Third Order Bragg Grating Filters in
Silicon-On-Insulator Waveguides

by

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A thesis presented to the School of Electronics and Physical Sciences,
University of Surrey, for the award of Doctor of Philosophy (Ph.D.)

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September 2005
Abstract

The subject of this thesis is the design, analysis, fabrication and characterisation of third order Bragg grating optical filters on silicon-on-insulator (SOI) rib waveguides. New design guidelines for small cross sectional SOI waveguides have been proposed and described to address the issue of satisfying polarisation independence and single mode conditions simultaneously. This waveguide design will be used as a building block for the realisation of Bragg grating filters. The reflection spectral response of the deep Bragg grating operating in a third diffraction order on a single mode rib SOI waveguide has been studied theoretically using Floquet-Bloch Theory (FBT) developed in Politecnico di Bari, Italy in comparison with optical modelling software utilising Coupled Mode Theory (CMT). A series of Bragg gratings with different grating etch depths and lengths were fabricated at Southampton University to investigate the agreement between experimental results with theoretical predictions. The wavelength tuning capability of these Bragg grating filters in SOI waveguide structures were also investigated and implemented using the thermo-optic effect, through Joule heating of thin film aluminium heaters situated on top of the rib structure.

The SOI rib waveguides with 1.5μm height are designed to exhibit polarisation independence and single mode operation. The Bragg grating filter is designed to operate at a wavelength of 1.55μm with a grating period of 689nm. The less rigorous fabrication tolerance of third order grating in comparison with that required by 228nm first order gratings is highly desirable only at the expense of slightly lower maximum reflectivity. The maximum reflectivity measurements of approximately 0.42 for third order grating are in agreement with theoretical prediction by FBT. The Bragg grating filters were thermally tuned to shift the Bragg resonance wavelength by up to 3.5nm with heater power of approximately 190mW. The tuning range of the filter is inhibited by the short lifetime of the heater caused by electromigration. At the time this work was carried out, this is the first demonstration of thermo-optic tuning through an integrated heating element, of third order Bragg grating filters based on small cross sectional SOI waveguide. The temperature sensitivity of the Bragg grating filters was
analysed using a 2-D finite element method (FEM) and was consistent with the experimental results.

Key words: silicon-on-insulator (SOI), single mode condition, polarisation independent, Bragg gratings filter, Floquet-Bloch theory, Coupled Mode theory, thermo-optic.
This work is dedicated to my father and mother, for working hard to provide me with the best educational opportunities and for supporting all of my decisions.
Acknowledgements

This thesis would not have been possible without the excellent guidance, patience and encouragement of my supervisor, Prof. Graham Reed. Prof. Reed’s direction proved invaluable with regard to technical matters, research approaches and the presentation of this work. I have benefited from many stimulating conversations with Dr. Vittorio Passaro; many of the grating simulation presented in this work could not have been accomplished without his helpful advice and assistance. I am grateful to Prof. A. G. R. Evans, Dr. G. Ensell and Dr. R. M. H. Atta for device fabrication. I would like to thank Dr. D. Prather and Dr. J. Murakowski for graciously providing a test grating sample.

I would like to thank Agilent Technologies (Singapore) and University of Surrey for supporting my Ph.D. studentship. Working with the members of Advanced Technology Institute’s Silicon Photonics group has been a great pleasure. I am indebted to a number of talented people, including Dr. C. E. Png, Dr. S. T. Lim and Dr. G. Masanovic, W. Headley for countless days and nights spent working in the laboratory, discussing work and sharing bitter sweet moment together. I couldn’t possibly enumerate the ways in which W. Headley and Dr. G. Y. Chen have helped me out in the lab and SEM analysis. It has been a pleasure to work with my research colleagues B. Timotijevic, F. Gardes, S. Howe, P. Waugh, P. Yang and D. Thompson. I would like to extend my gratitude to Dr. B. Sekhawat, Dr. R. Smith and Dr. B. Colombeau for their continuous encouragement and support. Special thanks also go to Dr. R. T. M. Wong, Dr. T. G. Lim, Dr. H. N. Ang, Dr. D. Stephens, Dr. S. Galata, Ms. J. Mefo, Ms. M. Webb and Mr. P. Mistry for further enhance my experience at Surrey. Several individuals outside the research group have been a constant source of moral and warmth support, including Mr. S. P. Chang, Ms. Julie Leong, Ms. Emily Yip, Ms. R. Laoarpasuwong, Ms. Venetia Ng, Ms. Catherine Ching, Mr. J. Waterer and Ms. N. Takano.

Finally, I would like to acknowledge my parents, Chan Chun Hing and Loke Ling Sin, sister, brother and grandmother for their tireless love and unconditional support at every stage of my life.
Publications


## Contents

Abstract ii  
Acknowledgements v  
Publications vi  
Contents viii

### 1 Introduction

1-1  
References 1-5

### 2 Literature Review

2-1  
2.1 Introduction 2-1  
2.2 Silicon Photonics 2-1  
2.2.1 Single Mode SOI Waveguide 2-2  
2.3 Bragg Gratings on Waveguide Structures 2-12  
2.3.1 Gratings on Rib Waveguide Structures 2-13  
2.3.2 Bragg Reflector/Fabry-Perot on Waveguide Structures 2-22  
2.3.3 Thermo-Optic Effect (TOE) based Silicon Devices 2-27  
2.4 Summary 2-30  
References 2-31

### 3 Theory and Analysis

3-1  
3.1 Introduction 3-1  
3.2 Waveguide Design Theories 3-2  
3.2.1 Maxwell Equations 3-2  
3.2.2 Small Cross Sectional SOI Rib Waveguides 3-7  
3.2.3 Single-Mode Condition 3-8  
3.2.3.1 Numerical Simulation 3-10  
3.2.3.2 Waveguide Width and Etch Depth Influence 3-11  
3.2.3.3 Waveguide Height Influence 3-14  
3.2.4 Zero Birefringence 3-16  
3.2.5 Satisfying Single-Mode and Zero Birefringence Conditions Simultaneously 3.22  
3.2.6 Design Guidelines for Small Cross Sectional SOI Waveguides 3.26
3.2.7 Waveguide Design Summary

3.3 Bragg Gratings Theory

3.3.1 Coupled Mode Theory

3.3.2 Floquet-Bloch Theory

3.4 Characteristics of a Bragg Grating Filter

3.4.1 Resonance Wavelength

3.4.2 Bandwidth

3.5 Summary

References

4 Device Design

4.1 Introduction

4.2 Waveguide Bend and Y-Junction

4.3 Third Order Bragg Grating Filter

4.3.1 Coupled Mode Theory

4.3.1.1 Grating Coupling Strength

4.3.1.2 Grating Reflectivity and Grating Length

4.3.2 Floquet-Bloch Theory

4.3.2.1 Simulation of Modal Reflection

4.3.2.2 Leakage Factor

4.3.3 Comparison between CMT and FBT Simulation Results

4.4 The Thermo-Optic Effect

4.4.1 Aluminium Heater Design

4.4.2 Thermal Isolation Trench

4.4.3 Thickness of Buffer Layer

4.4.4 Resonant Wavelength Shift

4.5 Summary

References

5 Device Fabrication

5.1 Introduction

5.2 General Fabrication Processes

5.2.1 SOI Waveguide Dimensions
5.2.2 Photolithography
   5.2.2.1 Photoresist
   5.2.2.2 Stepper Photolithography
   5.2.2.3 Electron Beam Lithography (EBL)
5.2.3 Silicon Etching
5.2.4 Chemical Vapour Deposition (CVD)
5.2.5 Critical Dimension (CD) Control
5.3 Fabrication Process Flow
   5.3.1 Fabrication Steps
   5.3.2 Scanning Electron Microscopy (SEM) Analysis
5.4 Summary
References

6 Experiment Techniques
6.1 Introduction
6.2 Sample Preparation
   6.2.1 Polishing Technique
6.3 Experimental Techniques
   6.3.1 Coupling Loss
      6.3.1.1 Overlap of Excitation and Waveguide Field
      6.3.1.2 Influence of Waveguide Geometry Variation
      6.3.1.3 Fresnel Reflection
   6.3.2 Waveguide Losses
   6.3.3 Reflection Measurement
   6.3.4 Evaluation of Reflectivity
   6.3.5 Thermo-Optic Tuning
6.4 Summary
References

7 Experiment Results and Discussion
7.1 Introduction
7.2 SOI Waveguide Propagation Loss
7.3 Bragg Grating Reflection
7.3.1 Experimental Results 7-6
7.3.2 Comparison of Theory and Experimental Results 7-8
7.3.3 Analysis of Non-Functional Devices 7-19
7.4 Characterisation of Aluminium Heater 7-23
  7.4.1 Measured I/V and Simulated Results 7-23
  7.4.2 Temperature Dependent Resistance 7-26
  7.4.3 Electromigration of Aluminium Heater 7-28
7.5 Thermo-Optic Tuning of Bragg Grating Filter 7-32
7.6 Summary 7-39
References 7-41

8 Summary, Conclusion and Future Work 8-1
  8.1 Introduction 8-1
  8.2 Summary and Conclusion 8-1
  8.3 Future Work 8-5
References 8-9
Chapter 1

The grass withers, and the flowers fade, but the word of our God stands forever.

Isaiah 40:8

1 Introduction

There is a strong trend towards the fabrication of smaller photonic devices to improve device performance and cost efficiency [1.1]. Silicon-on-insulator (SOI) based photonics offers unique optical properties owing to the inherent large refractive index difference (~2.0) between silicon and silicon dioxide (SiO₂). This provides high optical confinement in the waveguide structure which is highly desirable for miniaturisation of waveguide dimensions.

The recent research breakthroughs in the emission and fast modulation of light in silicon have provided an opportunity for the monolithic integration of optical components compatible with existing microelectronics fabrication. Silicon based modulators using the plasma dispersion effect have been demonstrated experimentally to achieve modulation speed exceeding 1GHz [1.2] and showing potential to scale up to achieve bandwidth of 10Gb/s [1.3] with device optimisation. The demonstration of Raman effect lasing [1.4] in a silicon waveguide cavity on a single chip represents a critical milestone towards the realisation of silicon based light source [1.5]. Recently, a high speed and small size silicon electro-optical modulator [1.6] based on SOI ring resonator structure with 12 micrometers in diameter has been demonstrated, leading to the potential further miniaturisation of single chip integration with other silicon optical components. While many different materials have been explored to fabricate grating filters for wavelength division multiplexed system, SOI represents a platform that is truly compatible with standard microelectronics fabrication processing and highly promising for low cost and high volume production.

A Bragg grating is formed by creating a periodic corrugation or refractive index modulation in an optical waveguide. It is commonly achieved by imprinting in a
photosensitive optical fibre or physically patterned in planar or rib waveguide. These gratings structures can exhibit the characteristics of wavelength selective filters whereby they reflect a designated wavelength of interest while transmitting all the other remaining wavelengths. Bragg gratings are widely deployed in the field of optical telecommunication as filters, add/drop multiplexers and dispersion compensators. Some of the more prominent advantages in the implementation of Bragg gratings in waveguide structures are that they can achieve a desired filter response by tailoring the variation of grating etch depth, period and length. A high index contrast material with high optical confinement such as SOI allows the realisation of integrated Bragg gratings more compactly than their fibre counterparts. In addition, the SOI waveguide based Bragg gratings filter fabrication process can integrate multiple grating with Mach-Zehnder Interferometers (MZI) [1.7], filters [1.8], modulators [1.4] and wavelength sources [1.2] on the same silicon die, leading to the potential of an all optical system on a chip and large-scale integrated optical circuits. One of the critical challenges in the realisation of Bragg gratings in SOI is the requirement of submicrometer grating structures measuring approximately 114nm (228nm period) for 1.55μm operating wavelength patterned over a relatively long optical waveguide. Small cross sectional SOI waveguide structures are more sensitive to Bragg gratings because the perturbation of the refractive index modulation is proportionally larger. Hence, the combination of higher order diffraction gratings and moderate grating etch depth relaxes the strict fabrication requirement to achieve the filter response at the expense of smaller maximum reflectivity than the first diffraction order gratings.

The conventional Bragg gratings used in fibres usually have a weak grating perturbation, i.e. gratings are shallow with amplitude much less than a grating period or the refractive index modulation of the fibre gratings is usually small compared to the refractive index difference of the waveguide. These gratings can be theoretically described using standard Coupled Mode Theory (CMT) by taking into account only one forward and one backward propagating mode of the single mode waveguide. This is based on the fact that the gratings act as a small perturbation that mutually couples these modes, leaving radiation and higher order modes unexcited. The approach based on the coupling of two counter propagating modes is not sufficient for deeply etched
gratings on high refractive index difference structure such as SOI. From a modelling point of view, it can appear challenging to simulate the structure of Bragg grating filter with commercial available optical modelling tools using numerical methods such as the beam propagation method (BPM) or the finite different time domain (FDTD). However, the BPM cannot handle multiple reflections from the grating and rigorous method such as FDTD cannot simulate the whole of the gratings section without the requirement of large amount of memory, computation power and time. A quasi-3D Floquet-Bloch Theory (FBT) developed by Passaro and Armenise [1.9] has been utilised to explore the capabilities of the algorithm for deeply etched gratings on SOI waveguides.

A SOI waveguide based Bragg grating filter subjected to temperature changes through resistive heating can exhibit tuning capabilities due to the strong thermo-optic coefficient of silicon compared to silica. Upon driving the heater on top of the rib waveguide structure separated by a thin layer of top cladding SiO₂, the heat flux will flow towards the rib region where the majority of the propagating mode is concentrated, before spreading to the slab and substrate region. This subjects the propagation of optical mode in the rib waveguide region to effective index changes by thermo-optic effect in turn shifting the Bragg resonance wavelength.

This work was initiated to study the spectral properties of deeply etch gratings on SOI waveguides with FBT in comparison with experimental observations. Prior to this, we numerically analysed and provided a new design guideline for the single mode condition and polarisation independence of small cross sectional SOI waveguides on which the gratings will be built. The tuning capabilities of the third order diffraction Bragg grating filter was further explored using thermo-optic effect through Joule heating of an integrated thin film heater.

This thesis is organised into the following chapters describing the design, fabrication and measurement of third order diffraction Bragg grating filters on small cross sectional SOI waveguide.

Chapter 2 will provide the overview of the design rules used in achieving single mode SOI waveguide. This is followed by reviewing different types of Bragg grating filters.
implemented on waveguide structures and thermo-optic effect in silicon based devices in the literature. Chapter 3 will describe the theoretical approach and the new design guidelines for deeply etched small cross sectional SOI waveguide. This is followed by presenting the merit of FBT and CMT for the simulation of Bragg gratings.

Chapter 4 will detail the design and analysis of Bragg gratings and the thermo-optic effect in the waveguide structure. The principal contribution from this portion of the work will be to identify the critical SOI waveguide fabrication requirements to achieve single mode condition and polarisation independence simultaneously. By CMT and FBT numerical simulation, the gratings geometry such as grating etch depth, length and periods was designed and selected to achieve a desired spectral response.

Chapter 5 will describe the development and implementation of fabrication techniques for Bragg gratings on SOI rib waveguides. Each of the fabrication steps involved in this work is discussed briefly. In chapter 6, the sample preparation procedures and techniques to produce good facet quality for optical measurement is studied. Subsequently, the experimental setups to measure the propagation loss of waveguide, reflectivity measurement and thermo-optic tuning of the Bragg grating filter are presented.

Chapter 7 will compare the measured reflection spectral response of the Bragg grating filter with FBT theoretical predictions. The characterisation of the integrated aluminium heater and thermo-optic tuning performance of the filter are discussed. The influence of heater temperature on the effective index changes on the filter is compared with 2D finite element method (FEM) and experimental results. Finally in chapter 8 conclusions are drawn, the summary of achievements in this work is given and future improvements and suggestions concerning the research are presented.
Chapter 1: Introduction

References:


Chapter 2

You are the light of the world—like a city on a mountain, glowing in the night for all to see.  

Matthew 5:14

2 Literature Review

2.1 Introduction

This chapter consists of two main sections of the literature review. The first section gives an overview of recent developments in silicon photonics technology. This is then followed by the review of low loss SOI waveguides along with the single mode and birefringence free condition. The second section is devoted to the investigation of Bragg grating and Bragg reflectors on waveguide structures, particularly the Bragg grating on a rib waveguide. Subsequently, silicon based devices which exploit the high thermo-optic effect in silicon will be described.

2.2 Silicon Photonics

In the past decades, silicon has received relatively low interest as a viable alternative optical material in comparison with more exotic III-V materials such as indium phosphide (InP), gallium arsenide (GaAs) and lithium niobate (LiNbO3). According to Reed [2.1], there are two main reasons for this. First, silicon does not have an inherent mechanism for the emission of light: it is an indirect bandgap material, which means that its crystalline structure makes it impossible to fabricate a laser. Second, silicon does not exhibit a linear electro-optic effect known as the Pockels effect, which is an important characteristic for fast modulation of light.

Recently, there has been dramatic progress towards a silicon light source such as doping with erbium to overcome the indirect bandgap in silicon [2.2], dislocation engineering [2.3] and optical amplification through the Raman effect [2.4]. The recent break-through developments in silicon such as fast silicon modulator in the gigahertz region [2.5, 2.6] and continuous-wave Raman silicon laser [2.7, 2.8] have gone some way to overcome the two main aforementioned obstacles. These exciting
developments in silicon photonics have paved the way for real monolithic integration on a single silicon chip using conventional microelectronics fabrication infrastructure to drive the cost down and all optical circuit can be truly realised in the near future.

### 2.2.1 Single-mode SOI Waveguide

Silicon-on-insulator (SOI) is an attractive optical material since it offers the potential of monolithic integration of optical and electrical circuits on a single substrate. In addition, silicon is transparent at telecommunication wavelengths in particular from 1.53-1.61μm and SOI technology provides a strong confinement of the optical mode, leading to the realisation of small optical components due to the inherently high refractive index difference between the silicon guiding and the insulating layer.

SOI technology is based on a simple wafer structure: a thin layer of high quality, monocrystalline silicon on an insulating substrate or on a conductive substrate with an intermediate insulating layer. A typical SOI planar waveguide configuration is shown in Figure 2-1. The silicon guiding layer is separated from the silicon substrate by the buried silicon dioxide (BOX) layer. The purpose of the BOX layer is to act as lower cladding to prevent the evanescent optical field from leaking into silicon substrate.

![Figure 2-1: (a) Cross section area of SOI planar waveguide and (b) 1D optical field confinement.](image)

The SOI planar waveguide provides one dimensional confinement of optical field vertically because of the high refractive index contrast between the guiding layer of silicon \(n_{Si} \approx 3.5\) and buried SiO2 \(n_{SiO2} \approx 1.4\) layer. Rib waveguides are usually used to achieve optical confinement in two dimensions; this can be achieved by introducing additional geometrical confinement through etching the silicon guiding layer using dry reactive ion etching or wet chemical etching techniques. Using the former technique, the resulting rib waveguide structure will have vertical sidewalls and the
latter will result in sloping sidewalls. The single mode condition for both rib waveguide geometries will be reviewed in the next section.

It is often assumed that the cross section dimensions of a 3D rib waveguide must be similar to the thickness of a single mode slab region in order to allow only the lowest order optical (fundamental) mode to propagate. A numerical example in [2.1] which used the effective index method (EIM) to find the number of planar waveguide, demonstrated that in order for a single-mode operation in an SOI waveguide at $\lambda_0 = 1.3\mu m$, the waveguide height need to be less than approximately $0.2\mu m$. It is rather surprising that rib waveguides with silicon overlayer thickness of several microns, which constitutes a large cross section, are claimed to exhibit single mode operation in the literature [e.g. 2.10, 2.11, 2.16 2.20].

It was first demonstrated by Petermann [2.10] using a mode matching technique, that rib waveguides for a large cross section area (compared to wavelength) can exhibit single-mode behaviour. The author argued that no higher order vertical mode can exist in the rib waveguide region, since higher order vertical modes under the rib region of waveguide height, $H$ couple to the slab modes $(h)$ with higher effective index values, therefore yielding high leakage losses. Figure 2-2 illustrates (a) the cross section of a vertical sidewall SOI waveguide with corresponding waveguide parameters and (b) fundamental optical mode profile. The authors expressed this mathematically via the following equation related to waveguide parameters [2.10]:

\[\text{ equation }\]
Chapter 2: Literature Review

\[ V = \frac{\pi}{2} \frac{W}{H_{\text{eff}}} \sqrt{\left(\frac{H_{\text{eff}}}{h_{\text{eff}}}\right)^2 - 1} \]  

(4.1)

Where \( H_{\text{eff}} \) and \( h_{\text{eff}} \) denote effective heights of center rib and slab region when the evanescent field decaying outside the silicon waveguide is accounted for. In 1991, Soref et al. [2.11] published an outstanding research paper that demonstrated this effect theoretically, using the beam propagation method (BPM) to simulate the higher order modes leaking out to the slab region, leaving only the fundamental mode propagating in the rib region. This is shown in Figure 2-3 by a series of simulated cross sections of the optical mode profile at different propagation distances in the \( z \)-direction. A Gaussian beam was deliberately launched off axis in the rib waveguide structure to excite higher order modes existing in the waveguide. In this example, it becomes apparent that higher order modes slowly coupled to the slab region until \( z = 2000\mu\text{m} \), where only the fundamental mode remains in the rib waveguide. The authors then derived a simplified expression for the single-mode condition (SMC) for relatively large rib waveguides:

\[ \frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1 - r^2}} \]  

(4.2)

\[ W \leq 0.3H + \frac{h}{\sqrt{1 - \left(\frac{h}{H}\right)^2}} \]  

(4.3)

\[ 0.5 \leq r < 1.0 \]

Equation (4.3) imposed the restriction of the analysis in parameter \( r \) (see Figure 2-2(a)). Thus, the analytical equation is limited to rib waveguides with shallow etch depth. Since the publication of this work, many authors have demonstrated low loss single-mode waveguides with large cross section both for sloping (trapezoidal) [2.12, 2.13] sidewall and near vertical [2.14, 2.15] sidewall SOI waveguides. The former waveguide structure has a sidewall angle of 54.74°, arising from anisotropic chemical etching whereas the latter waveguide structure can be realised with reactive ion
etching technique. Fabrication techniques in SOI waveguide will be further discussed in chapter 5. It is perhaps a little surprising that equation (4.2) was used by Schmidtchen et al. [2.12] and Zinke et al. [2.13], and widely accepted in their analysis to determine single-mode operation although this equation was initially derived for vertical sidewall SOI structure, and their structures were formed by wet etching, and had angled rib walls.

\[
\begin{align*}
  n_0 &= 1.00 \\
  n_1 &= 3.50 \\
  n_2 &= 1.45 \\
  z &= 0 \mu\text{m} \\
  z &= 250 \mu\text{m} \\
  z &= 500 \mu\text{m} \\
  z &= 1000 \mu\text{m} \\
  z &= 2000 \mu\text{m}
\end{align*}
\]

Figure 2-3: Beam propagation simulation of a rib waveguide [2.11].

The precise conditions to describe single mode behaviour for vertical and sloping wall SOI rib waveguide have been pursued by several authors based on experimental observation and theoretical analysis. In 1994, Rickman et al. [2.14] fabricated a matrix of rib waveguides of different waveguide dimensions to study the effect of waveguide rib etch depth, width, interface roughness and mode characteristics of SOI structures. In the author's analysis, single mode propagation criterion was not included in the discussion. Thus, Pogossian et al. [2.16] used experimental results of Rickman et al. [2.14] and effective index method (EIM) to reconsider the single mode conditions proposed in equation (4.2). The authors postulated that more stringent
criteria needed to be imposed in order to satisfy single mode requirement for vertical sidewall rib waveguide.

By utilising curve fitting techniques and EIM analysis, their new design criterion can be expressed by:

\[
\frac{W}{H} \leq c + \frac{r}{\sqrt{1-r^2}}
\]

\[
W \leq cH + \frac{h}{\sqrt{1-\left(\frac{h}{H}\right)^2}}
\]

The authors used a variable \( c \) for comparison with equation (4.2), but in their analysis the variable took the value of 0, hence imposing more restrictive conditions on the waveguide design process. Nevertheless, all the design equations reported in the literature so far are limited to shallow rib etches where the ratio of slab to rib height is bigger than 0.5. Referring to Figure 2-4 in the region within the limit of a deep etch (\( r \)
< 0.5), it is clearly shown the lack of experimental data points imply that neither the
curves of EIM nor BPM theoretical analysis is convincing enough. If additional data
points are available in those deeply etch regions, it will enable a clearer distinction
between the two approaches since those data points will influence the slope of the
fitted curve and in turn the variable $c$ in equation (4.4). Furthermore, it has been
demonstrated that polarisation independent operation [2.17-2.18, 2.25-2.27] can be
obtained by employing deep etched rib in SOI waveguide. The single mode condition
in rib waveguide for parameter $r < 0.5$ has to be addressed since it is desirable to
realise a waveguide which satisfy both single mode and polarisation independent
condition simultaneously. In theory, by carefully controlling waveguide width to
height ratio, it is possible to design birefringence free waveguide and possibly single
mode operation necessary for many photonic components. It is commonly known that
both conditions may not be satisfied simultaneously in all cases. This design issue is
discussed further in Chapter 4.

![Figure 2-5: General structure of vertical and trapezoidal SOI rib waveguides [2.20].](image)

Powell [2.20] made a more general analysis for rib waveguides with angled sidewalls,
finding a simple analytical expression for such waveguides that was in good
agreement with the original work of Soref et al. [2.11]. Figure 2-5 shows the cross
sectional schematic diagram of angled sidewall SOI rib waveguides. With simple
trigonometry for the slope of 54.74°, the waveguide width at the top region is related
by:

$$W_t = W_b - \sqrt{2}(H-h)$$  \hspace{1cm} (4.5)

He demonstrated that scalar approximation in BPM is sufficiently accurate for large
rib waveguides with shallow etch depth (large parameter $r$), where the mode intensity
and distribution are similar for both polarisations. The author plotted Figure 2-6 to
compare the boundary between single mode/multimode with other published work [2.11, 2.16]. With inclusion of geometrical considerations in equation (4.5) and BPM simulation, the author derived a new expression for a single mode condition for trapezoidal large cross section depicted in Figure 2-5 as:

\[
\frac{W_b}{H} \leq 0.3 + \frac{h}{H} \sqrt{1 - \left(\frac{h}{H}\right)^2 - \frac{(H-h)^2}{\sqrt{2W_bH}}} \tag{4.6}
\]

The restriction of equation(4.3) also applies in here to enable vertical modes in the planar/slab region on each side of the rib to become higher than the effective index of vertical modes in the rib, other than the fundamental mode. However, he did not discuss the validity of this equation when the cross section of the SOI waveguide is reduced, where polarisation effect imposed on the waveguide geometry becomes dominant. Cheben et al. [2.21] suggested that trapezoidal waveguides are more robust, which makes fabrication tolerance less stringent when scaling down photonics waveguide devices dimensions. These authors addressed the polarisation issue by presenting novel approaches to control the waveguide birefringence using the stress in an overcladding film [2.22] and inducing form birefringence through deposition of alternating layers of high and low index materials.

![Figure 2-6: Waveguide width to height ratio, \(W/H\) as a function of slab to waveguide height ratio for single-mode cut-off for different approximations based on trapezoidal rib structure [2.20].](image)
In 2002, Vivien et al. [2.18] presented a theoretical analysis of the influence of waveguide parameters on the polarisation properties for single mode SOI rib waveguides. The SOI rib waveguide dimensions (height, width and etch depth) leading to the requirements of single mode propagation and polarisation independence being calculated for waveguide heights ranging from 0.75μm to 2μm for operating wavelength of λ₀ 1.53μm and 1.61μm, shown in Figure 2-7. In this work, it has been shown that the single mode condition limits the waveguide width, but it is also valid for deeply etched waveguides unlike previous published work [2.10, 2.11].

Figure 2-7: SOI rib waveguide parameters supporting single-mode and polarisation independent for waveguide height H from 0.75μm to 2μm at 1.53μm.

In their analysis, much attention was drawn to the etch depth influence on waveguide birefringence for different waveguide heights, but the single mode conditions were not discussed in detail and only referred to via the design equation (4.2) for single mode operation. Considering the SOI rib waveguide dimensions in their work, this constitutes analysis of small cross sectional devices compared to other larger cross section[2.10 - 2.12], this raises some concern whether the same design equation (4.2) is applicable and sufficient to describe the single mode behaviour with small waveguide dimensions.

Lousteau et al. [2.24] suggested that the widely used large cross section SOI rib waveguide design criteria proposed by Soref et al. [2.11] is not sufficient to ensure single mode behaviour. Waveguide geometries that the design formula [2.11] predicts should be single mode, were shown to support higher order vertical modes that did not
couple or leak to the slab region. In order to remain consistent with Rickman et al.'s [2.14] experimental observation, the authors employed waveguide heights, $H$ of 7.5µm and 3µm and operating wavelength of 1.523µm to calculate the complex modal index which in turns gives attenuation constants for all the modes existing in the waveguide geometry of interest.

![Contour plot of attenuation as a function of geometry for SOI rib waveguides](image)

**Figure 2-8**: Contours of equal loss as a function of geometry for SOI rib waveguides operating at 1.523µm for $HE_{20}$ through $HE_{50}$ modes [2.24]. The triangular and dot in the plot indicated experimental data exhibit single mode and multimode from Rickman et al. [2.14].

Figure 2-8 represents the contour plot of attenuation as a function of waveguide geometry obtained for $HE_{20}$ through $HE_{50}$ modes in comparison with experimental results of Rickman et al. [2.14] and boundaries between single and multimode behaviour predicted by Soref et al. [2.11] and Pogossian et al. [2.16]. The analysis applied here is restricted to $r > 0.5$, i.e., deeply etched ribs are not considered. A high attenuation constant in the contour plot indicates that the particular waveguide geometry is high loss in nature, hence only fundamental mode remains in the waveguide. The results from the authors suggested that some higher order modes $HE_{n0}$ ($n > 1$) are guided with low loss, implying that these waveguides are effectively multimode. It is therefore apparent that the single mode design criteria is more complex than previously understood.

Recently, Aalto et al. [2.28] proposed a new single mode condition for SOI rib waveguides and numerically analysed waveguide heights of 3µm and 10µm in particular. They utilised full vectorial modal analysis to observe optical mode profiles of the waveguide geometries of interest and validated with a 3D BPM. Figure 2-9 depicts the theoretical and simulated single mode conditions for 3µm rib waveguides.

2-10
at TE and TM polarisations. The “transition zone” as suggested by the authors, where the higher order mode is expected to leak according to simulations (black dots), is illustrated with grey colour separately for horizontal 10 mode and vertical 01 mode. The authors then derived an equation based on their simulation results to describe the single mode condition in two regions yielding:

\[
W < W_{\text{SM}} = \begin{cases} 
W_{\text{Soref},Q} & \text{if } (Q + h)^2 - 4(Q + H)^2 \leq 0 \\
\min\left(W_{\text{Soref},Q}, W_{10}\right) & \text{if } (Q + h)^2 - 4(Q + H)^2 > 0
\end{cases}
\] (4.7)

\[
W_{10} = c_t (Q + H) + \frac{1}{\sqrt{(Q + h)^2 - 4(Q + H)^2}}
\] (4.8)

\[
Q_{\text{TE}} = \frac{\lambda}{\pi \sqrt{n_{1}^2 - n_{0}^2}} \quad \text{for TE polarisation and}
\]

\[
Q = \begin{cases} 
Q_{\text{TE}} \left(\frac{n_{1}}{n_{0}}\right)^2 & \text{for TM polarisation}
\end{cases}
\] (4.9)

where \(W_{10}\) represent the cut-off limits for 10 and 01 modes indicated by the dashed lines in Figure 2-9. \(W_{\text{Soref}}\) describes Soref et al. [2.11] single mode limit, \(c_t\) is a
numerical fitting parameter with optimum value of -0.1, $Q$ is the effective height which taken into account of evanescent field decaying in different polarisation. The authors did highlight that the single mode condition can be achieved in deeply etched ribs ($r < 0.5$) for relatively large cross section, however failed to address polarisation independent operation and systematic studies of small cross section SOI rib waveguide in their design. The author has continued this work, presenting an analysis that evaluates both the single mode condition and polarisation independence. This is discussed further is Chapter 3.

2.3 Bragg Gratings on Waveguide Structures

Wavelength filters are an essential component in modern long-haul and metropolitan optical fiber communication systems. The need to lower system costs is driving a trend toward the increased integration of optical devices into more compact subsystems with higher functionality. Waveguide-based integrated-optical technologies are being developed to address this requirement. In this section, numerous integrated waveguide filters, such as Bragg gratings on waveguides and Fabry-Perot cavities formed by deeply etch grating are reviewed. A Bragg grating is formed by creating a periodic corrugation or refractive index modulation in optical waveguides and fibres. These structures function as a wavelength selective filter, reflecting a narrow band of wavelengths while transmitting all other wavelength. The spectral response of such a filter can be configured or tailored to achieve a desired filter response with the implementation of shallow or deep grating etches.

Physically patterned Bragg gratings in planar and rib waveguide structures offer a number of advantages compared to implementation of gratings in photosensitive optical fibre. For the realization of gratings in optical fibers, GeO$_2$ doped silica fiber is exposed to ultraviolet (UV) light to increase the refractive index periodically in the guide core and the maximum refractive index change observed is often small. The filters are typically several millimetres to several centimetres long, consisting of thousands of periods. Bragg grating in integrated optical devices can be realised using processes such as doping, implantation or various etching processes where the strength of the refractive index perturbation could be significantly higher then
achieved in fibre, which would result in more compact devices. Integrated gratings can contain precise phase shifts and variation in grating strength to achieve a desired filter response. In addition, one can realise Bragg gratings in non-photosensitive material such as silicon utilising mature process technology and potentially monolithic integration with other optical components such as modulators, ring resonators, arrayed waveguide gratings etc. to provide additional functionality in a single optical chip.

2.3.1 Gratings on Rib Waveguide Structures

Narrow band optical filters are vital components for optical network links which incorporate wavelength division multiplexing (WDM). Grating filters in periodically corrugated rib waveguides have been shown to exhibit high extinction ratios over a narrow band of frequencies [2.44]. Their reflection response can be tailored by proper apodisation of the grating structure [2.43]. Using rib waveguide structures as the design platform, the polarisation effect on the waveguide can be minimised or controlled with appropriate waveguide height to width ratio. The selection of a rib waveguide structure as the design platform is more favourable than fibre systems that are highly susceptible to stress induced birefringence. Since standard single mode fibres do not maintain polarisation, devices insensitive to polarisation are required for the operation in wavelength division multiplexing (WDM) systems. In this section, we review alternative device structures supporting the implementation of gratings besides the aforementioned planar waveguide and optical fibre platform. In the published literature, Bragg gratings can be configured as shallow and long periodic refractive index perturbations on the top [2.41 - 2.43] or sidewall [2.44] of the rib waveguide. In addition, Bragg grating also can form grating resonator filters [2.56, 2.59] which resemble the Fabry-Perot etalon where the mirrors are replaced by a pair of distributed Bragg reflectors (DBR) with deep and short grating etch on the waveguide structure.

In 1987, Yi-Yan et al. [2.38] reported and demonstrated first-order narrowband Bragg grating in GaAs/GaAlAs based on rib waveguide structures for operation at \( \lambda_0 = 1.5 \mu m \). The waveguide dimensions supporting single mode operation with rib widths ranging from 2 to 5 \( \mu m \) and grating length of 2500 \( \mu m \) and grating period of 225nm. The proposed grating filter was based on a rib waveguide height of 1.8 \( \mu m \), slab height
Chapter 2: Literature Review

of 1.0μm and surface corrugation depth of 400nm. Figure 2-10 shows the top view SEM image of the fabricated device with rib width of 2μm. The authors observed that with angular displacement of 2° misalignment between the patterned grating mask and waveguide mask, leading to reduction of coupling efficiency to 44% for rib width of 5μm. This grating filter not only exhibits high reflectivity of 92% at TE polarisation, low polarisation dependence of 0.2nm also being observed which translated into small birefringence of 4.4×10⁻⁴. This pioneering work has created an enormous interest in this class of narrowband grating filter being explored in other materials such as InP and silicon.

Figure 2-10: Top view SEM image of a 2μm wide rib waveguide based GaAs/GaAlAs Bragg grating filter with grating period of 225nm [2.38].

In 1989, Cremer and co-workers [2.39] fabricated various type of grating filters based on planar, rib and stripe geometry, shown in Figure 2-11. A first-order Bragg grating on the InP material system for the 1.5μm wavelength region, with 230nm grating periods were implemented on top of the device structures. It was found that the waveguide structure with InP as cover layer exhibits polarisation independent operation where the Bragg wavelength difference in TE and TM modes can be reduced from 2.2nm to 0.3nm when rib waveguide structure was compared with strip geometry. The corresponding channel spacing of 1nm and filter bandwidth of 0.2nm with crosstalk attenuations of -10dB was observed for strip geometry.
In the same year, Cremer et al. [2.40] reinvestigated the potential of rib waveguide based Bragg grating filters in GaInAsP/InP material. Instead of realising filters with narrow spectral response [2.39], the authors fabricated a first-order Bragg grating broadband filter using deep reactive ion etching to achieve higher coupling coefficient and resulting devices with shorter length. The reflection bandwidth of 5nm at \(-10\,dB\) has been observed for TE polarisation and the Bragg resonance wavelength in TM polarisation was shifted approximately 5nm to a shorter wavelength, thereby the device is highly polarisation dependent. It should be pointed out that the bandwidth is mainly determined by the coupling coefficient, \(\kappa\) and the spectral response of a Bragg grating can not be broadened by the addition of grating length.

![Figure 2-11: Schematic diagram of proposed grating filter devices: (a) planar (b) planar, buried-heterostructure (BH) (c) rib (d) strip, BH [2.39].](image)

![Figure 2-12: Longitudinal (a) and transverse (b) sections of the proposed silicon modulator [2.41].](image)
Cutolo et al. [2.41] proposed and analysed a lateral p-i-n diode combined with a Bragg reflector. By means of varying refractive index by carriers injection via two lateral 0.5µm deep P' and N' regions, which in turn modulates the transmittivity of the Bragg mirror and hence modulates the intensity of light passing through the device. The authors predicted a 50% modulation depth achieved in response time of 12ns with a power dissipation of 4mW and exhibits insertion loss of 1.0dB. From Figure 2-12, the Bragg grating has a period $\Lambda = 227\text{nm}$ and grating etch depth $a = 45\text{nm}$. The shallow grating length of $L = 3200\mu\text{m}$ was implemented along a rib SOI waveguide, which is $W = 3\mu\text{m}$ and $H = 3\mu\text{m}$. The requirement of submicron grating period in first-order Bragg gratings for operation at 1.55µm wavelength is likely to increase the fabrication cost associated with strict requirement of grating uniformity in the device.

![Figure 2-13: Three dimensional schematic diagram of p-i-n silicon modulator with Bragg reflectors on top of the rib waveguide [2.42].](image)

Following the work of Cutolo et al. [2.41], Irace and co-workers [2.42] predicted 1.4GHz operating bandwidth for an SOI modulator with Bragg reflectors depicted in Figure 2-13. The device has a waveguide height and rib width 1µm, grating etch depth of 100nm and overall device length of 3000µm. It is apparent that by reducing the waveguide geometry from the original proposed waveguide width and height of 3µm to 1µm in [2.41], the device bandwidth increases from MHz to GHz region. The authors attributed this to the inherent high optical confinement of SOI waveguide, device geometry optimisation and suitable driving signal. It can be noted that the trend of SOI device miniaturisation has improved the bandwidth performance tremendously for the SOI based modulators. Nonetheless, the device polarisation,
single mode criteria and waveguide etch depth of the device were not reported by the authors, but it is commonly understood that Soref et al.'s [2.11] single mode equation is used to predict the behaviour of the device with relatively large cross section.

![Figure 2-14: SEM showing SOI rib waveguide with 223nm period Bragg grating patterned on the top surface [2.43].](image)

In 2001, Murphy et al. [2.43] demonstrated and characterised the first experimental Bragg grating reflection filter based on first-order grating period of 223nm on rib SOI waveguides. Figure 2-14 shows the cross section area of rib SOI waveguide fabricated features waveguide height \( H = 3\mu m \), waveguide width, \( W = 4\mu m \), waveguide etch depth, \( D = 800\text{nm} \) and grating depth = 150nm. The measured transmission spectral response for 4000\( \mu \text{m} \) Bragg grating filter has a bandwidth of 15GHz (0.12nm) at 1.543\( \mu \text{m} \), and peak reflectivity of 50% and 90% for TM and TE polarisations respectively. The complicated dual mask layers and lithography steps involved during the fabrication leads to an increase in complexity and overall cost as well. The experimental measurements show good agreement with theoretical models based on couple mode theory (CMT), since the surface grating perturbation of 150nm is considered shallow in terms of overall waveguide height and hence CMT is sufficiently accurate as a modelling tool. However, the difference in Bragg resonance wavelength between TE and TM polarisation was separated by 0.40nm, where the authors attributed the dominant source of birefringence is that of modal birefringence. In addition, they also reported higher order leaky modes in the single mode rib waveguide geometry. It is possible to reduce the influence of higher order leaky modes by shrinking the dimensions of the waveguide but at the expense of reduced fibre coupling efficiency.
Chapter 2: Literature Review

Figure 2-15: Cross section of SOI rib waveguide with Bragg grating on the sidewall [2.44].

Figure 2-16: SEM of different sections of SOI waveguide with sidewall grating: (a) plots the waveguide-grating geometry and indicates where the micrographs were acquired, (b), (c) and (d) show the sidewall grating structure after RIE [2.44].
Hastings et al. [2.44] reported a new class of apodized Bragg grating filter based upon rib SOI waveguide with the utilisation of grating perturbation in the sidewall of the waveguide as shown in Figure 2-15. The device comprises waveguide geometry of waveguide height, \( H = 2.2\mu m \), waveguide width, \( W = 1.6\mu m \), waveguide etch depth, \( D = 800nm \) and gratings are fully etched to the slab region. The grating profile utilised in the sidewall has a raised cosine function along the interaction length of 3000\( \mu m \) with grating period of 224.9nm instead of the commonly used uniform rectangular profile [2.41- 2.43]. Figure 2-16 shows SEM images of the raise cosine apodization function along the length of the grating. It should be noted that the rib narrows slightly as the grating depth increases into the waveguide width. The measured transmission response with raised cosine profile exhibits lower side-lobes compared to its unapodized counterpart. Nonetheless, both devices show high dependency on modal birefringence in their transmission spectrum. The major advantage of the placement of Bragg grating in the sidewalls of integrated waveguide is facilitating the fabrication of grating based devices in a single lithography step. This technique is flexible and can be applicable to variety of grating based devices and material systems.

Aalto et al. [2.45] realised their waveguide grating design, based on rib SOI waveguides with a large cross section measuring \( H = 9\mu m \), \( W = 6\mu m \) and waveguide etch depth of \( D = 4.3\mu m \) to ease coupling light from standard single mode fibre. The novelty of the structure is the deep gratings of 1\( \mu m \) extend beyond the top of the rib waveguide. The authors predicted the spectral response using rigorous diffraction theory [2.46]. The simulations suggested that the extended grating region to the slab region will increase the grating perturbation without causing any excessive scattering.
Chapter 2: Literature Review

and radiation loss. First-order and second-order grating periods of 225nm and 450nm were fabricated respectively on SOI waveguide. However, the first-order grating suffers from aspect ratio dependent etch (ARDE) effect whereby the etch rate changes drastically when the grating etch deepens with respect to the grating linewidth. On the other hand, second-order Bragg gratings with grating periods of 450nm exhibit almost vertical sidewalls and are free from ARDE since the structure has a wider and smaller aspect ratio. This research demonstrated that it is viable to achieve a high aspect ratio in higher diffraction order Bragg grating filters without significant fabrication difficulties.

Figure 2-18: SEM images of cross section area of the proposed (a) SOI waveguide dimensions (b) top view of surface Bragg grating achieved via FIB milling [2.47].

The realisation of surface grating on SOI waveguide was further exploited by Ta’eed and co-workers [2.47, 2.48]. In their work, they reported an interesting alternative method to define a grating other than Electron-beam lithography on SOI waveguides. Bragg gratings were defined by focused ion beam (FIB) milling on the top of the SOI rib waveguides after rib waveguides were fabricated using standard photolithography and reactive ion etching techniques. They designed and fabricated a waveguide with a goal of obtaining a large cross section area for maximising coupling efficiency from single mode fibre. Figure 2-18 shows the fabricated cross section of SOI rib waveguides with height, \( H = 5\mu m \), rib width, \( W = 4.7\mu m \), waveguide etch depth of \( 2.4\mu m \) and grating depth of 40nm. The device yields a grating period of 240nm and grating length of 330\( \mu m \), along a waveguide length of 2000\( \mu m \). Since the overall rib waveguide dimensions are relatively large, not surprisingly higher order leaky modes were also observed in the device, consistent with experimental results in [2.43]. Their
Chapter 2: Literature Review

results suggested that smaller waveguide dimensions than required for single mode operation is needed to minimise the existence of higher order mode in the grating structures.

### 2.3.2 Bragg Reflector/Fabry-Perot on Waveguide Structures

A Fabry-Perot resonant cavity is formed by two parallel reflective mirrors. It works on the principle of partial beam transmission where light entering the input mirror experiences multi-beam interference inside the cavity. At a given optical path length between the mirrors, only certain wavelengths are resonant within the cavity.

The Fabry-Perot mirrors can be realised by a silicon wafer with both sides carefully polished. Iodice et al [2.51] used this approach to construct a simple and low cost solution for tracking the frequency of WDM channels, based on the thermo-optic tuning of single cavity Fabry-Perot silicon optical filter. They demonstrated the device is capable of resolving up to five 100GHz spaced channels with a crosstalk of -14dB at wavelength around 1.55µm. Niemi et al [2.52] constructed a similar device to Iodice et al [2.51], instead of using Air-Silicon interfaces as mirrors, they produced high reflectivity mirrors on both sides of a silicon wafer by depositing three quarter wavelength stacks of Si$_3$N$_4$ and SiO$_2$. Their device yielded a tuning range of 30nm with heating power of 350mW. The entire silicon wafer based Fabry-Perot mentioned were only single cavity device, which commonly suffered from low finesse with limited free spectral range (FSR).

Cocorullo et al [2.53] have proposed a coupled cavity Fabry-Perot device to address this problem and improve the free spectral range (FSR). The authors reported theoretically a device capable of tuning over a range of 31.6nm by means of heating of about 380°C. The proposed device was constructed by two separate silicon wafers with one side of each coated with one pair of SiO$_2$-Si layers; following by using SiO$_2$ spacers to firmly join the two wafers, ensuring in the middle the presence of an air gap of controlled thickness. The requirement of a precise polishing process to control the wafer thickness and difficulty to integrate into optical circuits make a waveguide based device more favourable.
Chapter 2: Literature Review

The mirrors of the Fabry-Perot cavity can also be constructed by Bragg reflectors, which consist of multiple pairs of quarter-wave stacks. The implementation of Bragg reflectors in silicon waveguides can be obtained by deep etching to form air-Si pair [2.54] or filling the etched trench with SiO₂ to form high reflectivity Si/SiO₂ [2.59] reflectors. The transmission spectral response of these structures near their resonance wavelength is highly sensitive to small refractive index changes in the cavity. Hence, the effective index modulation within the cavity can be achieved using either by free carrier dispersion or the thermo-optic effect with low electrical or thermal power to produce the desired phase change. However, if current injection is chosen to induce the refractive index changes within the F-P cavity, higher current density may induce undesirable thermo-optic changes due to the heating of the structure, leading efficiency reductions because the thermo-optic effect and free carrier dispersion produce refractive index changes with opposite sign.

Figure 2-19: (a) Schematic diagram of the proposed F-P based SOI modulator (b)SEM image of Fabry-Perot cavity in between two waveguide Bragg reflector defined by 12 quarter-wave trenches [2.54].

In 1996, Liu et al. [2.54] proposed a silicon waveguide based modulator based on high finesse Fabry-Perot (F-P) cavity. Figure 2-19 show the schematic of the proposed and a SEM image of the fabricated modulator. The pair of pseudo-mirrors was realised and fabricated using two Bragg reflectors consisting of periodic quarter-wave trenches in SOI using electron-beam lithography and reactive ion etching techniques. The modulator was designed to operate at 1.3μm with grating period of 260nm with planar waveguide thickness of 200nm and trench depth of 100nm. Using the high reflectivity of the Bragg reflectors enables large intensity modulation to be achieved with small modulator length of 18.3μm, leading to faster modulation operation. The
authors suggested that Bragg reflectors reflectivity can be controlled by varying the number of etched trenches employed in the structure. Therefore a tunable filter with narrower resonance peak and larger intensity modulation can be achieved by increasing number of Bragg reflector etched trenches.

The implementation of tunable filter in an F-P waveguide was further pursued by Tsang et al. [2.56] when they reported a etched cavity InGaAsP/InP waveguide filter by current injection. The schematic of this structure is illustrated in Figure 2-20. Instead of utilising multiple etched trenches as in previously reported work [2.54], the F-P mirrors were formed by high reflectivity dielectric coatings deposited onto the two etched facet of the cavity. In order to obtain a wide FSR, the cavity length of this device was chosen to be 40μm for an FSR of 8nm. The filter was able to tune over a range of 4nm by 50mA current injection and exhibited an FSR of 9nm with contrast ratio of 10dB. However, the filter tuning range of 4nm limits its application in WDM optical networks which require at least 30nm, spanning across C-band of the spectrum.

Ishikawa and co-workers [2.55] demonstrated another fabrication method of Bragg reflectors by using silicon compatible technology of low energy multiple SIMOX combined with silicon molecular beam epitaxy (MBE) to achieve high reflectance Si/SiO₂ Bragg reflector. Their approach has the potential of reducing scattering loss which usually occurs between the silicon-air interfaces at the Bragg reflectors by introducing a quarter-wave SiO₂ layer for better refractive index matching with silicon. However, the epitaxial growth process is time consuming and complicated, leading to the high cost of fabrication. The realisation of high reflectivity Si/SiO₂ Bragg reflectors can be obtained by simple deposition of chemical vapour deposition of SiO₂ into the etched trenches in the device previously proposed by Liu et al. [2.54].
In 2003, Barrios et al. [2.58] proposed and theoretically analysed a compact electrooptic modulator on a SOI rib waveguide with deep Si/SiO₂ Bragg reflectors, as shown in Figure 2-21. The microcavity facilitates confinement of the optical field in a small region, and the transmission of the device near its resonance is highly sensitive to small index changes in the cavity. This would require less injected carriers to achieve the required refractive index changes and hence phase shift. The rib width and silicon thickness are 1.5μm, and the etch depth is 0.45μm. The 20μm long device is predicted to require a dc power of the order of 25μW at an operating wavelength of 1.55μm, to achieve 31MHz operating bandwidth with transmittance of 86% and a modulation depth of 80%.

Recently, Barrios et al. [2.59] fabricated a low power consumption silicon tunable F-P resonator similar to previous work [2.58] with reduced rib waveguide dimensions.
Figure 2-22 illustrates a top view SEM images of the fabricated device, Si/SiO₂ DBR and isolation trench implemented on the slab region, with a spacing of 6μm from the rib waveguide. The height and width of the rib waveguide were 0.43μm and 1.0μm whereas DBR period and length of trenches were 311nm and 173nm. The device exhibited modulation depth of 53% while requiring 20mW power electrically. The authors predicted that the reduction of modulation depth is attributed to the scattering losses in the device and the influence of the thermo-optic effect within the cavity. Table 2-1 shows a summary of silicon waveguide based Bragg grating devices in the literature reviewed in this section. All the waveguide dimensions stated are in micrometers.

### Table 2-1: Summary of waveguide dimensions employed in silicon waveguide based Bragg grating devices in the literature.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>H (μm)</th>
<th>W (μm)</th>
<th>D (μm)</th>
<th>Λ (μm)</th>
<th>Grating Depth (μm)</th>
<th>Length (μm)</th>
<th>Optical Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Liu et al. [2.54]</td>
<td>0.2</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>18.3</td>
<td>4000</td>
<td>Planar F-P</td>
</tr>
<tr>
<td>2001</td>
<td>Murphy et al. [2.43]</td>
<td>3.0</td>
<td>4.0</td>
<td>0.8</td>
<td>0.223</td>
<td>0.15</td>
<td>3000</td>
<td>Rib BG</td>
</tr>
<tr>
<td>2002</td>
<td>Hastings et al. [2.44]</td>
<td>2.2</td>
<td>1.6</td>
<td>0.8</td>
<td>0.225</td>
<td>N/A</td>
<td>6750</td>
<td>Rib BG</td>
</tr>
<tr>
<td>2002</td>
<td>Aalto et al. [2.45]</td>
<td>9.0</td>
<td>6.0</td>
<td>4.3</td>
<td>0.225</td>
<td>1.00</td>
<td>500</td>
<td>Rib BG</td>
</tr>
<tr>
<td>2003</td>
<td>This work</td>
<td>1.5</td>
<td>1.0</td>
<td>0.9</td>
<td>0.680</td>
<td>0.20</td>
<td>300</td>
<td>Rib BG</td>
</tr>
<tr>
<td>2004</td>
<td>Ta’eed et al. [2.47]</td>
<td>5.0</td>
<td>4.7</td>
<td>2.4</td>
<td>0.240</td>
<td>0.04</td>
<td>4000</td>
<td>Rib BG</td>
</tr>
<tr>
<td>2004</td>
<td>Barrios et al. [2.59]</td>
<td>1.5</td>
<td>1.0</td>
<td>0.43</td>
<td>N/A</td>
<td>N/A</td>
<td>20</td>
<td>Rib F-P</td>
</tr>
</tbody>
</table>
2.3.3 Thermo-Optic Effect (TOE) based Silicon Devices

The variation of refractive index as a function of temperature can be described by a thermo-optic coefficient (TOC). Among the common thermo-optical materials, silicon shows the highest thermo-optical coefficient, \( \frac{dn_{Si}}{dT} = 1.86 \times 10^{-4} K^{-1} \) [2.60] at the fiber optic wavelength of 1.55\( \mu \)m, which is double the coefficient of LiNbO\(_3\) and even 15 times that of silica. This particular characteristic in conjunction with the mature fabrication associated with silicon technology has stimulated the proposal of new devices in modulators and filters. The strong thermo-optic effect (TOE) in silicon has been exploited for the fabrication of silicon Mach-Zehnder interferometers (MZI) modulators by Treyz [2.61] as long ago as 1991. Modulation depths of 40% were obtained for switching powers of 30mW and switching times of 50\( \mu \)s for a device length of 500\( \mu \)m and waveguide width of 3\( \mu \)m. TOE modulation was achieved via electrical power dissipation in a resistive layer of thin film heater formed in one of the arms of the MZI from a 0.25\( \mu \)m thick film of coevaporated nickel and chromium (80% Ni: 20% Cr).

![Figure 2-23: Cross section of single mode optical switch based on SOI [2.62].](image)

In 1994, Fischer et al. [2.62] further improved the thermo-optic switch reported by Treyz [2.61]. The schematic diagram in Figure 2-23 depicts the cross section of the author's waveguide configuration. They realised the single mode waveguide with large cross section to improve switching characteristics and minimise mode mismatch with single mode fibre. The measured switching power of 150mW and switching rise time of 5\( \mu \)s showed an improvement of an order of magnitude in speed but at the expense of three fold in power consumption. In the same year, Cocorullo and co-workers [2.63] reported their silicon Fabry-Perot (FP) modulator based on TOE and achieved 55% modulation depth and power consumption less than 100mW. The short
cavity length of 10μm meant that the F-P modulator exhibited insensitivity to ambient temperature variations and theoretical operating frequency in the region of hundreds of kilohertz. The authors published subsequent paper in 1995 [2.64] in which a thermo-optic based silicon micromodulator with a 700kHz at -3dB bandwidth, 60% modulation depth corresponding to π/2 shift was reported.

Clark et al. [2.65] investigated a series of lower power thermo-optic phase modulating devices fabricated using multi-micron, large cross section rib structures in SIMOX material. The authors reported a device that delivered π phase shift with power consumption of 10mW for a 500nm device length. This improvement was achieved through the suspension of the waveguide over a v-groove to provide thermal isolation from the substrate. However, this low power consumption configuration is at the expense of a reduction of bandwidth of 1.1 kHz.

![Figure 2-24: SEM image of TOE based silicon modulator [2.66].](image)

Iodice et al. [2.66] presented a combined thermal and optical simulation study and transient analysis for an all silicon waveguide integrated thermo-optic Fabry-Perot modulator to access the impact of the driving signal shape on the device speed performances. Figure 2-24 illustrates a SEM image of the proposed device realised in rib SOI structure, where waveguide width, height and etch depth are 8μm, 8.5μm and 2.2μm respectively. The 35μm short Fabry-Perot cavity length is defined by means of two 10μm deep trenches realised by reactive ion etching. The authors argued that the cooling phase after the application of a heat pulse constitutes the true speed limiting factor of this device. Hence, they suggested applying a thermal bias and holding the modulator at a higher average temperature with respect to the environment and the
substrate heat sink at the cooling phase. With this approach, a new and optimised driving signal was proposed and predicted by finite element thermal simulation to achieve a transmission rate of 2.2Mb/s.

![Schematic diagram of MZI thermooptic switch and cross section proposed in [2.65].](image)

In 2003, Espinola et al. [2.67] designed and fabricated a MZI thermo-optic switch using UNIBOND SOI wafers. Figure 2-25 shows the design, consisting of 3μm input-output multimode waveguides that were in-tapered and out-tapered respectively over a distance of 10μm, to a 0.6μm width single-mode strip waveguide. The branches of the MZI had a length of 160μm and a branching angle of 3.8°. The MZI arms had a length of 1200μm. The Cr–Au heaters were 700μm long and 14μm wide with a resistance of 60Ω. This device exhibits low switching power of 50mW and rise time of 3.4μs. However, there is a slight polarisation dependence on the amplitude of the input and output power, which may be caused by the asymmetrical stress effect of the heater. The authors suggested by implementing optimised heater geometry and placement; the polarisation dependence effect should be able to be overcome.

Recently, Harjanne et al. [2.68] demonstrated a sub-microsecond switching time with 10-90% modulation in a SOI thermo-optic MZ switch. The waveguide dimensions of the device are depicted in Figure 2-26, in which large cross section single mode
waveguides with waveguide height, width and etch depth of 9\( \mu \text{m} \), 10\( \mu \text{m} \) and 5\( \mu \text{m} \) respectively. A 500nm thick aluminium heater was deposited on top of the rib waveguide separated from the waveguide surface by a 1\( \mu \text{m} \) thick SiO\(_2\) buffer layer to prevent optical mode attenuation from heater element and from damage during facet polishing. A differential control method which utilised the driving of both heaters in MZI arm simultaneously with different signal can result in shorter rise and fall time of 725ns and 700ns. The drawback of this approach is the additional power consumption of 10mW and 110mW during rise and fall time compared to conventional switching signals. The authors suggested that the switching speed is limited by the heater breakdown point, the speed of the controller circuit and possibly temperature heat build-up within the circuit.

![Figure 2-26: Cross section of rib waveguide in MZ thermooptic switches [2.68].](image)

**2.4 Summary**

There is a trend in photonic circuits to move to smaller device dimensions for improved cost efficiency and device performance. However, the trend also comes at some cost to performance, notably in the single mode operation and polarisation dependence of the circuits, the difficulty in coupling to the circuits, and in some cases, in increased device complexity. In this section, various design criteria and analytical approaches to design single mode and polarisation independent operation in large and small cross section SOI rib waveguides have been reviewed.

Various types of Bragg gratings and Fabry-Perot structures based on rib geometries in grating filter have been reviewed. There is also an undoubted trend towards smaller waveguides due to benefits of greater packing density, higher efficiency but at the...
expense of fabrication cost. In particular, much attention was devoted to the dimensions of rib waveguide and grating period upon which those devices were built. Silicon modulators based on the thermo-optic effect were also studied since its flexible configuration can be changed to an optical filter by implementing Bragg grating into the structure. The author envisages that the SOI Bragg grating structure is a versatile platform to realise a low cost reflection filter and potentially tunable optical filter utilising the inherent high thermo-optic effect in silicon for optical communication.

References:


2-32


Chapter 3

I am the light of the world. If you follow me, you won’t be stumbling through the darkness, because you will have the light that leads to life. John 8:12

3 Theory and Analysis

3.1 Introduction

This chapter discusses and provides a relatively comprehensive summary of the theoretical and numerical techniques which are necessary for designing and building Bragg grating filter on silicon-on-insulator (SOI) waveguides. The key issues affecting the small cross sectional rib waveguide design such as single mode condition and polarisation dependence will be presented. We will begin by deriving the basic Maxwell equations which describe the eigenmodes of waveguides and relate these equations to full-vectorial and semi-vectorial mode of the waveguides. The criteria in defining single mode conditions and polarisation independent for SOI waveguide with small cross sectional area will be defined, resulting in new design rules for such waveguides. It is important to fulfil these requirements in order to improve devices performance while maintaining low propagation loss. Gratings are implemented by periodically modulating the waveguide’s dimensions or refractive index profile. This can be achieved in a waveguide structure by introducing periodic gratings on top of the waveguide structure. The numerical techniques and equations leading to the computation of Bragg gratings such as Coupled Mode Theory (CMT) and Floquet-Bloch Theory (FBT) will be discussed. The CMT presented here is based on a commercially available optical modelling program [3.1] while the analytical model and algorithms for FBT is developed by Passaro [3.2] and presented by the author in [3.3]. The basic operating characteristics of a Bragg grating filter along with parameters such as central wavelength and device bandwidth will also be defined.
3.2 Waveguides Design Theories

Dielectric waveguides consist of a higher refractive index core region surrounded by a lower refractive index cladding region. Light is guided in the core region by total internal reflection, and the boundary conditions yield discrete solutions to Maxwell's equations. These solutions describe the waveguide’s modes of the waveguide propagation which will be subjected to discussion in the following section.

3.2.1 Maxwell Equations

One of the most commonly used SOI geometries is the rib waveguide structure as shown in Figure 3-1. Light is confined vertically utilising high refractive index contrast between guiding layer \(n_1\) and the top \(n_3\) and lower \(n_2\) cladding layer, while the rib protruding from the high index contrast slab region provides further lateral optical confinement. Figure 3-1 depicts a schematic diagram of a rib optical waveguide which can be described by a refractive index profile \(n(x, y)\).

![Figure 3-1: Schematic diagram of a rib optical waveguides. The red circle under the rib represents typical fundamental mode optical confinement in SOI.](image)

The refractive index profile is related to the dielectric constant \(\varepsilon\) by:

\[
\varepsilon(x, y) = \varepsilon_0 n^2(x, y)
\]  

(3.1)
where \( \varepsilon_0 \) is the permittivity of free space. The refractive index profile is assumed to be real, meaning that the material does not have gain or loss. However, this can be included in the modelling by adding an imaginary component to the refractive index profile. The material comprising the waveguide is considered to be non-magnetic which can be expressed by:

\[
\mu(x, y) = \mu_0
\]

(3.2)

where \( \mu_0 \) is the permeability of free space. The eigenmodes of an optical waveguide are found by applying Maxwell equations with appropriate boundary conditions to the refractive index profile:

\[
\nabla \times E = -\mu_0 \frac{\partial}{\partial t} H
\]

(3.3)

\[
\nabla \times H = n^2 \varepsilon_0 \frac{\partial}{\partial t} E
\]

(3.4)

\[
\nabla \cdot (n^2 E) = 0
\]

(3.5)

\[
\nabla \cdot (H) = 0
\]

(3.6)

The above equations govern the electric (\( E \)) and magnetic (\( H \)) fields in the optical waveguide with no current sources:

\[
J = \sigma E
\]

\[
J = \sigma = 0
\]

(3.7)

where is \( \sigma \) the conductivity of the material. If we assumed that all the field components are having a time dependence of \( e^{j\omega t} \):

\[
E(x, y, z, t) = \text{Re}\{\overline{E}(x, y, z)e^{j\omega t}\}
\]

(3.8)

\[
H(x, y, z, t) = \text{Re}\{\overline{H}(x, y, z)e^{j\omega t}\}
\]

(3.9)

The Maxwell equations can then be rewritten in terms of complex field of \( \overline{E} \) and \( \overline{H} \).

\[
\nabla \times \overline{E} = -j \omega \mu_0 \overline{H}
\]

(3.10)
\[ \nabla \times \vec{H} = j \omega \varepsilon \varphi \vec{E} \]  
(3.11)

\[ \nabla \cdot (n^2 \vec{E}) = 0 \]  
(3.12)

\[ \nabla \cdot (\vec{H}) = 0 \]  
(3.13)

By taking the curl of equation (3.3), the full-vectorial eigenvalue equation can be derived from Maxwell's equations as described in [3.5]:

\[ \nabla \times \nabla \times \vec{E} = -j \omega \mu_0 \nabla \times \vec{H} = k^2 n^2 \vec{E} \]  
(3.14)

where \( k \) denotes the free space wave vector, which can be related to:

\[ k = \omega \sqrt{\varepsilon_0 \mu_0} \]  
(3.15)

Equation (3.14) can then be simplified using vector identity,

\[ \nabla \times (\nabla \times \vec{E}) = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E} \]  
(3.16)

We can rewrite the divergence in equation (3.16) as:

\[ \nabla \cdot (n^2 \vec{E}) = \nabla (n^2) \cdot \vec{E} + n^2 \nabla \cdot \vec{E} = 0 \]  
(3.17)

\[ \nabla \cdot \vec{E} = -\frac{1}{n^2} \nabla (n^2) \cdot \vec{E} \]  
(3.18)

Combining equation (3.16) and equation (3.18) yield the vectorial wave equation for the complex electric field \( \vec{E} \) as:

\[ \nabla^2 \vec{E} + \nabla \left( \frac{1}{n^2} \nabla (n^2) \cdot \vec{E} \right) + k^2 n^2 \vec{E} = 0 \]  
(3.19)

There are only two \( \vec{E} \) or \( \vec{H} \) field components necessary to specify a solution to the above equation, usually the transverse components of the electric field are considered.
Chapter 3: Theory and Analysis

The full-vectorial wave equation can be expressed in terms of transverse component, $E_t$ if the refractive index in $z$ direction is assumed uniform and a $z$-dependence of $e^{jeta z}$:

$$
\nabla^2 E_t + \nabla \left( \frac{1}{n^2} \nabla \left( n^2 \right) \cdot E_t \right) + k^2 n^2 E_t = \beta^2 E_t
$$

(3.20)

where $\beta$ is the propagation constant of the waveguide. After some derivation [3.1], equation (3.20) can be rewritten in terms of transverse field components $E_x$ and $E_y$ for a straight waveguide [3.1]:

$$
\begin{bmatrix}
  P_{xx} & P_{xy} \\
  P_{yx} & P_{yy}
\end{bmatrix}
\begin{bmatrix}
  E_x \\
  E_y
\end{bmatrix} = \beta^2 \begin{bmatrix}
  E_x \\
  E_y
\end{bmatrix}
$$

(3.21)

where $\beta^2$ is the eigenvalue and $P_{xx} \ldots P_{yy}$ are differential operators defined as:

$$
P_{xx} E_x = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial \left( n^2 E_x \right) }{\partial x} \right] + \frac{\partial^2 E_x}{\partial y^2} + n^2 k^2 E_x
$$

(3.22)

$$
P_{yy} E_y = \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial \left( n^2 E_y \right) }{\partial y} \right] + n^2 k^2 E_y
$$

(3.23)

$$
P_{xy} E_y = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial \left( n^2 E_y \right) }{\partial y} \right] - \frac{\partial^2 E_x}{\partial x \partial y}
$$

(3.24)

$$
P_{yx} E_x = \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial \left( n^2 E_x \right) }{\partial x} \right] - \frac{\partial^2 E_x}{\partial y \partial x}
$$

(3.25)

It is clear that the two coupled transverse field component of $E_x$ and $E_y$ are the eigenvector of $P$ and the corresponding eigenvalue is $\beta^2$. The solutions of the above eigenvalue equation determined the modes of the propagation for the waveguide. From analytical point of view, the mode of a waveguide is polarisation dependent due to different boundary conditions at interfaces when $P_{xx} \neq P_{yy}$. The non-zero diagonal terms of $P_{xy} \neq 0, P_{yx} \neq 0$ account for polarisation coupling for both $E_x$ and $E_y$ field, this means the eigenmodes of an optical waveguide are usually not purely TE or TM in nature. It was commonly known in the literature as either hybrid modes or quasi-
TE/quasi TM mode of the waveguide. The full-vectorial approach is highly desirable for the computation of propagation modes for waveguide feature sizes smaller than several micrometers when the minor component becomes more dominant. Figure 3-2 illustrates a full-vectorial mode solved for 1.5µm height SOI rib waveguide with dominant $E_x$ component located in the center of the rib waveguide and minor $E_y$ component concentrated at the intersection between the slab and rib waveguide corners. This means that any variation of waveguide fabrication such as influence of corners or sloping walls in the cross sectional structure will have a significant influence on the hybrid modes.

![Figure 3-2: The full-vectorial mode of a SOI rib waveguide with (a) dominant $E_x$ component and (b) minor $E_y$ component.](image)

When the minor component is small, $P_{xy} = P_{yx} = 0$, the full-vectorial wave equation can be simplified into two semi-vectorial approximation equations:

$$P_{xx}E_x = \beta_x^2 E_x \quad (3.26)$$

$$P_{yy}E_y = \beta_y^2 E_y \quad (3.27)$$

For quasi-TE modes:

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{1}{n^2} \frac{\partial}{\partial x} \left( n^2 \frac{\partial E_x}{\partial x} \right) + \frac{\partial^2 E_x}{\partial y^2} + n^2 k^2 E_x = \beta_x^2 E_x \quad (3.28)$$

For quasi-TM modes:

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial}{\partial y} \left( n^2 \frac{\partial E_y}{\partial y} \right) \right] + n^2 k^2 E_y = \beta_y^2 E_y \quad (3.29)$$
In this case, the transverse field components are decoupled and provide a good approximation for the solution while retaining the most dominant polarisation effects. Most integrated optical devices are designed to be single mode waveguides; this means that equation (3.21) has only one eigenmode for each polarisation state. The full-vectorial approach using beam propagation method will be used to determine the single mode condition for small cross sectional SOI waveguide in the following section.

### 3.2.2 Small Cross Sectional SOI Rib Waveguides

There is a current trend in silicon photonic circuits to move to smaller device dimensions for improved cost efficiency and device performance. The trend can also come at some cost to performance, notably in the polarisation dependence of the circuits if they are not carefully designed. The fabrication restrictions that need to be imposed on the geometry of optical waveguides to make them behave as single mode devices are well known for relatively large waveguides, with shallow etch depth. However, the restrictions for small waveguides (~1μm or less in cross section), are not well understood. Furthermore, it is usually a requirement that these waveguides are polarisation independent, which further complicates the issues. In this section, we present simulations of the conditions for both single-mode behaviour and polarisation independence, for small and deeply etched SOI waveguides. The aim is to satisfy both conditions simultaneously. The results show that at larger waveguide widths, waveguide etch depth has little effect on the mode birefringence because the TE mode (horizontal polarized mode) is well confined under the rib region. However, at smaller rib widths, the etch depth has a large influence on birefringence. An approximate equation relating the rib waveguide width and etch depth to obtain polarisation independent operation is derived. It is possible to achieve single mode operation at both polarizations whilst maintaining polarization independence for each of the waveguide heights used in this work, but may be difficult for other dimensions. For example, a 1μm SOI rib waveguide with an etch depth of 0.64μm and rib width of 0.52μm is predicted to exhibit polarisation independence but does not satisfy the single mode condition.
3.2.3 Single-Mode Condition

Since the early investigation of propagation loss and polarisation dependence of SOI waveguides, the interest in SOI photonic devices has increased enormously. Research activities in SOI range from study of basic building blocks such as waveguides [3.6-3.10] and bends [3.13] to more complex devices such as modulators [3.14], ring resonators [3.15], Bragg gratings [3.3, 3.5], and even light sources in silicon [3.16]. Single-mode SOI rib waveguides with large cross section have been studied extensively by a number of researchers [3.6-3.10] to find single mode behaviour at the same time as low propagation loss. The majority of these photonic devices in SOI have been studied in waveguides that are multi-micron in cross sectional dimensions (of the order of 5µm), to facilitate low-loss coupling to and from optical fibres.

![Figure 3-3: Cross section and waveguide parameters of a SOI waveguide](image)

Soref et al. [3.6] first proposed a simple expression for these large ribs waveguides, related to their geometry to ensure that they satisfied the single-mode condition (SMC):

\[
\frac{W}{H} \leq \alpha + \frac{r}{\sqrt{1-r^2}}
\]  

(3.30)

For \(0.5 \leq r \leq 1.0\)

(3.31)
where $r$ is the ratio of slab height to overall rib height, $W/H$ is the ratio of waveguide width to overall rib height, and $\alpha = 0.3$. The scanning electron micrograph (SEM) of Figure 3-3 show a typical fabricated SOI rib waveguide with $H = 1.20\mu$m, $W = 0.98\mu$m and $D = 0.76\mu$m using UNIBOND™ SOI wafer. The analysis of the waveguides was limited to shallow etched ribs as stated in equation (3.31) ($r > 0.5$), where deeply etched rib waveguides are not considered. Furthermore, the waveguide dimensions are larger than the operating wavelength. Their analysis was based on the assumption that higher order vertical modes (i.e. modes other than the fundamental mode) confined under the rib waveguides, were coupled to the outer slab region during propagation, therefore yielding high propagation losses for the higher order modes. Thus the waveguides behave as single mode waveguides, as all other modes are lost. The analytical Effective Index Method (EIM) was used by Pogossian et al.[3.7] for a similar analysis, and suggested that more stringent geometrical constraints needed to be imposed for single mode operation, resulting in an alternative value of $\alpha = 0$, in equation (3.30). Powell [3.8] also made a more general analysis for rib waveguides with vertical or angled sidewalls, finding a simple analytical expression for such waveguides that was in good agreement with the original work of Soref et al. [3.6], as well as using a simple scalar approximation in his analysis. He showed that the scalar approximation is sufficiently accurate for large rib waveguides with shallow etch depth (large $r$), where the mode profiles are similar for both polarisations. This situation was discussed extensively in the literature review of chapter 2.

The widely used design criteria stated in equation (3.30) was revisited recently [3.10] using the full-vectorial beam propagation method (BPM) to demonstrate this simple equation is not sufficient to ensure single-mode behaviour. The prediction by the design formula in equation (3.30) that waveguides should be single-mode was questioned in this analysis when some waveguides were shown to support other higher order vertical modes. Nevertheless, this and all the other work presented on this specific issue to date has been limited to waveguides of large cross section with shallow etch depths ($r > 0.5$).


3.2.3.1 Numerical Simulation

The modal analysis of the small cross section SOI rib waveguides is based on the BPM algorithm [3.11] using the correlation mode solving technique, particularly useful for z-invariant structures. In the correlation approach, an arbitrary field is launched for each dominant polarisation into the waveguide structure off-centre, to excite high order modes and allow propagation in z direction via normal BPM. During the propagation stage, the following correlation function between the input field and the propagating field is computed:

\[
P(z) = \int \int \phi_{in}(x,y,0) \phi(x,y,z) \, dx \, dy
\]  

(3.32)

The correlation method resolves all high-order modes supported in the structure by determining the mode spectrum, where eigenvalues (effective index values) of all guided modes and leaky modes are found. The computed mode spectrum is the Fast Fourier Transform (FFT) of the correlation function. It will exhibit a peak at the frequency of each of the guided modes, with a height equal to the fraction of power in the launched field contained in the mode.

![Figure 3-4: Cross section area of SOI rib waveguide showing both the geometries and the calculated intensity distribution (scale of 10) of the fundamental (a)TM and (b)TE mode for \( \lambda_0 = 1550\text{nm} \). Waveguide height of 1.50\text{\mu m}, width of 1.0\text{\mu m}, etch depth of 0.89\text{\mu m} \( n_{el} = 3.477 \) and \( n_{sio2} = 1.444 \) are considered here.](image-url)

To maintain consistency of the analysis with others, we have employed the notation [3.6, 3.10] of \( EH_{nm} \) and \( HE_{nm} \) where \( n = 0, 1, 2, 3..., m = 0, 1, 2, 3... \) and where \( EH \) refers to the dominant vertical polarisation and \( HE \) to dominant horizontal
polarisation. They are commonly known as quasi-transverse-electric modes (quasi-TE) for $HE_{nm}$ modes and quasi-transverse magnetic (quasi-TM) for $EH_{nm}$ modes. The waveguide geometry and the fundamental modes of a SOI rib waveguide are illustrated in Figure 3-4, and will be considered as our reference model where $H = 1.5 \mu m$, $W = 1.0 \mu m$, $r = 0.405$ and Etch depth, $D = 0.89 \mu m$.

3.2.3.2 Waveguide Width and Etch Depth Influence

This section presents the influence of waveguide width and etch depth of the rib waveguide geometry to design small cross section area waveguide supporting the fundamental mode only. The single mode simulation was setup using the waveguide structure shown in Figure 3-3, which is a rib waveguide of silicon, Si ($n_s=3.477$) on silica, SiO$_2$ ($n_s=1.444$) and has an upper cladding that is air ($n_c=1$). We have made the reasonable, usually satisfied assumption of no coupling between the quasi-TE and quasi-TM modes. The energy fields in both majority and minority components are taken into consideration because minority field component has the potential of changing the effective index value for small waveguide cross sections.

A Gaussian field was chosen to approximate an optical fibre mode, and it is deliberately launched off-centre at one third of the waveguide width to excite higher order modes supported in the structure. The propagation length was chosen to be 4mm, which is sufficiently long to allow potentially guided higher order modes to leak out from the rib waveguide. The number of vertical and horizontal guided modes was restricted to three ($HE_{n0}$, $n < 3$ and $EH_{m0}$, $m < 3$) for both polarisations during the computation, in order to minimise the computation time. However, this is more than sufficient to determine the single mode/multimode transition. In the simulations, the waveguide height ($H$), etch depth ($D$), and slab height ($h$) were kept constant whilst increasing the waveguide width in increments of 0.01$\mu m$ to find the boundary between single-mode and multimode behaviour. The iteration of the simulation was repeated with different values of the slab height ($h$) to waveguide height ($H$) ratio (parameter $r = h/H$). Hence the process is one in which we gradually increase the waveguide width until a second-order mode is guided ($EH_{01}$, $HE_{01}$). The boundary of the single/multimode can therefore be determined by computing the minimum waveguide width at which the first higher-order mode is supported by the waveguide structure. In Figure 3-5, our simulation results are presented together with a scalar
approximation [3.8] and other approaches of Soref et al. [3.6] and Pogossian et al. [3.7], for an SOI rib waveguide height of 1.50µm and operating wavelength $\lambda = 1550$nm. It should be noted that the original data of [3.6, 3.7] does not extend to the range of $r < 0.5$ and so here we have simply extended these results by extrapolation. Figure 3-5 shows that the scalar approximation and quasi-TE (HE) results are very similar for a large range of values of parameter $r$ (above $\sim r=0.4$).

![Graph showing single-mode and multi-mode regions](image)

**Figure 3-5**: Comparison of scalar and full-vectorial numerical simulation methods for quasi-TE and quasi-TM single mode cut-off dimensions for a rib waveguide of 1.50µm. The trend lines and data points indicate the boundary between single and multi-mode regions.

This scalar approximation result also approaches the results of [3.7] for values of parameter $r$ less than approximately 0.40. However, it can be seen that the results of the quasi-TM (EH) simulation is very different from both the scalar and quasi-TE computation for $r < 0.5$, where the boundary of the single/multimode regime for EH and HE modes diverge. This simulation data suggests that the single-mode cut-off condition for deeply etch rib waveguides is different from commonly used design rules [3.6, 3.7] and the strict criteria for the cut-off condition, where parameter $\alpha = 0$ [3.7] are less useful than the other simulations, either for small or large values of...
parameter $r$. This also re-affirms that the work of Soref et al. [3.6], or even that the scalar approximation can be used as a basis of design of single mode waveguides only for shallow etched rib waveguides ($r > 0.5$) with large cross section. The primary issues however, are the differences between the single mode conditions for different polarisations at smaller values of parameter $r$, which are significant, particularly in small waveguides. This is because the optical confinement for such small waveguides is dominated by the boundary conditions, which are well known to be different for quasi-TE and quasi-TM modes.

![Figure 3-6: Calculated intensity distribution of (a) TE$_{10}$ and (b) TE$_{01}$ modes when reference waveguide width is increased from 1.0μm to 1.50μm as indicated by a red circle in Figure 3-5, which is far away from the single/multi-mode cut-off boundary line.](image)

![Figure 3-7: Calculated intensity distribution of (a) TE$_{10}$ and (b) TE$_{01}$ modes when reference waveguide etch depth is increased from 0.89μm to 1.05μm as indicated by a blue circle in Figure 3-5, which is close to the single/multi-mode cut-off boundary line.](image)

In order to have a better understanding the influence of waveguide width and etch depth on the single mode condition, we investigated the TE polarisation mode profiles at two distinctive locations in the SMC plot as indicated by the red and yellow circles.

3-13
in Figure 3-5. Waveguide height was kept constant and observations were made when it deviated from our reference model which is indicated by the yellow circle. As expected when waveguide width is increased, the circle deviates and shifted upwards from the reference model. Figure 3-6 indicates the calculated intensity plots for TE_{10} and TE_{01} which are located far away (red circle in Figure 3-5) from both quasi-TE and quasi-TM single/multimode boundary lines. It becomes apparent that by increasing the waveguide width from our reference model of 1.0\mu m to 1.5\mu m, higher order modes start to emerge in the waveguide structure. On the other hand, if waveguide etch depth is increased from our reference model of 0.89\mu m to 1.05\mu m as shown in Figure 3-7, the width to height ratio data will be shifted horizontally to the left (blue circle), which is very close to the transition line between single and multimode region. However with higher etch depth, the transition line for the quasi-TM single mode condition is situated farther from the quasi-TE trend line compared to our reference model. This means that with proper fabrication control of waveguide width according to our reference model, we can determine the single-mode operation for rib SOI waveguides.

### 3.2.3.3 Waveguide Height Influence

In order to consider the influence of guiding layer height \((H)\), SOI rib waveguides with an overall height of 1.00\mu m, 1.35\mu m and 1.50\mu m are analysed at a wavelength of 1.55\mu m, related to examples of design geometries used in our previous work, such as silicon optical modulators [3.14], ring resonators [3.15] and waveguide based Bragg gratings [3.3]. By evaluating the TE and TM propagation constants for a series of waveguide widths and etch depth in terms of width to height ratio and parameter \(r\), the single mode cut off boundary can be determined using the same approach applied in section 3.2.3.2. It is instructive to plot the data associated with parameter \(r\) in a way that is related to waveguide etch depth \((D)\). In the remainder of this chapter, we adopt this approach as it clarifies some of the design issues.

Figure 3-8 and Figure 3-9 summarise the data for both TE and TM polarisations. Also included on these graphs are the extrapolated single mode conditions from both Soref \textit{et al.} [3.6] and Pogossian \textit{et al.} [3.7], for reference. It is observed that the TE polarisation reached cut off earlier than the TM polarisation, even though its effective
index is higher than its counterpart. In addition, the simulation results suggested that it is not possible to fulfil Pogossian et al. [3,7]'s strict design requirement for both polarisations and the rib waveguide height has little effect on single mode condition for TM polarisation as shown in Figure 3-9. Reducing the rib waveguide heights in effect, reduces the overall size of the rib waveguide; imagine that the mode under the rib is pushed downwards, leading to the weak lateral confinement of the mode in both polarisation. It is clear that neither of these design rules that are reasonable for large waveguides, are suitable for small deeply etched waveguides, when considering both TE and TM modes for the aforementioned guiding layer height. If we turn our attention to the design of birefringence free waveguides, we can also provide guidelines for achieving both single mode and birefringence free behaviour simultaneously.

![Graph](image)

**Figure 3-8**: The boundary between single mode and multimode region for waveguide width to height ratio as a function of parameter $r$ in quasi-TE polarised mode for various waveguide height operating wavelength $\lambda = 1550\text{nm}$. 
3.2.4 Zero Birefringence

The increased polarisation dependence in small waveguides is derived from the increasingly differing mode shapes of the quasi-TE and quasi-TM modes. The question arises as to whether the prime concern is to maintain similar losses for the TE and TM modes or to provide similar propagation constants in order to maintain similar phase performance for interferometric based devices, because it is not generally possible to maintain both. In principle, waveguide birefringence can be removed by appropriate choice of rib waveguide width to height ratio \([3.9]\) or by employing stress engineering \([3.17]\) to tailor the thickness of SiO\(_2\) for polarisation compensation. Similarly, as discussed above, it is also possible to design a rib waveguide supporting only a single mode with an appropriate selection of the rib width and height \([3.10]\). The degree of influence of waveguide width and etch depth on waveguide birefringence for a given rib height is demonstrated by further simulations here. Once again we have used rib waveguide heights of 1.00\(\mu\)m, 1.35\(\mu\)m and 1.50\(\mu\)m, and have evaluated the effective indices of the fundamental quasi-TE and quasi-TM modes. If we assume an operating wavelength of 1550nm, we can
Figure 3-10: Effective index difference calculation between quasi-TE and quasi-TM polarized modes using the FEM [3.12], for waveguide heights (a) 1.00\,\mu m (b) 1.35\,\mu m (c) 1.50\,\mu m

Chapter 3: Theory and Analysis
produce a graph of the variation of the quasi-TE/TM fundamental mode effective index difference ($\Delta N = N_{TE} - N_{TM}$) for various etch depths ($D$) and waveguide widths ($W$).

Figure 3-10 (a), (b) and (c) show various curves of waveguide width against effective index difference, each for a different waveguide height. By using an appropriate etch depth for each waveguide height, the curves cross the zero birefringence (ZBR) axis twice when the effective index of both polarisation modes is the same, which indicates it is possible to produce birefringence free waveguides of two different waveguide widths when a deep etch depth is employed ($r < 0.5$). The wider waveguide width is highly preferable compared to its narrower counterpart when we consider that the wider devices will result in more flexibility during fabrication and optical coupling. If we consider $H = 1.50\mu m$, $D = 0.90\mu m$, the birefringence free waveguide widths, $W$, can be determined from Figure 3-10 (c) as $0.90\mu m$ and $1.05\mu m$. If we now introduce an etch depth uncertainty of $10\text{nm}$, we see that the latter width is more desirable as the impact of the uncertainty on change in birefringence is reduced from $6.03 \times 10^{-4}$ to $3.28 \times 10^{-4}$. The same trend can also be observed in Figure 3-10 (b) and (c). The study on etch control of silicon in a $0.13\mu m$ CMOS process technology has determined experimentally [3.20] that the etch depth tolerances are of the order of $\pm 1\%$ to $\pm 2\%$. Therefore, if we consider a $1\mu m$ etch depth to form an SOI waveguiding structure, the tolerance will be of the order of $\pm 10\text{nm}$. As process technology moves to the next generation beyond the critical dimensions (CD) of $90\text{nm}$, following the International Technology Roadmap for Semiconductors (ITRS) [3.21], the reactive ion etching (RIE) process control will be improved and continue to be driven by the CD requirement of advanced lithographic processes. However, most optical devices made from silicon are likely to have CD of hundreds of nanometers for the foreseeable future, which means that the infrastructure already exists for the next several generations of optical circuits, if they are fabricated in silicon.

A gradual increase of the etch depth is also used in the simulations to show the influence of etch depth on the modal birefringence. The result shows that at larger waveguide widths, waveguide etch depth has little effect on the mode birefringence because the quasi-TE mode (horizontal polarised mode) is well confined under the rib.
region. However, at smaller rib widths, the etch depth has a large influence on birefringence. It is clear that in each of the plots in Figure 3-10, the curves have gone through three transitions. For large waveguide widths, the quasi-TE mode effective index dominates as most power is confined under the rib region, this makes the device exhibit slab-like behaviour, allowing higher order modes to couple to the slab region. As the width is reduced gradually, the effective index of the quasi-TM mode becomes similar to that of the quasi-TE mode and then the effective index difference can become negative. When the waveguide width becomes very small, most of the mode power will again be confined under the slab regions, and as a result the quasi-TE mode effective indices once again become higher than those of the quasi-TM modes.

To confirm the trends of the data in the simulations, waveguide birefringence for etch depth of 880nm in Figure 3-10 (c) have been computed by the full-vectorial finite element method (FEM) [3.12], finding good agreement with results produced by BPM, as shown in Figure 3-11.

![Graph](image)

**Figure 3-11:** Comparison of numerical simulation results for waveguide birefringence in FEMLAB [3.12] and BeamProp [3.11] for waveguide etch depth of 880nm.

Drawbacks associated with small waveguide geometries are that it is difficult to fabricate such devices accurately, and it becomes difficult to couple light efficiently.
into the waveguides. Although computer simulations enable us to generate detailed designs of rib waveguides with polarisation independence, we must take into account variations in the fabrication process such as etch depth uniformity, etching profile and CD as well as process control of waveguide width. Real-time in situ monitoring of micro-electro-mechanical systems (MEMS) using deep RIE processing has been demonstrated [3.22] in high aspect ratio etching in SOI wafers. Process variables in RIE also have been studied extensively in [3.23]. Both approaches are nondestructive and provide real-time process analysis. Hence, this will lead to improved process accuracy and controllable process repeatability. If we now plot the locus of the points in Figure 3-10 that cross the zero birefringence axis, we observe similar trends for all three rib waveguide heights. We have also added simulated zero birefringence data for waveguide heights of $H = 1.20\mu m$, $1.75\mu m$ and $2.00\mu m$.

![Figure 3-12: Etch depth influence on waveguide width in SOI structure to support zero birefringence for various waveguide heights at $\lambda = 1550nm$, reflecting the etch depth tolerance requirements in relation to process technology.](image)

This is shown in Figure 3-12, where we plot etch depth against waveguide width for a variety of waveguide heights, and fit with 2nd order polynomial. We note that there is a minimum etch depth ($D_{min}$) for each waveguide design, which must be matched to a
specific waveguide width if the polarisation independent condition is to be met. Hence, we can use this data to predict the rib waveguide width and etch depth needed for polarisation independent operation by assuming that the relationship between \( D_{\text{min}} \) and waveguide height is linear. This relationship can be expressed by the following approximate equation after linear regression fitting of simulation data, for waveguide heights, \( H < 2 \mu m \):

\[
D_{\text{min}} = 0.06 \times 10^{-6} + 0.556H
\]  \hspace{1cm} (3.33)

This finding is particularly useful to aid the design of waveguides meeting the requirement of polarisation independence. The low curve gradient at the minimum etch depth depicted in Figure 3-12 also makes the minimum etch depth a good choice from a fabrication perspective, because the impact of the tolerances of the etching process is minimised.

![Figure 3-13: Minimum etch depth to waveguide height \((D_{\text{min}}/H)\) ratio and parameter \(r\) plotted as a function of waveguide height. This relationship indicates the requirement of minimum etch depth tolerance to achieve zero birefringence increases as the waveguide height is reduced.](image)
It is also interesting to note that as a proportion of the waveguide height \( D_{\text{min}}/H \), the minimum etch depth increases as the waveguide height is reduced, which in turn means that for smaller waveguide height, the smaller the maximum value of parameter \( r \) becomes and a higher etching tolerance must be satisfied to maintain the zero birefringence condition. For instance, an etch depth error of 10nm will introduce a modal birefringence difference of \( 3.2 \times 10^{-4} \) for \( H = 1.50 \mu m \) compared to \( 2.7 \times 10^{-3} \) for \( H = 1.00 \mu m \). This is clearly illustrated in Figure 3-13 and can be expressed as:

\[
\begin{align*}
    r_{\text{max}} &= 1 - \frac{D_{\text{min}}}{H} = 1 - \frac{0.06 \times 10^{-6} + 0.556H}{H} \\
    r_{\text{max}} &= 0.444 - \frac{0.06 \times 10^{-6}}{H}
\end{align*}
\]  

(3.34)

where \( r_{\text{max}} \) is the maximum parameter \( r \) related to minimum etch depth requirement to satisfy waveguide birefringence free.

### 3.2.5 Satisfying Single-mode and Zero Birefringence Conditions Simultaneously

Although the requirements for zero birefringence (ZBR) and single mode condition (SMC) can be met using appropriate rib design, so far in this chapter, both requirements have not been presented simultaneously when small waveguide dimensions are considered. We have combined the single mode condition for quasi-TE and quasi-TM modes \((H = 1.00 \mu m, 1.35 \mu m \text{ and } 1.50 \mu m)\) together with zero birefringence curves to demonstrate that both conditions can be met under certain conditions. Unlike other authors, we have presented the data in terms of the absolute waveguide dimensions rather than using normalised values of \( W/H \) ratio and parameter \( r \), because this provides a clearer indication of the design problem. All the data points which cross the zero birefringence axis in Figure 3-12 were used in Figure 3-14 and Figure 3-15 in terms of waveguide width \((W)\) and etch depth \((D)\), to plot a locus of the birefringence free condition for varying waveguide dimensions. This data is now used to show the relationship between single mode operation and birefringence free operation and the possibility of satisfying both conditions simultaneously.
Chapter 3: Theory and Analysis

Simulation data of waveguide heights, $H = 1.0\,\mu m$, $1.35\,\mu m$ and $1.50\,\mu m$ are again used. Experimental results of [3.18], in which the device exhibits low polarisation dependence and supports only a single mode give us confidence in our numerical results. Figure 3-14 and Figure 3-15 (a)-(b) show plots of both the single mode condition and the birefringence free locus for each of the three waveguide heights. These figures suggest that it is possible to achieve single mode operation at both polarisations whilst maintaining polarisation independence for each of the waveguide heights used. In order to satisfy both the requirements of single mode operation and polarisation independence, we must choose a point on the birefringence free locus that is below the single mode boundary for both quasi-TE and quasi-TM modes. However, it should be noted that the trend lines are approximate because they are the result of curve fitting, and therefore, for a specific design, data points should be used instead of the trend lines.

Figure 3-14: Trend and boundary lines for single mode cut-off dimensions and zero birefringence condition as a function of waveguide dimensions for an operating wavelength of $\lambda = 1550\,\mu m$ for $H = 1.00\,\mu m$. 
Figure 3-15: Trend and boundary lines for single mode cut-off dimensions and zero birefringence condition as a function of waveguide dimensions for an operating wavelength of $\lambda = 1550\text{nm}$ for (a) 1.35\(\mu\text{m}\) (b) 1.50\(\mu\text{m}\)
Chapter 3: Theory and Analysis

Figure 3-16: Waveguide geometries that exhibit single-mode and birefringence free behaviour simultaneously for waveguide heights, $H = 1.00 \mu m$, $1.35 \mu m$ and $1.50 \mu m$ at design wavelength of $\lambda = 1550 \text{nm}$

The design rules for the single mode condition $\alpha = 0.3$ [3.6] and $\alpha = 0$ [3.7] were also extrapolated for comparison with our numerical simulation. It is interesting to note that the intersection between the birefringence free locus and the quasi-TE graphs determines the limit of the waveguide width to guide not only the fundamental quasi-TE mode, but multiple quasi-TM modes. For instance, the maximum values of rib width ($W$) are $0.77 \mu m$, $0.98 \mu m$ and $1.05 \mu m$ for waveguide heights ($H$) of $1.00 \mu m$, $1.35 \mu m$ and $1.50 \mu m$ respectively, to satisfy the quasi-TE single mode condition and the birefringence free condition. However, if we also wish to satisfy the single mode condition for quasi-TM polarisation, narrower waveguides are required. In this case the waveguide widths must be $0.52 \mu m$, $0.83 \mu m$, and $0.92 \mu m$ respectively.

The crossing points for the two polarisations between the birefringence free condition and both single mode boundary lines are closer to each other as the waveguide height is increased. Hence it is easier to satisfy both conditions for waveguide heights of $1.35 \mu m$ and $1.50 \mu m$ compared to waveguides with a height of $1.00 \mu m$ or less in the context of fabrication tolerance. As the etch depth ($D$) increases (or parameter $r$
decreases), the waveguide width must also be reduced to maintain only single-mode operation for a designated polarisation. This can be observed for all the ZBR data points below which the quasi-TM boundary line intersects the zero birefringence locus plots in Figure 3-16. These results of the SMC and the ZBR curves give us confidence in the possibility to achieve SOI waveguides satisfying both requirements, as required in many applications. However, in some cases the relevant requirement of the waveguide width may be too narrow for fabrication purposes and impractical when coupling light into the small waveguide structure.

3.2.6 Design Guidelines for Small Cross Sectional SOI Waveguides

The single mode condition for these small waveguides with deep etch depth ($r < 0.5$) is effectively limited by the boundary condition set by the quasi-TM mode. We have produced a generalised equation in terms of waveguide dimensions, using the simulation data already presented and following the notation used in [3.6]:

$$W \leq 0.05 + \frac{(0.94 + 0.25H)r}{\sqrt{1-r^2}}$$

(3.35)

$$0.3 < r < 0.5 \text{ and } 1.0 \leq H \leq 1.5$$

It is interesting to examine the usefulness of the above approximate equation by comparing with experimental SOI devices. Following the approach given in reference [3.7], we have compared the experimental results from Rickman et al. [3.18] who experimentally investigated the dependency of waveguide geometries supporting only fundamental mode operation, to our approximate equation, even though the results of [3.7] are based upon waveguides much larger than those simulated in this paper. We have adopted this approach because there is insufficient experimental data in the literature to compare and study with our modelling, to unequivocally confirm our design rules. However, our simulation results were in reasonable agreement with the experimental observations for waveguide height of 4.3μm, even for large etch depths [3.18]. We can observe from Figure 3-17 that, in contrast to the boundary prediction of both Pogossian et al. [3.7] and Soref et al. [3.6], equation (3.35) marks a clear
Chapter 3: Theory and Analysis

separation between the boundary of single and multi-mode regions over a large range of etch depth and rib width values, giving us additional confidence in the equation.

Figure 3-17: A comparison of our design equation for small cross section SOI waveguide with different design rules in the literature together with experimental observation for large waveguide dimensions from [3.17].

3.2.7 Waveguide Design Summary

We have systematically analysed the design parameters of rib waveguide structures to satisfy both the single mode and polarisation independence conditions for small cross section SOI waveguides. The requirement of birefringence free waveguides can be fulfilled by using a deep etch depth when using small cross sectional waveguide dimensions; it is more restrictive to design waveguide dimensions to achieve single mode operation and polarisation independence simultaneously. Not surprisingly the scalar approximation is accurate enough to design single mode waveguides with large cross section for $r > 0.5$, in agreement with results in [3.6] and [3.8]. However, for deeply etched, small waveguides the situation is more complex. We have proposed approximate design rules for small waveguides, but for critical designs, individual design simulations should be used to achieve single mode and birefringence free operation simultaneously.
3.3 Bragg Gratings Theory

3.3.1 Coupled Mode Theory

A Bragg grating is formed by creating a periodic corrugation or refractive index modulation in an optical waveguide. Such a structure behaves as a wavelength selective filter, reflecting a narrow band of wavelengths while transmitting all other wavelengths.

![Diagram of Bragg grating](image)

Figure 3-18: Schematic diagram of a uniform surface corrugated periodic on a waveguide.

Figure 3-18 illustrates typical Bragg grating fabricated in an optical waveguide. Although Bragg gratings are commonly imprinted in photosensitive optical fiber, physically pattern gratings in waveguides offer a number of advantages. One can build Bragg gratings in non-photosensitive material such as silicon. In addition, integrated gratings can contain precise phase shifts and variations in grating strength to better achieve a desired filter response. Furthermore, the fabrication process can integrate multiple grating with splitters, couplers and other optoelectronic components on a single chip.

The Coupled Mode Theory (CMT) is often used as a technique for obtaining quantitative information about the diffraction efficiency and spectral dependence of waveguide based gratings. Due to its simplicity and accuracy in modelling the optical properties of most fibre gratings, CMT becomes one of the popular methods of explaining the behaviour of Bragg gratings. Although the coupled mode theory was initially developed for fibre gratings, the same principles could be applied to
waveguide grating width surface corrugation as shown in Figure 3-18. The examples of the application of such structures include distributed feedback lasers [3.24] and all optical filters for WDM systems [3.25]. The derivation of coupled mode theory closely follows the work by Erdogan [3.26] and Othonos et al. [3.27]. We start by writing the transverse component of the electric field in the ideal mode approximation to coupled mode theory as a superposition of the ideal modes (the modes in an ideal waveguide where no grating perturbation exist).

\[
E^T (x, y, z, t) = \sum_m [A_m (z) \exp(i \beta_m z) + B_m (z) \exp(-i \beta_m z)] e^T_m (x, y) \exp(-i \omega t)
\]  

(3.36)

where the coefficient \( A_m (z) \) and \( B_m (z) \) are slowly varying amplitudes of the \( m \)th mode travelling in the +\( z \) and -\( z \) directions, \( \beta \) is propagation constant and \( e^T_m (x, y) \) the transverse mode field. The derivatives of the amplitude coefficient in terms of propagation in \( z \)-direction can be expressed by [3.26]:

\[
\frac{dA_m}{dz} = i \sum_q A_q (C^T_{qm} + C^L_{qm}) \exp[i(\beta_q - \beta_m)z] + \sum_q B_q (C^T_{qm} - C^L_{qm}) \exp[-i(\beta_q + \beta_m)z]
\]

(3.37)

\[
\frac{dB_m}{dz} = -i \sum_q A_q (C^T_{qm} - C^L_{qm}) \exp[i(\beta_q + \beta_m)z] - \sum_q B_q (C^T_{qm} - C^L_{qm}) \exp[-i(\beta_q - \beta_m)z]
\]

(3.38)

where the transverse coupling coefficient \( C^T_{qm} \) between the \( m \) and \( q \) modes in the above equations is given by the following integral:

\[
C^T_{qm} (z) = \frac{\alpha_0}{4} \int \Delta \varepsilon (x, y, z) e^T_m (x, y) dx dy
\]

(3.39)

where \( \Delta \varepsilon (x, y, z) \) is the permittivity perturbation. The longitudinal coupling coefficient \( C^L_{qm} \) is defined in a similar way to the above transverse coupling.
Chapter 3: Theory and Analysis

coefficient $C_{q_m}^x$. The Bragg grating will create a coupling between optical waveguide modes and grating regions wherever the difference between their propagation constant is equal to:

$$\beta_q - \beta_m = l \frac{2\pi}{\Lambda} \quad (3.40)$$

where $\Lambda$ is the grating period and $l$ represents an integer. Equation (3.40) is well known as phase matching condition; when this condition is satisfied, the $q$th and $m$th mode will be resonantly coupled via the $l$th Fourier component of the periodic perturbation $\Delta \varepsilon(x, y, z)$ [3.28].

Let us assume that the period $\Lambda$ of the perturbation is chosen so that $l \frac{2\pi}{\Lambda} = 2\beta_q$ for some integer $l$. The phase matching condition can thus be satisfied by the coupling between the mode $\beta_q$ and its reflected mode which has a propagation constant of $-\beta_q$, since $\beta_q - (-\beta_q) = 2\beta_q = l \frac{2\pi}{\Lambda}$. If we consider a waveguide with grating section of length $L$ as in Figure 3-18; a wave with amplitude $A(0)$ is incident from the left on the grating section. The boundary conditions are $A(z) = A(0)$ at $z = 0$ and $B(z) = 0$ at $z = L$, we obtain the following expressions for mode amplitudes [3.28]:

$$A(z) = A(0)e^{i\frac{1}{2} \Delta \beta z} \left[ \frac{s \cosh s(L-z)+i\frac{1}{2} \Delta \beta \sinh s(L-z)}{s \cosh sL+i\frac{1}{2} \sinh sL} \right]$$

$$B(z) = A(0)e^{-i\frac{1}{2} \Delta \beta z} \left[ \frac{-i k s \sinh s(L-z)}{s \cosh sL+i\frac{1}{2} \sinh sL} \right]$$

where $s$ and $\Delta \beta$ are given by:

$$s = \sqrt{k^* k - \left(\frac{1}{2} \Delta \beta\right)^2} \quad (3.42)$$
by substituting equation (3.43) into (3.42), we get

\[ s = \sqrt{\kappa^2 - \left( \beta_q - l \frac{\pi}{\Lambda} \right)^2} \]  
(3.44)

with \( \delta_q \) being the tuning from the resonant coupling and \( \kappa \) is the grating coupling strength.

\[ \delta_q = \beta_q - l \frac{\pi}{\Lambda} \]

(3.45)

This gives the Bragg condition for the gratings:

\[ \lambda_d = \lambda_{\text{mags}} = 2\eta_n \Lambda \]  
(3.46)

where \( l = 1 \), representing 1\textsuperscript{st} order Bragg grating. The fraction of power coupled to the backward propagating mode (-\( \beta_d \)) is called the mode reflectivity is defined as:

\[ R = \frac{|B(0)|^2}{|A(0)|} \]  
(3.47)

After some derivation of equation (3.41), it can be expressed by:

\[ R = \frac{\kappa^* \kappa \sinh^2 sL}{s^2 \cosh^2 sL + \left( \frac{1}{2} \Delta \beta \right)^2 \sinh^2 sL} \]  
(3.48)
Under phase matching conditions $\Delta \beta = 0$ and $\kappa = s$, this lead to the reflectivity $R$ reaches its maximum value according to equation (3.48):

$$R_{\text{max}} = \tanh^2 |\kappa L|$$

(3.49)

where $L$ is the grating length of the device and $\kappa$ is the grating coupling strength. In order to demonstrate the effect of both parameters on the overall spectral response of the grating, the reflectivity for a periodic rectangular profile grating is computed.

Figure 3-19: Reflection spectral responses versus wavelength for uniform Bragg gratings on SOI waveguide with etch depth of 0.22µm and grating length of 400µm and 1500µm.

Figure 3-19 shows the reflectivity of a uniform Bragg grating calculated from (3.48) for grating length of 400 µm and 1500µm as a function of operating wavelength. It was assumed that the grating etch depth of 0.220µm is constant, hence the grating strength, $\kappa$ is the same. It is interesting to note that for a given $\kappa L$ with increasing number grating period or length, the reflectivity bandwidth becomes narrower, in other words, longer gratings produce narrower spectral linewidth. The magnitude of the gratings induced refractive index changes can be controlled using different etch depths imposed on the waveguide structure. Furthermore, the Bragg gratings can be configured as a narrowband transmission or a reflection filter depending on where the output or input signal path is collected from such devices.
3.3.2 Floquet-Bloch Theory

Most of the simulations of Bragg gratings that have been reported have been carried out by using the coupled mode theory (CMT) which involves the study of the grating as a mode coupler [3.29]. This method gives an approximate evaluation of the losses as induced by the presence of the grating and is limited to weakly coupled waves. It has been shown that the leaky mode propagation (LMP) [3.30, 3.31, 3.32] derived from Floquet-Bloch Theory (FBT) offers some significant advantages in terms of very low computational time, absence of any a priori theoretical assumptions and capability of simulating the actual behavior of the device as a reflector. In this section, the leaky mode propagation (LMP) approach is reviewed and the analysis is applied to one dimensional (1-D) finite waveguide periodic structures because high depth gratings are strong enough to be considered a one dimensional photonic bandgap structure [3.33]. The numerical results are presented for an optimum value of grating etches in 3rd order Bragg grating structures in SOI.

![Schematic diagram of a finite length periodic structure on homogeneous planar waveguide](image)

Figure 3-20: Schematic diagram of a finite length periodic structure on homogeneous planar waveguide

A guided mode $\Psi_i$, incident at $z = 0$ on the grating region from the unperturbed planar waveguide, "sees" the second grating interface at $z = L$, where $L$ is the grating length, and produces a number of diffracted orders depending on the vectorial phase condition:

$$\bar{\beta}_q = \bar{\beta}_o + qK \quad q = 0, \pm 1, \pm 2, \pm 3, ... \quad (3.50)$$

where $\bar{\beta}_q$ and $\bar{\beta}_o$ are the propagation constant vectors of $q$-th diffracted and incident waves respectively. $K=2\pi/\Lambda$ is the grating vector module and $\Lambda$ is the period of the
grating. In general, the incident wave will exchange power with a number of diffracted orders, depending on the grating properties, i.e. its strength (grating depth and groove index change) and its length. It is well known that, in particular for guided modes, different diffraction regimes can be encountered with Bragg condition as a function of the incidence angle (depending on the guided wavelength). In particular, it must be noticed that, being the grating vector \( \mathbf{K} \) along \( z \), the Bragg condition of power exchange between forward and backward waves, i.e. between \( \beta_0 \) and \( \beta_{-1} \), is perfectly verified only if the vector triangle is symmetric and, then, the relationship can be expressed as:

\[
\lambda = 2N_{\text{eff}} A \quad (3.51)
\]

where \( N_{\text{eff}} \) is the incident wave effective index. Moreover, this power exchange is strongly influenced by the asynchronism condition which occurs between each pair of coupled waves, e.g. the incident and the first diffracted order \( (q = 0 \text{ or } q = +1) \), the first and the second diffracted order \( (q = +1 \text{ and } q = +2) \), and so on. The asynchronism is measured by the difference between the effective indices of the coupled waves, i.e. between their phase velocities.

The power exchange will increase with decreasing this difference and the value will be maximised under a quasi-synchronous condition. This occurs when the grating strength is relatively moderate when its presence does not perturb significantly the guiding structure, and the propagation constants of the fundamental \( (n = 0) \) harmonic in both the unperturbed and perturbed structures are almost equal. Under this situation, the power exchange between the two guided modes (the incident mode and the mode inside the grating region) is maximum (approaching 100%) and the power coupled to each of the other diffraction orders in equation\(3.50\) is negligible. It must be considered that the grating influence is moderate with respect to the planar waveguide characteristics. This means that the grating depth has to be small in planar waveguides with low field confinement but larger in those with high confinement. Therefore, the model is particularly useful in high confinement structures, such as \( \text{III/V} \) semiconductor or silicon guiding structures. The model developed for finite length guided-wave gratings is based on the condition of quasi-synchronism for the
calculation of the reflectivity and transmittivity properties. The assumption is verified with high accuracy for structures not heavily perturbed by the grating when:

\[ \Delta \beta / \beta < 10\% \]  

Therefore this approach neglects the unguided waves which, under certain incidence angles can be excited by the interaction of the incident beam with the grating, causing power scattering in the semi-infinite regions - upper layer and substrate, results in the reduction of guided power. Consequently, the incident wave produces only two guided waves, one reflected and the other transmitted. In the grating region, the electromagnetic field can be described by Floquet-Bloch formalism as a superposition of guided leaky modes of the infinite structure [3.30] when each leaky mode is described as a sum of space harmonics \( f_n(x) \) in the form:

\[ \sum_n f_n(x) \exp(-jk_{cu}z) \]  

Each one satisfying Maxwell’s equations and having their propagation constants related by the Floquet phase condition:

\[ k_{cu} = k_{c0} + \frac{2\pi n}{\Lambda} \quad n=0, \pm 1, \pm 2, \pm 3, ... \]  

where \( k_{c0} = \beta_0 - j\alpha \) is the zero order propagation constant and \( \alpha > 0 \) is the mode leakage factor. The field description as a superposition of leaky modes is valid if the grating length is larger than the guided wavelength which is related to:

\[ L = N_{\text{grat}}\Lambda > \lambda_g \]  

where \( N_{\text{grat}} \) is the number of periods. The above equation indicates the minimum number of period is very small \( (N_{\text{grat}} > 2) \) for perfect matching since it requires \( \lambda_g = 2\Lambda \). Inside the grating region, the solution is assumed as a linear combination of the two modes, one forward and the other backward:
where the coefficients $a^*$, $b^*$ depend on the boundary conditions at the finite grating input $z = 0$ and output $z = L$, interfaces and $\Psi$ is the mode transverse field distribution. If $\beta_u$ and $\Psi_u$ are the propagation constant and the transverse distribution of the mode incident on the grating from the planar waveguide respectively, then the incident($i$), reflected($r$) and transmitted($t$) modes can be written as:

\[
\Psi_i(x,z) = \Psi_u(x)e^{j\delta_n}e^{-j\beta_n z}
\]

(3.57)

\[
\Psi_r(x,z) = \rho \Psi_i(x)e^{-j\beta_n z}e^{j\delta_n}
\]

(3.58)

\[
\Psi_t(x,z) = \tau \Psi_u(x)e^{j\delta_n}e^{-j\beta_n z}
\]

(3.59)

where $\delta_n = K - \beta_n$, $\rho$ is the amplitude reflection coefficient and $\tau$ is the amplitude transmission coefficient. Since no optical power is incident on the interface $z = L$ (end of the grating section) from the unperturbed waveguide; it is possible to derive the grating reflection ($\rho$) and transmission coefficients ($\tau$) as a function of the overlapping integrals between the incident wave and the leaky mode space harmonics by combining equations (3.57) to (3.59), and the modal reflection and transmission coefficient can be expressed as:

\[
R_p = |\rho|^2
\]

(3.60)

\[
T_p = |\tau|^2
\]

(3.61)

Subsequently, the out of plane losses $L_p$ can be evaluated as:

\[
L_p = 1 - R_p - T_p
\]

(3.62)

where $L_p$ is the modal reflection coefficient and $T_p$ is the transmission coefficient for the gratings.
3.4 Characteristics of a Bragg Grating filter

3.4.1 Resonance Wavelength

As mentioned in equation (3.46), the Bragg wavelength is determined by the period of the Bragg gratings. Therefore for a given waveguide, the grating period for a desired Bragg wavelength, \( \lambda_b \), can be expressed as:

\[
\Lambda = \frac{n_{eff} \lambda_b}{2 n_{eff}}
\]  

(3.63)

where \( n_{eff} \) is the effective index of the waveguide mode (usually the fundamental mode) and \( m \) is the integer representing the diffraction order of the grating. The choice of diffraction orders used in the grating design highlights the trade-off between fabrication equipment capabilities and reflection grating performance.

3.4.2 Bandwidth

The bandwidth of the reflected spectrum is determined by both grating length and grating strength which is related to the following equation [3.26]:

\[
\frac{\Delta \lambda}{\lambda_b} = \sqrt{\left(\frac{\delta n_{eff}}{n_{eff}}\right)^2 + \left(\frac{2 \Lambda}{L}\right)^2}
\]  

(3.64)

Where \( \delta n_{eff} \) is the change in effective index induced by the grating and \( L \) is the grating length. For a weak grating modulation, \( \delta n_{eff} \) is very small, which results in the 1st term in equation (3.64) being negligible compared with the 2nd term. Hence, the bandwidth can be simplified as:

\[
\frac{\Delta \lambda}{\lambda_b} = \frac{2 \Lambda}{L} = \frac{2}{N}
\]  

(3.65)

where \( N \) is the number of grating periods. From the above equation, we can deduce that the bandwidth of the reflection spectrum is directly inverse proportional to the
grating length. For strong grating modulation, the 1\textsuperscript{st} term is more dominant than the 2\textsuperscript{nd} term, where the bandwidth can be simplified as:

\[
\frac{\Delta \lambda}{\lambda_i} = \frac{\delta n_{\text{eff}}}{n_{\text{eff}}}
\]  \hspace{1cm} (3.66)

In this instance, the grating length does not have a significant effect on the spectrum since the input signal has been reflected completely by the first several gratings section. The rest of the gratings will have no effect on the reflected spectrum. Hence, it is vital to consider the trade-off between the grating strength (grating etch depth) and the grating length. A uniform distributed grating may exhibit high side-lobes in comparison with reflection spectrum, leading to increased cross-talk between wavelengths. Apodisation of the grating, that is changing the strength of the grating along the waveguide filter is usually employed in fibre grating to address this issue. In practise, the main lobe bandwidth and the level of side-lobes are strongly dependent on the profile of the grating apodization, and therefore proper selection and optimisation of the apodization function is necessary to achieve the desired level of side-lobes for a given bandwidth [3.34].

3.5 Summary

In this chapter the single-mode and polarisation independent conditions have been shown to be viable in small cross section SOI rib waveguides and the influence of waveguide etch depth parameters was discussed in relation to available fabrication technology. An approximate design rules have been proposed for small waveguides, but for critical designs, individual design simulation should be used to achieve single-mode and birefringence-free operation simultaneously. The numerical simulation to calculate reflection spectrum of gratings have been discussed using Coupled Mode Theory and Floquet-Bloch Theory. CMT approach gives accurate results when the periodic perturbation is weak, and the refractive index profile and guiding layer thickness are very similar. However, it may be difficult to estimate the radiation loss due to the periodic gratings in the CMT. The FBT is more complex but can be used for accurate calculation of the field profiles and grating period of the grating filter for
strong periodic perturbation. In FBT, the grating is assumed to be infinite in length (i.e. the length is much larger than the wavelength) leading to the number of spatial harmonics is infinite as well. In addition, the radiation loss associated with the gratings can also be estimated using FBT. Treatments of the basic operating characteristics of an optical grating filter along with crucial parameters such as resonance wavelength and bandwidth have been reviewed.

References:


Chapter 3: Theory and Analysis


3.11 BeamPROP Version 5.1.8.5 by RSoft Design Group, Inc., 200 Executive Group Blvd. Ossining, NY 19562


3.21 International Technology Roadmap for Semiconductors (ITRS) WEB site at http://public.itrs.net/


Chapter 4

It must be done, because we must do everything that is right. Matthew 3:15

4 Device Design

4.1 Introduction

Simulation is carried out to predict the behaviour of a device in advance of its fabrication or to quantify discrepancies between simulation and experimental results. The basic theory employed in the simulation will be used as a reference to compare with experimental results since device fabrication tolerance inevitably influences and affects the predictions of simulation. The simulation model is applied to a particular geometry and permits the designer to predict the behaviour of highly complex geometries. When the underlying theory is validated, simulation can also be used to provide data on device performance and observe changes in behaviour with variation of geometrical or physical parameters of the device model.

The objective of this chapter is to discuss design issues of integrated Bragg gratings on SOI waveguides. The simulated waveguide dimension that supports both single mode and polarisation independent as discussed in section 3.2.3 will be used as a waveguide platform to design waveguide bend and Y-junction which forms part of the grating filter. The integrated Bragg gratings were modelled by Coupled Mode Theory (CMT) and Floquet Bloch Theory (FT) with first and third order diffraction gratings. Description of these two modelling theories was given in section 3.3 The variation of grating parameters such as grating period, etch depth and grating length were also presented, all of which can affect the grating device's performance significantly. The thermo-optic effect on the embedded SOI grating will also be investigated which has the potential of realising a tunable Bragg reflection filter.
4.2 Waveguide Bend and Y-Junction

Figure 4-1: 3D schematic diagram of Bragg grating implemented on inverted Y-junction

Figure 4-2: Top to down view of Bragg grating device with waveguide design parameters.
Figure 4-1 and Figure 4-2 depict the 3D schematic layout (not to scale) and overall Bragg grating design parameter of the inverted Y-junction. The design and integration the Y-junction with the Bragg grating will facilitate the ease of coupling from optical fibre and compactness of the device, leading to higher packing density in a chip. In this section, we will discuss the component design of the Y-junction, which consists of bead radii, waveguide splitter and taper.

The objective of designing a waveguide with curvature is to minimise radiation losses, transition losses and higher-order mode excitation between the straight and bend waveguides. It is well known that the modal mismatch between the modal profiles of the fundamental mode in curved waveguide and straight waveguides results in transition loss, and excitation of higher order modes at the junctions between straight waveguide and curve waveguides. It has been proposed that transition loss, \( \delta_{tr} \) can be reduced by offsetting the curved waveguide towards the centre of its curvature [4.2] related by the following equation:

\[
\delta_{tr} = \frac{\pi^2 n_{eff}^2 w_0^4}{\lambda^2} \left( \frac{1}{R} \right)
\]  

(4.1)

where \( n_{eff} \) is the effective index of the fundamental mode, \( w_0 \) is the spot size, \( R \) is the bending radius and \( \lambda \) is the operating wavelength. If the waveguide dimensions employed in the design are strictly single mode as discussed in section 3.2.3, this will effectively reduce the potential of higher order mode excitation and complexity of the design problem. The presence of higher order modes can affect or even compromise the performance of integrated optic components such as a Y junction, star coupler or arrayed waveguide grating. Therefore, their waveguide dimensions have to be chosen to support strictly fundamental mode operation only.

Another dominant loss mechanism in curved waveguide is radiation loss. It arises from the transformation from a straight single mode waveguide into a bend structure. When an electromagnetic wave travels along a waveguide with a constant bend radius, the wavefronts associated with the eigenmodes of the bent waveguide are
curved. This curvature of the wavefront gives rise to radiation away from the waveguide core, in the case of SOI waveguides to the slab waveguide region. Melloni et al. [4.3] have introduced a detailed design of curved waveguide based on coupled mode theory with optimum bend radius and bend angle to minimise both radiation and transition loss. For a given bend angle, only a number of discrete bend radii can satisfy the criteria of minimal loss at the junction. The analytical solution presented by the authors is highly dependent on waveguide dimensions, hence for each different waveguide structure the optimum bend radius and bend angle must be considered individually. The Effective index method (EIM) [4.4] also has been used to estimate the radius of curvature of deeply etched rib waveguides in which the higher order mode becomes leaky and radiates away from the core of the waveguide to the slab region.

![Figure 4-3: Predicted TE\(_{00}\) and TM\(_{00}\) waveguide bend loss at \(\lambda = 1550\text{nm}\)](image)

Although this method has been successfully applied in designing bend radius of III-V rib waveguides, it is not suitable for waveguide system with high refractive index contrast such as in SOI waveguides. Our computation method of bend radius is based on application of semi-vectorial BPM to the deeply etched waveguide section as shown in section 3.2.3 based on an SOI rib waveguide width of 1.0\(\mu\text{m}\), etch depth of
0.89µm and height of 1.50µm. We then evaluated bend loss as a function of bend radius for both TE₀₀ and TM₀₀ polarisation modes, for bend angle of 15° at λ = 1550nm.

It is apparent that the simulation predicts that waveguide bend loss will be negligible for bends with radius greater than 500µm for both polarisations. The calculated bend radius with minimal losses is significantly smaller than the value of 4mm by Rickman [4.5]. This is expected since our SOI waveguide dimensions are much smaller, and the modes will be proportionately smaller. For TE₀₀ mode the loss may be greater as the lateral field is less well confined than for TM₀₀. In addition, our modelling does not include the side wall roughness [4.6] which will increases bend losses and scattering losses for both polarisations, although not by the same amount.

Figure 4-4: Schematic diagram shows a typical S-bend structure

We can form S-bend structure shown in Figure 4-4 with two identical but opposite bend radius structure connected with a straight waveguides. The S-bend is commonly employed in directional couplers, power splitters and Mach-Zehnder interferometers (MZI). The Y-junction structure which we will be investigating essentially consists of two identical S-bends. In order to reduce the loss from modal mismatch and radiation loss caused by an abrupt transition of waveguide width [4.7, 4.8] from the combination of two waveguide bends, a width taper [4.9, 4.10] is used to form a gradual and smooth transition from a single mode waveguide to two single mode

4-5
waveguide branches. Y-junctions operate through the coupling of local mode in the transition region of the Y where the single mode waveguide increases in width. The transition region extends to the point where the spacing of the two branch waveguides has grown to a dimension where the fundamental modes supported in each branch no longer couple. Various angle-bend and S-bend configurations have been considered in [4.11] to study the inter-modal power transfer and radiation losses at the recombination junction of the MZI. A similar approach can be considered in a BPM simulation to analyse the distribution of power, power splitting ratio and tapered region which connect both branch of the curved waveguides [4.12], providing a method of analysing characteristics of tapered rib waveguides. Whilst this has not been studied extensively here, a width tapered rib waveguide region which slowly increases in width from 1.1μm straight waveguide to 2.2μm, 1mm in length was selected based on full-vectorial BPM as shown in Figure 4-5.

![BPM simulation of waveguide transition from taper region to Y-branch. The blue curve shows the overlap integral between fundamental mode and waveguide mode when wide angle BPM power monitor feature is turn on, whereas green curve indicated otherwise.](image)

The power monitor graph suggested the power loss in the transition region is approximately 18% from its initial fundamental TE mode profile. The power monitor
feature is based on the overlap integral between the fundamental TE mode and the fundamental mode of width tapered waveguide. Although the input straight waveguide supports only a single mode, as the width is increased gradually in z direction; higher order modes in the tapered region could exist and the simulation does not take this into account.

Together with the SOI waveguide analysis of section 3.2.3 and width tapered rib waveguide, these techniques allow one to design a Y-junction with the desired power splitting ratio. However, these calculations can only accurately predict the power splitting ratio at one specific wavelength and for one polarisation state. If the wavelength and polarisation change, the eigenmodes of the waveguides also change and therefore so does the power splitting ratio. Figure 4-6 depicts the calculated power splitting ratio for a Y-junction waveguide with bend angle of 15° and bend radius of 1500µm, as a function of wavelength. This particular Y-junction was designed to have a power splitting ratio of 50% at a wavelength of 1550nm but over
the span of 70nm the calculated ratio varies between 48% and 50% for quasi-TE and quasi-TM polarisation. The variation of power splitting ratio for both polarisation result from different modal confinement in the waveguide and losses associated with the width tapered region. Even in applications where the wavelength and polarisation are well defined and carefully controlled, small deviations or non uniformities in the fabrication process, material properties or device operating condition can significantly alter the power splitting ratio. Other researchers [4.12] have described the design of directional couplers which yield a power splitting ratio that is insensitive to wavelength, polarisation and fabrication parameters. Their approach utilises the relationship of high correlation between phase shifts of two cascaded couplers. By choosing appropriate phase shift via the thermo-optic or the electro-optic effect, the power splitting ratio can be compensated.

Figure 4-7: FDTD simulation showing the power transmission (red and green curves) and reflection (blue curve) from the Y-junction.
Figure 4-7 shows a simulation using the finite difference time domain (FDTD) method in [4.13] to calculate the power splitting ratio between the two branches of Y-junction and at the same time observe the possible back reflection resulting from the abrupt discontinuity of waveguides at the junction. The power monitor plot in Figure 4-7 reaffirmed the BPM result computation where the power splitting ratio is approximately 44% and back reflection is negligible at 1% of the input power. The rest of the power was scattered and radiates away from junction where the waveguide starts to diverge.

The SOI waveguide dimensions which support both single mode and polarisation independence were then used to design a Y-junction structure. The analysis was carried out to predict the radiation loss and power splitting ratio of two branches of the Y-junction with various curvature of the bend radius with a given bend angle of 15°. The power splitting ratio of two arms of the Y-junction varies for each polarisation and operating wavelength due to different optical confinement. In addition, the imbalance of the ratio may be caused by the losses in the tapered region between the straight waveguide and the bend structure. The back reflection was also found to be negligible compared to scattering of power resulting from the discontinuity of the waveguide where two waveguides starting to diverge.

4.3 Third Order Bragg Grating Filter

Bragg gratings are formed by introducing periodic surface corrugation or periodic refractive index changes. The reflection Bragg grating can be considered as a one-dimensional diffraction grating which diffracts light from the forward-travelling mode into the back travelling mode. The condition for diffraction into the reverse travelling mode is called the Bragg condition. Reflected travelling modes will interfere constructively at wavelengths where the phase difference between each of the reflections is an integer number of wavelengths. It will exhibit the characteristics of a wavelength selectivity filter, reflecting a narrowband of wavelengths when the Bragg condition is satisfied:
\[ \lambda_b = \frac{2N_{\text{eff}}A}{m} \]  

(4.2)

where \( \lambda_b \) is the Bragg wavelength, \( A \) is the period of the grating, \( N_{\text{eff}} \) is the effective index of the optical mode and \( m \) is the grating order. Generally, 1\(^{\text{st}}\) order Bragg gratings \((m=1)\) are usually implemented in waveguide material because the diffraction efficiency is strongest for first diffraction order. However, higher order diffraction grating can also be implemented to relax the required grating periods hence simplifying the fabrication process. Table 4-1 shows typical grating periods for silica and silicon waveguides at 1550nm. Based on equation(4.2), the spectral responses of the Bragg gratings can be customised with refractive index modulation via precise etch depth, period and order of grating.

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index</th>
<th>Si</th>
<th>SiO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{\text{st}}) order Bragg grating Period</td>
<td>3.478</td>
<td>223nm</td>
<td>538nm</td>
</tr>
<tr>
<td>3(^{\text{rd}}) order Bragg grating Period</td>
<td>669nm</td>
<td>1.614(\mu)m</td>
<td></td>
</tr>
</tbody>
</table>

The realisation of Bragg gratings in Silicon-On-Insulator (SOI) waveguides offers the possibility to extend the functionality of integrated optics towards much more compact miniaturized devices. Its unique properties of high optical confinement and low losses in the order of 0.1dB/cm [4.14] make SOI an attractive option as design platform for optical integrated circuit. Bragg grating based devices have increasingly been employed in various passive and active optical components such as tunable filters [4.15], optical modulators [4.16, 4.17] and narrow-band reflection filters [4.18, 4.19]. The implementation of uniform submicron scale of 1\(^{\text{st}}\) order grating period over the length of waveguide increases the complexity and high cost of fabrication. This makes higher order diffraction grating in 3\(^{\text{rd}}\) order a very attractive alternative where fabrication tolerance is less stringent. The simulated SOI waveguide dimensions which operate in single mode regime and exhibit low polarisation dependence in
section 3.2.3 will be used as the waveguide platform for the grating design. This section is organised in the following order: it starts by investigating the grating parameters such as grating etch depth, grating length which will influence the reflectance, transmittance and bandwidth in the Bragg grating devices. Simulations of the grating device are based on Coupled Mode Theory (CMT) utilised by a commercially available optical simulator, GratingMOD and Floquet Bloch Theory (FBT) coded in the MATLAB programming language by Passaro [4.20, 4.21]. Both computer simulations allow the comparison and prediction of the device characteristics of the designed device to be achieved using different numerical simulation approach.

4.3.1 Coupled Mode Theory (CMT)

The most common way of analysing Bragg gratings is to use coupled mode formulations [4.22, 4.23]. The response of a grating can be calculated by treating it as a small perturbation which produces a coupling between the forward and backward modes of an unperturbed waveguide. However, it is important to note that a Bragg grating does not have eigenmodes in the same way that a waveguide does.
Chapter 4: Device Design

Bloch Theory can be used to understand the propagation of electromagnetic fields in a crystal lattice. The analysis of Little [4.24] has clarified the relationship between the Floquet analysis and the more simple coupled mode analysis. The topic of Bragg grating modelling theory is reviewed in chapter 3; only the numerical modelling of both aforementioned techniques and results will be discussed here. Using coupled mode theory, the reflection spectrum of a grating is derived with variations of grating etch depth. It is shown that a properly designed grating can give a spectral response that matches the application of a grating filter.

In SOI waveguides, the periodic perturbation in the waveguide can be achieved by reactive ion etching (RIE) across the waveguide to modulate the effective refractive index ($N_{eff}$). Figure 4-8 illustrates the schematic of Bragg grating devices considered in this work. It has been shown that high periodic modulation can be achieved by introducing deeply etched grating [4.25-4.28] but at the expense of increased scattering loss. From a lithography standpoint, it is difficult to form a sub micron pitch grating with a grating width to depth ratio much larger than 1:2, which corresponds to a maximum grating depth of about 200nm for silicon rib waveguides; without sacrificing the integrity of vertical grating sidewall. Therefore, most authors consider shallow grating etch with grating length in the region of multiple millimetre on their devices [4.18, 4.19] to minimise potential scattering loss.

4.3.1.1 Grating Coupling Strength

Commercially available optical design software GratingMOD [4.29] is used to facilitate grating simulation studied; the algorithm is based on the combination of CMT and the transfer matrix method. CMT is used to derive the governing equations based on orthogonal modes, while the transfer matrix method is used to solve the coupled mode equations. Detailed analysis of the CMT is discussed in chapter 3, therefore only numerical simulation results are shown here. In chapter 3, we have derived the coupled mode equation to numerically compute the spectral response for a Bragg grating. The influences of grating etch depth on the bandwidth and overall spectral response of the Bragg grating is related to grating strength ($\kappa$). By giving some numerical examples of 1st and 3rd order Bragg grating implemented on SOI
waveguide with variation of grating etch depth; we can predict the spectral response dependency on grating etch depth. Numerical simulation by Murphy [4.30] showed that the grating strength can be expressed by the following equation for a rectangular grating profile:

\[ \kappa = \frac{k^2}{2\beta} \left( n_{\text{core}}^2 - n_{\text{clad}}^2 \right) \frac{\sin(m\pi D)}{m\pi} \Gamma \]  

(4.3)

where \( \Gamma \) has a value of less than 1 whereby it describes the overlap integral between the grating and unperturbed waveguide region; \( m \) is the order of Bragg grating and \( D \) represents the duty cycle of the Bragg grating. We determined the grating strength relationship with duty cycle for variations of etch depth using a semi-vectorial approach to calculate the overlap integrals between the grating and unperturbed waveguide region. Using this approach, we assume the transverse field components are much bigger than the longitudinal field component and the latter are considered negligible. If the unperturbed waveguide dimensions and material parameters remain constant, equation (4.3) can be simplified as:

\[ \kappa \propto \frac{\sin(m\pi D)}{m\pi} \Gamma \]  

(4.4)

In Figure 4-9, we plot the grating strength and length product as a function of duty cycle for various grating depths for quasi-TE and quasi-TM polarisation on SOI rib waveguides with 200\( \mu \)m grating length. The grating strength is symmetrical at duty cycle of 50\%, which can be observed at both plots. There is also polarisation dependence for the grating strength calculation for TM polarisation, where the data is substantially smaller than its TE polarisation counterpart for the same grating etch depth and duty cycle. Utilising deeper grating etch will result in higher modulation depth, leading to the increase of grating strength according to equation(4.4). However, this will inevitably cause the designed Bragg resonance to shift to lower wavelength due to the strong effective refractive index modulation by the surface corrugation as proposed by Ctyroky [4.26].
Figure 4-9: Calculated grating strength and length product against duty cycle for SOI rib waveguide in (a) quasi-TM and (b) quasi-TE polarisation. The grating etch depth range from 50nm to 250nm for 1st order Bragg grating.
Wiesmann et al. [4.31] have overcome this problem by adjusting the grating period along the grating length to compensate the Bragg resonance wavelength shift. Alternatively, Bradley et al. [4.32] conducted a systematic experiment to control the fabrication tolerance of the Bragg grating period constant to ±0.04nm over the majority of the exposed wafer. This study has an enormous impact on improving the grating period uniformity and hence the yield of the devices.

It is instructive to evaluate the grating strength of 3rd order Bragg grating in a rib waveguide in comparison to that of a 1st order of Figure 4-9 (a) and (b). In 3rd order diffraction Bragg gratings, the periodic modulation is created by increasing the grating period while maintaining the Bragg resonance wavelength according to equation (4.2) but at the expense of lower reflection coefficient. Figure 4-11 (a) and (b) show the relationship between grating strength and grating duty cycle for 3rd order Bragg gratings on SOI waveguides for TE and TM polarisation. Notice that strongest grating strength occurs when the duty cycle is 50% whereas the lowest is approximately at 30% and 70% for both polarisations.
Figure 4-11: Calculated grating strength and length product against duty cycle for SOI rib waveguide in (a) quasi-TE and (b) TM polarisation. The grating etch depth range from 50nm to 250nm for 3rd order Bragg grating with 684nm grating period.
This sinusoidal-like relationship for 3rd order Bragg grating differs significantly from 1st order results shown in Figure 4-9 even though both show symmetry at duty cycle of 50%. From the numerical simulation, we can choose duty cycle and grating etch depth for the Bragg grating to maximise the mode overlap integral between the grating region and the unperturbed waveguide. It is difficult to keep the grating period uniform across a long grating length without introducing grating period variation [4.32], which in turn might cause Bragg resonance wavelength shift and potentially render the grating device useless. Hence, the fabrication technique and available facilities in the laboratory will play a major role in determining the choice of grating length implemented on the SOI rib waveguide structure.

4.3.1.2 Grating Reflectivity and Grating Length

The reflection spectrum of the Bragg grating can be expressed and related to the product of $kL$ [4.30] as:

$$ R_{\text{max}} = \tanh^2 (kL) $$

(4.5)

For instance, Figure 4-12 show the spectral response of 3rd order Bragg grating on SOI waveguide with period of 684nm and grating etch depth of 100nm with increasing grating length (500 \(\mu\)m, 1000 \(\mu\)m, 2200 \(\mu\)m and 4400\(\mu\)m), grating parameters were kept constant in the CMT calculation in order to preserve the resonance Bragg wavelength and coupling strength ($\kappa$) to show the influence of the grating reflectivity and grating length in equation (4.5). When the $kL$ product is smaller than 1, the reflection spectrum of the Bragg grating can be characterized by a sinc-like response curve centered at Bragg resonance condition, whose bandwidth is inversely proportional to the grating length.
For gratings where the product $kL$ is greater than 1, the spectral response has a plateau-like response and high reflectivity in the stop band at its resonance wavelength. Beyond the stop band, the spectral response shows a series of side lobes, which decay rapidly as it moves away from the Bragg condition. The maximum reflectivity, $R_{\text{max}}$, essentially is determined by the grating coupling strength and grating length. However, as the calculation in Figure 4-12 predicted the shape of spectral response and bandwidth being influenced by the increasing grating length when the grating etch depth remains constant.

With the gradual increase of grating length, the peak reflectivity rises close to the value of 1 and side lobes shift closer together. In this section, we show that the spectral response of Bragg gratings is dependent on grating length and grating coupling strength. It will be useful to relate the maximum reflectivity achievable for various grating etch depths and compare with $1^{\text{st}}$ and $3^{\text{rd}}$ order of Bragg gratings. Figure 4-13 and Figure 4-14 plot the calculated reflection as a function of grating length for various grating etch depth in two different orders ($1^{\text{st}}$ and $3^{\text{rd}}$) Bragg gratings in SOI waveguide structures, for quasi-TE polarization.
Chapter 4: Device Design

Figure 4-13: Power reflectivity plotted as a function of grating length for 1\textsuperscript{st} and 3\textsuperscript{rd} order Bragg grating with grating depth of 100nm and 140nm using CMT approach at $\lambda_0 = 1550\text{nm}$.

Figure 4-14: Power reflectivity plotted as a function of grating length for 1\textsuperscript{st} and 3\textsuperscript{rd} order Bragg grating with grating depth of 200nm and 220nm using CMT approach at $\lambda_0 = 1550\text{nm}$.
Note that 1\textsuperscript{st} order Bragg grating can achieve reflectivity close to 1 with relatively short length compared to their 3\textsuperscript{rd} order counterpart. This means that smaller and more compact grating devices such as add/drop filter \cite{4.34} can be realized but at the expense of more complex fabrication of grating period of the order of 228nm.

Figure 4-15: Power reflectivity versus grating length for 3rd order Bragg grating with various grating etch depth candidates of our grating design in quasi-TE polarisation using CMT approach at $\lambda_0 = 1550\text{nm}$.

Although the implementation of higher order grating is preferable due to relaxation of fabrication tolerance, the integrity of uniform grating periods and constant etch depths across the grating length have to be maintained to realise highly efficient grating filters. The fabrication issues associated with realisation of grating filters will be discussed in chapter 5. The selection of the grating length and etch depth for our Bragg grating devices is based on the practical realization of the device with available facilities. We will fabricate a series of short (<200\textmu m) and long (>500\textmu m) 3\textsuperscript{rd} order grating on SOI waveguide and compared the theoretical calculation of CMT with experimental value. Figure 4-15 depicted the reflectivity as a function of grating length for various grating etch depth in quasi-TE polarisation. As described earlier, we chose a grating etch depth of 220nm (15\% of overall waveguide height) in order to reduce the potential introduction of scattering losses caused by the non vertical grating etch. From a lithography stand point, it is difficult to form a submicron grating period while maintaining grating width to depth ratio (small lateral dimensions in
comparison with their thicknesses) much larger than 1:2 as demonstrated by Aalto et al. [4.35].

4.3.2 Floquet Bloch Theory (FBT)

Coupled mode theory (CMT) is commonly used to design and predict the behaviour of grating structures such as the grating assisted directional coupler (GADC) [4.36-4.38]. This structure consists of a periodic grating structure located between two waveguides in close proximity which can lead to power transfer between the waveguides. In addition to CMT, the Transfer Matrix Method (TMM) approach uses mode matching techniques to determine power coupling and scattering in a GDAC [4.39]. However, both the CMT and TMM approaches are based on the assumption that the interacting modes are mutually orthogonal. These approaches predict the behaviour of the structure with higher accuracy when the periodic grating perturbation is weak (kL<1) and the coupled waveguides possess very similar refractive index profile and guiding layer thickness (quasi-synchronous condition).

The Floquet Bloch theory (FBT) has been used to analyse the radiation loss in GADC in terms of Leaky Mode Propagation (LMP) [4.40, 4.41]. This method is based on the expansion of the composite modes of the structure in an infinite number of space harmonics due to the presence of grating. The power carried by each harmonic is partially guided along the propagation direction and partially radiated in the external

Figure 4-16: Schematic diagram of a finite length periodic structure on SOI rib waveguide
semi-infinite regions. The power exchange between each pair of space harmonics is governed by the Floquet theorem. A detailed discussion of FBT approach has been presented in chapter 3, therefore we only present numerical simulation of LMP [4.40] based on FBT approach to analyse 3rd order Bragg grating structures in SOI waveguides with the application of two dimensional (quasi-3D) finite waveguide approximations. Figure 4-16 illustrates the schematic diagram of a finite length periodic grating structure implemented on top of the SOI rib waveguide.

4.3.2.1 Simulation of Modal Reflection

The LMP based on FBT is an attractive numerical simulation approach since it does not require any conceptual approximation and allows one to take into account all the physical phenomena [4.21] occurring when a wave propagates in a periodic layer, including the photonic bandgap (PBG) region and radiation region, where some power is radiated into the cladding [4.20].

![Figure 4-17: Convergence study of number of space harmonics in FBT calculation for reflection spectral response as a function of wavelength](image)

We intend to evaluate the spectral response of the reflected and transmitted power based on the physical grating parameters, i.e., grating etch depth, grating length, duty
cycle and waveguide dimensions. In the numerical evaluation, the infinite space harmonics must be truncated and an appropriate number of space harmonics should be carefully chosen to ensure sufficient accuracy of the calculation without any significant increase of computation effort.

![Graph showing leakage factor and convergence study](image)

**Figure 4-18:** Leakage factor showed the convergence study of FBT using different number of space harmonics.

A convergence study of different number of space harmonics used in FBT [4.43] suggested that propagation constants converge with increasing number of harmonics. When 9 space harmonics are chosen, the relative error of the propagation constant is predicted to be less than 0.01%. Before a detailed FBT study can commence, a study is required to ensure the number of space harmonics are sufficient and a brief account is given here. Figure 4-17 and Figure 4-18 show the reflection spectral responses and leakage factor of Bragg gratings evaluated for a number of space harmonics, either 7, 9 or 11. The grating structure we considered is formed by SOI waveguide with small cross section where waveguide parameters are the same as in section 3.2.3: \( n_{Si} = 3.477, n_{Sio2} = 1.444 \), waveguide height \( H = 1.50\mu m \), waveguide etch depth \( D = 0.89\mu m \), waveguide width \( W = 1.00\mu m \), grating period \( \Lambda = 0.687\mu m \) and grating length \( L = 500\mu m \) (728 periods). The inset of Figure 4-17 shows the close-up near the
maximum reflectivity of the grating. It clearly shows the differences of Bragg resonance wavelength and maximum reflectivity for 9 and 11 space harmonics in our studies are within 0.03%. Therefore, 9 space harmonics are selected for our numerical evaluation in this section. When designing the optimum value of grating depth, we need to consider the trade-off between the etch depth and the designated length of the grating device. From a fabrication point of view, it is desirable to fabricate short gratings with deep etching in order to avoid grating non-uniformity across the long grating length. However, deep grating etches on the device will increase the radiation losses into the substrate and upper cladding layer causes by the large refractive index discontinuity between the guiding layer and grating trench. The radiation loss associated with grating etch depth can be determined by the leakage factor in LMP simulations. This will be shown in the next section. In order to select an optimum grating etch depth for our device, we investigated the spectral response of the 3rd order grating by implementing a gradual increase of grating etch depth in the simulation to show its influence on Bragg wavelength shift and the maximum value of reflectivity ($R_{\text{max}}$). Figure 4-19 illustrates the calculation of power reflectivity $|\rho|^2$ for grating length (500μm) in 3rd order grating periods with 50% duty cycles, rectangular profiles, and for grating etch depth ranging from 50nm to 400nm. It is clear that $R_{\text{max}}$, occurring at the Bragg wavelength, does not exhibit any increment when grating etch depth is gradually being increased. This is contrary to results predicted by CMT. However, $R_{\text{max}}$ does demonstrate an oscillating behaviour for 3rd order grating in SOI rib waveguide with small cross section. A detailed investigation of its oscillation trend will be discussed in section 4.3.3 for different values of waveguide width. The resonance Bragg wavelength of the grating structure depends on the Bragg condition, i.e. grating period and mode effective index. If we assume the ideal condition whereby the grating period is constant during the simulation, the Bragg resonance peak is expected to shift to lower wavelength as a result of decreasing effective index by increasing grating etch modulation. From shallow grating etch depth ranging from 50nm to deep etch of 400nm, the computed Bragg wavelength shift spanned 20nm – almost covering half of the C band (1525nm-1562nm) range. It is clear that the $R_{\text{max}}$ of 80% can be obtained at 350nm of etch depth. The potential to control and shift the Bragg resonance condition through its dependence on effective index modulation by
grating etch depth is an attractive solution to compensate irregular patterning in grating period definition. Bradley et al. [4.32] have developed a grating fabrication process in waveguides to control the shift of Bragg wavelength over a 10-20nm suitable for distributed Bragg reflector (DBR) laser array. With the development of RIE depth monitoring with real time capability [4.33], this has enhanced the fabrication process ability to accurately achieve the designated etch depth, hence minimise the effect of shifting in Bragg resonance condition from non-uniform grating period fabrication. The grating depth for the design is chosen to have a moderate depth of 200nm which constitutes 22% of total waveguide height in order to avoid high scattering losses associated with deep grating etches. In practice, the value of the selected grating etch depth is based on the availability of fabrication facilities and capabilities.

![Figure 4-19: LMP power reflectivity as a function of wavelength for 3rd order (687nm) Bragg grating on SOI rib waveguide with variation of grating depth at λ\text{c}=1550nm](image)
Figure 4-20: Comparison of 3rd order Bragg grating spectral response using LMP approach for grating etch depth of 200nm and 220nm with grating period of (a) 687nm (b) 690nm at TE polarisation operating at \( \lambda_o = 1550\) nm.

Figure 4-20(a) and (b) show the computed spectral response of Bragg grating of etch depth 200nm (22%) and 220nm (24.4%) for different grating periods of 0.687\( \mu \)m and 0.690\( \mu \)m at \( \lambda_o = 1550\) nm for rectangular grating profile. The condition of maximum reflectivity \( R_{\text{max}} \) occurs only where the Bragg condition between the incident wave and the third order space harmonics is perfectly specified. The inclusion of differences...
in grating etch depth and grating period in the simulation were intended to take into account of variation of etch depth control and variation of Electron beam lithography width definition. The result evaluated by the LMP approach shows the Bragg wavelength shifted 2.4nm to a shorter wavelength when the difference of grating etch depth of 20nm is being considered. The full width at half maximum (FWHM) bandwidth for the 0.687μm grating period is 0.814nm for the 200nm grating etch and 2.452nm for the 220nm grating etch; while the 0.690μm grating period exhibits a similar increment of 3 times in bandwidth of 0.9nm for 200nm grating etch and 2.429nm for 220nm grating etch. The influence of grating depth and duty cycle in the spectral bandwidth can also be observed in all the simulations.

Figure 4-21: Reflectivity Spectral responses of 3rd order Bragg grating (λ = 687nm) for grating duty cycle of 50% and 60% and grating etch of 200nm at λ = 1550nm

Figure 4-21 shows the strong dependency of FWHM bandwidth of a 3rd order Bragg grating response with etch depth of 200nm when duty cycle (DC) changes from 50% to 60%. It can be noted by changing the grating duty cycle from 50% to 60% while maintaining the grating depth and period, the bandwidth of FWHM is increased from 0.782nm to 2.525nm. The DC induced Bragg wavelength shift was predicted to shift 2.1nm to a longer wavelength. The increase of duty cycle tends to reduce the influence imposed by other grating parameters such as etch depth and grating period.
All the simulation results of 3rd order Bragg grating show a completely different behaviour of gratings compared to the first order gratings [4.17-4.19]. The characteristic stop-band and side lobes presented in the first order grating around the Bragg resonance wavelength of 1550nm can not be observed because the 3rd order grating is operating in a spectral region with high scattering losses. The guided power incident on the grating is easily scattered towards air or substrate by the higher order space harmonics excited inside the grating. The oscillation behaviour is found when duty cycle is increased from 50% to 60%, as might be caused by Fabry-Perot interference in a grating of finite length. Wiesman et al. [4.31] has demonstrated that with a larger grating etch depth and duty cycle, the undesirable interference effects might become more dominant in the reflection spectrum.

4.3.2.2 Leakage Factor

The dominant loss associated with the Bragg grating devices consists of grating radiation loss, the diffraction loss at both interfaces of the grating edges.

![Figure 4-22: Calculation of leakage factor versus wavelength by LMP approach for various grating depth in 3rd order Bragg grating period of 687nm and duty cycle of 50.](image)

Leakage factor, \( \alpha \), is usually used to account for the overall loss of the device which can be defined as:
where $|\rho|^2$ is modal reflection and $|\tau|^2$ is modal transmission of the grating devices. We calculated the leakage factor as a function wavelength for different grating depth, as shown in Figure 4-22. At shallow grating depth (below 150nm) where the value of effective index modulation of the grating is small, the leakage factor curve provides a symmetrical behaviour of the reflectivity curves. This is in good agreement with the CMT predictions where the effects of the leakage factor are neglected \[4.21\]. As the grating depth increases, the leakage factor $\alpha$ curve loses its symmetry and a secondary maximum to the left of the Bragg wavelength appears as illustrated both in Figure 4-23 and Figure 4-24, producing a radiation loss of a portion of guided optical power. As a result, the irregular behaviour of the reflectivity curves in the corresponding spectral region are expected. The transition occurs in between grating depths of 200-250nm when symmetry of the leakage factor $\alpha$ curve is broken as the grating evolves from shallow to deeply etched.

The irregular behaviour in the LMP region for a strong grating can be investigated by Figure 4-23; and Figure 4-24.; which depict the reflectivity and leakage factor of the Bragg gratings for grating depths of (a) 200nm (b) 220nm when grating periods of 0.687µm and 0.69µm are being considered. It is apparent that the modal reflections for both grating periods shift to shorter wavelength with increasing grating etch. It can be explained by equation (4.2) where the relation holds between Bragg wavelength and modal effective index of waveguide if the grating period and diffraction order of grating remain unchanged. If the grating depth considered is between the transition region where the symmetrical of the leakage factor $\alpha$ curve is no longer preserved, higher order modes and radiation modes also take part in the energy transfer. Moreover, the lowering of effective refractive index changes caused by grating modulation further enhances the effect of Bragg resonance wavelength shortening. Since prediction of CMT does not take into account losses associated with grating and the interacting modes can not be leaky, and not surprisingly coupled mode analysis can not provide sufficient accurate modelling of the physical effect in the devices.
Figure 4-23: Calculation of power reflection showing the influence of leakage factor on the overall spectral response for grating depth of (a) 200nm and (b) 220nm for 3rd order Bragg grating ($\lambda=687\text{nm}$) on small cross section SOI rib waveguide in TE polarisation.
Figure 4-24: Calculation of power reflection showing the influence of leakage factor on the overall spectral response for grating depth of (a) 200nm and (b) 220nm for 3rd order Bragg grating (Λ=690nm) on small cross section SOI rib waveguide in TE polarisation.
4.3.3 Comparison between CMT and FBT Simulation Results

The most important aspects in a Bragg grating characterisation are their resonance wavelength and maximum reflectivity, which depends on grating period, grating depth and length. It is interesting to compare the modelling results of commonly used CMT and the more rigorous approach of waveguide Bragg grating modelling based on FBT. Our numerical modelling results of 3D CMT are based on GratingMOD [4.29], whereas the LMP approach is based on quasi-3D FBT by Passaro [4.40, 4.41]. We have considered SOI rib waveguide dimensions of $H = 1.5\mu m$, $D = 0.89 \mu m$ and $W = 1.0\mu m$. The Bragg grating parameters are 687nm as grating period, duty cycle of 50% and grating length of 500\mu m.

![Graph showing comparison between CMT and FBT simulation results](image)

**Figure 4-25**: Maximum grating reflectivity ($R_{\text{max}}$) as a function of grating etch depth using CMT and LMP based on FBT approach for waveguide width $W = 3\mu m$, grating period $\lambda = 687\text{nm}$, duty cycle of 50% and $L = 500\mu m$

Figure 4-25 shows the calculated maximum reflectivity of the waveguide based small cross section SOI Bragg grating as a function of grating depth in TE polarisation.
operating at $\lambda_0 = 1550$nm. Both curves show very good agreement at very shallow grating depth, since shallow grating etch does not induce significant radiation loss.

![Figure 4-26: Comparison of power reflectivity spectral response for grating etch depth of 120nm between CMT and FBT approaches for waveguide width $W = 1$μm.](image)

Hence, the leakage factor $\alpha$ curve is low and its symmetry is preserved in FBT; whereas in CMT the grating is only accurately modelled when the index modulation amplitude is small. Using FBT, the Bragg grating structure exhibits slight oscillation in $R_{\text{max}}$; this effect is also observed in single grating couplers [4.44] and grating-assisted directional couplers [4.40], due to the interference of the field reflected at both interfaces of the grating castellation. Similar grating maximum reflectivity is predicted where both curves intersect at a grating etch of 120nm, approximately 8% of the overall waveguide height. The graph in Figure 4-26 represents the reflection spectrum of 120nm grating depth. This figure clearly suggests that the reflectivity is shifted against the design value of 1550nm towards shorter wavelength. Although the Bragg resonance wavelength differs by 5nm at grating etch of 120nm, both curves predicted by FBT and CMT show relatively good agreement in terms of FWHM bandwidth and overall spectral shape. The deviation from the design wavelength is also shown in Figure 4-27. Note that with relatively shallow grating depth, both approaches exhibit good agreement; however the Bragg resonance wavelength starts to diverge with increasing grating depth, where CMT becomes increasingly inaccurate.

4-33
Figure 4-27: Resonance Bragg wavelength shift as a function of grating etch depth for CMT and FBT approaches for waveguide width $W = 1 \mu m$.

Figure 4-28: Maximum grating reflectivity ($R_{max}$) as a function of grating etch depth using CMT and LMP based on FBT approach for waveguide width $W = 3 \mu m$, grating period $A = 687 nm$, duty cycle of 50% and $L = 500 \mu m$. 
Chapter 4: Device Design

If we increase the waveguide width of the device to 3μm while maintaining all other parameters constant, rapid decrease of maximum reflectivity beyond grating depth of 240nm can be observed in Figure 4-28. It is also apparent that there is very good agreement between both methods for calculation of maximum reflectivity at shallow grating etches and the gradual increase of $R_{\text{max}}$ simultaneously. At grating depth of 240nm, the spectral response of both theories differs significantly (Figure 4-29) although their maximum reflectivity value results in a similar value. The spectral response predicted by CMT preserves its symmetrical shape due to the fact that it did not take into account any loss induced by grating etch depth in the calculation. On the contrary, the FBT approach determines the maximum reflectivity and its Bragg resonance condition is based on minimum leakage factor for the 240nm grating etch. Consequently, we not only have to consider the maximum achievable reflectivity for a given grating etch depth but also its corresponding grating spectral response and Bragg resonance shift as well. Since the grating device is long and deep, a weak grating analysis such as CMT based on the perturbation approach would not be sufficient to address the grating radiation loss. For instance, beyond the grating etch of 240nm, the deep grating etch causes the device to operate in a higher scattering and radiation loss region therefore reducing $R_{\text{max}}$. As we increase the waveguide width from the initial 1μm to 3μm, the overall waveguide dimension slowly evolves from a small to a larger cross section and resembles a grating perturbation on a planar waveguide. This explains why the influence of grating modulation on the Bragg resonance wavelength difference between the two methods is greatly reduced from 17.27nm to 5.69nm as observed in both Figure 4-27 and Figure 4-30. Hence, we can use planar waveguide approximation to compute numerical simulation of grating on large cross section waveguide.
Chapter 4: Device Design

Figure 4-29: Comparison of power reflectivity spectral response for grating etch depth of 120nm between CMT and FBT approaches for waveguide width $W = 3\mu m$.

Figure 4-30: Resonance Bragg wavelength shift as a function of grating etch depth for CMT and FBT approaches for waveguide width $W = 3\mu m$. 
4.4 The Thermo-Optic Effect (TOE)

The refractive index of a material is not independent of temperature over the range of operational temperature for the optical devices. The variation of refractive index with temperature at a constant pressure is described by its thermo-optic coefficient (TOC). The manipulation of refractive index via the TOC \( \frac{dn}{dT} \) by introducing a heating source such as thin film heater has been reported in literature [4.45 - 4.47]. This section aims to introduce the reader to the methods of simulation employed in the operation of a Bragg grating filter fabricated in SOI material based on TOE. A finite element analysis (FEA) simulation package such as FEMLAB [4.49] by COMSOL is used to develop the model by utilising the high TOC \((-1.86 \times 10^{-4}\text{K}^{-1}\) at 1.55\text{µm}) in silicon. Waveguide parameters such as thickness of an oxide buffer layer, thermal isolation trenches which influence the temperature distribution and heat confinement within the waveguide structure were investigated. Wavelength shift and polarisation sensitivity of the resonant Bragg wavelength of the SOI waveguide based Bragg grating are modelled based on the assumption that thermo-optic coefficient is constant and fabricated grating periods and etch depth are uniform across the grating length. It would appear that temperature dependent thermal characteristics of a material need to be considered in the model to simulate the behaviours of devices under realistic operating condition with non-ideal material characteristics. Clark [4.45] developed thermal modelling for various waveguide geometries for steady state and transient thermal analysis of SIMOX phase modulators. Whilst a detailed thermal modelling was not carried out here, a simplified steady state thermal simulation to demonstrate the principle of thermo-optic modulation of a Bragg grating embedded in the proposed small cross sectional SOI rib waveguide in section 4.3 has been carried out. A hybrid approach combining BPM and FEA for optical and thermal simulation provides quick computation and it is easy to implement the analysis for different waveguide and grating parameters. The thermal analysis will only focus on conduction since it is the most dominant factor in determining the heat transfer in the system.
4.4.1 Aluminium Heater Design

By applying a change of temperature locally on the Bragg grating device, the effective index of the device changes, leading to the resonance wavelength shift. Temperature changes can be introduced by a thin film heater where a pattern of resistive material defined on the surface of the platform is used to achieve joule heating. As current flows through the highly resistive heater, some electrical energy is converted to heat which in turn increases the temperature of the heater. The thin film heaters are commonly located on top of the grating structures separated by SiO₂ top cladding layer, which allows optical isolation and localised heat transfer from the heating structure. The aluminium based thin film heater with 3μm and 0.5μm in width and thickness is used as a heater structure, as shown in Figure 4-31. It is connected via two contact pads (200μm²) in which their surface area is several orders of magnitude larger than the aluminium heater; therefore most of the voltage drop will occur across the grating section, leading to high resistive ohmic heating. The volume resistivity of

Figure 4-31: Aluminium thin film heater in L-edit CAD layout.
a material is a parameter that indicates the electrical resistance and allows the calculation of the resistance when the physical dimensions are known. The relationship can be expressed by:

\[ R = \frac{\rho L}{tW} \]  

where \( \rho \) is the material resistivity, \( t \) is the thickness, \( L \) is the length and \( W \) is the width of the material. Resistance is proportional to heater length and inversely proportional to the cross sectional area. Hence, one would like to design a long and small cross sectional area resistive heater without exceeding the maximum current density of the material. The resistivity, \( \rho \) of aluminium is not constant and it varies with temperature.
Figure 4-33: The relationship of aluminium heater resistance with temperature for heater various length, thickness of 500nm and width of 3μm.

Figure 4-32 shows the resulting plot with data extracted from [4.63] showing linear relationship between aluminium resistivity and temperature within the range of 0°C to 600°C. With aluminium resistivity and equation (4.7) which relates to heater physical dimensions, the heater resistance can be evaluated, as demonstrated in Figure 4-33. The variation of heater resistance with the temperature is vital information in determining the heater temperature as a result of joule heating. This can be easily accomplished by measuring the voltage drop across the heater and the current supplied.

4.4.2 Thermal Isolation Trench

The strong thermo-optic effect in silicon has been exploited for the realisation of various thermo-optic switches [4.51] and sensor application [4.48]. Although silica based devices [4.57] have been reported, the higher thermo-optic coefficient in silicon is preferable as it results in smaller devices and lower power consumption. Conduction heat transfer mechanisms in SOI material can be categorised by longitudinal and lateral temperature distributions. When heat is applied constantly on
top of the waveguide structure depicted in Figure 4-34, the efficiency of the thermal distribution of the system is determined by the thickness of oxide between the heater and top of the rib waveguide and the dimensions of the waveguide. Assuming the waveguide dimension and oxide thickness remain constant, heat is not readily absorbed into the substrate through the buried oxide layer (BOX) via conduction mechanisms, but can be spread laterally into the slab region. The thermal diffusion length, $L_{th}$, the length over which a given temperature falls to $e^{-1}$ of its original value spreading laterally in two dimensions from the heat source, for a leaky substrate can be described by the following equation [4.51]:

$$L_{th} = \sqrt{d \cdot t} \sqrt{\frac{\sigma_{Si}}{\sigma_{SiO_2}}}$$

where $d$ and $t$ are the buried oxide and the silicon slab layer thickness and $\sigma_{Si}$ and $\sigma_{SiO_2}$ are the thermal conductivities. Using room temperature values for the thermal conductivities of silicon (156 W/m/K [4.58]) and silica (1.4 W/m/K [4.59]) and with buried oxide layer of $d = 3\mu m$ and a waveguide slab height of $t = 0.6\mu m$, the calculated thermal diffusion length is 14.16\mu m.

![Figure 4-34: Heat diffusion of rib SOI waveguide. The arrows indicate possible direction of heat diffusion from top of heat source to the slab region and silicon substrate [4.51].](image)
Fischer et al [4.51] also expressed the calculation of switching power using a one-dimensional (1D) analytical treatment of the heat flow in an MZI switch as:

\[ P_x = \frac{\lambda}{2l_{\text{active}}} \left( \frac{dn_{\text{eff}}}{dT} \right)^{-1} \sigma_{\text{SiO}_2} \left( \frac{b + L_h}{l_{\text{active}}} \right) \frac{l_{\text{active}}}{d} \quad (4.9) \]

where \( b \) denotes the width of the heating element and \( l_{\text{active}} \) is the length of arm of the MZI without the heater. This equation can be modified to:

\[ P_x = \frac{\lambda \sigma_{\text{SiO}_2}}{2} \left( \frac{dn_{\text{eff}}}{dT} \right)^{-1} \left[ \frac{b}{2d} + \frac{L_h}{l_{\text{active}}} \right] \quad (4.10) \]

where \( \frac{dn_{\text{eff}}}{dT} \) denotes the TOC calculated by two-dimensional (2D) FEM as an effective value [4.55] which depends on all the layers in the waveguide structure as opposed to the bulk silicon TOC considered in the literature.

Figure 4-35: Driving power requirement for one degree change in silicon rib waveguide for various top SiO\(_2\) cladding layers.
This issue will be discussed in section 4.4.3. Although our modelling structure is not configured as an MZI optical switch, we can redefine $l_{active}$ from equation (4.9) as heater length, $L$ and compute the applied power which causes the change in temperature ($\Delta T$) in the waveguide structure as [4.51]:

$$\Delta T = \left( \frac{\partial n}{\partial T} \right)^{-1} \frac{\lambda}{2l_{active}} \quad (4.11)$$

Equation (4.9) can be rearranged as:

$$P = \Delta T \sigma_{SiO_2} \left( \frac{Lb + 2dL_\theta}{d} \right) \quad (4.12)$$

From equation (4.8), diffusion length can be controlled by choosing appropriate wafers with designated BOX layer thickness and slab height. The changes of both parameters are not trivial as the waveguide dimensions are critical in preserving the single mode condition and polarisation independence whilst the selection of BOX layer thickness has to be thick enough to achieve thermal isolation of the waveguide from the substrate. Figure 4-35 illustrates the influence of driving power requirement as a function of top oxide cladding thickness on a silicon rib waveguide with different BOX layer thickness of 1.00\(\mu\)m and 3.00\(\mu\)m.

Neumann [4.60] proposed placing a trench outside the curved waveguide to prevent light from spreading outward toward larger radius, hence improving optical confinement. The same approach [4.56] has been reported to improve thermal and optical confinement of SOI modulators by utilising thermal isolation trenches to prevent lateral heat flow. Isolation trenches can be realised by means of removal of a small slab region on either side of the rib using a simple etching process to improve the maximum temperature rise that can be achieved for a given input power. Steady state thermal analysis has been applied to investigate the effect of etching filled with low temperature oxide (LTO) on the overall temperature rise in the core of the waveguide in the following section.
Figure 4-36 depicts polished facets and the implementation of isolation trench on SOI rib waveguide with spacing of 7μm from the centre of the rib observed under 100x Leica optical microscopes. To maintain consistency of the simulation, the conduction heat transfer simulation was setup using a 2D mesh generated according to the waveguide dimension stated in section 4.2 by FEMLAB modelling software as shown in Figure 4-37. Please note that the maximum element size of the mesh grid is set at 0.8×10^-7 at the core of the waveguide and heating element to enable higher accuracy of the calculation at the crucial interface between them. In the simulation shown in Figure 4-38, a 3μm width thin film metal heater was deposited on top of an SOI rib waveguide separated by a 200nm SiO₂ layer. It is assumed that the waveguide structure is infinite in the direction of the propagating wave and ambient temperature of 23°C. The longitudinal and vertical heat flow and temperature distribution of the waveguide structure influenced by the isolation trench spacing and etch depth of the trench is investigated. By controlling the temperature on the heating element, the temperature distribution profile with or without the isolation trench and its associating refractive index changes can be studied. Table 4-2 shows all the material properties parameters used in the computation at an operating wavelength of 1550nm.
Figure 4-37: FEMLAB generated mesh grid of rib waveguide structure and heating element at the top of the waveguide separate by a thin layer of $\text{SiO}_2$.

Table 4-2: The material parameters used in FEMLAB thermal optic simulation.

<table>
<thead>
<tr>
<th>Material/ Material Parameters</th>
<th>Thermal Conductivity (W/m/K)</th>
<th>Density (kg/m$^3$)</th>
<th>Specific Heat (J/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon [4.58]</td>
<td>163</td>
<td>2330</td>
<td>714</td>
</tr>
<tr>
<td>Silica [4.59]</td>
<td>1.38</td>
<td>2600</td>
<td>703</td>
</tr>
<tr>
<td>Aluminium [4.65]</td>
<td>235</td>
<td>2700</td>
<td>935</td>
</tr>
<tr>
<td>Air [4.65]</td>
<td>0.0257</td>
<td>1.2</td>
<td>1005</td>
</tr>
</tbody>
</table>
Chapter 4: Device Design

Figure 4-38: Temperature distribution and heat flows: 2μm isolation trench spacing from core waveguide and 200nm oxide buffer layer, 100°C applied on heating element.

Figure 4-39: Calculation of temperature of the waveguide core and refractive index changes as a function isolation trench distance at ambient temperatures of 23°C.
The temperature rise from the centre of the rib waveguide after 100°C supplied via the heating element was plotted as a function of isolation trench spacing in Figure 4.39. The refractive index change due to the temperature rise is also presented in the same graph. When the isolation trench is fully etched to the BOX layer, the numerical simulation suggested that the closer trench spacing from the rib waveguide restricts the heat flow, therefore resulting in higher heat confinement in the structure and hence higher refractive index changes. Figure 4.40 shows the resulting refractive index changes caused by the TOE when the isolation trench height is varied from fully etched to no etching for two different spacing distances. It clearly indicates a fully etched isolation trench has a better ability to contain the lateral and vertical heat flow. For shallow isolation etch trenches up to 50% of slab height, the spacing distance does not have any significant impact on the refractive index variation. A half etched isolation trench might allow some higher order mode from the waveguide to leak out through slab region in order to avoid modal interference within the waveguide system. However, one should note that the isolation trench spacing has to be implemented
without causing any interaction with the fringe of the mode profile in the slab region. Hence, the optical mode profile of the waveguide structure operating at desired polarisation will be considered in the following section.

### 4.4.3 Thickness of Buffer Layer

It is favourable to place the heater directly on the top of the rib waveguide; however in practice the heater might cause changes in polarisation dependent loss and optical attenuation in the waveguide. Usually, a buffer layer is placed between the heating element and the top of the rib waveguide. There are two main factors that determine the thickness of the buffer layer, the effectiveness of heat transfer from the heating element to the rib waveguide and the distance in which the evanescent wave extends from the interface of the rib waveguide. The thickness of the layer is chosen in such a way that it is not too thick to reduce the effectiveness of heating and at the same time thick enough to contain the evanescent wave. In addition, the thickness of oxide buffer layer chosen should not be greater than few micrometers to minimise stress on the layer and prevent the influence of polarisation in the waveguide. Nonetheless, it might be a useful additional fabrication parameter as shown in [4.52], by manipulating the thickness of oxide deposited on the waveguide to control waveguide birefringence.

![Computed Transverse Mode Profile](image)

Figure 4-41: Fundamental mode profile of SOI waveguide with 0.40um SiO₂ buffer layer.
BeamPROP was used to calculate the optimum thickness of buffer layer. The computation grid spacing of $x = 0.005\mu m$, $y = 0.01\mu m$, $z = 0.04\mu m$, $n_{Si} = 3.477$ and $n_{SiO_2} = 1.444$ were used for the simulation. We have assumed the thermal conductivities for both silicon and SiO$_2$ remain constant in the calculation. Figure 4-41 shows that the TE polarised evanescent wave extends approximately $0.30\mu m$ from the top of the rib waveguide and lateral modal mode profile extends approximately $1.20\mu m$ from the side of rib waveguide. In order to contain the thermal energy within the rib waveguide to maximise the effect of the thermo-optic effect, the thermal isolation trench is formed by etching the slab region down to the buried oxide. This isolation trench will provide a better lateral thermal confinement in the waveguide, while still allowing higher order modes to leak out in the slab region. The placement of the isolation trench $7\mu m$ away from the side rib waveguide is based on the simulated result shown in Figure 4-41 and considering the thermal diffusion length evaluated in section 4.4.2. The thick buried oxide layer of $3\mu m$ in the standard 4 inch UNIBOND wafer will provide good thermal isolation between the guiding layer and the BOX layer. Therefore, this will allow only a fraction of the heat to diffuse into the silicon substrate hence increasing the lateral and vertical thermal confinement in the rib waveguide.

![Image of rib SOI waveguide with 0.22μm SiO2 buffer layer.](image)

Figure 4-42: SEM image of rib SOI waveguide with 0.22μm SiO2 buffer layer.
Figure 4-42 shows a SEM image of a fabricated SOI rib waveguide with buffer oxide layer measuring 0.22μm in thickness. The buffer layer of 5μm SiO₂ is sputtered on the rib waveguide before being back polishing using chemical mechanical polishing (CMP) to the designated thickness. It is evident that the shape of the SiO₂ and its thickness in the slab region is slightly different from the modelling shown in Figure 4-41, due to polishing tolerance during the CMP process. Hence, this issue can be overcome by trial and error technique to calibrate the required time in achieving the optimum buffer layer thickness.

Numerical simulation of refractive index changes with variation in oxide buffer layer thickness is shown in Figure 4-43. The temperature applied from the heating element ranged from 50 to 200°C, and causes the refractive index changes via the TOE that increase following an exponential trend when the oxide thickness is gradually reduced down to 100nm. For 500nm in thickness and above, the heat transfer from the heating element to the rib waveguide is inefficient due to the low thermal conductivity of the SiO₂. Thus, the refractive index change remains relative constant even with the increase of applied temperature. In order to optimise the temperature rise in the rib waveguide, we investigated the maximum temperature rise that can be achieved by combining the effect of the SiO₂ top buffer layer thickness and the placement of the thermal isolation trenches in the waveguide structure. Figure 4-44 shows the results of our 2D FEM thermal analysis. It becomes apparent by choosing thinner buffer layers and close placement of the isolation trench to the center of the rib waveguide that heat diffusing is sufficient from the heat source into the rib waveguide structure. Nonetheless, we need to consider whether the position of the isolation trench impinges on the optical mode of the waveguide, in case there is the potential of exciting higher order mode propagation in the waveguide which supports only fundamental mode operation.
Chapter 4: Device Design

Figure 4-43: Refractive index changes by TOE plotted as a function of SiO$_2$ top buffer layer thickness with various heater temperature sources.

Figure 4-44: Simulation of temperature in the rib waveguide as a function of heater temperature show improvement of thermal confinement with the implementation of closer isolation trench spacing and thinner oxide buffer layer.
4.4.4 Resonant Wavelength Shift

In this section, we will demonstrate the temperature dependence of the resonance wavelength of a Bragg grating in a small cross sectional SOI rib waveguide covered with a specific surface oxide buffer layer. The resonant Bragg wavelength of Bragg gratings in SOI rib waveguides will exhibit a temperature drift based on the TOE of silicon. The thermal drift numerical calculation is the combination of 2D heat transfer model in section 4.4.3 and Bragg grating modelling of section 4.3.2.1. As a result, the integrated grating with high resonance thermal shift can be designed by this numerical simulation method. The Bragg wavelength of an SOI surface corrugation grating can be expressed by equation (4.2). Hence, the thermal variation of the resonant Bragg wavelength is given by:

\[
\frac{d\lambda_B}{dT} = \frac{2}{m} \left( \frac{dN_{\text{eiffel}}}{dT} + N_{\text{eiffel}} \frac{d\Lambda}{dT} \right)
\] \hspace{1cm} (4.13)

As stated by Kokubun et al. [4.61, 4.62], the second term in equation corresponds to the relationship of grating period variation caused by temperature change and it is influenced by the coefficient of the thermal expansion (CTE) of material. Typically quoted values of the CTE for silicon is larger than SiO₂ where its value is 2.6x10⁻⁶ K⁻¹ and 0.6x10⁻⁶ K⁻¹ respectively.

Figure 4-45 shows the comparison between wavelength variation for TE and TM polarisation for Bragg gratings with different top oxide buffer layer. The temperature drift of the Bragg wavelength for both polarisations is very close; on the contrary, temperature sensitivity is significantly different with 4.12pm/°C and 3.12pm/°C for 200nm and 400nm oxide thickness. Thus, the oxide layer thickness essentially limits the heat flow hence TOE refractive index modulation of the grating. The grating period variation’s contribution to the wavelength thermal shift is considered negligible for low temperature rises as shown in Figure 4-46. These data correspond to the maximum variation of the Bragg wavelength over a rising temperature range of 120°C.
Figure 4-45: 3rd order Bragg grating ($\lambda = 687\,\text{nm}$) resonance wavelength shift caused by TOE versus applied heater temperature with different SiO$_2$ top buffer layer thickness in TE and TM polarisation operating at free space wavelength of 1550nm.

Figure 4-46: Comparison of 3rd order Bragg grating ($\lambda = 687\,\text{nm}$) resonance wavelength shift with/without inclusion of grating period variation as a function of grating temperature with TE polarisation $\lambda_0 = 1550\,\text{nm}$. 
The induced refractive index changes in the silicon via the thermo-optic effect will cause the peak transmission of a grating to shift forward due to the positive value of thermal optic coefficient. If backward tuning is required, rather than letting the rib waveguide cool down naturally, a thermo-electric cooler or heat-sink is needed to mount at the base of the substrate to remove the thermal energy in the waveguide more efficiently.

4.5 Summary

The design of SOI waveguides on small cross section was used to determine the waveguide bends and Y-junction with 50% power splitting ratio, which forms part of the Bragg grating filter structure. The BPM based Y-junction branch design yields a relatively good agreement with 2D-FDTD method for the design of power splitting ratio and abrupt discontinuity of waveguides at the junction. Leaky mode propagation — a rigorous numerical approach based on Floquet Bloch Theory has been presented and compared with Coupled Mode Theory in order to investigate 3rd order Bragg gratings on small cross section SOI rib waveguide for a waveguide height of 1.50μm.

We emphasised our analysis on the influence of grating depth to the reflected power and modal power loss due to the radiation effect in the spectral range shorter than the Bragg condition wavelength. The wavelength peak in the grating structure depends on the Bragg condition, i.e. on the grating period and modal effective index. Therefore, the spectral response of the grating device can be tailored for a specific application. On the contrary, it can also be influenced by the undesirable effect of grating period uniformity across the wafer and grating depth control. We included some numerical simulations to predict the overall spectral response of the grating in order to take into account variation of grating period and etch depth.

Grating structures based on single mode and polarisation independent SOI waveguides were used to compare the results produced by the Floquet Bloch approach, and results obtained by coupled mode theory. These show some significant discrepancies in deeply etched gratings. However, good agreement is observed between two theoretical approaches only at shallow grating and for wider waveguide width. CMT calculates the effective index of the overall structure without considering...
the physical presence of grating (via the overlap integral between waveguide equivalent to the highest and lowest grating profile) but approximating using the effective index approach. In contrast, FBT employs rigorous numerical approach on the effective index of the resonant mode in the presence of the grating.

Given an increase in etch depth, this effective index will decrease and the wavelength peak will be shifted to lower wavelengths. Clearly, we see that the discrepancy in wavelength shift between CMT and FBT increases with the etch depth as expected. Furthermore, the scattering effect as induced by the grating is taken into account by FBT through the leakage factor (which cannot be considered by CMT). We also provided the first theoretical demonstration of an oscillating behaviour in maximum reflectivity of 3rd order grating in SOI rib waveguides with small cross section for waveguide width of 1.0 μm and 3.0 μm. During the evaluation of 3rd order Bragg gratings, the power transfer effect to radiated modes (considered by the leakage factor) and the power transfer between guided leaky modes can be stronger in this case with respect to a simple 1st order Bragg grating, therefore the description of the field in terms of leaky modes (using FBT approach) suits the problem better, especially when high index contrast material such as SOI are used, compared to CMT.

References:


4.65 http://www.engineeringtoolbox.com/ah-properties-19_156.html
Chapter 5: Device Fabrication

5 Device Fabrication

5.1 Introduction

In this chapter, the fabrication of the third-order Bragg grating on with SOI rib waveguide with small cross section shown in Figure 5-1 is described. The first section describes the general silicon photonics fabrication process involved in our work. The fabrication of the devices is conducted in Southampton University Microelectronics facility, whereas a test sample was also provided from the University of Delaware. The next section will be devoted to the fabrication steps, scanning electron microscopy (SEM) and atomic force microscopy (AFM) analysis to investigate the correlation between designed and fabricated devices. We also highlight some challenges in realising sub-micrometer Bragg grating periods on small SOI rib waveguides.

Figure 5-1: Third-order Bragg grating in SOI rib waveguides with small cross section.
5.2 General Fabrication Processes

5.2.1 SOI Waveguide Dimensions

The objective is to design a SOI rib waveguide structure with small cross section, which will exhibit polarization independence and support only fundamental mode operation. The resultant rib waveguide dimensions were used as a design platform for third-order Bragg grating filters. Using numerical simulation methods such as BPM and FEM as discussed in Chapter 4, we can calculate rib waveguide dimensions required to satisfy both conditions simultaneously.

Figure 5-2: Single mode and polarization independent SOI waveguide dimensions [5.5].

Figure 5-2 shows the boundaries between single-mode and multimode region and zero birefringence (ZBR) curve plotted against rib waveguide parameters for waveguide height of 1.5μm. It is apparent that single-mode conditions are different for quasi-TE and quasi-TM when small cross section rib waveguides are considered [5.5]. The degree of influence of waveguide width and etch depth on waveguide birefringence for a given waveguide height is presented by the ZBR curve. Any waveguide parameters situated below the boundary lines for both polarizations indicate single-mode operation only. The limitation of achieving the designated waveguide dimensions will be photolithography resolution and silicon etching techniques.
employed to control the rib height and angle of the sidewall. For instance, if we select minimum waveguide etch depth of 0.90μm and assume that photolithography tools introduce ±5% uncertainties for the definition of waveguide width; this will provide waveguide dimensions as indicated by the red dotted circle in Figure 5-2 potentially satisfy both conditions simultaneously.

The 4 inches UNIBOND® wafers fabricated by SOITEC [5.4] were chosen as the raw material for the fabrication of our device. The wafer has the surface thickness of 1.5μm with thickness uniformity of ±5nm. The buried oxide (BOX) layer is 3μm in thickness with uniformity of ±15nm. The thickness of the BOX layer is sufficient enough to prevent evanescent mode coupling into the silicon substrate as the size of the waveguide core is reduced. This has been discussed in Chapter 4. The top silicon layer is P-type silicon which has the range of resistivity of 14 - 22Ωcm and <100> orientation with carrier concentration of 3.8×10¹⁵cm⁻³. The substrate is N-type silicon, with 10 - 20Ωcm resistivity, <100> orientation.

5.2.2 Photolithography

Active and passive optical devices can be fabricated on the same substrate using lateral patterning techniques based on photolithography. Since epitaxial growth processes do not provide any controlled lateral variations in material properties, lithography techniques are needed to change lateral properties of the devices. While new advances in lithographic techniques are introducing continuous changes when the feature size shrinks in accordance with the ITRS roadmap [5.1], the following discussion will provide the reader with a general overview of the process used in this work.

5.2.2.1 Photoresist

In order to transfer a design pattern to the surface of the wafers, photoresist, which is sensitive to optical or electron beam illumination, is needed to make the wafer sensitive to an image or design pattern.
Chapter 5: Device Fabrication

Photoresist is spread on the wafer by a process called spin coating. There are some criteria which are vital for the reliability of the resist such as good bonding to the substrate and thickness uniformity across the wafers. A post-spin soft bake is usually required to drive off most of the solvent in the resist whilst improving resist uniformity and adhesion. Figure 5-3 illustrates two different types of photoresist development, namely positive and negative resist.

For positive resist, the resist is exposed with UV light wherever the underlying material is to be removed. In these resists, exposure to UV light changes the chemical structure of the resist so that it becomes more soluble in the developer. The exposed resist is then washed away by the developer solution, leaving windows of the bare underlying material. The mask, therefore, contains an exact copy of the pattern which is to remain on the wafer. In contrast, negative resist exposure to the UV light causes the negative resist to become polymerised, hence becoming more difficult to dissolve. Therefore, the negative resist remains on the surface wherever it is exposed, and the developer solution removes only the unexposed portions. Masks used for negative photoresist, therefore, contain the inverse of the pattern to be transferred.
Chapter 5: Device Fabrication

Hard bake is the final step in the photoresist process. It is used to stabilise and harden the developed photoresist prior to processing steps that the resist will mask. It is carried out at a temperature of 90 - 140°C for several minutes. Any remaining traces of the coating solvent or developer will be removed. For silicon etching, a hard mask such as silicon dioxide or silicon nitride are generally used. Figure 5-3 process flow shows the photoresist process is used as a mask for etching the silicon dioxide, which is subsequently used as a hard mask.

5.2.2.2 Stepper Photolithography

Optical lithography typically uses step and scan systems in which a laser source illuminates a rectangular section of a mask of the reticle. The pattern is imaged by a projection lens with a 1:5 reduction ratio to expose a photoresist-coated wafer, as shown in Figure 5-3. During exposure, the reticle (see Figure 5-4) and the wafer are scanned in opposite directions relative to the lens until one shot exposure is completed. A GCA 6300 step and repeat projection printer providing a 5:1 reduction was used to generate the pattern on the wafer. The scanning motion moves the slit area over the entire reticle to expose the whole pattern, with the reticle moving five times as fast as the wafer scan due to the 5X magnification. The scanner then steps the wafer to the next exposure area and repeats the exposure. This cycle continues until the full area of the wafer is exposed. Figure 5-5 show the schematic design layout for the Bragg gratings devices, which includes design mask layer for integrated heater and SOI rib waveguides.

Figure 5-4: Reticle mask of y-junction rib waveguide layer.
Chapter 5: Device Fabrication

Figure 5-5: Reticle mask - kA69rw showing the schematic layout of Bragg grating on SOI waveguide with integrated heater. The numerical number situated below the Y-junction indicated the grating length employed for the corresponding devices.

5.2.2.3 Electron Beam Lithography (EBL)

The development of electron-beam resist systems used for photomask fabrication has been focused on improving the sensitivity, resolution and etch resistance of the resist materials [5.6]. Polymethy methacrylate (PMMA) resist is commonly used in EBL for direct-write. In our work, the gratings were patterned using an e-beam direct write process on photoresist across the SOI wafer. Using computer aided design software such as L-edit, allows one to directly generate a designed grating pattern in a reticle as shown in Figure 5-6. With the assistance of alignment mark, the direct written grating photoresist layer was aligned with the rib waveguide design layer. Once both layer had been accurately aligned with the grating pattern on the wafer surface, the wafers are then etched to the desired depth. Detail fabrication steps used in our work will be further discussed in section 5.3.
5.2.3 Silicon Etching

Silicon etching involves controlled removal of material via chemically reactive and physical processes. There are two types of etching technique commonly used in silicon photonics fabrication, wet chemical and dry etching. Low loss SOI waveguides with waveguide height greater than 3μm have been fabricated by both wet [5.8, 5.9] and dry etching [5.10] techniques.

Wet etching consists of isotropic etching and anisotropic etching. isotropic etching removes material from the target at the same rate in all crystallographic directions, but has the disadvantages that it etches horizontally under the etch mask (undercutting) at
the same rate as it etches through the material. On the other hand, isotropic etching technique has different etch rates in different directions. The principles of anisotropic and isotropic wet etching are illustrated in Figure 5-7.

![Chemical etch enhanced by ion bombardment](image)

**Figure 5-8:** A combination of chemical and physical etching by RIE dry etching technique.

Dry etching is a more suitable etching technique which provides tight tolerances and reproducible production of silicon optical waveguide. Reactive ion etching (RIE) is a commonly used dry etching technique to achieve effectively vertical sidewall, which combines chemical reaction and physical etching. During the chemical process of RIE, the substrate is placed inside a reactor in which several reactive gas species, such as CF$_4$ or SF$_6$ are introduced. An RF power source is used to strike plasma from the gas mixture, breaking the gas molecules into ions. These neutral or/and ionised atoms interact with the material's surface to form volatile products. The physical process of RIE which is similar to sputtering deposition process uses high energy positive ions.

![Mask Erosion](image)

**Figure 5-9:** Potential problem experienced by RIE etching technique.

These positive ions are accelerated and strike the substrate with high kinetic energy, hence transferring some of their energy to the surface atoms which then lead to the removal of the material. Ion bombardment is very useful to maintain the
directionality, or anisotropy of the etching process. During reactive ion etching chemistries, a product is formed that is not a volatile product. In some cases this effect could be exploited to protect vertical walls from isotropic chemical etching, while the same protecting film is removed from the bottom surface by energetic ions. Some common problems experienced by RIE are illustrated in Figure 5-9, such as mask erosion, deposition of inhibitor on the sidewall, trenching effects and undercutting.

Figure 5-10 depicts SEM image of an isolation trench formation using RIE techniques with relatively vertical sidewalls with SiO₂ passivation layer. The air void formed by the deposition of a silicon dioxide will not affect the optical operation of the devices since the rib waveguide (optical mode) is situated far from the isolation trench. Some RIE trenching effects are visible close to the sidewall.

**5.2.4 Chemical Vapour Deposition (CVD)**

Chemical vapour deposition is a chemical reaction which transforms gas molecules (precursor) into a solid material in the form of thin film or powder on the surface of a substrate. Silane (SiH₄) and nitrous oxide (N₂O) are often used as precursors for plasma enhanced CVD silicon dioxide deposition. The stress of plasma-deposited films can be adjusted when a dual frequency reactor is employed [5.7]. The deposition of a silicon dioxide layer can be used as trench fill material in applications of shallow trench isolation and conventional etched-aluminium metallization.
Figure 5-11 shows the SEM image of an SOI wafer after PECVD of silicon dioxide and CMP to achieve a flat planar surface ready for metallization of an aluminium heater for our devices. Plasma-deposited silicon dioxide layers and silicon nitride ($\text{Si}_3\text{N}_4$) are widely employed when conformality is not critical in the application, such as a final passivation layer for optical waveguides.

### 5.2.5 Critical Dimension (CD) Control

With decreasing feature size, control of the linewidth (critical dimensions) in the exposed pattern becomes increasingly important if the waveguide is to perform as designed. If the accepted tolerance for CD is approximately 10% [5.13], 60nm features must be controlled to within ±6nm. Umatate et al. [5.13] have suggested several important factors influence CD uniformity such as synchronisation between reticle and wafer scanning, projection lens and illumination system. We do not attempt to offer a comprehensive, review of CD control, but rather to introduce the reader to CDs applied in the SOI rib waveguide fabrication process. Further information of CD control requirements for the next generation of process technology can obtained in the International Technology Roadmap for Semiconductors (ITRS) [5.1]. We have discussed some of the requirements for waveguide dimensional control [5.5] as shown in Figure 5-12 in relation to the demand of current fabrication processes to realise SOI rib waveguides structure which are insensitive to polarisation.
Chapter 5: Device Fabrication

Figure 5-12: SOI rib waveguide etch depth influence on waveguide width to support polarisation independent for small silicon overlayer thickness at $\lambda_o = 1550$nm, reflecting the etch depth tolerance requirement in relation to waveguide process technology [5.5].

The width of the rib ($W$) is defined by a photolithography process. The linewidth variation across the wafer introduced by photolithography stepper and scanner might result in width of the etched rib, smaller than the designed value. Other factors such as selection of material for photoresist and resist postprocessing also influence the final width of the rib waveguide.

The rib height ($H-h$) or etch depth and the rib sidewall angle ($\theta$) are determined by the silicon etching method, namely dry or wet chemical etching technique. The former will produce a relatively vertical sidewall whereas the latter will result in a trapezoidal shape SOI waveguide. Real-time etch depth monitoring system utilising infrared interferometric spectrometry techniques [5.11, 5.12] have been reported with a good degree of accuracy. However, the requirement of SiO$_2$ passivation achieved via thermal oxidation and metallization on the upper oxide cladding layer have the potential to reduce the critical dimensions. This is attributed to the consumption of silicon during thermal oxidation when oxygen and silicon atoms react.
5.3 Fabrication Process Flow

5.3.1 Fabrication Steps

In this section, the complete fabrication process of the devices is described and aided by illustration in Figure 5-13. Then, the lab management system (LMS) list of the fabrication process flow at Southampton University is shown in Figure 5-15. The combination of fabrication flow and LMS will provide the reader with a clearer view of the important steps involved in fabrication of third-order Bragg gratings in SOI rib waveguides.

According to the fabrication process flow diagram, the process can be divided in three stages:

1. Grating Definition
2. Waveguide Fabrication
3. Aluminium Heater Deposition

Using files created by the L-edit software package, masks have been written by EBL direct write. The reticle patterns (design pattern number: k969rew) are printed on wafers by the step and repeat printing process. The process started with SOI wafer preprocessing. Impurities must be removed from the surface of the wafer before and after various process steps such as chemical vapour deposition and etching process. In each photolithography stage throughout the fabrication processes, RCA cleaning is essential after photoresist stripping. This procedure was designed to remove organic surface films by oxidative breakdown or dissolution to expose the silicon or oxide surface for subsequent decontamination reactions. The wafer was rinsed in Ammonia (NH₃) + Hydrogen peroxide (H₂O₂) for 10 minute, followed by another 10 minutes rinse in Hydrochloric acid (HCl) + H₂O₂. Deionised water is used in intermediate and final rinses. This is followed by 150nm oxide deposition on top of the SOI wafer using the Plasmalab System 90 (DEP 90) via plasma enhanced chemical vapour deposition (PECVD). Wet chemical etching (fuming nitric acid (FNA) clean) has been applied after the deposition of thin oxide layer to remove impurities remaining on the wafer surface.
Chapter 5: Device Fabrication

Figure 5-13: Fabrication process flow of Bragg grating on SOI rib waveguides.

An alignment mask was required to provide precision positioning of different mask layers and increase the tolerance for mask error. The reticle pattern (kat59rw) produced in Figure 5-5 were then carefully aligned to SOI wafers using alignment marks on the masks and the wafer to register the patterns prior to direct write of grating using EBL.

The gratings were patterned by Leica/Cambridge EBMF 10.5 Electron Beam Lithography System on 400nm thick layer of negative resist as shown in Figure 5-14 (a). The grating pattern on the reticle was transferred onto the wafer surface using photolithography, and the SiO$_2$ which is not covered with the photoresist was anisotropically etched using the Plasmalab 80+ etcher from Oxford Plasma Technology with a gas content of CHF$_3$ and Argon. A Technics Plasma 3000 resist asher was used to remove residual resist and follow by RCA cleaning.
Figure 5-14: Schematic diagram of fabrication process flow for 3rd order Bragg grating on SOI rib waveguides.

Figure 5-14(b) illustrates the second stage of the fabrication, the process started with transferring a rib waveguide layer using photolithography on 1.1μm resist thickness with the assistance of alignment mark. Subsequently, the rib waveguides were defined by etching the silicon using hydrogen bromide (HBr) in an inductively coupled plasma (ICP) system as indicated by the dotted line in Figure 5-14(c). The resist for the rib waveguides was stripped before etching of the grating using the same approach. Subsequently, the thermal isolation trench layer on the reticle was patterned on the photoresist using stepper photolithography. A 600nm thick of silicon layer was etched to the BOX layer of the SOI wafer to form the isolation treches. Figure 5-14(d) shows the schematic diagram of the device with Bragg gratings prior to SiO$_2$ deposition.

In the final stage of the process, the wafers were exposed to thermal oxidation at 900C and oxidation time of 10 minutes to achieve 20nm SiO$_2$ in thickness; this technique
was used to reduce the process induced surface roughness. Then, the PECVD DEP80
was used for deposition of 1.5±0.15μm thick SiO₂. This is followed by chemical
mechanical polishing (CMP) using a Strasbaugh 6EC to polish off 1.0-1.3μm of the
SiO₂ for wafer planarisation. This procedure leaves a thin 200-500nm SiO₂ overlayer
on top of the rib waveguide to provide a buffer layer for metalisation of aluminium
heater.

Aluminium is deposited by sputtering 1μm Al/Si(1%) in a Trikon Sigma sputterer.
Aluminium heater layer on the reticle was patterned on the photoresist using stepper
photolithography. An SS1C Metal Etcher was used to define the heater pattern.
Lastly, the wafers were cleaned using a combination of Cl₂ +SiCl₄ + Argon. LMS is
an official database of all fabrication processes at the facility in Southampton
University. All these steps are shown in LMS list in Figure 5-15. The fabrication of
the Bragg grating is presented in two branch process, one with the aluminium heater
on top of the rib waveguide separated by the upper cladding oxide layer, whilst the
second one is without the aluminium heater.
## Chapter 5: Device Fabrication

**Figure 5-15:** Lab management system (LMS) list of the Bragg grating fabrication.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Coul.</th>
</tr>
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<tr>
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<td><strong>X2540a</strong></td>
<td>R-MHA - Bragg Gratings using dual mask</td>
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<td>2</td>
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<td>3</td>
<td>G-1P</td>
<td>Lithography Notes</td>
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<tr>
<td>4</td>
<td>G-1</td>
<td>Notebook page</td>
</tr>
<tr>
<td>5</td>
<td>W-1</td>
<td>RCA clean</td>
</tr>
<tr>
<td>6</td>
<td>LQ-150</td>
<td>LTO deposition: 150nm +/- 15nm at 490degC SIA and O2</td>
</tr>
<tr>
<td>7</td>
<td>W-2</td>
<td>Fuming Nitric acid clean, 2nd pot only</td>
</tr>
<tr>
<td>8</td>
<td>P-GS1</td>
<td>STEPPER Photolith: reticle kaf98w, Layer ALN Dark Field: nom. 1.1um resist STANDARD (Alignment)</td>
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<td>9</td>
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<td>Hardbake for dry etch</td>
</tr>
<tr>
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<td>P-RS</td>
<td>Resist strip</td>
</tr>
<tr>
<td>12</td>
<td>W-C2</td>
<td>Fuming Nitric acid clean, 2nd pot only</td>
</tr>
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</tr>
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<td>P-RS</td>
<td>Resist strip</td>
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<td>18</td>
<td>W-C2</td>
<td>Fuming Nitric acid clean, 2nd pot only</td>
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<td>21</td>
<td>G-2</td>
<td>See Engineer for instructions</td>
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<td>22</td>
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<td>Hardbake for dry etch</td>
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<td>Resist strip</td>
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<tr>
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<td>P-RHBD</td>
<td>Hardbake for dry etch</td>
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<tr>
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<td>D-4</td>
<td>Dry etch: Shallow etch Si, Anisot. 0.7um ICP HBR</td>
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<tr>
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<td>P-RS</td>
<td>Resist strip</td>
</tr>
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<td>W-C7</td>
<td>Post CMP clean</td>
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<td>Sputter 1000nm AuSi 1% in TRIKON SIGMA RESIST PROHIBITED</td>
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<td>G-2</td>
<td>See Engineer for instructions</td>
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<td>P-RHBD</td>
<td>Hardbake for dry etch</td>
</tr>
<tr>
<td>44</td>
<td>D-MA1</td>
<td>Etch Al, AuSi and/or Ti, for OPTICAL resist SRS SS1C CI2+SiC4+Ar (WHOLE 4&quot; wfrs)</td>
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<tr>
<td>45</td>
<td>P-RS</td>
<td>Resist strip</td>
</tr>
</tbody>
</table>

5-16
5.3.2 Scanning Electron Microscopy (SEM) Analysis

In this section, SEM images of each part of the 3rd order Bragg grating on SOI rib waveguides are shown. They were obtained using a Hitachi S-4000 SEM at University of Surrey. This SEM analysis is broken down into three parts: rib waveguides, gratings and the aluminium heater.

Figure 5-16 (a) depicts SEM image of SOI rib waveguide with $H = 1.45\mu m$, $W = 1.15\mu m$ and $D = 0.85\mu m$ and the thickness of the SiO$_2$ layer measuring from the top of the rib is approximately 250nm after CMP process. An even surface uniformity of the SiO$_2$ layer is required to prepare for the later metallisation process of aluminium heater. In order to reduce the charging effect cause by the SiO$_2$ during SEM analysis for the waveguide dimensions, the rib waveguides were immersed in buffer hydrofluoric acid (HF) for 5 minutes follow by quick rinse in flowing water and blow dry with pressurised nitrogen gas. Figure 5-16 (b) shows the fabricated SOI waveguide dimensions of $H = 1.23\mu m$, $D = 0.84\mu m$, $W = 1.08\mu m$ and sidewall angle of 5° in accordance to the micrometer scale bar. Both the waveguide etch depth and width are within the fabrication tolerance of 3% of the designed value. The difference in waveguide geometries results in a change of refractive index from the design value, thus causing changes in waveguide birefringence and single mode condition. The SEM photographs in Figure 5-17 shows the Y-junction branch junction which consists of a width taper measuring 2.32µm at the interface between two rib waveguides width of 1.05µm. The device is separated by isolation trenches etched...
through the BOX layer. All those small white particles visible in the photograph are residual SiO$_2$ from previous SiO$_2$ removal process. Figure 5-18(a) and (b) show the input left and right arms of the input width taper of the device and isolation trenches. The width taper is implemented to facilitate the easy of coupling of optical fibre, leading to increase of coupling efficiency from fibre to rib waveguides.

Figure 5-17: SEMs of top view of Y-junction after removal of SiO$_2$ layer.

Figure 5-18: SEMs of (a)left and (b)right arm of y-junction and input taper with isolation trench.
Figure 5-19: Top SEMs view of 3rd order Bragg grating embedded on top of the rib waveguide and the slab region. 3µm gratings width are implemented across the waveguide illustrated (a) evenly aligned and (b) slight misalignment of 0.5µm the gratings.

Figure 5-20: SEMs of 3rd order Bragg gratings on SOI rib waveguides with a closer look at the grating reveals grating period of 640nm and grating etch of 360nm.

Figure 5-19(a) shows the 3rd order Bragg grating imposed across the rib waveguides where 3µm gratings are evenly distributed across the slab region of the waveguide. Figure 5-19 (b) indicates the intersection region between the Bragg gratings and the rib waveguide. It is evident that the distribution of grating etch across the waveguide suffers from uneven displacement of approximately 0.5µm as a result of misalignment between the E-beam lithography grating layer and rib waveguide reticle mask layer.
Figure 5-20 depicts a higher magnification of SEM showing 3rd order Bragg gratings with grating period of 640nm and grating etch of 360nm which results in duty cycle of 0.56.

After the SiO\textsubscript{2} layer was removed, Atomic Force Microscopy (AFM) was also used to measure the Bragg grating period and surface morphology of the grating. The grating surface had an rms roughness of 12.37nm, as shown in Figure 5-21. The figure also illustrates the reconstructed the 3-D Bragg grating structure and provides the grating period of 695nm measuring from bottom of the grating etch depth as indicated by the two red arrows. The result of the grating period suggests that the residual SiO\textsubscript{2} may be preventing the AFM probe from accurately measuring the grating etch depth, which in turn defines the grating period.
Figure 5-22: SEM of aluminium heater contact pad and a common ground linking the adjacent heater together. The Bragg gratings are underneath the thin heater and SiO$_2$ layer.

Figure 5-23: Micrographs of aluminium heater contact pad and heater on top of the SOI rib waveguide.
Figure 5-22 shows the micrograph of aluminium heater after metallization process. The dimension of the contact pads are 200\(\mu m^2\) and a common ground contact is linked to the adjacent heater across the devices as illustrated in schematic diagram in Figure 5-5. The Bragg gratings are hidden underneath the thin section of the aluminium heater and SiO\(_2\) passivation layer. Figure 5-23 provides the SEM image (a) normal and (b) tilted 20\(^\circ\) to the facet of the waveguide shows the aluminium heater deposited on top of the SOI rib waveguide separated by a thin SiO\(_2\) buffer layer. Note that the final alignment between aluminium heater and the rib waveguide is complex because the waveguide is hardly visible underneath the SiO\(_2\), leading to potential misalignment or offset of aluminium heater from the top of the rib waveguide.

5.4 Summary

In summary, the author has described the fabrication technology available which enables the realisation of third-order Bragg grating reflection filter on SOI platform. The fabrication is divided into three stages: grating patterning, fabrication of SOI rib waveguide with small cross section and definition of the aluminium heater via a metallization process.

One of the main challenges to fabricate integrated Bragg grating for this work is the requirements of submicrometer grating period over a relatively small cross sectional waveguide. The grating patterns for a particular filter are designed for a predetermined grating strength. Stitching errors at field boundaries correspond to phase errors along the grating which in turn distort the filter’s spectral response. A comprehensive study of the influence of stitching errors on the Bragg grating filter performance has been provided by Hasting [5.16]. The degree of distortion depends on the magnitude of the phase error and its location with respect to quarter-wave shift. Therefore, precise control of the grating period uniformity across the grating length is vital for the operation of this grating filter.
References:

5.1 International Technology Roadmap for Semiconductor, http://public.itrs.net/


5.15 L-edit, Tanner EDA, 2650 East Foothill Blvd., Pasadena, CA 91107, U.S.A.

Chapter 6: Experiment Techniques

6.1 Introduction

This chapter is focused on the experimental techniques used for measuring the fabricated devices to evaluate experimental data and simulation predictions. The procedures of sample preparation suitable for waveguide dimensions up to several micrometers are presented with polishing grid up to 50nm resolution. Reflectivity calculations are derived from the measured reflected power from the Bragg grating devices, and include measurement uncertainties contributed by the fibre to waveguide coupling efficiency, fabricated waveguide tolerances and Fresnel reflections. The chapter concludes with presentation of thermo-optic modulation procedure applied to reflectivity measurement to observe the tuning range of the Bragg grating filters.

6.2 Samples Preparation

Experimental procedures which utilise end fire coupling excitation of waveguide require high optical quality waveguide facets. It is possible to achieve reasonable end face quality by cleaving SOI wafers but this method is not reliable and the sample can be damaged. Polishing is the most common method of preparing a waveguide facet. The sample endface is polished by lapping with abrasive material. It is important that polishing process must remove the damage introduced by previous steps by using successively finer abrasive particles to achieve a smooth surface. Polishing procedures vary according to the device dimensions. The main objective is to yield highest possible optical quality of the facets of the waveguide in order to reduce optical scattering loss.
Before embarking on the polishing procedure, the diced chip (sample) measuring 117mm² as shown in Figure 6-1 is mounted on the side of a custom made aluminium sample holder using wax heated to approximately 100°C. The sample holder comprises two parts, a base and an upper section where the samples were mounted. Two drilled holes on the upper section of sample holder enable the user to handle or
reverse the unit to polish the other side of the facet without damaging the samples. A dummy sample is also adhered on the other side of the upper section of sample holder in order to provide mechanical support during the polishing process. Figure 6-2 illustrates the arrangement, which was assembled on a thermostatic hot plate and then allowed to cooling before further processing. The samples extended out approximately 0.5mm from the upper section of the sample holder. Increasing the protruding distance of the sample from base has a greater risk of the sample being detached from the sample holder during the polishing procedure; therefore care must be taken to keep this distance to a minimum according to the intended grinding length and polishing requirements.

6.2.1 Polishing Technique

A polishing procedure has been formulated to obtain good quality facets for SOI waveguide dimensions in the region of 1.5μm in height. At end of each stage of the polishing procedure, the facet quality of the sample was observed under a high magnification microscope. Example images are shown in Figure 6-4.

This sample preparation procedure was developed through observation, trial and error. This optimum method comprises grinding and polishing. The same procedure is
repeated on the opposite surface by reverse mounting of the fixture without removing the sample from the holder.

Once both the device under test and dummy sample were strongly adhered to the holder after the wax had cooled down, the samples were levelled by hand using 1200 grit silicon carbide (SiC) paper and water lubrication. The hand levelling process using coarse grit SiC paper is required to remove or grind away excessive silicon to reduce polishing time since the actual device structures were at least 1mm away from the facet of the diced sample. The same procedure was repeated on the second facet for 1 minute.

The sample holder was then mounted in a METASERV® 2000 grinder polisher which is illustrated in Figure 6-3 (a). The sample fixture was positioned approximately in the middle section of the polishing wheel and the polishing wheel was rotated anticlockwise at 100rpm. Care must be taken to ensure the rotation of polishing wheel always moves toward the top surface of sample and polishing pressure was not excessive (see Figure 6-3 (b)). If it moves away, it will inevitably break off or chip away the top layers of the SOI samples. The pressure applied is determined by the ring on the clamper pressure indicator; in this instance, the pressure applied is fixed at ring number 2 which corresponds approximately to 10 Newtons with 4000 grit SiC paper for 5 minutes. The resulting facet quality of the sample at this stage is is shown in Figure 6-4 (a).

In order to improve the quality of the polished samples, finer resolution polishing paper is required for the subsequent steps of the procedure until resolution of the polishing grid is smaller than the device dimension in the final step. Next, 1μm resolution aluminium oxide is used for approximately 8 minutes and clamping pressure ring is fixed at number 3 (15 Newtons). In this step, surface roughness of the samples required constant visual inspection of the facet quality using high magnification (200x) of optical microscope. This is shown in Figure 6-4 (b).

The procedure then proceeds to the next stage with finer polishing resolution until after visual inspection of the facet quality, the facet is sufficiently smooth. The
samples were then polished using 300nm and 50nm grit paper for 20 minutes with pressure ring fixed at number 4 (20 Newtons). Figure 6-4 (c) and (d), indicate the slab and the rib waveguide with sufficiently good optical surface using this formulated polishing procedure by observing the surface roughness at substrate of the devices. This formulated procedure is simplified and described in Table 6-1. Once the polishing procedure is completed, the samples were removed from their sample holder by heating on thermostatic hot plate (120°C) and followed by immersing of the sample in acetone to remove any remaining wax. The facet of the sample is carefully wiped with Acetone using cotton buds to avoid any accidental chipping of the waveguides.

Figure 6-4: Optical microscope images of facet quality with grid resolution of (a) 5µm (b) 1µm (c) 300nm (d) 50nm
Table 6-1: Polishing techniques for SOI rib waveguide with overlay thickness of 1.5 μm.

<table>
<thead>
<tr>
<th>Polishing Stage</th>
<th>Type of Grid Pad</th>
<th>Polishing Duration (mins)</th>
<th>Clamping Pressure</th>
<th>Grid Resolution (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silicon Carbide 1200</td>
<td>1</td>
<td>Hand levelled</td>
<td>19000</td>
</tr>
<tr>
<td>2</td>
<td>Silicon Carbide 4000</td>
<td>5</td>
<td>10 N</td>
<td>5000</td>
</tr>
<tr>
<td>3</td>
<td>Aluminium oxide</td>
<td>8</td>
<td>15 N</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>Aluminium oxide</td>
<td>20</td>
<td>20 N</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>Aluminium oxide</td>
<td>20</td>
<td>20 N</td>
<td>50</td>
</tr>
</tbody>
</table>

6.3 Experimental Techniques

In this section, an introduction to optical measurements is given which focuses on the characterisation of the Bragg grating filters. For waveguides and Bragg gratings filters with small cross section area, the uncertainty in the fibre to waveguide coupling loss makes it difficult to characterise propagation loss over small lengths. A numerical simulation using BPM is presented that predicts the coupling loss as a result of positioning between fibre and waveguide, and fabricated waveguide geometry variation. The propagation loss of the optical waveguides was evaluated using the Fabry-Perot resonance method. Since reflective waveguide filters are sensitive to fabrication variations, filter analysis techniques combined with post-fabrication methods are critical to successfully demonstrating optical filters predicted by numerical simulation. The thermo-optic characteristic of the Bragg grating filter was also investigated using Joule heating via an integrated aluminium heater.

6.3.1 Coupling Loss

When the input optical fibre is perfectly aligned to the optical waveguide, the efficiency with which the light is coupled into the waveguide is determined by reflection from the waveguide facet (Fresnel reflection), quality of the waveguide facet and mode matching between the excitation and waveguide modes. The optical
scattering is attributed to the optical quality of the waveguide endface. If the waveguide polishing procedures are implemented according to section 6.2.1, the scattering loss can be minimised and considered negligible. The mode mismatch between the excitation and the waveguide field can be calculated using the overlap integral between the field profile of a lensed fibre and the SOI rib waveguide. BPM based optical simulation was also carried out for optimisation of the excitation field launch position to minimise coupling loss caused by spatial misalignment from input fibre to small rib waveguide dimensions.

6.3.1.1 Overlap of Excitation and Waveguide Field

Mode profile mismatch between the waveguide and excitation fields can be evaluated by overlap integral between the two fields. The coupling loss resulting from misalignment of the lens fibre to the SOI rib waveguide was calculated using a BPM based mode solver, BeamProp. Figure 6-5 (a) and (b) depict the fundamental mode profiles for lensed fibre with 4μm diameter and an SOI rib waveguide with an etch depth of 0.89μm, and a rib width of 1.0μm. The relationship between launching position of the input fiber (excitation field) was varied in the simulation to obtain an optimal position curve to achieve maximum coupling between these two fields as shown in Figure 6-5 (c).

Figure 6-5: Fundamental mode profile of (a) lensed fiber mode, (b) SOI rib waveguide and (c) simulation results on coupling efficiency between the fiber and waveguide as a function of lens fiber launch y-position and x-position.
In addition, optimum excitation field launch positions can also be predicted in the simulation. At the optimised launch position of \( x = 0 \) and \( y = 1.0 \), the coupling efficiency can be predicted as about 57%. From the plot, it is clear that the maximum coupling efficiency can be maintained up to \( \pm 0.2\% \) if the alignment sensitivity of the fibre can be controlled to \( \pm 0.2\mu m \) in launching y-position. The Melles Griot NanoMax XYZ micro-positioning stages are capable of manipulating the mounted input fibre with 5nm resolution. Hence, the predicted maximum coupling efficiency can be maintained for coupling of lens fibre into small cross section SOI rib waveguide.

**6.3.1.2 Influence of Waveguide Geometry Variation**

The relationship between mode mismatch between the launch field (input lensed fibre) and rib waveguide geometry resulting from fabrication variation was established by utilising coupling efficiency BPM simulations. Firstly, the optimised launching \( x \) and \( y \)-position for each waveguide geometry is determined. By using the optimised launching positions, the coupling efficiency resulting from variation of etch depth and waveguide width is evaluated.

![Figure 6-6: Coupling loss from 4μm diameter lens fiber to 1.5μm height SOI rib waveguide as a function of waveguide width and etch depth.](image-url)
Figure 6-6 gives a clear indication that mode mismatch due to waveguide geometry variation is highly dependent on waveguide etch depth as compared to rib width. It is interesting to note that the maximum coupling efficiency predicted at 55% is relatively constant and is not significantly influenced by the variation of rib width at a waveguide etch depth of 0.80μm. For our waveguide dimensions, the maximum coupling efficiency that can be achieved is 50±1% if the rib width fabrication tolerance can be controlled within 50nm. As our design waveguide etch depth is beyond the 0.80μm range, the coupling efficiency is improved as the rib width increases, due to stronger lateral confinement. However, the waveguide width cannot be too wide if the waveguide is to remain single mode. The single mode width for this case is \( W < 1.1 \mu m \) as calculated earlier in chapter 3.

### 6.3.1.3 Fresnel Reflection

Let us consider the beam of light incident on the boundary surface between silicon and air (endface of an SOI waveguide). Part of the incident light will be reflected from such a boundary surface while the other part will be refracted through the interface. The proportion of the intensities in these two reflected and refracted beams will depend upon the refractive index difference between the medium, the angle of incidence and the polarisation and direction in which the light beam passing the interface (from silicon to air or from air to silicon). By using the Fresnel equations \([6.1]\), the reflection coefficient \( r_{TE} \) and \( r_{TM} \) for TE and TM polarisation can be expressed as:

\[
r_{TE} = \frac{E_r}{E_i} = \frac{n_i \cos \theta_i - n_s \cos \theta_t}{n_i \cos \theta_i + n_s \cos \theta_t}
\]

\[
r_{TM} = \frac{E_r}{E_i} = \frac{n_i \cos \theta_i - n_s \cos \theta_t}{n_i \cos \theta_i + n_s \cos \theta_t}
\]

Using Snell's law, both equations (4.1) and (4.2) for TE and TM polarisation can be simplified to:

\[
R_{TE} = r_{TE}^2 = \frac{\sin^2 (\theta_1 - \theta_2)}{\sin^2 (\theta_1 + \theta_2)}
\]

6-9
Chapter 6: Experiment Techniques

\[ R_{TM} = R_{TM}^2 = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)} \]  

(4.4)

where \( R = r^2 \) is the reflectivity of the interface between air and silicon. The dependencies for the reflection coefficients, \( R \) are given in Figure 6-7.

![Figure 6-7: Reflection coefficient as a function of incident angle for air/silicon interface.](image)

We can observe from the figure that for the light propagating at normal incidence from the air into the silicon, there is no difference between the TE and TM polarisation. If we introduce coupling of fibre onto the facet of the silicon waveguide at near normal incidence, we can deduce equations (4.3) and (4.4) as:

\[ R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2 \]  

(4.5)

For an silicon/air interface, this reflection \( R \) is approximately 31%, which can be translated to an additional loss of 1.6dB per interface. A thin film antireflection coating can be inserted between two media to reduce the loss introduced by Fresnel reflection. Antireflection coatings work by producing two reflections which interfere destructively with each other (180° out of phase). A single quarter-wavelength (\( \lambda/4 \)) thickness coating of optimum index can greatly eliminate reflection at one wavelength of interest. It can be shown that for normal incidence, the net reflectivity is given by [6.4]:

6-10
Chapter 6: Experiment Techniques

\[ R = \left| \frac{n_1 n_2 - n_{ar}^2}{n_1 n_2 + n_{ar}^2} \right|^2 \]  

(4.6)

where \( n_{ar} \) is the refractive index of the antireflection coating. The reflectivity \( R \) can be reduced to zero if:

\[ n_{ar}^2 = n_1 n_2 \]
\[ n_{ar} = \sqrt{n_1 n_2} \]  

(4.7)

For a silicon/air interface this means that \( n_{ar} \) needs to be approximately 1.87. Silicon oxynitride (SiO\(_x\)N\(_y\)) can be used as an antireflection coating with a variety of refractive index ranging from 1.46 (SiO\(_2\)) to 2.05 (Si\(_3\)N\(_4\)) by changing the relative oxygen and nitrogen concentrations. Alternatively, Hafnium dioxide (HfO\(_2\)) is another suitable candidate for antireflection coating application with refractive index value of 1.89 at wavelength of 1550nm. Figure 6-8 shows the calculated reflection spectrum [6.2] of HfO\(_2\) as a function of wavelength with \( \lambda/4 \) thickness of 205nm. It can be seen that we can keep the reflectance below 0.1% over a wavelength range of 100nm. By introducing coating thickness tolerance of \( \pm 10 \)nm, we can also predict the behaviour of the reflectance as a result of deviation from the design value.

![Figure 6-8: Reflectance spectrum of Hafnium Dioxide (HfO\(_2\)) a single quarter-wavelength stacks of 205nm in thickness as anti-reflection coating on the facet of the SOI rib waveguides [6.2].](image)
6.3.2 Waveguide Losses

The commonly used technique to prepare the facets of an optical device is polishing as discussed in section 6.2.1. Both facets were polished normal to the waveguides to facilitate the measurement of propagation loss using the Fabry-Perot (FP) resonance method. The waveguide forms a Fabry-Perot cavity when the chip facets are polished normal to the waveguide due to the multiple internal reflections between the air and silicon interface along the waveguide and back. By measuring the spectral response of this cavity, it is possible to estimate the waveguide propagation loss. The relationship between the transmitted optical intensity ($I_t$) and the incident light intensity ($I_0$) in FP cavity can be described as [6.1]:

\[
\frac{I_t}{I_0} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2 + 4Re^{-\alpha L} \sin^2 \left( \frac{\phi}{2} \right)}
\]

(4.8)

where $R$ is the facet reflectivity, $L$ is the waveguide length, $\alpha$ is the loss coefficient and $\phi$ the phase difference between successive waves in the cavity. The equation (4.8) goes through a periodic value of maximum when $\phi = 0$ or multiple of $2\pi$, thus yielding:

\[
\frac{I_{\text{max}}}{I_0} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2}
\]

(4.9)

When $\phi = \pi$, the equation yields a periodic minimum value, that is:

\[
\frac{I_{\text{min}}}{I_0} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2 + 4Re^{-\alpha L}} = \frac{(1-R)^2 e^{-\alpha L}}{(1+Re^{-\alpha L})^2}
\]

(4.10)

The ratio of maximum and minimum intensity distribution can be related by:

\[
\xi = \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{(1+Re^{-\alpha L})^2}{(1-Re^{-\alpha L})^2}
\]

(4.11)
If the reflectivity $R$ is known, we can evaluate the loss coefficient, $\alpha$ of the waveguide by arranging equation (4.11) as:

$$\alpha = -\frac{1}{L} \ln \left( \frac{1 - \sqrt{R}}{R + 1} \right)$$

(4.12)

The value of intensity distribution in the Fabry-Perot cavity is periodic when phase $\phi$ passes through multiples of $2\pi$. This is usually achieved by varying the wavelength of the light source within the Fabry-Perot cavity of the device under test. The transfer function of the Fabry-Perot cavity in equation (4.8) is plotted in Figure 6-9 for 3 different reflectivities by Reed et al. [6.1]. The reflectivity values plotted were 0.1, 0.31 and 0.5, with $\alpha L = 0.023$ which corresponds to an approximate loss of 0.1 dB/cm.

By observing the distortion of the spectral response, a Fabry-Perot scan also provides additional information about whether the waveguide is single mode, slightly multimode or highly multimode. If the waveguide is operating under single mode conditions, the spectral responses will exhibit solid curves as indicated in Figure 6-9. If additional interference or distortion is observed, this indicates the waveguide is
multimode. Nonetheless, it is not possible to quantify the number of modes operating within the waveguide. Numerical simulation of the single mode condition according to the fabricated waveguide dimensions will provide information about higher order modes operating within the waveguide which we can correlate with the experimental observation.

![Figure 6-10: Experimental setup for the Fabry-Perot resonance method to measure waveguide propagation loss.](image)

The waveguide propagation loss experimental setup is depicted in Figure 6-10. A tunable light source (TLS) operating in the wavelength range, $\lambda = 1510-1620\text{nm}$ from Agilent 81640A which has an optical power meter module, is coupled into the waveguide under test by a microscope objective lens with 63x magnification. The outgoing beam of the waveguide is imaged onto the infrared camera by the 40x magnification objective lens and the partially reflecting mirror, which can be tilted and translated in beam direction to the optical power meter. The combination of image acquisition of the facet of waveguide at the outgoing beam and observation of optical power measurement enable efficient coupling from the light source to the device under test. The polarisation half wavelength rotator enables the polarisation direction of the incoming beam to be rotated, hence controlling and determining the polarisation state (TE or TM) of the laser source during the experiment.
6.3.3 Reflection Measurement

The experimental setup for characterisation of SOI Bragg gratings is shown in Figure 6-11. Agilent 81640A TLS is connected to fibre polarisation rotator via the connection of Port 1 of Optiwork optical circulator ($\lambda = 1530-1610$ nm). Port 2 of the circulator is then connected to OZ Optics tapered polarisation maintaining lensed fibre, placed on top of the tapered grooved fibre holder. The holder is then mounted on top of the NanoMax-TS three axis stage which allows the manoeuvre of the fibre in its x, y and z directions. The NanoMax-TS three axis stage is then connected to the piezoelectric actuators for precision control.

![Figure 6-11: Experimental setup to measure the SOI rib waveguide Bragg gratings reflection spectrum.](image)

An optical circulator is used to collect reflectance from the SOI Bragg gratings by diverting the reflected wavelengths $\lambda_b$, which satisfy Bragg condition and transmitted all other wavelengths. The reflected light is collected by the same lens fibre back to Port 2 and emerges from Port 3 of the circulator. The grating spectral characteristics are analysed using data acquisition software interfaced with the optical power modules from the TLS mainframe, where a wavelength scan is performed.
Chapter 6: Experiment Techniques

The middle stage consists of the NanoMax-TS three axis stage where the grating device under test (DUT) is placed. A microscope is situated above the DUT which allows movement in the x and z direction in order to locate the waveguides. The microscope is connected to a monitor to facilitate the ease of alignment of the fibre to the waveguides.

In the output stage of the setup, light transmitted by the grating device is collected by 40x objective lens focused on the MicroPhysic infrared camera to ensure optimal alignment and coupling of light between the input lens fibre and the grating device. An alternative setup that uses a singlemode fibre to replace the focusing lens is considered. This singlemode fibre is mounted on top of the NanoMax-TS three axis stage to collect the transmitted optical output power from the devices. A broadband amplified spontaneous emission (ASE) light source can be used to replace the TLS to observe the spectral response of the grating without going through the time consuming wavelength scan. The grating both reflects and transmits the broadband light source, depending on the designed grating period. The output from Port 3 of the circulator is then connected to an optical spectrum analyser (OSA) to analyse the spectral characteristic.

6.3.4 Evaluation of Reflectivity

Since the reflected signal is travelling in the same waveguide as the input, an optical circulator is used to separate it from the input. Figure 6-12 illustrates the experimental setup for the calculation of reflectivity of the Bragg gratings where lensed fibre is used on both input and output of the grating devices to maximise coupling efficiency. The experimental setup is similar to Figure 6-11 except the output focus objective lens is replaced by polarisation maintaining lens fibre. In order to calculate the reflectivity of the Bragg gratings, the reflection power, $P_r$ at port 3 of optical circulator and the transmitted power, $P_t$ from the output of the Bragg gratings device are recorded. The measured transmitted power at the output, $P_t$ effectively includes two fibre to waveguide coupling losses, two Fresnel reflection losses, waveguide propagation loss and scattering loss from gratings.

$$P_L = P_{in} - P_t$$

(4.13)
where $P_\text{L}$ is the total insertion loss of the measurement setup. Hence, the transmission measurement at non-resonance of Bragg wavelength, $\lambda_b$ through Bragg gratings is useful to obtain a reference power level for calculating reflectivity of the gratings.

![Figure 6-12: Experimental setup to determine Bragg gratings reflectivity using transmitted and reflected power measurement.](image)

Figure 6-12: Experimental setup to determine Bragg gratings reflectivity using transmitted and reflected power measurement.

![Figure 6-13: Optical circulator port 2-3 insertion loss measurement](image)

Figure 6-13: Optical circulator port 2-3 insertion loss measurement

The reflected signal from the Bragg gratings travels back to port 2 again after experiencing the reflectance of the gratings and is directed to port 3 of the circulator before being detected by the optical power meter. The reflectivity calculation must take into account insertion loss of the optical circulator from port 2-3 as shown in Figure 6-13. Thus, the reflectivity of a reflective filter can be determined by normalising the reflected power passing from port 2-3 of the circulator with the transmitted reference power level measured at the output of the DUT.
6.3.5 Thermo-Optic Tuning

The high thermo-optic coefficient in silicon implies that the change of refractive index in the material can be introduced by temperature. Typically, temperature tuning of the waveguide is achieved by thermoelectric cooler (TEC) heating up the whole DUT. However, the overall device dimension can be reduced by introducing an integrated aluminium heater fabricated on top of the silicon waveguide Bragg gratings separated by the planarised SiO₂ layer for thermo-optic tuning. The temperature dependence of resonance wavelengths of a Bragg grating, \( \lambda_b \) in a silicon waveguide covered with a top SiO₂ cladding will induce a wavelength shift of the peak reflection from the gratings.

![Figure 6-14: Circuit diagram of resistive heating setup](image)

Joule heating occurs when an electrical current is passed through a material and the material's resistivity causes heat generation. Figure 6-14 illustrates the schematic circuit diagram to accomplish temperature tuning by supplying the current across the heater. The aluminium heater and contact pad resistance were in series with an ammeter to provide measurement of the current and parallel to a voltmeter for voltage measurement across the heater. The current and voltage measurement will enable the estimation of driving power requirement to control specific wavelength shift in the Bragg grating filter. The two connecting dots in the circuit diagram are replaced by two probe tips contacted to the 200\( \mu \text{m}^2 \) contact pad on the device surface in practice. One of the probes is positioned on the common contact pad which provides electrical conductivity across the waveguide heater for Joule heating.
Figure 6-15 illustrates the experimental setup which combines the Bragg gratings reflectivity measurement described in Section 6.3.3 and thermo-optic wavelength tuning for the grating devices. A TEC was mounted on the sample holder using a thin layer of adhesive to minimise thermal gradient across the interface. The aluminium diving board shaped holder not only provides mechanical support for the TEC but acts as a heatsink to dissipate thermal energy during heating of the device under test. Another smaller size aluminium block was put on the Peltier cooler using permanent thermal adhesive and a thermistor was mounted using thermal grease for temperature feedback to the temperature controller. The Peltier cooler is driven by a temperature controller (ILX Lightwave LDT-5900) to maintain DUT substrate temperature at a desired level. The temperature reading in the controller was accurate to 0.1°C. A thermistor with 10kΩ resistance and 100μA sensing current was chosen, which is
capable of maintaining the temperature between -6°C to 54°C using a 5A drive current from the temperature controller. The dotted lines in Figure 6-15 which link in series with ammeter to the aluminium waveguide heater represent two metal probe tips positioned on both heater contact pads. In order to ensure good contact between both probes and heater contact pad, a digital multi-meter was used to measure the heater resistance and compared its resistance value measured from the I-V characteristics of the heater. The measured heater resistance values will be presented in section 7.3.2 of Chapter 7. Prior to the temperature tuning experiment, the temperature controller was allowed to warm up for at least 10 minutes and stabilise the DUT substrate temperature to 27°C, higher than ambient temperature of 20°C with the Peltier cooler. With the DUT in place, the reflection measurement technique as discussed in section 6.3.4 was implemented together with the thermo-optic tuning.

A wavelength scan of the reflection spectra of the Bragg grating was performed before connecting the driving circuit of the grating heater. By providing suitable direct current into the grating heater, it is possible to analyse the optical response of the Bragg grating with different driving power. The recorded optical output power will exhibit a bandpass filter like behaviour in its reflection spectrum as described in section 4.3.4, with driving current. The reflected power from the Bragg gratings is detected using the Agilent InGaAs detector (Model: 81624B). The difference in Bragg resonant wavelength prior to Joule heating and that that is required to achieve a 1nm wavelength shift was then recorded, with the corresponding driving current. Thus, by increasing the current, the power dissipated in the series resistance of the heater is increased, resulting in the heating of the gratings and leading to the strong thermo-optic modulation effect. The iteration of wavelength scan measurement is performed for each increment of current, and hence we can observe the temperature shift of the Bragg wavelength. Thus, the influence of driving power on temperature sensitivity of the grating can be determined.

6.4 Summary

In this chapter, the author has described the sample preparation prior to optical measurement. Through trial and error and observing the waveguide facet quality at each polishing stage, a polishing recipe is formulated to achieve waveguide facet
roughness down to 50nm. Hence, this polishing procedure is applicable to waveguide in sub-micrometer dimensions. The influence of waveguide geometry variation and positioning of the input fibre to the coupling efficiency between the fibre to waveguide are discussed. The experimental setup and measurement technique for optical waveguide propagation loss and reflection filter spectral response has been presented. The experimental technique for utilising Joule heating to achieve tuning capability of the waveguide Bragg gratings filter via the thermo-optic effect was discussed. The experimental results obtained from aforementioned measurement techniques will be presented in Chapter 7.

References:


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Chapter 7

We fix our eyes not on what is seen, but on what is unseen. For what is seen is temporary, but what is unseen is eternal. 2 Corinthians 4:18 NIV

7 Experiment Results and Discussion

7.1 Introduction

This chapter is aimed to provide discussion and analysis of the experimental results for the 3rd order Bragg gratings on silicon-on-insulator (SOI) waveguides. The waveguide gratings development effort was concentrated on the influence of grating etch depth in conjunction with the study of single mode and polarisation behaviour of small cross sectional SOI waveguides. Therefore, there were two fabrication runs in this work. Both fabrication runs were based on the same physical dimensions of SOI waveguides as a platform modelled in Chapter 3 where the Bragg gratings will be implemented. In the first fabrication run, the objective of the development was to realise 350nm and 400nm deep surface gratings on top of the SOI rib waveguides and the 3μm width gratings are extended to the slab region. In the second run, the 200nm deep gratings are confined only on top the SOI waveguides using a dual mask fabrication process as discussed in the Chapter 5. The fabrication process was performed at the University of Southampton. The purpose of these devices is to enable the author to compare experimental observation and theoretical simulation of grating responses. Therefore, it was necessary to determine the suitable candidates (Couple Mode Theory and Floquet-Bloch Theory) for numerical grating simulation in high index contrast structure such as SOI waveguides.

In section 7.2, the results of propagation losses of SOI rib waveguides with 1.5μm in height through Fabry-Perot resonance method will be presented. This is followed in section 7.3 with the presentation of experimental results for the second fabrication runs of Bragg gratings and their corresponding scanning electron micrograph (SEM)
and atomic force microscope (AFM) analysis. Unfortunately in the first fabrication runs of deep gratings, the author did not observe any characteristic reflection spectra for any of the devices, although they exhibited optical transmission. The potential failure modes of the devices in the first fabrication run are investigated and presented. The experimental results for 3rd order Bragg gratings in small SOI waveguides are discussed and presented in comparison with theoretical simulation results.

In section 7.4, analysis and investigation is carried out to characterise the integrated thin film aluminium heater in terms of its operating current and resistance. This heater structure was used to induce thermo-optic change of the refractive index of silicon through joule heating, leading to thermo-optic tuning of the Bragg grating filters.

### 7.2 SOI Waveguide Propagation Loss

Prior to the measurement of propagation loss of the waveguides, both facets of the straight SOI rib waveguides were polished using the polishing recipe cited in section 6.2.1 in order to minimise scattering loss from the waveguide facet. A Fabry-Perot (FP) cavity will be formed between the input and the output of the waveguide as a result of the polishing procedure. Subsequently, the propagation loss of the waveguide is evaluated using the FP resonance method as described in section 6.3.2.

![Figure 7-1: The facet of rib SOI waveguide displayed on the infrared camera at the output stage (a) before and (b) after the coupling from the tunable laser source.](image)

The tunable light source is coupled into the input of the waveguide using 63x magnification objective lens and the output power is detected via 40x magnification
Chapter 7: Experiment Results and Discussion

objective lens focused on the optical power meter. By using an image reflector at the output stage, the output facet of the waveguide is imaged onto the infrared camera to assist in the alignment procedure as shown in Figure 7-1 (a). The aforementioned procedure is repeated again after turning on the laser source to maximise the coupling efficiency by fine adjustment of the piezoelectric controller XYZ stage until the observation of strong light confinement under the rib waveguide as shown in Figure 7-1 (b). The transmission power of the straight waveguides was collected by the optical power module connected to the data acquisition software after initiating the wavelength scan from the tunable laser source. The length of the straight waveguides used in the propagation loss measurement was measured using a Mitutoyo Series 500 Metric Caliper with an uncertainty of ±20µm. The length of the waveguide is typically in the range of 500 – 550µm depending on the polishing procedure.

Figure 7-2: Measured Fabry-Perot transmission spectrum for a 520µm in length straight SOI waveguide in TE polarisation and theoretical fit for 510µm (red) and 530µm (blue).

The power of the transmission spectrum was measured by performing a wavelength scans of the FP cavity as shown in Figure 7-2. The measured transmission power is normalised against the input optical power to take into account the wavelength drift and non uniform optical power of the laser source in the wavelength range of interest. The propagation loss coefficient of the waveguide, \( \alpha \) is given by [7.1]:

\[
7-3
\]
Chapter 7: Experiment Results and Discussion

\[ \alpha = -\frac{1}{L} \ln \left( \frac{\frac{I_{\text{max}}}{R} \sqrt{\frac{1}{I_{\text{min}}} - 1} - 1}{\sqrt{\frac{1}{I_{\text{min}}} + 1}} \right) \]  

(7.1)

where \( L \) is the waveguide length, \( R \) is the reflectivity between the silicon and air interface, and \( I_{\text{max}} \) and \( I_{\text{min}} \) are the peak and minimum intensity of each resonance respectively as indicated in Figure 7-2. The theoretical transfer function of the FP response for the 510\( \mu \)m and 530\( \mu \)m straight waveguide is plotted in the same graph to compare with the measured FP resonance in transmission power. It shows a relatively good agreement between the theoretical FP transfer function and the measured transmission power. The ratio of maximum to minimum power intensity can be derived from the measured power transmission spectrum, whereas the value of \( R \) is approximately 0.31 between air and silicon interface and the length of the straight waveguide is measured at 520\( \mu \)m. Hence, we can evaluate the propagation loss of the SOI waveguide, yielding approximately 4.8dB/cm for TE polarisation. The measured propagation loss is higher than we anticipate compared with 0.1dB/cm [7.2] reported in the published literature.

![SEM image showing an SOI rib waveguide with sidewall roughness viewed at 30°](image)

Figure 7-3: SEM image showing an SOI rib waveguide with sidewall roughness viewed at 30°

The high propagation loss might be attributed to the scattering losses on the rib waveguide sidewall, which are sometimes significantly higher for small rib waveguides dimensions. Lee et al. [7.3] performed an extensive study on the effect of
waveguide size and surface roughness on transmission losses in silicon waveguide system. The authors suggested that the losses of the waveguide increase as the waveguide width decreases and demonstrated the dominant component of the propagation loss comes from the waveguide sidewall roughness. A SEM analysis was carried out to investigate our waveguide sidewall roughness. Figure 7-3 depicts the SOI rib waveguide sidewall roughness viewed at an angle of 30°. It clearly indicates significant roughness which may lead to the high waveguide propagation loss, which in turn is attributed to the etching processes and stitching errors of e-beam photolithography.

7.3 Bragg Grating Reflection

The reflection experiment was performed by using an Agilent 81640A tunable laser source (TLS) (1520-1620nm) as the input optical source which was connected to a polarisation maintaining tapered lensed fibre coupled into the SOI rib waveguides. The reflected optical signals were collected via an optical circulator connected to the input tapered lensed fibre and recorded by an optical power meter module of the TLS. The detailed experimental setup was discussed in section 6.3.3 and a schematic diagram of the experiment is presented in this section again for better illustration of the experimental procedures (Figure 7-4). All the experiments were conducted using transverse electric (TE) polarisation.

![Figure 7-4: The schematic diagram layout for the evaluation of Bragg gratings reflectivity.](image)

- Laser Source
- Optical Circulator
- Lens Fibre
- Transmission Detector
- Reflection Detector
- P\textsubscript{in}
- P\textsubscript{out} = P\textsubscript{t}
- Waveguide loss
- 2x Fibre to waveguide coupling loss
- 2x Fresnel loss
- Scattering loss from gratings
7.3.1 Experimental Results

In order to obtain the reflectivity from the 3\textsuperscript{rd} order Bragg gratings, the input power range from the tunable laser source and the insertion loss of the optical circulator at the wavelength of interest needs to be investigated. Figure 7-5 (a) and (b) depict the input power range from the tapered lensed fibre (0.66 mW - 0.83 mW) and the insertion loss of the optical circulator (1.29 dB - 1.55 dB) in the region of 1540-1560 nm operating wavelength. The transmission measurement of the gratings is essential to act as a normalising factor for the evaluation of Bragg grating reflectivity. The output power provided by the transmission spectrum at non-resonance enabled the author to estimate the signal reflected by the Bragg grating at the input of tapered lensed fibre. It is assumed that the transmission spectrum includes the propagation loss of the waveguide, two fibre to waveguide coupling losses and Fresnel losses, and scattering loss from the gratings.

![Figure 7-5: Input power from tunable laser optical source connected to (a) port 1-2 optical circulator and lens tapered fibre prior coupled into the Bragg gratings SOI rib waveguides and (b) the insertion loss of Port 2-3 optical circulator.](image)

Figure 7-6 shows the transmission and reflection spectrum for 3\textsuperscript{rd} order Bragg gratings with a 1500 \textmu m grating length over the 1540-1560 nm wavelength range. The Bragg grating filter exhibits a characteristic “dip” at the transmission spectrum. The measured Bragg resonance peak wavelength was approximately at $\lambda_B = 1553$ nm with full width at half maximum (FWHM) of 3.75 nm and sidelobe suppression of 8 dB. Figure 7-7 shows another reflection spectrum of a grating filter with Bragg resonance wavelength of 1569 nm and FWHM of 3 nm. Note that both the transmission
Figure 7-6: Experimentally measured reflected power at port 3 of optical circulator and transmission power at the output of the Bragg gratings device.

Figure 7-7: Experimentally measured reflected power showing Bragg resonance wavelength at 1.553μm and 1.569μm with 2177 grating periods.
and reflection power are relatively low, in the range less than 10µW. This can be attributed to the high fibre to waveguide coupling loss to small SOI waveguides, scattering loss induced by the Bragg gratings and the waveguide sidewalls. In an attempt to explain the low detected optical signal, we present an analytical approach to estimate the losses introduced during the experiment. The overlap integral between input fibre to waveguide modes was evaluated by the beam propagation method (BPM) to calculate theoretical coupling efficiency yielding 56% for the best case scenario as discussed in section 6.3.1.1. Assuming the Fresnel reflection between the silicon and air interface is 0.3, the measured SOI waveguide propagation loss is 4.8dB/cm at TE polarisation while the input power is 0.78mW at 1553nm according to Figure 7-5. The theoretical transmitted power of 14.7µW was calculated based on the aforementioned assumption. The discrepancy between the measured transmission (average 4.5µW) and theoretical values may arise from the deviations of alignment between fibre to waveguide coupling and exclusion of grating scattering losses in the theoretical studies.

During the investigation of Bragg reflection, the majority of the Bragg gratings do not show good stability, caused by the thermal induced drifting of the piezo-electric controlled stages, leading to the misalignment between fibre and input waveguide. This can be overcome by allowing the alignment stages to stabilise for at least 5 minutes before proceeding to optimising the coupling again to repeat the measurement.

7.3.2 Comparison of Theory and Experimental Results

As stated previously, two fabrication runs were used to realise two types of Bragg gratings which differ in the location of grating implementation. The first successful fabrication run comprises Bragg gratings with a period of 0.687µm realised on top of the SOI waveguides where the deep grating etch in the region of 350-400nm extended to the slab region [7.4]. Although these devices worked optically, they did not exhibit any characteristic reflection spectra as predicted by the theoretical FBT and CMT simulations. In the second fabrication run where the successful realisation of shallow Bragg gratings measuring 200nm in depth were confined only on top of the SOI
waveguides. Some of these grating devices exhibited sufficiently good reflection spectra for comparison with theoretical prediction. In order to perform a good comparison between the theory and experimental results among those working devices, both SEM and AFM analysis were used to study the Bragg gratings surface features such as grating period and etch depth. The analysis also extended to those non-functional devices in the first fabrication run and possible corrective actions are suggested to overcome problems. The SEM analysis is performed using an FEI Quanta 200F, whereas AFM analysis was conducted using a Digital Instrument Dimension 3100, both at the Advanced Technology Institute, University of Surrey.

![SEM image of fabricated SOI rib waveguide structure with 1.36μm in height, etch depth of 0.86μm and width of 1.00μm. The top SiO₂ cladding layer is approximately 200nm from the top of the waveguide.](image)

Figure 7-8: SEM image of fabricated SOI rib waveguide structure with 1.36μm in height, etch depth of 0.86μm and width of 1.00μm. The top SiO₂ cladding layer is approximately 200nm from the top of the waveguide.

Figure 7-8 depicts the waveguide dimensions of SOI waveguides on one of the functional devices which exhibited good reflection characteristics in the second batch. The fabricated waveguide height of 1.36μm deviates from the intended design value of 1.5μm due to over etching of the guiding layer during the grating etch process. The variation of the fabricated geometry will inevitably influence the overall effective index (N_{eff}) of the waveguides, leading to the change of Bragg resonance condition. Since the waveguide dimensions were taken from the operational devices, they will be used as a reference for FBT grating modelling for comparison with experimental observations.
Chapter 7: Experiment Results and Discussion

Figure 7-9: SEM images of fabricated gratings with grating periods of 0.689μm view at 32.8 tilt angle after the top cladding SiO₂ layer was removed by buffered HF. The higher magnification image of the gratings revealed that the gratings are confined only on top of the rib waveguide.

The SiO₂ layer on top of the SOI waveguide structure featured in Figure 7-8 was subsequently stripped and removed by buffered HF in order to reveal the grating structures hidden beneath it (Figure 7-9). The thermal isolation trenches are clearly visible from the SEM which is placed approximately 6μm from the rib waveguide. There are two further close-up SEM images overlaying on the overall view of the Bragg gratings structures. The first close up image shows the top view of the grating with grating period estimated at 0.689μm and a waveguide width of 1μm. Although the waveguide width is consistent with the previous SEM analysis, the irregular and wave-like shape of the sidewall suggests the grating implementation further increases the surface roughness of the waveguide. The subsequent zoom in SEM image successfully demonstrated that the gratings are only confined on top of the small cross sectional SOI waveguides. The additional tilted inset image clearly shows the grating induced sidewall roughness which is in consistent with previous observations. Since it
Chapter 7: Experiment Results and Discussion

Figure 7-10: AFM images of 2μm scan for gratings sample in second fabrication run showed grating period of approximately (a) 0.696μm with grating etch of 190nm (b) 0.700μm gratings period with etch depth of 180nm.
is difficult to accurately determine the grating etch depth and period with SEM tools, AFM analysis was performed to further examine the Bragg grating features. Both AFM images in Figure 7-10 (a) and (b) show 2μm scans for two different Bragg grating period of 0.696μm and 0.700μm and their corresponding grating depth of 190nm and 180nm with grating duty cycles of 58% and 50%. Note that the grating depth measurement is limited by the length of the AFM tip where short probe tip is unable to reach the end of the grating “valley”, which means that high aspect ratio grating measurement cannot be accurately performed. This is further complicated by the fact that not all of the SiO₂ top cladding layer was removed, adding some uncertainties in attaining grating etch depth. This issue is clearly shown in Figure 7-10 (a) and (b) indicating the irregularity of the Bragg gratings etch depth. Figure 7-11 further demonstrates the residual SiO₂ problem by reconstruction of a 3D image of the grating using AFM data for a Bragg gratings period of 0.696μm.
As the designed and fabricated Bragg grating devices are working in 3rd order, the simulation in section 4.3.1 suggested that the maximum reflectivity achievable is much smaller than that for the 1st order grating with the same refractive index contrast, grating depth and grating length. Figure 7-12 shows the measured maximum reflectivity is 0.42 for grating length of 1500μm and grating period of approximately 0.689μm. The corresponding grating and waveguide dimensions determined in previous SEM inspections were used to simulate the spectral response by FBT with different grating duty cycles and these are presented on the same figure for comparison purposes. The calculated reflection peaks and spectral shape are relatively similar except the measured FWHM results of 3.75nm are much broader than the predicted values of 1.7nm when duty cycle of grating is 50%. The broadening of the bandwidth might be attributed to chirp and non uniformity of the fabricated gratings on the waveguides.
Chapter 7: Experiment Results and Discussion

The chirp can be defined as a non-periodic grating pitch, displaying an increase in spacing between grating planes. The simplest type of chirped grating structure is where the variation in the grating period is assumed to be linear:

\[ \Lambda(z) = \Lambda_0 + \Lambda_1 z \]  

(7.2)

where \( \Lambda_0 \) is the starting period and \( \Lambda_1 \) is the linear change along the length of the grating. Typically, the linear chirp grating is associated with chirped value per unit length, \( \Lambda_1 \) which is normally known as chirp coefficient:

\[ \Lambda(z) = \Lambda_0 + \Delta \Lambda \cdot \frac{z}{L}, \text{ where } -\frac{L}{2} \leq z \leq \frac{L}{2} \]  

(7.3)

\[ \Lambda_1 = \frac{\Delta \Lambda}{L} \]  

(7.4)

where the local period is \( \Lambda_0 \) at the center of the grating, and changes a total of \( \Delta \Lambda \) over the length of the grating, \( L \). Note that the coupling coefficient and period of the linearly chirped gratings vary along the \( z \) direction, \( k(z) \) and \( \Lambda(z) \) depending on the \( z \). We can consider such grating structure is made up of a series of smaller length
uniform Bragg gratings increasing in period. Since it is difficult to calculate and determine the chirp rate of the grating based on the fabricated gratings for numerical modelling, this is further complicated by the fact that our current FBT algorithm [7.5, 7.6] is unable to incorporate chirp gratings. However, we can demonstrate the influence of chirp grating on the reflection spectrum by comparison of a grating with chirp coefficient of 0.001 and uniform grating using CMT simulation as shown in Figure 7-13. It is clear that the gradual incremental of grating period along z-direction almost double the bandwidth from the grating without the chip effect. This might provide an explanation of the bandwidth broadening observed in the experimental results shown in Figure 7-12.

Figure 7-14: Reflection spectral response for 3rd order Bragg grating with 1500μm grating length, etch depth of 190nm and grating period of 0.696μm.

Figure 7-14 depicts the reflected spectral response for grating period of 0.696μm and grating etch depth of 190nm. The measured maximum reflectivity of 0.28 is much lower than 0.4 as predicted by FBT simulation for a grating duty cycle of 50%. If the grating duty cycle of 58% was used to estimate the spectral response in accordance with grating dimensions in AFM image of Figure 7-10 (a), the corresponding maximum reflectivity is closer to the measured results only with narrower FHWM. The influence of grating etch depth and grating period on the Bragg condition is
apparent, where grating depth induced effective index changes causing a Bragg resonance wavelength shift from 1553nm to 1569nm. The variation of Bragg resonance wavelength may also be attributed to the effect of stitching errors which is typically occurring in the fabrication of Bragg gratings by electron beam lithography. Tervo et al. [7.7] took the grating stitching errors into account for Bragg grating simulation and showed that the peak reflectance of the fundamental guided mode is shifted towards longer wavelength of approximately 0.4nm, when positive stitching error of 20nm was included in their analysis.

Figure 7-15 indicates better agreement between the FBT calculations and the measured 3rd order Bragg gratings with 50% duty cycle and approximately 0.700μm grating period according to AFM data in Figure 7-10 (b). The influence of duty cycle on the maximum reflectivity and FWHM are clearly shown in the graphs. The increment of duty cycle reduces the maximum reflectivity achievable by the gratings etch, at the same time narrowing the spectral response of the gratings. Figure 7-16 plots the calculated and measured Bragg resonance wavelength as a function of grating period variation. The Bragg resonance wavelength exhibits a linear
Chapter 7: Experiment Results and Discussion

relationship with grating period where they show excellent agreement between the calculated and measured results. It is well known that the CMT predicts that the peak reflectivity of a Bragg grating is:

\[ R_{\text{max}} = \tanh^2 (\kappa L) \]  \hspace{1cm} (7.5)

where \( L \) is the grating length and \( \kappa \) is the grating strength. Using this relationship, commercial available optical software, GratingMOD was used to predict the \( R_{\text{max}} \) from the grating depth and the known grating length.

Figure 7-16: Bragg wavelength, \( \lambda_b \) shows a linear shift as a function of grating period between simulation and measurement results, while the line is regression fit.
Figure 7-17: The maximum reflectivity as a function of the grating etch depth as calculated by Floquet-Bloch Theory and Coupled Mode Theory in comparison with experimental results.

Figure 7-17 shows the influence of grating etch depth on the peak reflectivity in comparison with FBT simulation and experimental results for grating length of 1500\textmu m. Error bars on the data are obtained by repeating the measurement of the same device for the evaluation of the peak reflectivity. The measured data agrees reasonably well with that predicted by the FBT in comparison with CMT. This result agrees with the hypothesis that, CMT technique is only suitable when grating perturbation is weak and refractive index contrast is low. A more complete range of grating etch might be needed to systematically evaluate the maximum achievable peak reflectivity which is induced by both weak and strong grating perturbation. Although the first fabrication run was intended to fabricate deep gratings (350-400nm) none of these devices exhibited any characteristic reflection spectra. Hence, the non functional devices were subjected to visual inspection to find out the failure mode and allow a recommendation to be made as to how to overcome these issues.
7.3.3 Analysis of Non-Functional Devices

As mentioned earlier, the first fabrication run is based on the implementation of Bragg gratings on top of the SOI rib waveguide and extended to slab region. It has been successfully demonstrated numerically [7.7] that grating perturbation on the slab region provides additional effective index modulation in addition from the top rib waveguide region to achieve high reflection to the gratings. In practice, gratings suffer from high scattering loss, stitching errors and grating misalignment from poor
fabrication, which prevents the reflection from the gratings being measured. These findings are consistent with those of Aalto's [7.8] where the author was unable to demonstrate successful gratings experimentally, when grating modulation was extended to the slab region. The SiO₂ top cladding layer was removed by buffered HF prior to any SEM analysis in order to avoid the charging effect from disrupting visual inspection. Figure 7-18 depicts a series of SEM images of Bragg gratings on SOI waveguides with grating misalignment. These images indicate gradual steps of misalignment slowly evolving from the one side of the slab region to the other side on the same chip. This systematic misalignment can be observed right across the wafer leading to low yield. The alignment between the 3μm wide grating patterns over relatively small waveguides appears to be more problematic than we anticipated. To address this issue, we employed dual mask grating fabrication techniques as proposed by Lim et al. [7.9] where the first etch run defines the grating features and a second etch defines the waveguide by etching away the grating on the slab region hence forming rib waveguides.

Figure 7-19: Top view of SEM images show (a)-(b) misalignment and (c)-(d) gratings implementation of 3rd order Bragg gratings on both top and slab region of SOI waveguides.
Figure 7-19 (a) and (b) show the intersection between the Bragg gratings and straight SOI waveguide at the beginning and the end of the devices. The 3µm wide gratings clearly missed the top section of the rib waveguide by approximately 1µm. This asymmetric grating implementation is further complicated by the fact that waveguide width appears to be widening to 1.5µm at the intersection which dramatically changes the polarisation and single mode conditions of the devices. Figure 7-19 (c) and (d) demonstrate the successful fabrication of Bragg gratings across the rib and slab regions. This class of devices were polished using the polishing procedure described in 6.2.1 which is more than sufficient for waveguide device measurement of 1.5µm in height. These devices exhibit transmission intensity after coupling from fibre to waveguide as shown in Figure 7-20 but not the characteristic reflection spectrum from the Bragg gratings. The output intensity of transmitted power is collected and collimated using a 40x objective lens. This objective lens was selected to image the output waveguide facet for coupling purposes prior to directing it into an infrared camera. The camera was also used to determine the confinement of light at the output waveguide. From Figure 7-20 (a) and (b), it is apparent that the optical power is confined under the rib region but higher optical intensity from either side of the slab region was also observed. This observation suggests that the effective index modulation induces high scattering comparable with the guided optical mode. The realisation of Bragg gratings confined to the top of the rib waveguides for effective index modulation enable minimisation of the scattering induced by the grating on the slab region and waveguide sidewalls.

Figure 7-20: Output power intensity of Bragg gratings which extended to slab region recorded by an infrared camera.
Figure 7-21: SEM images of (a)-(c) silicon pillars forming at the region of gratings on both sides of the slab region where (d) 0.3μm width SOI rib waveguide instead of designed value of 1μm.

Figure 7-21 (a)-(c) show SEM images, suggesting potential contamination of the mask when forming gratings at the slab region. The samples were cleaved at the grating region to clearly illustrate the issue. This may be attributed to the residual mask in the grating patterns left during the silicon etch to define the rib waveguides structure which causes micro-mask formation leading to growth of vertical silicon pillars. The SiO₂ layer of these samples was stripped and cleaned prior SEM visual inspection. A close up view of image at Figure 7-21(c) confirmed the forming of silicon pillars. Figure 7-21 (d) depicts narrowing waveguide width from the designed value of 1μm suggesting that the photoresist is not sufficiently thick to prevent erosion leading to under etching and the reduction of waveguide dimensions.
7.4 Characterisation of Aluminum Heater

In this section, characteristics of the aluminum thin film heater deposited on top of the PECVD SiO₂ top cladding layer, using electrical current/voltage (I/V) analysis is discussed. The temperature of the heater via Joule heating will be approximated using the linear temperature coefficient resistance of the material, which in turn will determine the maximum current sustainable by the heater for thermo-optic tuning of the Bragg grating filters. Whilst some heaters were successful, others failed. The failure analysis of such heaters will be presented in section 7.4.3.

7.4.1 Measured I/V and Simulated Results

The analysis of the aluminium electrical current/voltage characteristic (I/V) is performed by sweeping ±1V whilst measuring current in the heater. Figure 7-22 shows a number of fabricated aluminum heaters, where one of the contact pads is connected to adjacent heater to form a common ground. The I/V measurement is carried out and repeated 5 times for each heater length to ensure the contact probes landed on the two 200μm² contact pads does not add significant contact resistance to the measurement.

Figure 7-22: Top view SEM shows the fabricated aluminium heater of 600μm and 1100μm in length where the common ground is connected to the adjacent heater contact pads.
Figure 7-23 shows the I/V plots for both heater lengths of 2100μm and 2600μm yielding resistance values of 115.4Ω and 141.1Ω upon linear curve fitting. The same approach is repeated for all other heaters across the devices. The SEM analysis of the aluminum heater is essential to determine heater geometry for comparison of theoretical resistance calculation and experimental observations. The well known relationship between a conductor resistance and dimensions can be expressed by:

\[ R = \frac{\rho L}{Wt} \]  

(7.6)

where \( \rho \) is the conductor resistivity, \( L \) is the length, \( W \) is the width and \( t \) is the thickness of the conductor. Since the resistivity of aluminum varies with temperature, it is taken as \( 2.65 \times 10^{-2} \)Ω·μm [7.10] at an ambient temperature of 20°C for the resistance calculation. From Figure 7-24, the SEM displays the cross sectional area of a cleaved SOI waveguide with a heater thickness of 500nm. Furthermore, it can be seen from Figure 7-25 that the heater width, measuring 1.1μm is displaced approximately 1.0μm from the top of the Bragg gratings. This heater fabrication misalignment will cause a higher power requirement to raise the temperature in the grating filters.
Figure 7-24: SEM cross sectional area showing the thickness and displacement of the heater from the center of the rib waveguides.

Figure 7-25: SEM image of aluminium heater tilted at 32.8° showing heater width of 1.1μm and its displacement of 1μm from the top of the Bragg gratings. The surface roughness of the aluminium heater are clearly visible on top of the heater surface.
Figure 7-26: Comparison of Aluminium heater resistance calculation with I-V characterisation of various heater length. The calculation of aluminium resistivity is based on $\rho = 2.65 \times 10^{-5} \Omega \cdot \mu m$, at 20°C, heater width of 1.1μm and 500nm in thickness.

This inevitably will have an impact on thermo-optic tuning performance of the grating filters which will be the subject of discussion in section 7.5. The surfaces of the aluminium heaters are not smooth, as is clearly visible in Figure 7-25. The plots for both the modelled and experimental results of aluminium heater resistance for heater length ranged from 31.5Ω to 205.2 Ω for 600μm to 3600μm are shown respectively in Figure 7-26. Both plots exhibit a linear relationship between the heater resistance value and heater length as predicted by equation (7.6) and close agreement with slight differences. The discrepancy is possibly due to the nonuniformity of the thickness of the heater and the forming of contact resistance between the probes and contact pads during the I/V measurement.

### 7.4.2 Temperature Dependent Resistance

The heater resistance varies with temperature during the Joule heating process. It is desirable to make accurate measurements of the heater temperatures to evaluate the performance of the heater. This can either be achieved by non contact measurement (thermal imaging) or with a thermocouple in contact with the heater to be tested. Alternatively, we can approximate heater temperature by measuring the heater voltage.
and current, and hence determine its resistance during normal operation. The temperature influence on the resistivity of the aluminium can be expressed as:

\[ \rho = \rho_0 (1 + \alpha (T - T_0)) \]  

(7.7)

where \( \alpha \) is the thermal coefficient of resistivity which can be estimated to \( 4.3 \times 10^{-3} \)\(^{\circ}\)C according to data extracted from [7.10]. Hence, the temperature dependent resistance of the heater can be determined by:

\[ R = R_o (1 + \alpha (T - T_o)) \]  

(7.8)

where \( R_o \) is the resistance value at ambient temperature. The evaluation of heater temperature influence on resistance can be devised by the simple setup shown in Figure 7-27. The DC voltage source is supplied by Wier Instrument power supply (30V) which has maximum current limit of 1A and internal resistance value of 1.8kΩ.

For each heater length, the corresponding resistance value at ambient temperature is recorded prior to connection to the power supply unit. One should note that since the internal resistance of the power supply is in parallel with the measured heater resistance, the heater resistance at a specific temperature has to be evaluated as:
The heater temperature can be obtained by solving equation (7.8). Figure 7-28 shows the comparison between the measurement and theoretical calculation of the temperature of the thin film heater with $L = 3100\mu m$, heater width, $W_h = 1.1\mu m$ and thickness of $0.5\mu m$. Both plots exhibit a linear relationship and agree relatively well. The maximum achievable heater temperature is basically limited by the sustainable heater current without causing device failure by electromigration.

\[
R_{heater} = \frac{R_{source}R_{measured}}{R_{source} - R_{measured}}
\]  

(7.9)

Figure 7-28: The reference graph to determine the temperature of the aluminium heater based on the measurement of heater voltage and current in comparison with resistance computation derived from temperature dependent aluminium resistivity [7.10].

### 7.4.3 Electromigration of Aluminium Heater

Destructive measurements to evaluate the maximum current sustainable by the thin film aluminium heaters are carried out by gradual increment of the heater current until the structure failed. This deliberate destructive approach is necessary to determine the lifetime of the heater during high current operating conditions. The heater is driven by a direct voltage source as described in section 7.4.2. At each increment of heater voltage, we must allow heater current and temperature to stabilise before recording its
respective values. Comparison of the required drive current and its respective maximum current, $I_{\text{max}}$ for various heater lengths are illustrated in Figure 7-29 which ranged from 50mA to 60mA. At these high operating current regions, the heaters can only sustain average operation of 5 minutes before the heater current gradually reduces and fails. Therefore, in order to maintain the integrity of the heater, the supply current has to be kept to less than 50mA to prolong the operational lifetime of the heater during thermo-optic tuning of the Bragg gratings filter.

![Figure 7-29: The maximum attainable heater temperature and their corresponding heater current for various heater length.](image)

It can be seen from Figure 7-29 that the heater with longer length tends to have higher maximum achievable heater temperatures. For instance, maximum heater temperature of 180°C for 3600μm compared with 80°C for 1100μm. This observation is consistent with equation (7.6) where resistance is directly proportional to heater length. In order to test the failure mechanism, a 2100μm aluminium heater was exposed to 60mA continuously until the device failed on detection of open circuit. Figure 7-30 and Figure 7-31 show SEM pictures of the heater after being subjected to high current exposure in which signs of visible deterioration and deformation of heater are apparent.
Chapter 7: Experiment Results and Discussion

Figure 7-30: SEM top view of failed aluminium heater ($L = 2100\,\mu m$) results from electronmigration after exposed the 500nm thick heater to 60mA for 5 minutes.

Figure 7-31: SEM side view of showing a failed aluminium heater due to voids forming by electromigration at high operating current.
From Figure 7-30, there are visible signs of surface deterioration indicated by the higher contrast circular "holes" at the lower region of the voids where the open circuit of the heater occurs. This is caused by electromigration which is normally defined as the flow of electrons at high current causing mass transport resulting from the momentum transfer between the conducting electrons and lattice atoms. Aluminium thin films are characterised by small grains which offer high diffusivity grain boundary paths, making mass transport easier along these paths. This mass transport can lead to void growth where a depletion of atoms occurs.

The heater failure results from growth of voids over the heater line width that in turn causes breaking of the line as illustrated in Figure 7-31. Another region in the contact pads that might cause the potential failure of the heater is shown in Figure 7-32, where the deposition of the aluminium contact pads during the metallization process over the PECVD SiO₂ filled thermal isolation trenches is associated with the thinnest region across the contacts. Localised Joule heating and the highest rate of migration usually occurs at the thinnest part of the heater, which potentially leads to the failure of the contact pads.

![Image](image_url)

**Figure 7-32:** Top view of SEM shows the deposition of an aluminium contact pad over the isolation trench. The grain boundaries of the polycrystalline aluminium are also highly visible.
Chapter 7: Experiment Results and Discussion

The flow chart in Figure 7-33 shows the electromigration process caused by grain boundaries in polycrystalline aluminium. When the voids are formed, it causes the current density to increase in the vicinity around the void because it effectively reduces the cross sectional area of the heater. Since Joule heating is proportional to the square of current density, this leads to a local temperature rise around the void that in turn further accelerates the void growth. The whole process continues until the void is large enough to break the heater. It has been demonstrated by Ames et al. [7.12] that doping 4% copper to aluminium results in a decrease of aluminium diffusivity and thus increased resistance to electromigration.

![Flow chart showing electromigration process](Image)

Figure 7-33: Joule heating induces electromigration process at high operating current.

### 7.5 Thermo-Optic Tuning of Bragg Grating Filter

Silicon based optical tunable devices such as modulators, switches and filters operating at a wavelength of 1.55μm are key components to realise silicon CMOS compatible optoelectronics circuits for wavelength division multiplexing networks. Since crystalline silicon does not exhibit a linear electro-optic effect, silicon active devices use either the thermo-optic effect [7.20-7.22] or free carrier plasma dispersion effect [7.23] to change the refractive index of silicon and to produce phase modulation. In this section, we report on the characterisation of a 1500μm long thermo-optic tunable Bragg grating filter on SOI waveguides.

A Bragg grating in a small cross sectional area SOI waveguide has been realised with the surface grating etched to a depth of 220nm on top of the waveguides and covered
with a SiO₂ top cladding layer. The Bragg grating will reflect resonance wavelengths, \( \lambda_B \), that satisfy the Bragg condition:

\[
\lambda_B = \frac{2N_{\text{eff}}\Lambda}{m}
\]  

(7.10)

where \( N_{\text{eff}} \) is the effective index of the waveguide structure, \( \Lambda \) is the period of the grating and \( m \) is an integer representing the order of grating. Silicon inherently has a very high thermo-optic coefficient of \( \frac{dn}{dT} = 1.86 \times 10^{-4} \text{ / K} \) [7.14] at \( \lambda = 1.55 \mu\text{m} \) compared with other commonly used semiconductors and optical materials [7.15]. By utilising the thermo-optic effect in the Bragg grating structure, this will cause effective index changes as a result of temperature rises in the silicon guiding layer, SiO₂ top cladding and BOX layer in an SOI structure. As a result, the thermo-optic effect will induce changes in Bragg resonance condition and hence realisation of wavelength tuning in Bragg grating filters.

![Bragg resonance wavelength as a function of applied heater voltages.](image)

**Figure 7-34:** Bragg resonance wavelength as a function of applied heater voltages.

The Bragg gratings sensitivity to temperature changes is investigated by introducing Joule heating of the integrated aluminium heater deposited on top of the Bragg gratings as discussed in the experimental setup of section 6.3.5. The maximum
sustainable current for the integrated heaters of 1100µm in length are studied (Figure 7-29). From the graph, $I_{\text{max}}$ is 60mA for heater length of 1100µm, this corresponds to heater voltage of 4.7V. However, the applied heater voltage was kept at 4V in order to prevent it from being damaged by electromigration. Prior to any introduction of heating to the Bragg gratings, a wavelength sweep was performed for use as a reference to determine the relative wavelength shift due to the thermo-optic effect. A single wavelength sweep process usually takes 20 minutes (10pm scanning step size) to complete; this will allow sufficient time for the heater temperature to stabilise before increasing heater voltages. Figure 7-34 depicts the experimental data for applied heater voltages as a function of Bragg resonance wavelength shift. The non linearity in the relationship is apparent after the data were fitted using a second order polynomial fit. This can be explained by the fact that the silicon Bragg gratings also experienced thermal expansion which can be expressed by [7.17]:

$$\frac{d\lambda}{dT} = \frac{2}{m} \left( \Lambda \frac{dN_{\text{eff}}}{dT} + N_{\text{eff}} \frac{d\Lambda}{dT} \right)$$  \hspace{1cm} (7.11)

The second term in the equation corresponds to the thermal expansion of grating periods which contributes to additional wavelength shift. This effect may become dominant when the applied temperature changes become larger. It is convenient to display the corresponding wavelength spectral response as a result of supplied heater voltage to the Bragg grating filter. Figure 7-35 show the transmission spectral response of the Bragg gratings filter as a function of heater voltage. It can be seen that the Bragg grating exhibits thermo-optic tuning capabilities where a maximum wavelength shift of 3.5nm can be achieved at a heater voltage of 3.55V. The tuning range of the filter essentially is limited by the maximum sustainable current of the aluminium heater. Tuning range should improve with better quality of heater material such as nichrome [7.13] which has a higher melting point of 1500°C and resistivity of $107.5 \times 10^{-8} \Omega \text{m}$ [7.10] compared with 660°C and $2.65 \times 10^{-8} \Omega \text{m}$ [7.10] for aluminium. In addition, driving the heater beyond the limit of the allowable current will deteriorate heater lifetime which in turn inflicts permanent damage to the heater by enhancing the growth of voids. This phenomenon is consistent with the destructive measurement observation of the aluminium heater reported earlier in section 7.4.3.
Chapter 7: Experiment Results and Discussion

Figure 7-35: Bragg gratings filter transmission spectral response for different heater voltages with 1450 periods and grating period of 0.688μm.

Figure 7-36: The shift of Bragg resonance wavelength as a function of heater temperature and driving power for Bragg grating length of 1000μm and 0.688μm grating periods.
The relationship between the resonant wavelength shift and heater driving power is depicted in Figure 7-36. Their corresponding heater temperatures are also plotted at the same graph in order to determine wavelength shift as a function of heater temperature. The temperature of the heater is predicted by measuring the resistance of the heater during thermo-optic tuning. This assumes that the electrical power fed into the aluminium heaters is fully converted to Joule heating. It can be seen that the heater power consumption is approximately 190mW for the highest resonance wavelength shift of 3.5nm with heater temperature of 120°C±5°C. When a linear dependency is assumed between the wavelength shift and driving power, the slope of 18pm/mW can be evaluated from Figure 7-36. Using the same assumption, the tunability of the Bragg gratings can be derived as 34pm/°C change of temperature in the heater.

Figure 7-37: Temperature distribution and heat flux at heater temperature of 50°C for top SiO₂ cladding thickness of (a)10nm and (b)100nm.
It is interesting to investigate the dependence of the change in effective index with the applied heater temperature \( \frac{dN_{eff}}{dT} \), which provides an indication of relative contribution of thermo-optic effect to the wavelength tuning. It has been suggested by Barrios et al. [7.21] that this dependence can be estimated either from the change in effective index as a function of the dissipated power or temperature change for a given drive power. The author used the former approach and the combination of a one dimensional heat transfer approximation and BPM to predict a linear dependency of \( 8.7 \times 10^{-5} \) K\(^{-1}\). They argued that the smaller value of the dependence compared with the bulk silicon thermo-optic coefficient of \( 1.86 \times 10^{-4} \) K\(^{-1}\) is attributed to the existence of free carrier dispersion effect which opposes the thermo-optic effect.

![Graph showing the dependence of the change in effective index with temperature for various thicknesses of top SiO\(_2\) cladding.](image)

Figure 7.38: The dependence of the change in effective index with temperature for various thicknesses of top SiO\(_2\) cladding.

Following the approach of Passaro et al. [7.22], we predict the dependency of the change in effective index with temperature by performing a series of heat transfer simulation in the SOI rib waveguides with a 2D finite element method [7.24] and compare the simulation with experimental results. This method is significantly
different from other approaches in the literature [7.14, 7.15] where bulk thermo-optic coefficient is usually considered. The schematic diagram for the simulation of the waveguide cross section is depicted in Figure 7-37, where thermal isolation trenches are implemented on each side of the slab region to improve thermal confinement. The modelled SOI waveguide dimensions are \( H = 1.5 \mu m \), \( W = 1.1 \mu m \) and \( D = 0.9 \mu m \). The aluminium heater width of 1.1 \( \mu m \) and 0.5 \( \mu m \) in thickness are modelled in accordance with the heater dimensions shown by SEM images in Figure 7-24 and Figure 7-25. Both Figure 7-37 (a) and (b) show the temperature distribution and heat flux (thermal power per unit area) in the SOI rib waveguides when subjected to heater temperature of 50°C with top cladding SiO\(_2\) layer thickness of 10nm and 100nm. Not surprisingly the heat transfer from the aluminium heater to the waveguide is more efficient with the thinnest SiO\(_2\) layer. This waveguide structure with 10nm top SiO\(_2\) cladding layer will serve as a reference point when comparing with the bulk thermo-optic coefficient of silicon. We consider convection and radiation to ambient air to be negligible to the overall heat transfer process. The thermal properties (thermal conductivity and specific heat) of the material are assumed to be constant over the temperature range of interest (20°C - 200°C) and it is assumed that the heat flux is evenly distributed on the top surface of the heater. Under these conditions, it has been found that the dependence of \( \frac{dN_{eff}}{dT} \) for 10nm SiO\(_2\) top cladding thickness yields 1.7283 \( \times 10^{-4} \) K\(^{-1}\) as indicated in the legends of the graphs in Figure 7-38. In comparison to [7.21], our approach yields the thermo-optic coefficient value significantly closer to the bulk silicon of 1.86 \( \times 10^{-4} \) K\(^{-1}\)[7.14]. This observation enables the simulation of thermo-optic coefficient to proceed with confidence.

For the purpose of comparison between theoretical simulation and experimental results, we extracted the data of Bragg resonance wavelength for each of their corresponding approximate heater temperatures in Figure 7-36 and the change of effective index can be expressed by [7.21]:

\[
\Delta n_{eff} = N_{eff} \frac{\Delta \lambda}{\lambda_n} \tag{7.12}
\]
where $\Delta \lambda$ is the wavelength shift and $N_{\text{eff}} = 3.3814$ is the effective index of the fundamental TE-like mode and $\lambda_0 = 1550.93\text{nm}$. In Figure 7-38, we also evaluated the dependence of the effective index changes to temperature for different top SiO$_2$ cladding thickness of 10nm, 200nm, 400nm and 1$\mu$m by solving the slope of their respective plots. The results show that the experimental data yields the value of 7.57$x10^{-5}$ K$^{-1}$ which is in close agreement with FEM simulation prediction of 7.19$x10^{-5}$ K$^{-1}$ for 200nm SiO$_2$ top cladding layer. We consider the slight difference is attributed to the misalignment of the aluminium heaters as indicated by SEM analysis in Figure 7-25 and variation of SiO$_2$ thickness in the fabrication. Furthermore, it is very difficult to determine the actual heater temperature and the heat flux may not be uniformly distributed across the heater. Although it is desirable to reduce the thickness of the top cladding layer between the heater and rib waveguides for efficient joule heating, the optimum thickness has to be accomplished without causing any optical attenuation. This can be achieved by modelling a series of optical intensity mode profile plots for various SiO$_2$ thicknesses in TE and TM polarisation for a particular waveguide structure whilst observing the evanescent field extension between the interface of silicon and SiO$_2$.

### 7.6 Summary

In this chapter, we have demonstrated the potential of thermo-optic tuning of 3$^\text{rd}$ order Bragg grating filters fabricated in small cross sectional SOI waveguide. The propagation loss of SOI rib waveguides was investigated using Fabry-Perot resonance method yielding 4.8dB/cm. The sidewall roughness of the waveguide from the etching process becomes a dominant factor when waveguide dimensions were miniaturised in the region less than 1.5$\mu$m.

The measured reflection spectral responses for 3$^\text{rd}$ order Bragg gratings on SOI rib waveguide with gratings period in the region of 0.689$\mu$m exhibit maximum peak reflectivity of 0.42 with 8dB sidelobe suppression. The waveguides and gratings features taken from SEM and AFM analysis were then used to model the reflection response of the Bragg gratings. The maximum peak reflectivity attainable by variation of grating etch depth on the 3$^\text{rd}$ order Bragg gratings with grating length of 1500$\mu$m.
indicates relatively good agreement with the prediction of Floquet-Bloch Theory, when the depth of periodic corrugation of the grating induces strong perturbation. However, these results also suggested that the variation of duty cycle in the gratings has a significant impact on broadening the spectral response and changing the Bragg conditions of the grating, leading to the shift of Bragg resonance wavelength. SEM analysis was performed to investigate potential failure mode of the first fabrication run for deeply etch gratings. The implementation of Bragg gratings extended on both sides of the slab region does not exhibit the characteristic reflection spectral because it induces high scattering and possibly higher order modes in the devices. Hence, a dual mask fabrication approach is used to realise the gratings effective index modulation which is confined to the top rib region.

Finally, a systematic analysis was conducted to study the characteristics of the integrated thin film aluminium heater on top of the Bragg gratings which were used for thermal-optic tuning of the devices via joule heating. The temperature tuning capabilities of 3rd order Bragg gratings filter on SOI rib waveguide have been investigated. The Bragg resonance wavelength of the 1000μm in length gratings was thermally shifted to 3.5nm with heater power approximately 190mW. When a linear dependency is assumed, the tunability of the grating filter yields 34pm/°C. The tuning range of the filter can be improved using an alternative heater material (chromium and nichrome) which can withstand higher operating current with high material resistivity. The influence of the SiO2 top cladding thickness on thermo-optic tuning sensitivity of the filter was performed. A 2D FEM heat transfer model was used in comparison with experimental results. The observation of the simulation results was consistent with experimental observations.
References:


Chapter 7: Experiment Results and Discussion


7.10 CRC Handbook of Chemistry and Physics, 85th Edition, Section 12, Electrical resistivity of pure metals.


Chapter 7: Experiment Results and Discussion


Chapter 8

Believe in the light while there is still time; then you will become children of the light.

John 12:36

8 Summary, Conclusion and Future Work

8.1 Introduction

The purpose of this chapter is to review and draw conclusions from the work presented in this thesis and to suggest areas for future work.

8.2 Summary and Conclusion

The objective of this work presented in this thesis was to design, fabricate and characterise third order diffraction Bragg grating filters on small cross sectional silicon-on-insulator (SOI) rib waveguides. We have also demonstrated the thermo-optic tuning potential by shifting the Bragg resonance wavelength using an integrated aluminium heater deposited on top of the rib waveguide, separated by a thin layer of SiO₂ cladding. The comprehensive device designs studied in this work will enable researchers to extend their knowledge about the device optical performance with variation of waveguide geometries. More importantly, there is a potential for improving the heating efficiency of the thermo-optic filter and configuring it as a thermo-optic switch.

New design guidelines have been proposed for the design of small cross sectional SOI waveguides. As the trend of miniaturisation of waveguide dimensions is getting stronger in submicrometer scale, the commonly used design rules for large cross sectional SOI waveguides are no longer sufficient to address the polarisation independence and single mode condition issues. We have analysed a range of deeply etched SOI rib waveguides with small cross sectional dimensions using the full-vectorial beam propagation method (BPM) simulation to provide theoretical
predictions that certain waveguide geometries can lead to single-mode and polarisation independence simultaneously. In particular, the validity of the single-mode theory for very deeply etched ribs with waveguide heights less than a few micrometres have been considered. According to the simulation, the single-mode boundary is totally different for quasi-TE and quasi-TM modes when small cross section SOI waveguides are considered. The results also imply that the single mode condition for small waveguides with deep etch depth \( r < 0.5 \), is effectively limited by the boundary condition set by the quasi-TM mode. Separate simulations carried out using the full-vectorial BPM approach and finite element method (FEM), both showed good consistency for the polarisation results. The independent verification using two methods confirms the accuracy of the simulation. It has been shown that the waveguide etch depth is one of the critical waveguide parameters which has a significant impact on the waveguide birefringence. Hence, high waveguide etching tolerance with good reproducibility on the designed waveguide geometry is vital to satisfy zero birefringence. In practice, the birefringence caused by slight waveguide over etching can be compensated by tailoring the thickness of the SiO\(_2\) layer grown on top of the waveguide, to utilise the stress induced birefringence to counter balance the effect. The trends noted in the scaling of SOI waveguide dimensions can help in the study of other silicon photonic components such as modulators, ring resonators, tapers and couplers.

Having determined the waveguide dimensions of a rib SOI waveguide from the point of view of single mode and polarisation independence, the work then focused on modelling of deeply etched Bragg gratings on the waveguide. It is well known that in low index contrast technologies, gratings can be accurately modelled by Coupled Mode Theory (CMT) assuming that the interacting modes are mutual orthogonal. This treatment of the interacting modes provides accurate results when the periodic perturbation is weak. On the contrary, the CMT approach will be less accurate if the grating perturbation is strong and/or one of the modes is leaky and not well confined. In this work, we have established both theoretically and experimentally that the Floquet-Bloch Theory (FBT) is an effective analysis technique for the design and simulation of deeply etched Bragg gratings in SOI waveguides. The influence of a range of parameters on grating performance was examined, including grating depth, duty cycle and grating period. Deeper gratings increase the maximum achievable
reflectivity with the same grating length. The higher values of the duty cycle can also improve the full width half maximum of the filter. Therefore, these parameters can be used to determine the optimum filter response required by the designer.

Two fabrication runs were conducted in the realisation of the third order diffraction grating on SOI waveguide. The first run fabricated the design for gratings covering the top of the rib waveguide and extended to the slab region to provide further refractive index modulation. Unfortunately, the grating filters in this batch did not exhibit any characteristic reflection spectra. SEM and AFM techniques were used to investigate and check for possible fault incurred during the fabrication. The optical filters were found to exhibit grating misalignment and waveguide geometry variation across the wafer. Another useful result that arose from this work is the knowledge that the implementation of grating extended to the slab region has caused significant scattering loss to the devices which adversely affects the grating reflection spectrum. As a result of the observation, a dual mask fabrication technique was used to confine the grating on top of the rib waveguide to minimise the contribution of scattering losses. Hence, surface gratings are preferable from a scattering loss perspective.

Chapter 7 provided discussion of the experimental results obtained in this work. The measured results were compared with the modelling results. The Bragg grating filters with variation of etch depth range from 180nm to 220nm exhibited a reflection spectral response in close agreement with theoretical prediction by FBT. The maximum reflectivity achievable by the 1500μm gratings length is approximately 0.42 with 8dB sidelobe suppression. The maximum reflectivity of devices is probably limited by scattering loss attributed by waveguide sidewall and deeply etched gratings. The reflection bandwidth appears to be slightly broader in comparison with simulation, which may be caused by the variation of grating period and chirp in the gratings, which gradually changes the resonant wavelength along the grating length. The effect of chirp on the reflection spectrum has been predicted by numerical simulation suggesting the bandwidth of the filter increases compared to uniform gratings. Whilst offering a possible explanation for the broadening of the grating reflection spectrum, this hypotheses need to be further investigated to confirm the effect.
By utilising the inherently high thermo-optic coefficient of silicon, the Bragg resonance wavelength of the filter was dynamically tuned by an integrated aluminium heater situated on top of the gratings. The SOI Bragg grating filter exhibits a tuning range of 3.5nm with driving power of 190mW. The Bragg resonance wavelength of the filter was shifted by 34pm for every 1°C change of the heater temperature. To the best of the author’s knowledge, this is the first demonstration of thermo-optic tuning via an integrated heater for third order diffraction grating filters with small cross section SOI waveguides. Since the tuning range of the filter was limited by the lifetime of the aluminium heater, different material and heater thickness may improve the filter performance.

Whilst taking thermo-optic tuning measurements, the thermally induced movement of the device when being driven with electrical current affects the coupling between the fibre and waveguide. This is thought to be due to the linear thermal expansion of the devices due to high surface temperatures at the heater and around the contact probe tips. This means that coupling has to be re-optimised for every increment of the heater driving voltage, leading to higher time consumption for the measurement. This is further complicated by the fact that in this work, the yield of the working grating filter was low and the heater on the grating might fail during the measurement. Another useful result that arose from this work is the knowledge that the linear thermal expansion of grating period in silicon may contribute to the resonant wavelength shifting of the filter during thermo-optic modulation.

The influence of the heater temperature on effective index changes in the device was evaluated by 2D FEM heat transfer modelling and compares the reference model to the experimental results. The reference model is constructed of an SOI rib waveguide with an extremely thin layer of 10nm SiO₂ situated between the heater and the top of the waveguide. Subsequently, this reference model was checked against the bulk thermo-optic coefficient (TOC) of silicon, yielding the value of 1.73×10⁻⁴ K⁻¹ which is relatively in close to 1.86×10⁻⁴ K⁻¹ for silicon. Not surprisingly, the thinner layer of top SiO₂ cladding layer improves the thermal distribution and efficiency of the device. However, it is important to note that the optimum top cladding layer thickness needs
to be determined without causing adverse degradation to the optical power due to the metal heater situated on top of the rib waveguide structure.

Another significant result in this 2-D thermo-optic simulation, was that this approach tends to confirm that the simulation provides a high degree of accuracy in the prediction of temperature sensitivity of the device which is vital for the optimisation of heater and waveguide structures to improve the thermo-optic tuning efficiency and performance. The measured Bragg resonance shifting as a result of the thermo-optic tuning agrees well with theoretical prediction based upon FEM heat transfer analysis. Therefore, these devices could find application in tunable filters and switches where dynamic reconfiguration and routing of wavelengths are highly desirable in optical networking system.

We have successfully demonstrated third order diffraction Bragg gratings on SOI wavelength tunable filter based on thermo-optic effect. The modelling techniques used in this work, were in good agreement with experimental results. This work could be used for further thermo-optic optimisation which could be useful for future development of fast and low cost SOI filters in coarse wavelength division multiplexing (CWDM) networking systems.

8.3 Future Work

Recently, some of the challenges facing silicon photonics, such as the realisation of viable optical light sources and fast modulators have been addressed with the experimental demonstration of the respective devices. Despite the milestone achievements, the technology has yet to show the true integration with other silicon based optical components such as filters, coupler and array waveguide gratings. This thesis provides foundation studies of small cross sectional SOI waveguide upon which the thermo-optic tunable filter was built, leading to realisation of a dynamic wavelength selective filter which is compatible with conventional silicon based fabrication processes. The suggestions for future work may lead to greater understanding and advancement in miniaturisation of the device dimensions.
The new design rules for small cross sectional SOI waveguides need further experimental characterisation in terms of their respective propagation loss, single mode condition and polarisation independence in relation to their different waveguide geometry variation. This will provide additional support to the hypothesis that certain submicrometer rib dimensions can lead to single mode and polarisation independent SOI waveguides. By controlling the top cladding deposition conditions of SiO₂ on the waveguide, the stress induced birefringence can be used to counter balance the birefringence due to waveguide fabrication variation.

The contribution of the scattering loss of the gratings in relation to the etch depth must be studied and characterised since it becomes significant in submicrometer devices. A series of Bragg gratings with etch depth ranging from shallow to fully etched gratings will enable further comparison of theoretical studies with experimental results. New fabrication techniques for rapid prototyping of these devices will be fully realised with application of nanoimprint lithography (NIL) [8.1, 8.2]. This is a less costly alternative to common lithography techniques, which involves physically imprinting a resist on a substrate and subsequently creating features following an etching step as shown in Figure 8-1.

A three dimensional bi-directional beam propagation method [8.3] capable of simulating highly reflective structures and resonance cavities such as deeply etched
Bragg gratings and Fabry-Perot structures may be useful to aid the design and optimisation of the devices.

The application of anti-reflection coatings will minimise the reflection between the input fibre/gratings and the facet of the waveguide and the noise floor of the grating reflection measurement compared to time consuming angled polishing techniques. A straight waveguide should be place adjacent to each grating device in order to improve characterisation of the propagation loss and provide power normalisation against with the grating filters.

![Figure 8-2: Proposed new heater structures providing redundancy of series resistor.](image)

Alternative heater materials such as nichrome and chromium are suggested in order to improve the life time of the heater while providing high resistivity for Joule heating. Introducing a different pattern on the heater as shown in Figure 8-2 will enable redundancy of the heating element to be provided in case of failure.

The usage of infrared thermal imaging tools may be useful to determine the actual heater temperature through non contact temperature measurement. The heat patterns on the heater are very difficult to predict, this means that it is not always possible to know where to attach the thermocouples necessary to make accurate measurements and effectively evaluate heat dissipation. Furthermore, since the thermocouple needs
to be in contact with the component to be tested, it can influence the results of the measurement.

![Figure 8-3: Add/drop filter based on Mach-Zehnder interferometer with Bragg gratings.](image)

The device demonstrated in the present work could be used to realise a fully integrated add/drop filter [8.4] using Mach-Zehnder interferometer (MZI) with Bragg gratings placed on both of its arms as shown in Figure 8-3. In this device geometry, multiple wavelengths input into Terminal 1 will be equally split into the two arms with identical gratings. One of the wavelengths is the Bragg wavelength of the grating and is reflected back, while the rest of the wavelengths pass through. The reflected signals from both arms combine and emerge from Terminal 2 as a dropped wavelength while the pass through signals combine and emerge from Terminal 3. The tuning mechanism could be added to the MZI to offer dynamic wavelength selectivity using either thermo-optic effect or free carrier dispersion current injection to modulate the refractive index of the silicon waveguide.

For future study, different grating configurations (cascading two gratings), higher order diffraction gratings and grating profiles [8.5] should be investigated in SOI rib waveguides structures.
Chapter 8: Summary, Conclusion and Future Work

References:


8.3 FIMMPROP by Photon Design (Europe) Ltd, http://www.photond.com
