern the Bragg gratings on PMMA which was subsequently transferred to the SiO₂ layer via dry etching. The shot-shifting method was used to minimize the stitching field errors which were common problems in EBL. Then waveguides were overlay aligned on top of the Bragg gratings via optical lithography and dry etching. The final imprinted grating waveguide exhibited a 10dB transmission dip at the resonant wavelength and showed no observable polarization dependence. Furthermore, the spectral performance showed excellent agreement with the theoretical predictions. This is the first time that a polarization independent imprinted grating has been demonstrated and also the first time that the match with theory has been attained. Lengthening the demonstrated grating to 5mm would results in a 30dB transmission dip, and ~100nm features were demonstrated indicating some possibilities for apodising the grating based on duty cycle variation.

In Chapter 5, we started with design optimization of MMI and directional couplers, and the fabrication of these couplers was accomplished via the UV-NIL process. For MMI couplers, it was shown that low excess loss and power imbalance were achievable simultaneously by optimizing the input/output taper and MMI section widths. This appears to be the first time that this link has been made and MMIs were designed that showed unprecedentedly low excess loss. The imprinted MMI coupler however was unsuccessful because the MMI section suffered from distortion due to sagging of the soft mould.

The design optimization of 3-dB and 1310/1550nm WDM directional couplers focused on a design approach such that the performance was much less vulnerable to real world fabrication errors and the design was verified by Beam Propagation modeling. For the first time it was demonstrated that a single point exists in the design space where the device has considerable tolerance to variations in the waveguide width for both TE and TM polarizations. The imprinted 3-dB directional couplers proved more fabrication error

tolerant at the optimized designs; however the performance was not as good as the BPM simulation which was a result of significantly non-vertical sidewall angle introduced in the master stamp fabrication. The imprinted WDM couplers also showed superior immunity to fabrication errors at the optimized designs for 1550nm, however 1310nm exiting through the cross port suffered from low extinction ratio and was believed to be a result of phase mismatch between the waveguides caused by mask errors.

The optical properties of chalcogenide glasses were reviewed in Chapter 6. One of the major barriers of producing integrated chalcogenide waveguide devices lies in the difficulty of making bulk-like thin films. One solution attempted in this thesis was to conduct high temperature annealing. This experiment was designed to anneal As_2S_3 thin films beyond its glass melting temperature while preventing evaporation. Whilst the measured Raman spectra showed some improvement for annealing at 350°C compared to 135°C, high temperature was still not a promising route leading to bulk-like films. The second experiment used a small piece of bulk As_2S_3 and squashed into a $\sim 50\mu\text{m}$ film at 250°C. The measured Raman spectra exhibited great similarities compared to the bulk glass, and therefore proving hot squashing is a promising route for the fabrication of bulk-like chalcogenide films.

In Chapter 7, the first low loss chalcogenide rib waveguides fabricated by hot embossing were presented. Firstly, $\text{As}_{24}\text{Se}_{36}\text{S}_{36}$ waveguides were embossed at 190°C and the measured propagation loss yielded 0.26dB/cm which was an order of magnitude lower than the best result obtained previously. However this glass composition was not stable during nonlinear optics experiments and suffered from Rayleigh scattering caused by the nanoscale structures of the film. The same embossing process was applied to a more robust glass composition: As_2S_3 . However the As_2S_3 suffered from severe surface degradation at high temperature. The solution proposed was to use a protective coating to physically stop this phenomenon. Three types of protective coatings were used: Alumina, SU-8 and $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$. The best result was demonstrated with the use of 50nm $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ layer which was thermally evaporated on top of the 870nm As_2S_3 layer. The embossed waveguide showed an optical loss of $\sim 0.5\text{dB/cm}$ at both TE and TM polarizations, limited by a long period width variation which was believed to be a result of soft stamp

deformation. A four wave mixing experiment was used to measure the optical nonlinearity and the calculated nonlinear coefficient was shown to be $13.5\text{W}^{-1}\text{m}^{-1}$ on a $2.2\times 1\mu\text{m}$ waveguide which agreed with result obtained from dry etched waveguides.

8.2 Recommended Future Works

Nanoimprint lithography is a relatively new fabrication technique and it has found wide applications since its invention. Whilst this thesis emphasized on demonstrating good performance with direct moulding of optical waveguide devices, there are a number of further improvements that can be investigated.

Although the imprinted waveguide Bragg gratings showed excellent spectral response, the 10dB transmission dip at resonant wavelength was not ideal. It was shown in the simulation that a $\sim 50\text{dB}$ transmission dip could be obtained if duty cycle of the same grating was optimized to 50%. The fabrication bottleneck was the charging of the EBL system which produced a random variation in the effective dose. The challenge for future work is to eliminate charging on the sample during the E-beam exposure which will require the modification of the wafer chuck and better conductivity on the wafer surface. Clearly the fabrication of apodised gratings would also be of considerable interest and a combination of duty cycle variation and varying of the overlap of the grating with the waveguide could be used.

The four step UV-NIL process has demonstrated its unique capabilities to replicate complex structures, but it failed to reproduce large structures, e.g. the MMI section ($\sim 60\mu\text{m}$ wide and 1mm long). The sagging of the PDMS stamp created a distortion which was fatal to MMI devices. One solution will be using hard material (such as rigid quartz) for the backing of the imprint stamp, which will require commercial imprint equipment. It may also be possible to use an *h*-PDMS stamp (thin layer of hard *h*-PDMS backed with thick PDMS) which provides local rigidity and global flexibility. Certainly it would be of considerable interest to prove the modeling correct as ultra-low loss MMIs have not been fabricated to date.

The design optimization for 3dB-directional couplers showed it was possible to achieve high immunity to the real world fabrication errors. The fabricated directional couplers, however suffered from a significantly non-vertical waveguide sidewall angle (82°) which degraded the performance. This was a problem that originated from the photolithography and etching processes for the master after the etching tool had a preventative maintenance cycle performed on it. These processes need to be tuned to produce waveguide sidewall angles above 87° which were previously fabricated before the service and which the modeling show will have much closer performance to the expected design. It would also be interesting to extend the modeling to more complex 3-dB coupler designs targeted at wavelength independent operation, and to other index contrast systems to see if the fabrication tolerant design is more generally applicable.

The 1310/1550nm WDM coupler has demonstrated the capability of reaching high extinction ratio ($>30\text{dB}$) at 1550nm over a fairly wide range of width tolerance (600nm); however the output at 1310nm port suffered from low extinction ratio as a result of phase velocity mismatch possibly caused by a small ($\sim 50\text{nm}$) width error on the mask. Therefore the future improvement for this experiment will involve higher quality photomasks or moving to a reduction lithography system which is just about to come on line in the ANFF facilities in Sydney.

Chalcogenide glasses are mysterious materials and have been widely researched over the last a few decades. A classical challenge was to create bulk-like chalcogenide thin films. In Chapter 6, we showed it was possible to create bulk-like thick films by hot squashing bulk samples. Therefore, more efforts are required to develop a customized equipment which is capable to squash the film further down to a few microns. One route to accomplish this is relatively clear and was outlined, but significant commitment is required to realize this.

Lastly, waveguides fabricated from hot embossing approach, whilst showing great promise, need further work. The cause of the wavelength dependent loss in the As_2S_3 waveguides needs to be clarified and strategies to overcome it need to be researched. Further work is also needed to obtain good control in the final embossed waveguide core height and cladding film thickness. The final waveguide height is of great importance to

the waveguide dispersion. For the nonlinear signal processing, zero dispersion is often required. Therefore, efforts are required to engineer this hot embossing process to ultimately deliver low loss, dispersion engineered waveguides. For the highest embossing temperatures trailed, it was also clear that very thin residual layers were possible, and this raises the tantalizing possibility that the $500\times 500\text{nm}$ zero dispersion highly nonlinear nanowires recently demonstrated by etching in chalcogenides could be fabricated with embossing. This would clearly be an interesting opportunity given the very smooth sidewalls available with embossing.

Bibliography

1. A. G. Bell, (US, 1876).
2. K. C. Kao, and G. A. Hockham, "DIELECTRIC-FIBRE SURFACE WAVEGUIDES FOR OPTICAL FREQUENCIES," Proceedings of the Institution of Electrical Engineers-London **113**, 1151-& (1966).
3. T. C. Cannon, D. L. Pope, and D. D. Sell, "INSTALLATION AND PERFORMANCE OF CHICAGO LIGHTWAVE TRANSMISSION-SYSTEM," IEEE Trans. Commun. **26**, 1056-1060 (1978).
4. Luxtera, <http://www.luxtera.com>, Accessed July 5, 2011.
5. Intel, <http://www.intel.com/technology/io/thunderbolt/index.htm>, Accessed July 5, 2011.
6. "Personal communication with Sukanta Debbarma."
7. B. J. Eggleton, B. Luther-Davies, and K. Richardson, "Chalcogenide photonics," Nat. Photonics **5**, 141-148.
8. J. Leuthold, C. Koos, and W. Freude, "Nonlinear silicon photonics," Nat. Photonics **4**, 535-544.
9. S. Y. Chou, P. R. Krauss, and P. J. Renstrom, "IMPRINT OF SUB-25 NM VIAS AND TRENCHES IN POLYMERS," Applied Physics Letters **67**, 3114-3116 (1995).
10. ASML, <http://www.asml.com/asml/show.do?ctx=6717>, Accessed July 5, 2011.
11. R. H. French, H. Sewell, M. K. Yang, S. Peng, D. McCafferty, W. M. Qiu, R. C. Wheland, M. F. Lemon, L. Markoya, and M. K. Crawford, "Imaging of 32-nm 1 : 1 lines and spaces using 193-nm immersion interference lithography with second-generation immersion fluids to achieve a numerical aperture of 1.5 and a $k(1)$ of 0.25," J. Microlithogr. Microfabr. Microsyst. **4**, 14 (2005).
12. H. H. Solak, Y. Ekinici, P. Kaser, and S. Park, "Photon-beam lithography reaches 12.5 nm half-pitch resolution," J. Vac. Sci. Technol. B **25**, 91-95 (2007).
13. M. Deubel, G. Von Freymann, M. Wegener, S. Pereira, K. Busch, and C. M. Soukoulis, "Direct laser writing of three-dimensional photonic-crystal templates for telecommunications," Nat. Mater. **3**, 444-447 (2004).
14. W. Haske, V. W. Chen, J. M. Hales, W. T. Dong, S. Barlow, S. R. Marder, and J. W. Perry, "65 nm feature sizes using visible wavelength 3-D multiphoton lithography," Opt. Express **15**, 3426-3436 (2007).
15. P. Petric, C. Bevis, A. Carroll, H. Percy, M. Zywno, K. Standiford, A. Brodie, N. Bareket, and L. Grella, "REBL: A novel approach to high speed maskless electron beam direct write lithography," J. Vac. Sci. Technol. B **27**, 161-166 (2009).
16. M. D. Austin, W. Zhang, H. X. Ge, D. Wasserman, S. A. Lyon, and S. Y. Chou, "6 nm half-pitch lines and 0.04 μm^2 static random access memory patterns by nanoimprint lithography," Nanotechnology **16**, 1058-1061 (2005).

Bibliography

17. M. T. Li, L. Chen, and S. Y. Chou, "Direct three-dimensional patterning using nanoimprint lithography," *Applied Physics Letters* **78**, 3322-3324 (2001).
18. MolecularImprint, <http://www.molecularimprints.com/>, Accessed July 5, 2011.
19. J. Haisma, M. Verheijen, K. vandenHeuvel, and J. vandenBerg, "Mold-assisted nanolithography: A process for reliable pattern replication," *J. Vac. Sci. Technol. B* **14**, 4124-4128 (1996).
20. M. Bender, M. Otto, B. Hadam, B. Vratzov, B. Spangenberg, and H. Kurz, "Fabrication of Nanostructures using a UV-based imprint technique," *Microelectron. Eng.* **53**, 233-236 (2000).
21. H. Schmid, and B. Michel, "Siloxane polymers for high-resolution, high-accuracy soft lithography," *Macromolecules* **33**, 3042-3049 (2000).
22. D. Y. Khang, and H. H. Lee, "Sub-100 nm patterning with an amorphous fluoropolymer mold," *Langmuir* **20**, 2445-2448 (2004).
23. U. Plachetka, M. Bender, A. Fuchs, T. Wahlbrink, T. Glinsner, and H. Kurz, "Comparison of multilayer stamp concepts in UV-NIL," *Microelectron. Eng.* **83**, 944-947 (2006).
24. B. Vratzov, A. Fuchs, M. Lemme, W. Henschel, and H. Kurz, "Large scale ultraviolet-based nanoimprint lithography," *J. Vac. Sci. Technol. B* **21**, 2760-2764 (2003).
25. M. Bender, A. Fuchs, U. Plachetka, and H. Kurz, "Status and prospects of UV-nanoimprint technology," *Microelectron. Eng.* **83**, 827-830 (2006).
26. A. Fuchs, B. Vratzov, T. Wahlbrink, Y. Georgiev, and H. Kurz, "Interferometric in situ alignment for UV-based nanoimprint," *J. Vac. Sci. Technol. B* **22**, 3242-3245 (2004).
27. H. Hiroshima, M. Komuro, N. Kasahara, Y. Kurashima, and J. Taniguchi, "Elimination of pattern defects of nanoimprint under atmospheric conditions," *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **42**, 3849-3853 (2003).
28. A. Y. Abdo, L. Zheng, A. Wei, A. Mikkelsen, G. Nellis, R. L. Engelstad, and E. G. Lovell, "Simulating fabrication and imprinting distortions in step-and-flash imprint lithography templates," *Microelectron. Eng.* **73-4**, 161-166 (2004).
29. M. Colburn, B. J. Choi, S. V. Sreenivasan, R. T. Bonnecaze, and C. G. Willson, "Ramifications of lubrication theory on imprint lithography," *Microelectron. Eng.* **75**, 321-329 (2004).
30. S. Reddy, and R. T. Bonnecaze, "Simulation of fluid flow in the step and flash imprint lithography process," *Microelectron. Eng.* **82**, 60-70 (2005).
31. X. G. Liang, H. Tan, Z. L. Fu, and S. Y. Chou, "Air bubble formation and dissolution in dispensing nanoimprint lithography," *Nanotechnology* **18**, 7 (2007).
32. G. Kumar, H. X. Tang, and J. Schroers, "Nanomoulding with amorphous metals," *Nature* **457**, 868-872 (2009).
33. Microresist, <http://www.microresist.de/>, Accessed July 6, 2011.
34. Nanonex, <http://www.nanonex.com/>, Accessed July 6, 2011.
35. Sumitomo, <http://www.sumitomochem.co.jp/>, Accessed July 6, 2011.

Bibliography

36. S. Y. Chou, P. R. Krauss, W. Zhang, L. J. Guo, and L. Zhuang, "Sub-10 nm imprint lithography and applications," *J. Vac. Sci. Technol. B* **15**, 2897-2904 (1997).
37. F. Hua, Y. G. Sun, A. Gaur, M. A. Meitl, L. Bilhaut, L. Rotkina, J. F. Wang, P. Geil, M. Shim, J. A. Rogers, and A. Shim, "Polymer imprint lithography with molecular-scale resolution," *Nano Lett.* **4**, 2467-2471 (2004).
38. H. Schiff, "Nanoimprint lithography: An old story in modern times? A review," *J. Vac. Sci. Technol. B* **26**, 458-480 (2008).
39. W. Wu, B. Cui, X. Y. Sun, W. Zhang, L. Zhuang, L. S. Kong, and S. Y. Chou, "Large area high density quantized magnetic disks fabricated using nanoimprint lithography," *J. Vac. Sci. Technol. B* **16**, 3825-3829 (1998).
40. L. J. Guo, P. R. Krauss, and S. Y. Chou, "Nanoscale silicon field effect transistors fabricated using imprint lithography," *Applied Physics Letters* **71**, 1881-1883 (1997).
41. M. C. McAlpine, R. S. Friedman, and D. M. Lieber, "Nanoimprint lithography for hybrid plastic electronics," *Nano Lett.* **3**, 443-445 (2003).
42. M. D. Austin, and S. Y. Chou, "Fabrication of 70 nm channel length polymer organic thin-film transistors using nanoimprint lithography," *Applied Physics Letters* **81**, 4431-4433 (2002).
43. C. C. Cedeno, J. Seekamp, A. P. Kam, T. Hoffmann, S. Zankovych, C. M. S. Torres, C. Menozzi, M. Cavallini, M. Murgia, G. Ruani, F. Biscarini, M. Behl, R. Zentel, and J. Ahopelto, "Nanoimprint lithography for organic electronics," *Microelectron. Eng.* **61-2**, 25-31 (2002).
44. Y. Hirai, S. Harada, H. Kikuta, Y. Tanaka, M. Okano, S. Isaka, and M. Kobayasi, "Imprint lithography for curved cross-sectional structure using replicated Ni mold," *J. Vac. Sci. Technol. B* **20**, 2867-2871 (2002).
45. J. Wang, S. Schablitsky, Z. N. Yu, W. Wu, and S. Y. Chou, "Fabrication of a new broadband waveguide polarizer with a double-layer 190 nm period metal-gratings using nanoimprint lithography," *J. Vac. Sci. Technol. B* **17**, 2957-2960 (1999).
46. Intel, <http://www.intel.com/technology/silicon/itroadmap.htm>, Accessed July 6, 2011.
47. W. S. Kim, J. H. Lee, S. Y. Shin, B. S. Bae, and Y. C. Kim, "Fabrication of ridge waveguides by UV embossing and stamping of sol-gel hybrid materials," *IEEE Photonics Technol. Lett.* **16**, 1888-1890 (2004).
48. J. A. Rogers, M. Meier, A. Dodabalapur, E. J. Laskowski, and M. A. Cappuzzo, "Distributed feedback ridge waveguide lasers fabricated by nanoscale printing and molding on nonplanar substrates," *Applied Physics Letters* **74**, 3257-3259 (1999).
49. D. H. Kim, W. J. Chin, S. S. Lee, S. W. Ahn, and K. D. Lee, "Tunable polymeric Bragg grating filter using nanoimprint technique," *Applied Physics Letters* **88**, 3 (2006).
50. Y. Y. Huang, G. T. Paloczi, A. Yariv, C. Zhang, and L. R. Dalton, "Fabrication and replication of polymer integrated optical devices using electron-beam lithography and soft lithography," *J. Phys. Chem. B* **108**, 8606-8613 (2004).
51. G. T. Paloczi, Y. Huang, A. Yariv, J. Luo, and A. K. Y. Jen, "Replica-molded electro-optic polymer Mach-Zehnder modulator," *Applied Physics Letters* **85**, 1662-1664 (2004).

Bibliography

52. S. H. Kim, K. D. Lee, J. Y. Kim, M. K. Kwon, and S. J. Park, "Fabrication of photonic crystal structures on light emitting diodes by nanoimprint lithography," *Nanotechnology* **18**, 5 (2007).
53. M. Aryal, F. Buyukserin, K. Mielczarek, X. M. Zhao, J. M. Gao, A. Zakhidov, and W. C. Hu, "Imprinted large-scale high density polymer nanopillars for organic solar cells," *J. Vac. Sci. Technol. B* **26**, 2562-2566 (2008).
54. G. M. Whitesides, "The origins and the future of microfluidics," *Nature* **442**, 368-373 (2006).
55. S. Y. Chou, "Release surfaces, particularly for use in nanoimprint lithography," (U.S., 2001).
56. K. Thyagarajan, M. R. Shenoy, and A. K. Ghatak, "ACCURATE NUMERICAL-METHOD FOR THE CALCULATION OF BENDING LOSS IN OPTICAL WAVE-GUIDES USING A MATRIX APPROACH," *Opt. Lett.* **12**, 296-298 (1987).
57. I. C. Goyal, R. L. Gallawa, and A. K. Ghatak, "BENT PLANAR WAVE-GUIDES AND WHISPERING GALLERY MODES - A NEW METHOD OF ANALYSIS," *J. Lightwave Technol.* **8**, 768-774 (1990).
58. M. K. Smit, E. C. M. Pennings, and H. Blok, "A NORMALIZED APPROACH TO THE DESIGN OF LOW-LOSS OPTICAL WAVE-GUIDE BENDS," *J. Lightwave Technol.* **11**, 1737-1742 (1993).
59. D. E. Zelmon, J. T. Boyd, and H. E. Jackson, "LOW-LOSS OPTICAL WAVE-GUIDES FABRICATED BY THERMAL NITRIDATION OF OXIDIZED SILICON," *Applied Physics Letters* **47**, 353-355 (1985).
60. C. H. Henry, R. F. Kazarinov, H. J. Lee, K. J. Orlowsky, and L. E. Katz, "LOW-LOSS Si_3N_4 - SiO_2 OPTICAL WAVE-GUIDES ON Si ," *Appl. Optics* **26**, 2621-2624 (1987).
61. F. Morichetti, A. Melloni, M. Martinelli, R. G. Heideman, A. Leinse, D. H. Geuzebroek, and A. Borreman, "Box-shaped dielectric waveguides: A new concept in integrated optics?," *J. Lightwave Technol.* **25**, 2579-2589 (2007).
62. T. Miya, "Silica-based planar lightwave circuits: Passive and thermally active devices," *IEEE J. Sel. Top. Quantum Electron.* **6**, 38-45 (2000).
63. A. Kilian, J. Kirchhof, B. Kuhlow, G. Przyrembel, and W. Wischmann, "Birefringence free planar optical waveguide made by flame hydrolysis deposition (FHD) through tailoring of the overcladding," *J. Lightwave Technol.* **18**, 193-198 (2000).
64. E. Wildermuth, C. Nadler, M. Lanker, W. Hunziker, and H. Melchior, "Penalty-free polarisation compensation of SiO_2/Si arrayed waveguide grating wavelength multiplexers using stress release grooves," *Electron. Lett.* **34**, 1661-1663 (1998).
65. K. S. Chiang, and W. P. Wong, "Rib waveguides with degenerate polarised modes," *Electron. Lett.* **32**, 1098-1099 (1996).
66. W. P. Wong, and K. S. Chiang, "Design of optical strip-loaded waveguides with zero modal birefringence," *J. Lightwave Technol.* **16**, 1240-1248 (1998).
67. K. Worhoff, B. J. Offrein, P. V. Lambeck, G. L. Bona, and A. Driessen, "Birefringence compensation applying double-core waveguiding structures," *IEEE Photonics Technol. Lett.* **11**, 206-208 (1999).

Bibliography

68. M. Kawachi, "SILICA WAVE-GUIDES ON SILICON AND THEIR APPLICATION TO INTEGRATED-OPTIC COMPONENTS," *Opt. Quantum Electron.* **22**, 391-416 (1990).
69. S. Valette, S. Renard, H. Denis, J. P. Jadot, A. Fournier, P. Philippe, P. Gidon, A. M. Grouillet, and E. Desgranges, "SI-BASED INTEGRATED-OPTICS TECHNOLOGIES," *Solid State Technol.* **32**, 69-75 (1989).
70. G. Grand, J. P. Jadot, H. Denis, S. Valette, A. Fournier, and A. M. Grouillet, "LOW-LOSS PECVD SILICA CHANNEL WAVE-GUIDES FOR OPTICAL COMMUNICATIONS," *Electron. Lett.* **26**, 2135-2137 (1990).
71. T. Kitagawa, K. Hattori, K. Shuto, M. Yasu, M. Kobayashi, and M. Horiguchi, "AMPLIFICATION IN ERBIUM-DOPED SILICA-BASED PLANAR LIGHTWAVE CIRCUITS," *Electron. Lett.* **28**, 1818-1819 (1992).
72. T. Kitagawa, K. Hattori, Y. Hibino, and Y. Ohmori, "NEODYMIUM-DOPED SILICA-BASED PLANAR WAVE-GUIDE LASERS," *J. Lightwave Technol.* **12**, 436-442 (1994).
73. Q. Lai, M. Bachmann, and H. Melchior, "Low-loss 1xN multimode interference couplers with homogeneous output power distributions realised in silica on Si material," *Electron. Lett.* **33**, 1699-1700 (1997).
74. T. Goh, N. Yasu, K. Hattori, A. Himeno, M. Okuno, and Y. Ohmori, "Low-loss and high-extinction-ratio silica-based strictly nonblocking 16x16 thermo-optic matrix switch," *IEEE Photonics Technol. Lett.* **10**, 810-812 (1998).
75. Y. Hida, T. Fukumitsu, F. Hanawa, Y. Enomoto, S. Sumida, and N. Takato, "Highly compact silica-based PLC-type 1x32 splitters using 127 μ m-spacing output and 0.4%-Delta waveguides," *Electron. Lett.* **34**, 75-76 (1998).
76. R. A. Soref, J. Schmidtchen, and K. Petermann, "LARGE SINGLE-MODE RIB WAVE-GUIDES IN GESI-SI AND SI-ON-SIO₂," *IEEE J. Quantum Electron.* **27**, 1971-1974 (1991).
77. U. Fischer, T. Zinke, J. R. Kropp, F. Arndt, and K. Petermann, "0.1 dB/cm waveguide losses in single-mode SOI rib waveguides," *IEEE Photonics Technol. Lett.* **8**, 647-648 (1996).
78. F. Li, S. D. Jackson, C. Grillet, E. Magi, D. Hudson, S. J. Madden, Y. Moghe, C. O'Brien, A. Read, S. G. Duvall, P. Atanackovic, B. J. Eggleton, and D. J. Moss, "Low propagation loss silicon-on-sapphire waveguides for the mid-infrared," *Opt. Express* **19**, 15212-15220.
79. J. Takahashi, T. Tsuchizawa, T. Watanabe, and S. Itabashi, "Oxidation-induced improvement in the sidewall morphology and cross-sectional profile of silicon wire waveguides," *J. Vac. Sci. Technol. B* **22**, 2522-2525 (2004).
80. V. R. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," *Opt. Lett.* **28**, 1302-1304 (2003).
81. S. J. McNab, N. Moll, and Y. A. Vlasov, "Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides," *Opt. Express* **11**, 2927-2939 (2003).
82. D. Taillaert, W. Bogaerts, P. Bienstman, T. F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel, and R. Baets, "An out-of-plane grating coupler for efficient butt-coupling between compact planar waveguides and single-mode fibers," *IEEE J. Quantum Electron.* **38**, 949-955 (2002).

Bibliography

83. C. K. Tang, and G. T. Reed, "HIGHLY EFFICIENT OPTICAL-PHASE MODULATOR IN SOI WAVE-GUIDES," *Electron. Lett.* **31**, 451-452 (1995).
84. L. Colace, G. Masini, and G. Assanto, "Ge-on-Si approaches to the detection of near-infrared light," *IEEE J. Quantum Electron.* **35**, 1843-1852 (1999).
85. C. L. Schow, L. Schares, S. J. Koester, G. Dehlinger, R. John, and F. E. Doany, "A 15-Gb/s 2.4-V optical receiver using a Ge-on-SOI photodiode and a CMOS IC," *IEEE Photonics Technol. Lett.* **18**, 1981-1983 (2006).
86. H. S. Rong, R. Jones, A. S. Liu, O. Cohen, D. Hak, A. Fang, and M. Paniccia, "A continuous-wave Raman silicon laser," *Nature* **433**, 725-728 (2005).
87. L. Eldada, "Advances in telecom and datacom optical components," *Opt. Eng.* **40**, 1165-1178 (2001).
88. E. L. Wooten, K. M. Kissa, A. Yi-Yan, E. J. Murphy, D. A. Lafaw, P. F. Hallemeier, D. Maack, D. V. Attanasio, D. J. Fritz, G. J. McBrien, and D. E. Bossi, "A review of lithium niobate modulators for fiber-optic communications systems," *IEEE J. Sel. Top. Quantum Electron.* **6**, 69-82 (2000).
89. L. Eldada, and L. W. Shacklette, "Advances in polymer integrated optics," *IEEE J. Sel. Top. Quantum Electron.* **6**, 54-68 (2000).
90. GigOptix, <http://www.gigoptix.com>, Accessed July 5, 2011.
91. T. Watanabe, N. Ooba, S. Hayashida, T. Kurihara, and S. Imamura, "Polymeric optical waveguide circuits formed using silicone resin," *J. Lightwave Technol.* **16**, 1049-1055 (1998).
92. S. Herminghaus, D. Boese, D. Y. Yoon, and B. A. Smith, "LARGE ANISOTROPY IN OPTICAL-PROPERTIES OF THIN POLYIMIDE FILMS OF POLY(P-PHENYLENE BIPHENYLTETRACARBOXIMIDE)," *Applied Physics Letters* **59**, 1043-1045 (1991).
93. C. P. Wong, *Polymers for electronic and photonic applications* (Academic Press, New York, 1993).
94. A. Skumanich, and C. R. Moylan, "THE VIBRATIONAL OVERTONE SPECTRUM OF A THIN POLYMER FILM," *Chem. Phys. Lett.* **174**, 139-144 (1990).
95. W. Groh, "OVERTONE ABSORPTION IN MACROMOLECULES FOR POLYMER OPTICAL FIBERS," *Makromolekulare Chemie-Macromolecular Chemistry and Physics* **189**, 2861-2874 (1988).
96. W. B. Jackson, N. M. Amer, A. C. Boccara, and D. Fournier, "PHOTOTHERMAL DEFLECTION SPECTROSCOPY AND DETECTION," *Appl. Optics* **20**, 1333-1344 (1981).
97. H. Ma, A. K. Y. Jen, and L. R. Dalton, "Polymer-based optical waveguides: Materials, processing, and devices," *Adv. Mater.* **14**, 1339-1365 (2002).
98. Telcordia, <http://www.telcordia.com/services/genericreq/index.html>, Accessed July 5, 2011.
99. A. del Campo, and E. Arzt, "Fabrication approaches for generating complex micro- and nanopatterns on polymeric surfaces," *Chem. Rev.* **108**, 911-945 (2008).
100. Y. N. Xia, J. A. Rogers, K. E. Paul, and G. M. Whitesides, "Unconventional methods for fabricating and patterning nanostructures," *Chem. Rev.* **99**, 1823-1848 (1999).

Bibliography

101. R. Buestrich, F. Kahlenberg, M. Popall, P. Dannberg, R. Muller-Fiedler, and O. Rosch, "ORMOCER (R) s for optical interconnection technology," *J. Sol-Gel Sci. Technol.* **20**, 181-186 (2001).
102. M. Usui, M. Hikita, T. Watanabe, M. Amano, S. Sugawara, S. Hayashida, and S. Imamura, "Low-loss passive polymer optical waveguides with high environmental stability," *J. Lightwave Technol.* **14**, 2338-2343 (1996).
103. A. Norris, J. DeGroot, T. Ogawa, T. Watanabe, T. Kowalczyk, A. Baugher, and R. Blum, "High reliability of silicone materials for use as polymer waveguides," in *Linear and Nonlinear Optics of Organic Materials Iii*, M. G. Kuzyk, M. Eich, and R. A. Norwood, eds. (Spie-Int Soc Optical Engineering, Bellingham, 2003), pp. 76-82.
104. T. Watanabe, Y. Inoue, A. Kaneko, N. Ooba, and T. Kurihara, "Polymeric arrayed-waveguide grating multiplexer with wide tuning range," *Electron. Lett.* **33**, 1547-1548 (1997).
105. Gemfire, <http://www.gemfire.com>, Accessed July 5, 2011.
106. S. J. Madden, M. Zhang, B. Luther-Davies, and R. Charters, "Patterning of inorganic polymer glass waveguiding films by dry etching - art. no. 680107," in *Photonics: Design, Technology, and Packaging Iii*, W. Z. Krolikowski, C. M. Soukoulis, P. K. Lam, T. J. Davis, S. Fan, and Y. S. Kivshar, eds. (Spie-Int Soc Optical Engineering, Bellingham, 2008), pp. 80107-80107.
107. D. A. Chang-Yen, R. K. Eich, and B. K. Gale, "A monolithic PDMS waveguide system fabricated using soft-lithography techniques," *J. Lightwave Technol.* **23**, 2088-2093 (2005).
108. S. Kopetz, D. K. Cai, E. Rabe, and A. Neyer, "PDMS-based optical waveguide layer for integration in electrical-optical circuit boards," *AEU-Int. J. Electron. Commun.* **61**, 163-167 (2007).
109. S. Kopetz, E. Rabe, W. J. Kang, and A. Neyer, "Polysiloxane optical waveguide layer integrated in printed circuit board," *Electron. Lett.* **40**, 668-669 (2004).
110. M. Vogler, S. Wiedenberger, M. Muhlberger, I. Bergmair, T. Glinsner, H. Schmidt, E. B. Kley, and G. Grutzner, "Development of a novel, low-viscosity UV-curable polymer system for UV-nanoimprint lithography," *Microelectron. Eng.* **84**, 984-988 (2007).
111. A. Neyer, S. Kopetz, E. Rabe, W. J. Kang, and S. Tombrink, "Electrical-optical circuit board using polysiloxane optical waveguide layer," in *55th Electronic Components & Technology Conference, Vols 1 and 2, 2005 Proceedings(Ieee, New York, 2005)*, pp. 246-250.
112. R. A. Bellman, G. Bourdon, G. Alibert, A. Beguin, E. Guiot, L. B. Simpson, P. Lehuède, L. Guiziou, and E. LeGuen, "Ultralow loss high delta silica germania planar waveguides," *J. Electrochem. Soc.* **151**, G541-G547 (2004).
113. P. K. Tien, "LIGHT WAVES IN THIN FILMS AND INTEGRATED OPTICS," *Appl. Optics* **10**, 2395-& (1971).
114. Wikipedia, <http://en.wikipedia.org/wiki/Polydimethylsiloxane>, Accessed July 5, 2011.
115. T. W. Odom, V. R. Thalladi, J. C. Love, and G. M. Whitesides, "Generation of 30-50 nm structures using easily fabricated, composite PDMS masks," *J. Am. Chem. Soc.* **124**, 12112-12113 (2002).
116. H. D. Rowland, and W. P. King, "Polymer deformation and filling modes during microembossing," *J. Micromech. Microeng.* **14**, 1625-1632 (2004).
117. C2V, www.c2v.nl, Accessed December 3, 2011.

Bibliography

118. Y. Zhang, "Advanced polysiloxane waveguide components for telecommunications," in *Research School of Physics and Engineering*(Australian National University, 2007).
119. Bandwidth Foundry, www.bwfoundry.com/, Accessed December 3, 2011.
120. New Port, <http://www.newport.com>, Accessed December 3, 2011.
121. L. Zhu, Y. Y. Huang, W. M. J. Green, and A. Yariv, "Polymeric multi-channel bandpass filters in phase-shifted Bragg waveguide gratings by direct electron beam writing," *Opt. Express* **12**, 6372-6376 (2004).
122. J. W. Kang, M. J. Kim, J. P. Kim, S. J. Yoo, J. S. Lee, D. Y. Kim, and J. J. Kim, "Polymeric wavelength filters fabricated using holographic surface relief gratings on azobenzene-containing polymer films," *Applied Physics Letters* **82**, 3823-3825 (2003).
123. L. Eldada, C. Z. Xu, K. M. T. Stengel, L. W. Shacklette, and J. T. Yardley, "Laser-fabricated low-loss single-mode raised-rib waveguiding devices in polymers," *J. Lightwave Technol.* **14**, 1704-1713 (1996).
124. A. Kocabas, and A. Aydinli, "Polymeric waveguide Bragg grating filter using soft lithography," *Opt. Express* **14**, 10228-10232 (2006).
125. W. C. Chuang, C. K. Chao, and C. T. Ho, "Fabrication of high-resolution periodical structures on polymer waveguides using a replication process," *Opt. Express* **15**, 8649-8659 (2007).
126. T. E. Murphy, "Design, fabrication and measurement of integrated Bragg grating optical filters," in *Department of Electrical Engineering and Computer Science*(Massachusetts Institute of Technology, 2001).
127. A. Yariv, and M. Nakamura, "PERIODIC STRUCTURES FOR INTEGRATED-OPTICS," *IEEE J. Quantum Electron.* **13**, 233-253 (1977).
128. Y. Yamamoto, T. Kamiya, and H. Yanai, "IMPROVED COUPLED MODE ANALYSIS OF CORRUGATED WAVEGUIDES AND LASERS," *IEEE J. Quantum Electron.* **14**, 245-258 (1978).
129. A. Yariv, *Optical Electronics* (Oxford University Press, 1990).
130. G. E. Kohnke, C. H. Henry, E. J. Laskowski, M. A. Cappuzzo, T. A. Strasser, and A. E. White, "Silica based Mach-Zehnder add-drop filter fabricated with UV induced gratings," *Electron. Lett.* **32**, 1579-1580 (1996).
131. R. Kashyap, G. D. Maxwell, and D. L. Williams, "PHOTOCONDUCTION IN GERMANIUM AND PHOSPHORUS DOPED SILICA WAVE-GUIDES," *Applied Physics Letters* **62**, 214-216 (1993).
132. W. F. Liu, P. S. J. Russell, and L. Dong, "Acousto-optic superlattice modulator using a fiber Bragg grating," *Opt. Lett.* **22**, 1515-1517 (1997).
133. G. Gilardi, R. Asquini, A. d'Alessandro, and G. Assanto, "Widely tunable electro-optic distributed Bragg reflector in liquid crystal waveguide," *Opt. Express* **18**, 11524-11529 (2010).
134. G. Meltz, W. W. Morey, and W. H. Glenn, "FORMATION OF BRAGG GRATINGS IN OPTICAL FIBERS BY A TRANSVERSE HOLOGRAPHIC METHOD," *Opt. Lett.* **14**, 823-825 (1989).
135. K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, "BRAGG GRATINGS FABRICATED IN MONOMODE PHOTSENSITIVE OPTICAL FIBER BY UV EXPOSURE THROUGH A PHASE MASK," *Applied Physics Letters* **62**, 1035-1037 (1993).

Bibliography

136. G. Pakulski, R. Moore, C. Maritan, F. Shepherd, M. Fallahi, I. Templeton, and G. Champion, "FUSED-SILICA MASKS FOR PRINTING UNIFORM AND PHASE ADJUSTED GRATINGS FOR DISTRIBUTED FEEDBACK LASERS," *Applied Physics Letters* **62**, 222-224 (1993).
137. J. G. Goodberlet, J. T. Hastings, and H. I. Smith, "Performance of the Raith 150 electron-beam lithography system," *J. Vac. Sci. Technol. B* **19**, 2499-2503 (2001).
138. Showa-denki, <http://www.showa-denki.com/>, Accessed December 3, 2011.
139. RSoft, <http://www.rsftdesign.com/>, Accessed December 3, 2011.
140. J. Albert, S. Theriault, F. Bilodeau, D. C. Johnson, K. O. Hill, P. Sixt, and M. J. Rooks, "Minimization of phase errors in long fiber Bragg grating phase masks made using electron beam lithography," *IEEE Photonics Technol. Lett.* **8**, 1334-1336 (1996).
141. D. J. Dougherty, R. E. Muller, P. D. Maker, and S. Forouhar, "Stitching-error reduction in gratings by shot-shifted electron-beam lithography," *J. Lightwave Technol.* **19**, 1527-1531 (2001).
142. O. Bryngdahl, "Image formation using self-imaging techniques," *J. Opt. Soc. Am.* **63**, 416-419 (1973).
143. R. Ulrich, and T. Kamiya, "RESOLUTION OF SELF-IMAGES IN PLANAR OPTICAL-WAVEGUIDES," *Journal of the Optical Society of America* **68**, 583-592 (1978).
144. J. M. Heaton, R. M. Jenkins, D. R. Wight, J. T. Parker, J. C. H. Birbeck, and K. P. Hilton, "Novel 1-to-N way integrated optical beam splitters using symmetric mode mixing in GaAs/AlGaAs multimode waveguides," *Applied Physics Letters* **61**, 1754-1756 (1992).
145. M. Bachmann, M. K. Smit, P. A. Besse, E. G. H. L. B. Melchior, and Soldano, "Polarization-insensitive low-voltage optical waveguide switch using InGaAsP/InP four-port Mach-Zehnder interferometer," in *Conference on Optical Fiber Communication/International Conference on Integrated Optics and Optical Fiber Communication* (Optical Society of America, 1993), p. TuH3.
146. J. E. Zucker, K. L. Jones, T. H. Chiu, B. Tell, and K. Brown-Goebeler, "Polarization-Independent Electro-optic Waveguide Switch Using Strained InGaAs/InP Quantum Wells," in *Integrated Photonics Research* (Optical Society of America, 1992), p. PD7.
147. R. J. Deri, E. C. M. Pennings, A. Scherer, A. S. Gozdz, C. Caneau, N. C. Andreadakis, V. Shah, L. Curtis, R. J. Hawkins, J. B. D. Soole, and J. I. Song, "Ultracompact monolithic integration of balanced, polarization diversity photodetectors for coherent lightwave receivers," *Photonics Technology Letters, IEEE* **4**, 1238-1240 (1992).
148. M. T. Hill, X. J. M. Leijtens, G. D. Khoe, and M. K. Smit, "Optimizing imbalance and loss in 2 x 2 3-dB multimode interference couplers via access waveguide width," *J. Lightwave Technol.* **21**, 2305-2313 (2003).
149. N. Keil, C. Weinert, W. Wirges, H. H. Yao, S. Yilmaz, C. Zawadzki, J. Schneider, J. Bauer, M. Bauer, K. Losch, K. Satzke, W. Wischmann, and J. von Wirth, "Thermo-optic vertical coupler switches using hybrid polymer/silica integration technology," *Electron. Lett.* **36**, 430-431 (2000).
150. C. Z. Zhao, E. K. Liu, G. Z. Li, Y. Gao, and C. S. Guo, "Zero-gap directional coupler switch integrated into a silicon-on insulator for 1.3- μ m operation," *Opt. Lett.* **21**, 1664-1666 (1996).

Bibliography

151. S. Y. Lin, E. Chow, J. Bur, S. G. Johnson, and J. D. Joannopoulos, "Low-loss, wide-angle Y splitter at similar to 1.6- μ m wavelengths built with a two-dimensional photonic crystal," *Opt. Lett.* **27**, 1400-1402 (2002).
152. L. B. Soldano, F. B. Veerman, M. K. Smit, B. H. Verbeek, A. H. Dubost, and E. C. M. Pennings, "PLANAR MONOMODE OPTICAL COUPLERS BASED ON MULTIMODE INTERFERENCE EFFECTS," *J. Lightwave Technol.* **10**, 1843-1850 (1992).
153. D. J. Thomson, Y. Hu, G. T. Reed, and J. M. Fedeli, "Low Loss MMI Couplers for High Performance MZI Modulators," *IEEE Photonics Technol. Lett.* **22**, 1485-1487.
154. J. D. Love, and A. W. Snyder, *Optical waveguide theory* (Springer, 1983).
155. A. Takagi, K. Jinguji, and M. Kawachi, "SILICA-BASED WAVE-GUIDE-TYPE WAVELENGTH-INSENSITIVE COUPLERS (WINCS) WITH SERIES-TAPERED COUPLING STRUCTURE," *J. Lightwave Technol.* **10**, 1814-1824 (1992).
156. A. Takagi, K. Jinguji, and M. Kawachi, "DESIGN AND FABRICATION OF BROAD-BAND SILICA-BASED OPTICAL WAVE-GUIDE COUPLERS WITH ASYMMETRIC STRUCTURE," *IEEE J. Quantum Electron.* **28**, 848-855 (1992).
157. K. Jinguji, N. Takato, A. Sugita, and M. Kawachi, "MACH-ZEHNDER INTERFEROMETER TYPE OPTICAL WAVE-GUIDE COUPLER WITH WAVELENGTH-FLATTENED COUPLING RATIO," *Electron. Lett.* **26**, 1326-1327 (1990).
158. F. Gonthier, D. Ricard, S. Lacroix, and J. Bures, "WAVELENGTH-FLATTENED 2 X-2 SPLITTERS MADE OF IDENTICAL SINGLE-MODE FIBERS," *Opt. Lett.* **16**, 1201-1203 (1991).
159. M. G. F. Wilson, and G. A. Teh, "TAPERED OPTICAL DIRECTIONAL COUPLER," *IEEE Trans. Microw. Theory Tech.* **MT23**, 85-92 (1975).
160. R. C. Alferness, and R. V. Schmidt, "TUNABLE OPTICAL-WAVEGUIDE DIRECTIONAL COUPLER FILTER," *Applied Physics Letters* **33**, 161-163 (1978).
161. A. R. Hilton, "Optical Properties of chalcogenide glasses," *Journal of Non-Crystalline Solids* **2**, 28-39 (1970).
162. C. Quemard, F. Smektala, V. Couderc, A. Barthelemy, and J. Lucas, "Chalcogenide glasses with high non linear optical properties for telecommunications," *J. Phys. Chem. Solids* **62**, 1435-1440 (2001).
163. J. M. Harbold, F. O. Ilday, F. W. Wise, J. S. Sanghera, V. Q. Nguyen, L. B. Shaw, and I. D. Aggarwal, "Highly nonlinear As-S-Se glasses for all-optical switching," *Opt. Lett.* **27**, 119-121 (2002).
164. A. Prasad, C. J. Zha, R. P. Wang, A. Smith, S. Madden, and B. Luther-Davies, "Properties of GexAsySe1-x-y glasses for all-optical signal processing," *Opt. Express* **16**, 2804-2815 (2008).
165. J. S. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Applications of chalcogenide glass optical fibers," *C. R. Chim.* **5**, 873-883 (2002).
166. J. S. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Chalcogenide Glass-Fiber-Based Mid-IR Sources and Applications," *IEEE J. Sel. Top. Quantum Electron.* **15**, 114-119 (2009).
167. M. D. Pelusi, V. G. Ta'eed, L. B. Fu, E. Magi, M. R. E. Lamont, S. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Applications of highly-nonlinear chalcogenide glass devices

Bibliography

- tailored for high-speed all-optical signal processing," *IEEE J. Sel. Top. Quantum Electron.* **14**, 529-539 (2008).
168. J. Hu, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Maximizing the bandwidth of supercontinuum generation in As₂Se₃ chalcogenide fibers," *Opt. Express* **18**, 6722-6739 (2010).
169. J. C. Phillips, "TOPOLOGY OF COVALENT NON-CRYSTALLINE SOLIDS .1. SHORT-RANGE ORDER IN CHALCOGENIDE ALLOYS," *J. Non-Cryst. Solids* **34**, 153-181 (1979).
170. M. F. Thorpe, "CONTINUOUS DEFORMATIONS IN RANDOM NETWORKS," *J. Non-Cryst. Solids* **57**, 355-370 (1983).
171. K. Tanaka, "STRUCTURAL PHASE-TRANSITIONS IN CHALCOGENIDE GLASSES," *Phys. Rev. B* **39**, 1270-1279 (1989).
172. P. Boolchand, D. G. Georgiev, and B. Goodman, "Discovery of the intermediate phase in chalcogenide glasses," *Journal of Optoelectronics and Advanced Materials* **3**, 703-720 (2001).
173. D. A. P. Bulla, R. P. Wang, A. Prasad, A. V. Rode, S. J. Madden, and B. Luther-Davies, "On the properties and stability of thermally evaporated Ge-As-Se thin films," *Appl. Phys. A-Mater. Sci. Process.* **96**, 615-625 (2009).
174. J. A. Savage, "OPTICAL-PROPERTIES OF CHALCOGENIDE GLASSES," *J. Non-Cryst. Solids* **47**, 101-116 (1982).
175. A. B. Seddon, "CHALCOGENIDE GLASSES - A REVIEW OF THEIR PREPARATION, PROPERTIES AND APPLICATIONS," *J. Non-Cryst. Solids* **184**, 44-50 (1995).
176. A. M. Reitter, A. N. Sreeram, A. K. Varshneya, and D. R. Swiler, "MODIFIED PREPARATION PROCEDURE FOR LABORATORY MELTING OF MULTICOMPONENT CHALCOGENIDE GLASSES," *J. Non-Cryst. Solids* **139**, 121-128 (1992).
177. V. S. Shiryaev, S. V. Smetanin, D. K. Ovchinnikov, M. F. Churbanov, E. B. Kryukova, and V. G. Plotnichenko, "Effects of oxygen and carbon impurities on the optical transmission of As₂Se₃ glass," *Inorg. Mater.* **41**, 308-314 (2005).
178. T. Kanamori, Y. Terunuma, S. Takahashi, and T. Miyashita, "CHALCOGENIDE GLASS-FIBERS FOR MID-INFRARED TRANSMISSION," *J. Lightwave Technol.* **2**, 607-613 (1984).
179. J. Nishii, T. Yamashita, and T. Yamagishi, "CHALCOGENIDE GLASS-FIBER WITH A CORE CLADDING STRUCTURE," *Appl. Optics* **28**, 5122-5127 (1989).
180. J. S. Sanghera, L. E. Busse, and I. D. Aggarwal, "EFFECT OF SCATTERING CENTERS ON THE OPTICAL LOSS OF AS₂SE₃ GLASS-FIBERS IN THE INFRARED," *J. Appl. Phys.* **75**, 4885-4891 (1994).
181. M. Yamane., and A. Yoshiyuki, *Glasses for photonics* (Cambridge University Press, 2000).
182. A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, and A. L. Gaeta, "Tailored anomalous group-velocity dispersion in silicon channel waveguides," *Opt. Express* **14**, 4357-4362 (2006).
183. P. Klocek, *Handbook of infrared optical materials* (M. Dekker, 1991).
184. K. Shimakawa, A. Kolobov, and S. R. Elliott, "Photoinduced effects and metastability in amorphous semiconductors and insulators," *Adv. Phys.* **44**, 475-588 (1995).

Bibliography

185. K. Tanaka, "Photoinduced structural changes in amorphous semiconductors," *Semiconductors* **32**, 861-866 (1998).
186. M. Vlcek, and H. Jain, "Nanostructuring of chalcogenide glasses using electron beam lithography," *Journal of Optoelectronics and Advanced Materials* **8**, 2108-2111 (2006).
187. K. Tanaka, N. Toyosawa, and H. Hisakuni, "PHOTOINDUCED BRAGG GRATINGS IN AS₂S₃ OPTICAL FIBERS," *Opt. Lett.* **20**, 1976-1978 (1995).
188. T. V. Galstyan, J. F. Viens, A. Villeneuve, K. Richardson, and M. A. Duguay, "Photoinduced self-developing relief gratings in thin film chalcogenide As₂S₃ glasses," *J. Lightwave Technol.* **15**, 1343-1347 (1997).
189. M. Shokooh-Saremi, V. G. Ta'eed, N. J. Baker, I. C. M. Littler, D. J. Moss, B. J. Eggleton, Y. L. Ruan, and B. Luther-Davies, "High-performance Bragg gratings in chalcogenide rib waveguides written with a modified Sagnac interferometer," *J. Opt. Soc. Am. B-Opt. Phys.* **23**, 1323-1331 (2006).
190. N. Ho, J. M. Laniel, R. Vallee, and A. Villeneuve, "Photosensitivity of As₂S₃ chalcogenide thin films at 1.5 μ m," *Opt. Lett.* **28**, 965-967 (2003).
191. G. Yang, H. S. Jain, A. T. Ganjoo, D. H. Zhao, Y. S. Xu, H. D. Zeng, and G. R. Chen, "A photo-stable chalcogenide glass," *Opt. Express* **16**, 10565-10571 (2008).
192. E. M. Vogel, M. J. Weber, and D. M. Krol, "NONLINEAR OPTICAL PHENOMENA IN GLASS," *Phys. Chem. Glasses* **32**, 231-254 (1991).
193. T. M. Monro, and H. Ebendorff-Heidepriem, "Progress in microstructured optical fibers," *Ann. Rev. Mater. Res.* **36**, 467-495 (2006).
194. M. Sheikbahae, A. A. Said, T. H. Wei, D. J. Hagan, and E. W. Vanstryland, "SENSITIVE MEASUREMENT OF OPTICAL NONLINEARITIES USING A SINGLE BEAM," *IEEE J. Quantum Electron.* **26**, 760-769 (1990).
195. G. P. Agrawal, *Nonlinear fiber optics* (Academic Press Inc., 2007).
196. Y. L. Ruan, W. T. Li, R. Jarvis, N. Madsen, A. Rode, and B. Luther-Davies, "Fabrication and characterization of low loss rib chalcogenide waveguides made by dry etching," *Opt. Express* **12**, 5140-5145 (2004).
197. G. Lenz, J. Zimmermann, T. Katsufuji, M. E. Lines, H. Y. Hwang, S. Spalter, R. E. Slusher, S. W. Cheong, J. S. Sanghera, and I. D. Aggarwal, "Large Kerr effect in bulk Se-based chalcogenide glasses," *Opt. Lett.* **25**, 254-256 (2000).
198. R. E. Slusher, G. Lenz, J. Hodelin, J. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Large Raman gain and nonlinear phase shifts in high-purity As₂Se₃ chalcogenide fibers," *J. Opt. Soc. Am. B-Opt. Phys.* **21**, 1146-1155 (2004).
199. V. Mizrahi, K. W. DeLong, G. I. Stegeman, M. A. Saifi, and M. J. Andrejco, "2-PHOTON ABSORPTION AS A LIMITATION TO ALL-OPTICAL SWITCHING," *Opt. Lett.* **14**, 1140-1142 (1989).
200. M. Asobe, T. Kanamori, and K. Kubodera, "ULTRAFast ALL-OPTICAL SWITCHING USING HIGHLY NONLINEAR CHALCOGENIDE GLASS-FIBER," *IEEE Photonics Technol. Lett.* **4**, 362-365 (1992).

Bibliography

201. S. Spalter, H. Y. Hwang, J. Zimmermann, G. Lenz, T. Katsufuji, S. W. Cheong, and R. E. Slusher, "Strong self-phase modulation in planar chalcogenide glass waveguides," *Opt. Lett.* **27**, 363-365 (2002).
202. P. A. Thielen, L. B. Shaw, P. C. Pureza, V. Q. Nguyen, J. S. Sanghera, and I. D. Aggarwal, "Small-core As-Se fiber for Raman amplification," *Opt. Lett.* **28**, 1406-1408 (2003).
203. M. R. E. Lamont, B. Luther-Davies, D. Y. Choi, S. Madden, and B. J. Eggleton, "Supercontinuum generation in dispersion engineered highly nonlinear ($\gamma=10/\text{W/m}$) As₂S₃ chalcogenide planar waveguide," *Opt. Express* **16**, 14938-14944 (2008).
204. P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," in *24th European Conference on Optical Communication, Vol 1-3: Vol 1: Regular and Invited Papers; Vol 2: Tutorials and Symposium Papers; Vol 3: Postdeadline Papers* (Telefonica Espana Sa, Madrid, 1998), pp. 475-476.
205. V. G. Ta'eed, N. J. Baker, L. B. Fu, K. Finsterbusch, M. R. E. Lamont, D. J. Moss, H. C. Nguyen, B. J. Eggleton, D. Y. Choi, S. Madden, and B. Luther-Davies, "Ultrafast all-optical chalcogenide glass photonic circuits," *Opt. Express* **15**, 9205-9221 (2007).
206. T. D. Vo, H. Hu, M. Galili, E. Palushani, J. Xu, L. K. Oxenlowe, S. J. Madden, D. Y. Choi, D. A. P. Bulla, M. D. Pelusi, J. Schroder, B. Luther-Davies, and B. J. Eggleton, "Photonic chip based transmitter optimization and receiver demultiplexing of a 1.28 Tbit/s OTDM signal," *Opt. Express* **18**, 17252-17261 (2010).
207. J. M. Gonzalez-Leal, R. Prieto-Alcon, M. Vlcek, and E. Marquez, "Structural and optical characterization of amorphous As₄₀S₆₀ and As₄₀Se₆₀ films prepared by plasma-enhanced chemical vapor deposition," *J. Non-Cryst. Solids* **345**, 88-92 (2004).
208. J. M. Gonzalez-Leal, M. Stuchlik, M. Vlcek, R. Jimenez-Garay, and E. Marquez, "Influence of the deposition technique on the structural and optical properties of amorphous As-S films," *Appl. Surf. Sci.* **246**, 348-355 (2005).
209. D. Dijkkamp, T. Venkatesan, X. D. Wu, S. A. Shaheen, N. Jisrawi, Y. H. Minlee, W. L. McLean, and M. Croft, "PREPARATION OF Y-BA-CU OXIDE SUPERCONDUCTOR THIN-FILMS USING PULSED LASER EVAPORATION FROM HIGH-TC BULK MATERIAL," *Applied Physics Letters* **51**, 619-621 (1987).
210. K. E. Youden, T. Grevatt, R. W. Eason, H. N. Rutt, R. S. Deol, and G. Wylangowski, "PULSED-LASER DEPOSITION OF GA-LA-S CHALCOGENIDE GLASS THIN-FILM OPTICAL WAVEGUIDES," *Applied Physics Letters* **63**, 1601-1603 (1993).
211. R. Eason, *Pulsed laser deposition of thin films* (Wiley-Interscience, 2007).
212. S. Ramachandran, and S. G. Bishop, "Low loss photoinduced waveguides in rapid thermally annealed films of chalcogenide glasses," *Applied Physics Letters* **74**, 13-15 (1999).
213. W. C. Tan, M. E. Solmaz, J. Gardner, R. Atkins, and C. Madsen, "Optical characterization of a-As₂(S)₃ thin films prepared by magnetron sputtering," *J. Appl. Phys.* **107**, 6 (2010).
214. D. W. Harwood, E. R. Taylor, R. Moore, and D. Payne, "Fabrication of fluoride glass planar waveguides by hot dip spin coating," *J. Non-Cryst. Solids* **332**, 190-198 (2003).
215. A. K. Mairaj, R. J. Curry, and D. W. Hewak, "Chalcogenide glass thin films through inverted deposition and high velocity spinning," *Electron. Lett.* **40**, 421-422 (2004).

Bibliography

216. R. J. Nemanich, G. A. N. Connell, T. M. Hayes, and R. A. Street, "THERMALLY INDUCED EFFECTS IN EVAPORATED CHALCOGENIDE FILMS .1. STRUCTURE," *Phys. Rev. B* **18**, 6900-6914 (1978).
217. R. A. Jarvis, R. P. Wang, A. V. Rode, C. Zha, and B. Luther-Davies, "Thin film deposition of Ge₃₃As₁₂Se₅₅ by pulsed laser deposition and thermal evaporation: Comparison of properties," *J. Non-Cryst. Solids* **353**, 947-949 (2007).
218. M. Frumar, Z. Polak, and Z. Cernosek, "Raman spectra and photostructural changes in the short-range order of amorphous As-S chalcogenides," *J. Non-Cryst. Solids* **257**, 105-110 (1999).
219. J. M. Laniel, J. M. Menard, K. Turcotte, A. Villeneuve, R. Vallee, C. Lopez, and K. A. Richardson, "Refractive index measurements of planar chalcogenide thin film," *J. Non-Cryst. Solids* **328**, 183-191 (2003).
220. D. Y. Choi, S. Madden, D. Bulla, R. P. Wang, A. Rode, and B. Luther-Davies, "Thermal annealing of arsenic tri-sulphide thin film and its influence on device performance," *J. Appl. Phys.* **107**, 6 (2010).
221. F. Billes, V. Mitsa, I. Fejes, N. Mateleshko, and I. Fejsa, "Calculation of the vibrational spectra of arsenic sulfide clusters," *J. Mol. Struct.* **513**, 109-115 (1999).
222. R. P. Wang, S. J. Madden, C. J. Zha, A. V. Rode, and B. Luther-Davies, "Annealing induced phase transformations in amorphous As₂S₃ films," *J. Appl. Phys.* **100**, 4 (2006).
223. H. Kawazoe, H. Yanagita, Y. Watanabe, and M. Yamane, "IMPERFECTIONS IN AMORPHOUS CHALCOGENIDES .1. ELECTRICALLY NEUTRAL DEFECTS IN LIQUID SULFUR AND ARSENIC SULFIDES," *Phys. Rev. B* **38**, 5661-5667 (1988).
224. K. Tanaka, "CHEMICAL AND MEDIUM-RANGE ORDERS IN AS₂S₃ GLASS," *Phys. Rev. B* **36**, 9746-9752 (1987).
225. S. Hosokawa, Y. Sakaguchi, H. Hiasa, and K. Tamura, "OPTICAL-ABSORPTION SPECTRA OF LIQUID AS₂S₃ AND AS₂SE₃ OVER A WIDE TEMPERATURE-RANGE," *J. Phys.-Condes. Matter* **3**, 6673-6677 (1991).
226. V. V. Zigel, A. A. Litvinenko, G. K. Ulyanov, and G. A. Chalabyan, "ULTRASONIC DISPERSIVE WAVEGUIDE WITH A LAYER OF CHALCOGENIDE GLASS ON LITHIUM-NIOBATE," *Soviet Physics Acoustics-Ussr* **21**, 77-77 (1975).
227. Y. Ohmachi, "ACOUSTOOPTICAL LIGHT DIFFRACTION IN THIN-FILMS," *J. Appl. Phys.* **44**, 3928-3933 (1973).
228. S. Zembutsu, and S. Fukunishi, "WAVEGUIDING PROPERTIES OF (SE,S)-BASED CHALCOGENIDE GLASS-FILMS AND SOME APPLICATIONS TO OPTICAL-WAVEGUIDE DEVICES," *Appl. Optics* **18**, 393-399 (1979).
229. C. Meneghini, K. Le Foulgoc, E. J. Knystautas, A. Villeneuve, T. Cardinal, and K. A. Richardson, "Ion implantation: an efficient method for doping or fabricating channel chalcogenide glass waveguides," in *Materials Modification by Ion Irradiation* (Spie-Int Soc Optical Engineering, Bellingham, 1998), pp. 146-153.
230. K. Turcotte, J. M. Laniel, A. Villeneuve, C. Lopez, and K. Richardson, "Fabrication and characterization of chalcogenide optical waveguides," in *Integrated Photonics Research, Technical Digest* (Optical Soc America, Washington, 2000), pp. 305-308.
231. A. K. Mairaj, A. Fu, H. N. Rutt, and D. W. Hewak, "Optical channel waveguide in chalcogenide (Ga : La : S) glass," *Electron. Lett.* **37**, 1160-1161 (2001).

Bibliography

232. A. Feigel, Z. Kotler, B. Sfez, A. Arsh, M. Klebanov, and V. Lyubin, "Chalcogenide three-dimensional photonic structures," in *Integrated Optics Devices V* (Spie-Int Soc Optical Engineering, Bellingham, 2001), pp. 249-251.
233. O. M. Efimov, L. B. Glebov, K. A. Richardson, E. Van Stryland, T. Cardinal, S. H. Park, M. Couzi, and J. L. Bruneel, "Waveguide writing in chalcogenide glasses by a train of femtosecond laser pulses," *Opt. Mater.* **17**, 379-386 (2001).
234. A. Saliminia, A. Villeneuve, T. V. Galstyan, S. LaRochelle, and K. Richardson, "First- and second-order Bragg gratings in single-mode planar waveguides of chalcogenide glasses," *J. Lightwave Technol.* **17**, 837-842 (1999).
235. A. Saliminia, K. Le Foulgoc, A. Villeneuve, and T. Galstian, "Photoinduced Bragg reflectors in As-S-Se/As-S based chalcogenide glass multilayer channel waveguides," *Fiber Integrated Opt.* **20**, 151-158 (2001).
236. M. Shokooh-Saremi, V. G. Ta'eed, I. C. M. Littler, D. J. Moss, B. J. Eggleton, Y. Ruan, and B. Luther-Davies, "Ultra-strong, well-apodised Bragg gratings in chalcogenide rib waveguides," *Electron. Lett.* **41**, 738-739 (2005).
237. V. G. Ta'eed, M. Shokooh-Saremi, L. B. Fu, D. J. Moss, M. Rochette, I. C. M. Littler, B. J. Eggleton, Y. L. Ruan, and B. Luther-Davies, "Integrated all-optical pulse regenerator in chalcogenide waveguides," *Opt. Lett.* **30**, 2900-2902 (2005).
238. N. J. Baker, H. W. Lee, I. C. M. Littler, C. M. de Sterke, B. J. Eggleton, D. Y. Choi, S. Madden, and B. Luther-Davies, "Sampled Bragg gratings in chalcogenide (As₂S₃) rib-waveguides," *Opt. Express* **14**, 9451-9459 (2006).
239. K. Finsterbusch, N. Baker, V. G. Ta'eed, B. J. Eggleton, D. Choi, S. Madden, and B. Luther-Davis, "Long-period gratings in chalcogenide (As₂S₃) rib waveguides," *Electron. Lett.* **42**, 1094-1095 (2006).
240. J. Fick, B. Nicolas, C. Rivero, K. Elshot, R. Irwin, K. A. Richardson, M. Fischer, and R. Vallee, "Thermally activated silver diffusion in chalcogenide thin films," *Thin Solid Films* **418**, 215-221 (2002).
241. R. M. Bryce, H. T. Nguyen, P. Nakeeran, R. G. DeCorby, P. K. Dwivedi, C. J. Haugen, J. N. McMullin, and S. O. Kasap, "Direct UV patterning of waveguide devices in AS(2)Se(3) thin films," *J. Vac. Sci. Technol. A* **22**, 1044-1047 (2004).
242. R. G. DeCorby, N. Ponnampalam, M. M. Pai, H. T. Nguyen, P. K. Dwivedi, T. J. Clement, C. J. Haugen, J. N. McMullin, and S. O. Kasap, "High index contrast waveguides in chalcogenide glass and polymer," *IEEE J. Sel. Top. Quantum Electron.* **11**, 539-546 (2005).
243. C. C. Huang, and D. W. Hewak, "Silver-doped germanium sulphide glass channel waveguides fabricated by chemical vapour deposition and photo-dissolution process," *Thin Solid Films* **500**, 247-251 (2006).
244. J. F. Viens, C. Meneghini, A. Villeneuve, T. V. Galstian, E. J. Knystautas, M. A. Duguay, K. A. Richardson, and T. Cardinal, "Fabrication and characterization of integrated optical waveguides in sulfide chalcogenide glasses," *J. Lightwave Technol.* **17**, 1184-1191 (1999).
245. J. J. Hu, V. Tarasov, N. Carlie, N. N. Feng, L. Petit, A. Agarwal, K. Richardson, and L. Kimerling, "Si-CMOS-compatible lift-off fabrication of low-loss planar chalcogenide waveguides," *Opt. Express* **15**, 11798-11807 (2007).

Bibliography

246. J. J. Hu, N. N. Feng, N. Carlie, L. Petit, J. F. Wang, A. Agarwal, K. Richardson, and L. Kimerling, "Low-loss high-index-contrast planar waveguides with graded-index cladding layers," *Opt. Express* **15**, 14566-14572 (2007).
247. J. J. Hu, N. N. Feng, N. Carlie, L. Petit, A. Agarwal, K. Richardson, and L. Kimerling, "Optical loss reduction in high-index-contrast chalcogenide glass waveguides via thermal reflow," *Opt. Express* **18**, 1469-1478 (2010).
248. J. J. Hu, V. Tarasov, A. Agarwal, L. Kimerling, N. Carlie, L. Petit, and K. Richardson, "Fabrication and testing of planar chalcogenide waveguide integrated microfluidic sensor," *Opt. Express* **15**, 2307-2314 (2007).
249. J. J. Hu, N. Carlie, N. N. Feng, L. Petit, A. Agarwal, K. Richardson, and L. Kimerling, "Planar waveguide-coupled, high-index-contrast, high-Q resonators in chalcogenide glass for sensing," *Opt. Lett.* **33**, 2500-2502 (2008).
250. D. Y. Choi, S. Madden, A. Rode, R. P. Wang, and B. Luther-Davis, "Dry etching characteristics of amorphous As₂S₃ film in CHF₃ plasma," *J. Appl. Phys.* **104**, 6 (2008).
251. A. C. Y. Liu, X. Chen, D. Y. Choi, and B. Luther-Davies, "Annealing-induced reduction in nanoscale heterogeneity of thermally evaporated amorphous As₂(S)₃ films," *J. Appl. Phys.* **104**, 7 (2008).
252. D. Y. Choi, S. Madden, D. A. Bulla, R. Wang, A. Rode, and B. Luther-Davies, "Submicrometer-Thick Low-Loss As₂S₃ Planar Waveguides for Nonlinear Optical Devices," *IEEE Photonics Technol. Lett.* **22**, 495-497 (2010).
253. S. J. Madden, D. Y. Choi, D. A. Bulla, A. V. Rode, B. Luther-Davies, V. G. Ta'eed, M. D. Pelusi, and B. J. Eggleton, "Long, low loss etched As₂S₃ chalcogenide waveguides for all-optical signal regeneration," *Opt. Express* **15**, 14414-14421 (2007).
254. M. Galili, J. Xu, H. C. H. Mulvad, L. K. Oxenlowe, A. T. Clausen, P. Jeppesen, B. Luther-Davies, S. Madden, A. Rode, D. Y. Choi, M. Pelusi, F. Luan, and B. J. Eggleton, "Breakthrough switching speed with an all-optical chalcogenide glass chip: 640 Gbit/s demultiplexing," *Opt. Express* **17**, 2182-2187 (2009).
255. M. D. Pelusi, F. Luan, S. Madden, D. Y. Choi, D. A. Bulla, B. Luther-Davies, and B. J. Eggleton, "Wavelength Conversion of High-Speed Phase and Intensity Modulated Signals Using a Highly Nonlinear Chalcogenide Glass Chip," *IEEE Photonics Technol. Lett.* **22**, 3-5.
256. C. Vigreux-Bercovici, E. Bonhomme, A. Pradel, J. E. Broquin, L. Labadie, and P. Kern, "Transmission measurement at 10.6 μ m of Te₂As₃Se₅ rib waveguides on As₂S₃ substrate," *Applied Physics Letters* **90**, 3 (2007).
257. Z. G. Lian, W. Pan, D. Furniss, T. M. Benson, A. B. Seddon, T. Kohoutek, J. Orava, and T. Wagner, "Embossing of chalcogenide glasses: monomode rib optical waveguides in evaporated thin films," *Opt. Lett.* **34**, 1234-1236 (2009).
258. X. H. Zhang, Y. Guimond, and Y. Bellec, "Production of complex chalcogenide glass optics by molding for thermal imaging," *J. Non-Cryst. Solids* **326**, 519-523 (2003).
259. A. B. Seddon, W. J. Pan, D. Furniss, C. A. Miller, H. Rowe, D. Zhang, E. McBrearty, Y. Zhang, A. Loni, P. Sewell, and T. M. Benson, "Fine embossing of chalcogenide glasses - A new fabrication route for photonic integrated circuits," *J. Non-Cryst. Solids* **352**, 2515-2520 (2006).

Bibliography

260. W. J. Pan, H. Rowe, D. Zhang, Y. Zhang, A. Loni, D. Furniss, P. Sewell, T. M. Benson, and A. B. Seddon, "Step hot embossing of optical rib waveguides in chalcogenide glasses," *Microw. Opt. Technol. Lett.* **50**, 1961-1963 (2008).
261. M. Solmaz, H. Park, C. K. Madsen, and X. Cheng, "Patterning chalcogenide glass by direct resist-free thermal nanoimprint," *J. Vac. Sci. Technol. B* **26**, 606-610 (2008).
262. Dow-Corning, <http://www.dowcorning.com>, Accessed July 28, 2011.
263. Gelest, Barry C. Arkles, and G. L. Larson, *Silicon compounds: silanes and silicones* (Gelest Inc., 2008).
264. T. Qu, D. G. Georgiev, P. Boolchand, and M. Micoulaut, "The intermediate phase in ternary $\text{Ge}_x\text{As}_x\text{Se}_{1-2x}$ glasses," in *Supercooled Liquids, Glass Transition and Bulk Metallic Glasses*, T. Egami, A. L. Greer, A. Inoue, and S. Ranganathan, eds. (Materials Research Society, Warrendale, 2003), pp. 111-122.

Appendix

In Chapter 5, the design of optimization of Multimode interference (MMI) couplers is presented. Simulations using Beam Propagation method showed at small MMI section width, the corresponding MMI 1st order 3-dB lengths at minimum insertion loss and minimum power imbalance were different. With an increase in the MMI section width, this MMI lengths difference become smaller and this trend is shown by the following Figures.

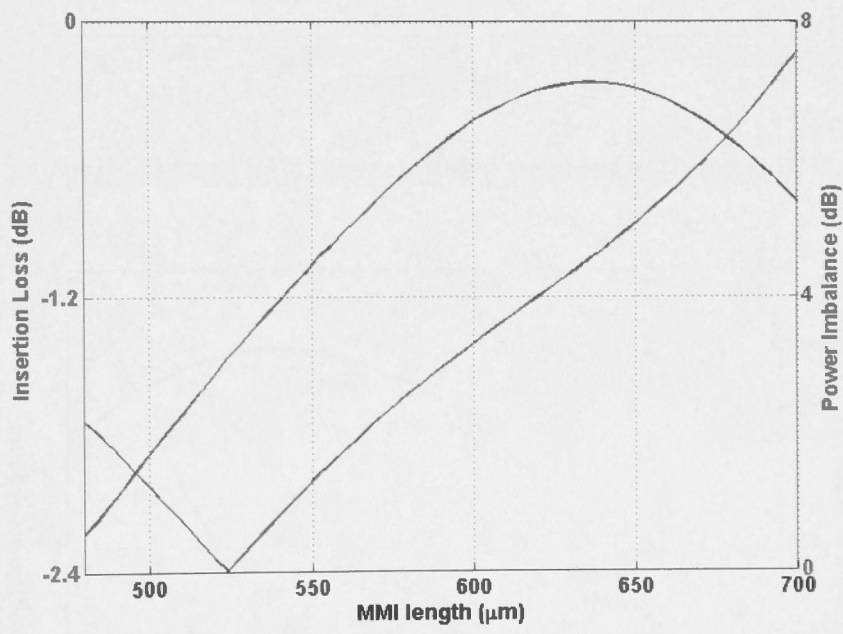


Figure A1: MMI insertion loss and power imbalance versus MMI length (MMI width = 30μm)

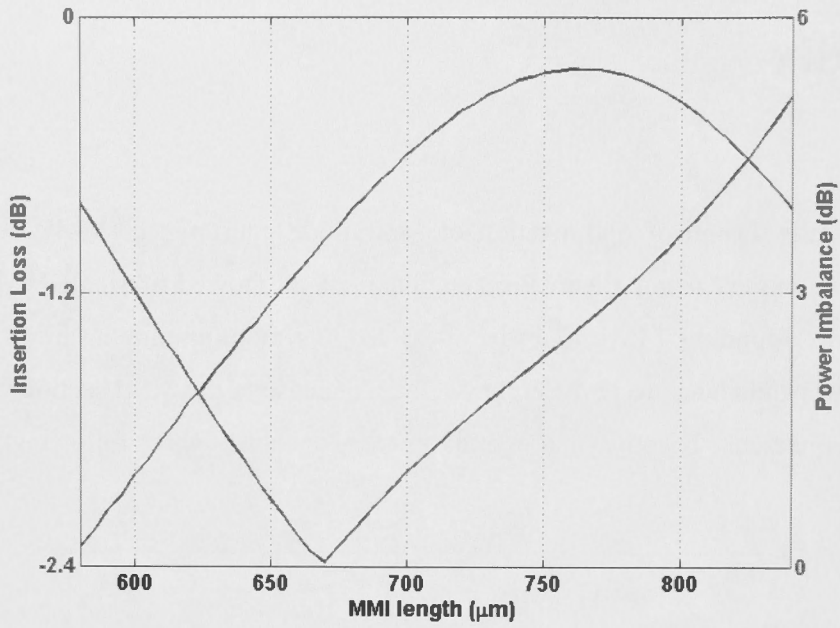


Figure A2: MMI insertion loss and power imbalance versus MMI length (MMI width = 33μm)

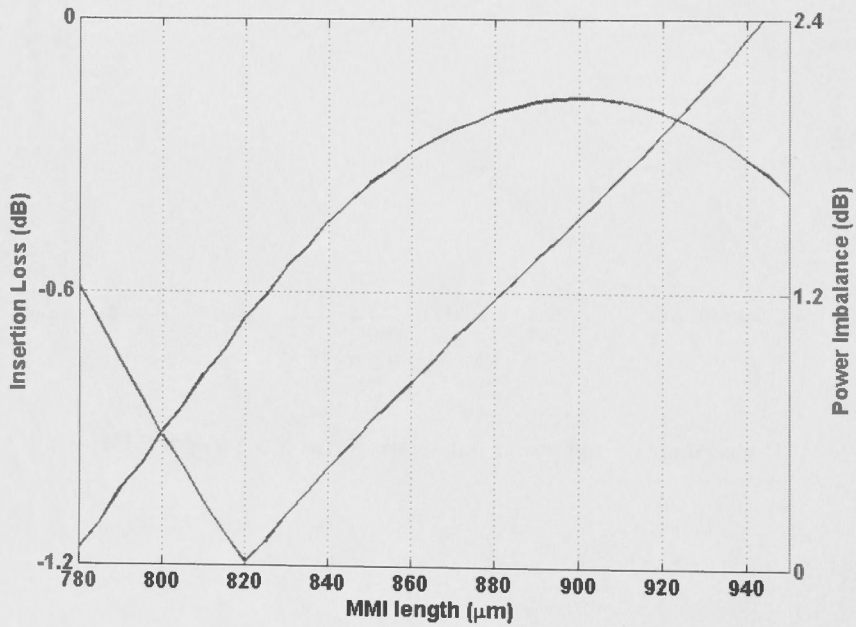


Figure A3: MMI insertion loss and power imbalance versus MMI length (MMI width = 36μm)

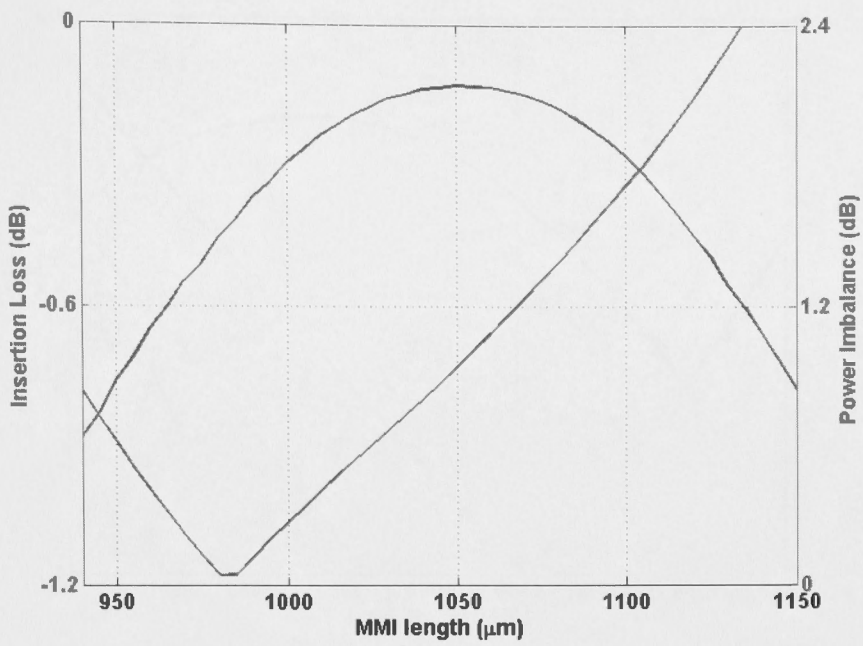


Figure A4: MMI insertion loss and power imbalance versus MMI length (MMI width = 39 μm)

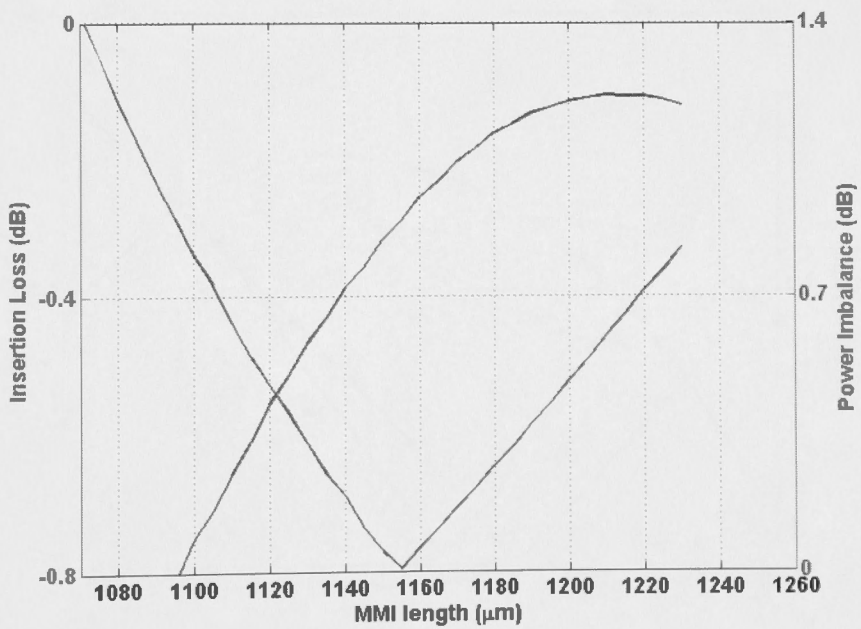


Figure A5: MMI insertion loss and power imbalance versus MMI length (MMI width = 42 μm)

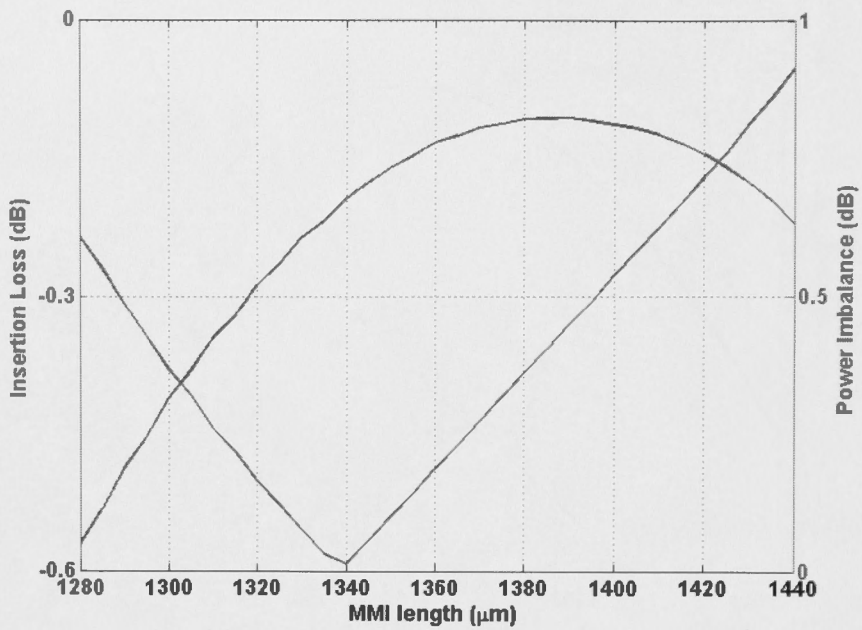


Figure A6: MMI insertion loss and power imbalance versus MMI length (MMI width = 45μm)

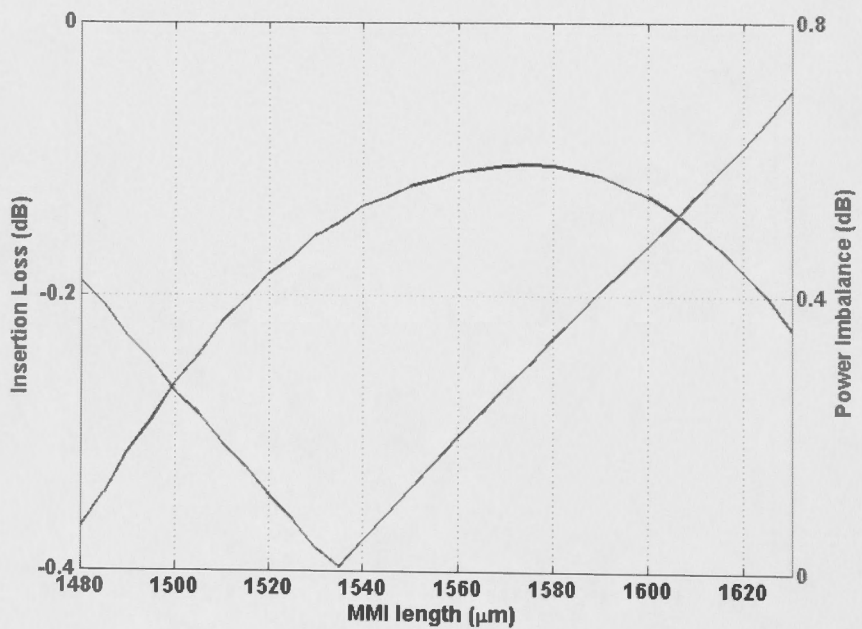


Figure A7: MMI insertion loss and power imbalance versus MMI length (MMI width = 48μm)

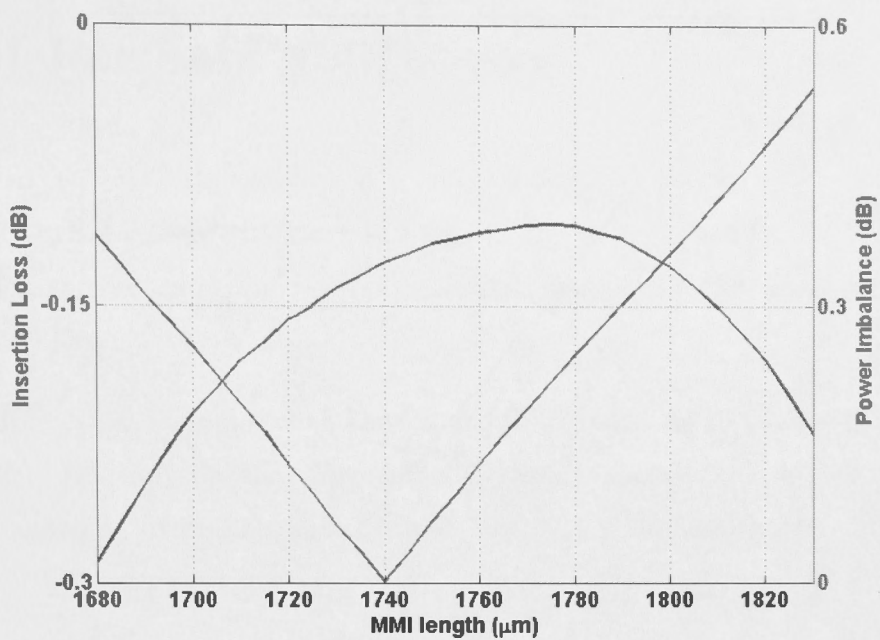


Figure A8: MMI insertion loss and power imbalance versus MMI length (MMI width = 51 μm)

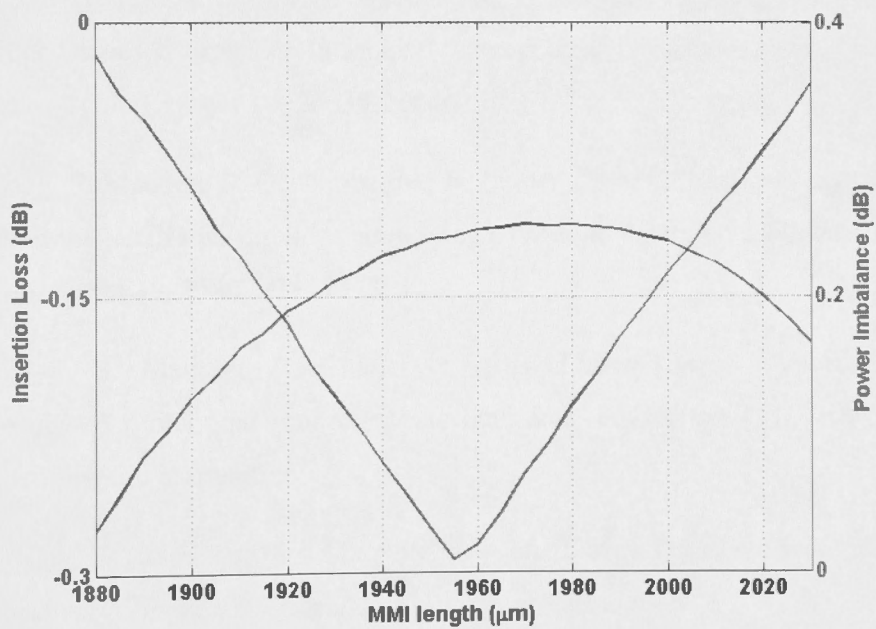


Figure A9: MMI insertion loss and power imbalance versus MMI length (MMI width = 54 μm)

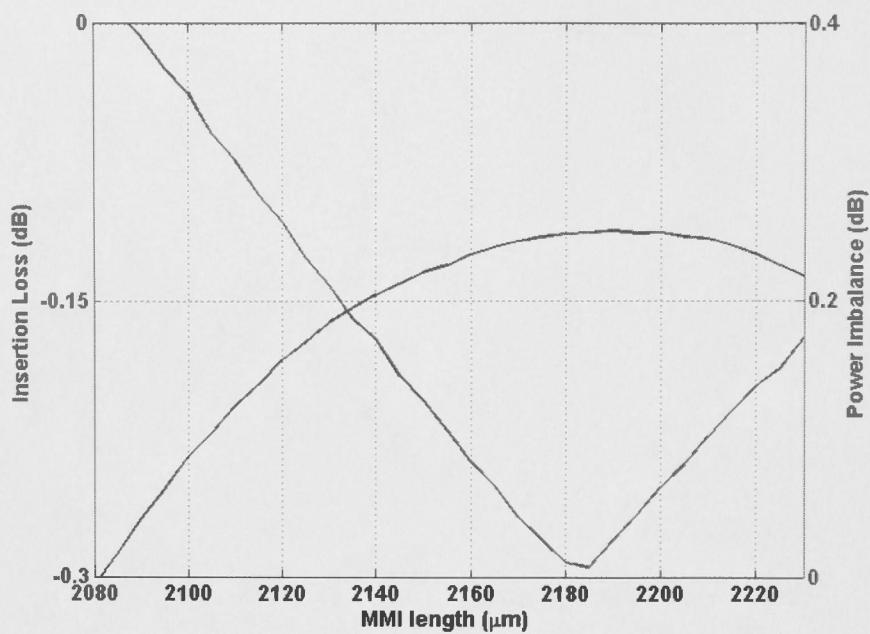


Figure A10: MMI insertion loss and power imbalance versus MMI length (MMI width = 57 μm)

List of Journal Publications

1. T. Han, S. Madden, M. Zhang, R. Charters, and B. Luther-Davies, "Low loss high index contrast nanoimprinted polysiloxane waveguides," Opt. Express 17, 2623-2630 (2009).
2. T. Han, S. Madden, B. Luther-Davies, and R. Charters, "High-Quality Polarization-Insensitive Polysiloxane Waveguide Gratings Produced by UV Nanoimprint Lithography," IEEE Photonics Technol. Lett. 22, 1720-1722 (2010).
3. T. Han, S. Madden, D. Bulla, and B. Luther-Davies, "Low loss Chalcogenide glass waveguides by thermal nano-imprint lithography," Opt. Express 18, 19286-19291 (2010).
4. X. Gai, T. Han, A. Prasad, S. Madden, D. Y. Choi, R. P. Wang, D. Bulla, and B. Luther-Davies, "Progress in optical waveguides fabricated from chalcogenide glasses," Opt. Express 18, 26635-26646 (2010).
5. T. Han, S. Madden, S. Debbarma and B. Luther-Davies, "Improved method for hot embossing As₂S₃ waveguides employing a thermally stable chalcogenide coating," Opt. Express 19, 25447–25453 (2011).
6. T. Han, S. Madden, R. Charters and B. Luther-Davies, "Fabrication error insensitive directional couplers, design and fabrication – 3-dB couplers" (Manuscript in preparation)
7. T. Han, S. Madden, R. Charters and B. Luther-Davies, "Fabrication error insensitive directional couplers, design and fabrication – 1310/1550nm WDM couplers" (Manuscript in preparation)