Optical Ring Resonators in Silicon-On-Insulator

William Robert Headley III

Submitted for the Degree of Doctor of Philosophy from the University of Surrey

UniS

Advanced Technology Institute
School of Electronics and Physical Sciences
University of Surrey
Guildford, Surrey GU2 5XH, UK

November 2005

© W. R. Headley 2005
Abstract

The aim of this thesis is to report the results of an investigation into the design and fabrication of a polarisation independent optical ring resonator in the silicon-on-insulator material system. By separating the resonator into its fundamental components and investigating each one in terms of its polarisation properties, it is hypothesized that a ring resonator can be constructed that functions as desired regardless of the input polarisation state. Two test chips were therefore fabricated which are based on experiments designed to validate this hypothesis.

A polarisation independent ring resonator has been realised on the first designed test chip which has a TE/TM resonance minimum alignment of better than 5pm, a Finesse of ~ 11 for both polarisations, and a calculated Q value of ~95,000. A second test chip was fabricated to quantify improvements to the first test chip. It yielded a resonator with a Finesse of 28 and a Q value of ~170,000.

Several other effects critical to the functionality of a polarisation independent resonator were also observed on devices from the second test chip. Polarisation conversion, with values as high as 45%, was observed on deep-etched bent waveguides with a bend radius of 100µm. Evidence of higher order modes as well as coupling outside the defined coupling were observed in the experimental results of a directional coupler experiment. Secondary resonance minima were observed in the resonator devices. It is likely that either higher-order modes or polarisation conversion are the cause.

Overall, the results of this work imply that the method of designing a polarisation independent racetrack resonator is valid. However, improvements are required in the accuracy of the modelling tools to properly design a polarisation independent device as well as explain unexpected results such as polarisation conversion.
Key Words: Silicon Photonics, Silicon-on-Insulator (SOI), racetrack resonator, ring resonator, directional coupler, rib waveguide, waveguide bend, polarisation independence, polarisation conversion
Dedication

I dedicate this thesis to Dr. Mario Paniccia. Through his selfless efforts, he provided an ordinary guy with an extraordinary opportunity. His friendship and guidance through the years have been a blessing. This chance to study abroad has enriched my life greatly, both academically and personally. For all of this I am eternally grateful.
Acknowledgements

I am grateful for the funding of this project which was provided by the Intel Corporation. I also wish to thank the Intel employees who have assisted in this project. I would like to thank: Mario Paniccia for overseeing the project, Ansheng Liu for his efforts in getting the project off the ground and for having the answer when I had a question, Drew Alduino and Jeffrey Tseng for their work in the sample preparation of the die, Dani Hak and Oded Cohen for their efforts in the fabrication of the test chips, Duc Tran for drawing the first test chip mask and his assistance with the second, Mike Morse for help in implementing this project, Mike Salib for technical discussions, and Richard Jones for his friendship and insightful discussions. These people were integral to the success of this project and their efforts are very much appreciated.

To my friends and colleagues, both past and present, Goran Masanovic, Jason Png, Sean Chan, Ken Lim, Martin Ang, Simon Howe, Bane Timotijevic, Frederic Gardes, Peter Waugh, David Thomson, and Kevin Yang, thank you for your help in all matters great and small. I thank you also for your patience for all the times I ‘borrowed’ equipment and took over the laboratory.

To my UK friends whom I have known since the first days in the UK, Melanie Webb, Daniel Bailey, Andy Smith, A.J. Miller, Paul Smith, Mirko Presser, Daniel Hawkins, Liliana Cuenca, Jane Mefo, Benjamin Colombeau; thank you for all of the great times and memories. To my international friends, Rachel Paniccia, Imre Pal, Miro Kopal, Benjamin and Melinda Maccall, Kyong An, Mark and Lisa Klopenstine; thank you for your support and lasting friendship.

To my parents, Brigita and Uldis, my sisters Katie, Ingrid and Amanda, my grandfather, Bill the 2nd, and to my numerous other family members, thank you for your love and support. And thanks to my new family, Herman, Lucia, Nele, and Stijn whose support and welcome have been wonderful, especially being so far away from home. To Lise, the
love of my life and woman of my dreams, thank you for your relentless understanding and infinite patience.

Finally I wish to express my deepest appreciation to Professor Graham Reed for his tutelage, kindness, and patience. He has made me feel welcome from the start and taught me the value of a good pint. He has made the complex seem obvious and has provided me with an understanding of my field that I never thought possible. To Graham, my loved ones, friends and colleagues, I wish to express my heartfelt thanks and gratitude.
Publications


Contents

1 Introduction ....................................................................................................................1
  1.1 Impetus..................................................................................................................1
  1.2 The ‘Superchip’ .................................................................................................2
  1.3 The Ring Resonator .........................................................................................3
  1.4 References........................................................................................................6

2 Literature Review ..........................................................................................................7
  2.1 Silicon Photonics ..............................................................................................7
  2.2 Ring Resonators ..............................................................................................17
  2.3 References........................................................................................................25

3 Theory, Modelling, and Device Design ....................................................................32
  3.1 The Wave Equation ..........................................................................................33
  3.2 The Waveguide ................................................................................................36
    3.2.1 The Slab Waveguide ..................................................................................36
    3.2.2 Two-Dimensional Confinement ..................................................................41
  3.3 Polarisation Independent Rib Waveguide Modelling ........................................43
  3.4 The Directional Coupler .................................................................................45
    3.4.1 Mathematical Derivation of the Directional Coupler .............................45
    3.4.2 The Beam Propagation Method .................................................................47
    3.4.3 Modelling of a Polarisation Independent Directional Coupler ..........49
  3.5 Waveguide Bends ..............................................................................................53
  3.6 Single Input/Output Ring Resonator Theory .....................................................56
  3.7 The Group Index ...............................................................................................59
  3.8 Measurement of Loss via Fabry-Perot Resonances ........................................62
  3.9 References........................................................................................................65

4 Test Chip Design .........................................................................................................66
  4.1 Mask Design Software ......................................................................................66
  4.2 First Test Chip Design .....................................................................................69
    4.2.1 Rib Waveguides .......................................................................................70
    4.2.2 Directional Couplers ...............................................................................70
    4.2.3 Bend Loss Experiment ..............................................................................72
    4.2.4 Ring Resonator Devices ..........................................................................73
| 4.2.5 | Tapers ........................................................................................................... | 74 |
| 4.2.6 | Device Duplication ...................................................................................... | 75 |
| 4.2.7 | Print Bias Corrections to Waveguide/Coupler Dimensions ....................... | 75 |
| 4.2.8 | On-Wafer Exposure Time Skew .................................................................. | 77 |
| 4.3  | Second Test Chip Design ............................................................................ | 78 |
| 4.3.1 | Recycled Experiments and General Modifications ..................................... | 80 |
| 4.3.2 | Directional Coupler Study ......................................................................... | 81 |
| 4.3.3 | Dual Input/Output Racetrack Resonator Devices ....................................... | 81 |
| 4.3.4 | 180° S-Bend Experiment ............................................................................ | 82 |
| 4.3.5 | Print Bias and On-Wafer Exposure Time Skew .......................................... | 83 |
| 4.4  | Dimension Calibration ............................................................................... | 84 |
| 4.5  | References .................................................................................................. | 86 |
| 5    | Wafer Fabrication and Device Preparation ................................................. | 87 |
| 5.1  | Silicon-On-Insulator (SOI) ......................................................................... | 87 |
| 5.2  | Device Fabrication ..................................................................................... | 88 |
| 5.3  | Sample Preparation .................................................................................... | 90 |
| 5.3.1 | Wafer Dicing ............................................................................................. | 90 |
| 5.3.2 | Facet Polishing .......................................................................................... | 91 |
| 5.3.3 | Anti-Reflection (AR) Coating ..................................................................... | 99 |
| 5.4  | References .................................................................................................. | 102 |
| 6    | Experimental Techniques ............................................................................ | 103 |
| 6.1  | The Free-Space Optical Test Setup ............................................................. | 103 |
| 6.2  | Hybrid Fibre-Free Space Setup .................................................................. | 110 |
| 6.3  | Calibration of the Polarisation Components ............................................. | 111 |
| 6.4  | Alignment of the Free-Space Experimental Setup ...................................... | 113 |
| 6.5  | Automated Measurement Control Programme ............................................ | 118 |
| 6.6  | Investigation of Thermal Effects on Measurement Accuracy ...................... | 121 |
| 6.7  | Calibration of the Scanning Electron Microscope ...................................... | 125 |
| 6.8  | Table of Components Used in the Free-Space Experimental Setup .............. | 127 |
| 6.9  | References .................................................................................................. | 130 |
| 7    | Experimental Results .................................................................................. | 131 |
| 7.1  | Waveguide Propagation Loss ...................................................................... | 131 |
| 7.1.1 | The First Test Chip Design ...................................................................... | 131 |
| 7.1.2 | The Second Test Chip Design ................................................................... | 134 |
List of Figures

Figure 1.1. A fully integrated optical ‘superchip’ [6]...............................................................2
Figure 2.1. Propagation loss as a function of the buried oxide thickness for a 7.4µm thick planar silicon waveguide [19].........................................................................................10
Figure 2.2. (a) Cross-sectional schematic of a single mode rib waveguide that defines the variables a, b, r, and (b) a plot of the ratio of a/b as a function of b to determine values of a single mode waveguide for the SiO2-Si-SiO2 material system [4]. .......................11
Figure 2.3. Single-mode and polarisation independent (ZBR) rib waveguide model for a waveguide height of 1.35µm [29]........................................................................................................13
Figure 2.4. Cross-sectional schematic of a three terminal p-i-n diode structure incorporated into a rib waveguide [35]........................................................................................................16
Figure 2.5. Plan view (a) schematic and (b) fabricated dual input/output strip waveguide racetrack resonator [48]...........................................................................................................18
Figure 2.6. Spectral response of the ring resonator in figure 2.3 showing a resonant peak (drop port) and dip (throughput port) [48]...................................................................................18
Figure 2.7. SEM image of a three-ring resonator [58]...............................................................20
Figure 2.8. SEM of a 3µm radius ring resonator in polysilicon [59]........................................21
Figure 2.9. Spectral response at the throughput port of the ring resonator for rings with radii of 4 and 5 µm [59]...........................................................................................................21
Figure 2.10. Schematic of a thermally tuneable ring resonator [40]........................................23
Figure 2.11. (a) Schematic and (b) SEM image of a vertically coupled ring resonator [67] .................................................................................................................................24
Figure 3.1. The definition of TE light for a slab waveguide.....................................................35
Figure 3.2. The demonstration of Snell’s Law for a light ray passing from a material of higher refractive index to a lower one..................................................................................36
Figure 3.3. Vertical confinement of a TEM wave due to total internal reflections inside a silicon slab........................................................................................................................38
Figure 3.4. Cross-sectional views of a (a) strip and (b) rib waveguide.................................42
Figure 3.5. (a) Cross-section profile of the rib waveguide used to determine the PI waveguide dimensions. (b) Modelling of the effective index to determine the correct rib etch depth for a PI waveguide (modelling by A. Liu of the Intel Corporation). .....44
Figure 3.6. Single mode, PI rib waveguides for various waveguide widths (Modelling by A. Liu of the Intel Corporation) .................................................................44
Figure 3.7. Cross-sectional view of a directional coupler ........................................49
Figure 3.8. Plan-view of a modelled directional coupler for TE and TM polarisation states (Modelling by A. Liu of the Intel Corporation) .................................................. 50
Figure 3.9. Modelling of the coupling length as a function of the waveguide separation in order to determine the dimensions of a PI directional coupler (Modelling by A. Liu of the Intel Corporation) ............................................................................. 51
Figure 3.10. Directional coupler modelling results for a waveguide width of (a) 0.7μm, (b) 0.8μm, and (c) 0.9μm. The waveguide height and rib etch depth were maintained at 1.35μm and 0.82μm respectively. ................................................................................52
Figure 3.11. Cross-sectional image of a modelled waveguide with a confined TE mode (a) in a waveguide bend (R=100μm) and (b) a straight waveguide. Both waveguides have the same cross-sectional dimensions as the PI rib waveguide with a width of 1.0μm. ...............................................................................................................................54
Figure 3.12. Cross-sectional image of a modelled waveguide bend demonstrating the polarisation dependence on slab leakage due to the bend radius (R=50μm). The (a) TM mode demonstrates little slab leakage whilst the (b) TE mode demonstrates a large amount of leakage. ........................................................................................54
Figure 3.13. Modelled loss of a 90° waveguide bend as a function of bend radius (modelled by A. Liu of the Intel Corporation) ................................................................................. 55
Figure 3.14. Plan-view schematic of a single input/output ring resonator .................. 57
Figure 3.15. Spectral response of a single input/output racetrack resonator as determined by equation 3.51 ......................................................................................... 57
Figure 3.16. Plot of the Sellmeier equation for silicon as compared with measured values of the index of refraction for silicon at various wavelengths ....................................................... 60
Figure 3.17. The effective index of a rib waveguide as a function of wavelength. The slope of the line is used to determine the dispersion due to the geometry of the waveguide ......................................................................................................................... 61
Figure 3.18. Spectral response of a waveguide due to the FP effect. .......................... 63
Figure 4.1. L-Edit layout design of a rib waveguide ................................................. 67
Figure 4.2. (a) Curve drawn in L-Edit demonstrating the polygonal path (b) Curve imported from Beamprop showing the same curve as in (a) but smooth............. 68
Figure 6.1. A pictograph of the free-space experimental setup ......................................104
Figure 6.2. Close-up of items 6, 7, and 8 from Figure 6.1 .............................................106
Figure 6.3. Piezoelectric controllers for manipulating the input/output stages ..............107
Figure 6.4. (a) Image of the output waveguide (b) with unfocused light (c) and focused
light ..................................................................................................................................108
Figure 6.5. Overhead imaging assembly ...........................................................................109
Figure 6.6. (a) Plan view of a flat-faced fibre and a (b) lensed fibre coupled to a
waveguide ..............................................................................................................................110
Figure 6.7. Alignment of the polarising cube beamsplitter .............................................112
Figure 6.8. Calibration data for the polarizer used in the experimental setup ...............112
Figure 6.9. Calibration data of the half-wave plate used in the experimental setup .........113
Figure 6.10. Plan-view of collimation stage showing the centring of the beam in the
objective lens .......................................................................................................................114
Figure 6.11. (a) Light from the IR camera imaging tube projected onto the output of the
chip (b) Plan-view image of the projected light as observed with the overhead camera
............................................................................................................................................116
Figure 6.12. Use of the unconnected end of the fibre from the fibre optic light source to
determine the approximate position of the objective lens to the desired waveguide
input ......................................................................................................................................117
Figure 6.13. Interface of the automated scan programme used to measure the spectral
response of the fabricated racetrack resonators ...............................................................118
Figure 6.14. Phase shift of a racetrack resonator’s spectral response due to heating .......122
Figure 6.15. (a) Thermal control setup and (b) a close-up view of the TEC and chip ...123
Figure 6.16. Thermal drift over time of a TEC stabilized racetrack resonator ...............123
Figure 6.17. Shift in the resonance minima of a racetrack resonator due to heating ......124
Figure 6.18. Thermal drift of a racetrack resonator minimum over time without
attempting to thermally stabilize the chip .........................................................................125
Figure 6.19. Image of the calibration standard as viewed with an ESEM. The
measurement bars were subsequently added with analysis software ...............................127
Figure 7.1. SEM cross-sectional image of a fabricated straight rib waveguide ..........132
Figure 7.2. Typical FP response of a straight waveguide ................................................133
Figure 7.3. Modelled (a) TE and (b) TM modes using the dimensions of the fabricated rib
waveguide shown in Figure 7.1 .........................................................................................134
Figure 7.4. Cross-sectional SEM images of the targeted PI rib waveguides using the second test chip design
...........................................................................................................................................135

Figure 7.5. Plan-view schematic of a directional coupler demonstrating the definition of the cross-state and pass-state
...........................................................................................................................................137

Figure 7.6. Cross-sectional SEM view of a directional coupler from wafer W812
...........................................................................................................................................138

Figure 7.7. Spectral response of a directional coupler from wafer W812
...........................................................................................................................................138

Figure 7.8. Modelling results of the directional coupler in Figure 7.6 with asymmetric waveguide widths
...........................................................................................................................................139

Figure 7.9. Sinusoidal power transfer between two asymmetric waveguides in a directional coupler as a function of distance into the coupling region
...........................................................................................................................................141

Figure 7.10. Modelling results of a directional coupler comprised of waveguides with asymmetric widths
...........................................................................................................................................141

Figure 7.11. Cross-sectional SEM image of a directional coupler from the shallow-etched wafer W712
...........................................................................................................................................142

Figure 7.12. Spectral response of a functioning directional coupler from wafer W712
...........................................................................................................................................143

Figure 7.13. Cross-section SEM of a directional coupler used in the directional coupler experiment
...........................................................................................................................................144

Figure 7.14. Directional coupler experimental results for (a) TE and (b) TM polarisation states
...........................................................................................................................................145

Figure 7.15. Comparison of the curves used to fit the pass state data in Figure 7.14
...........................................................................................................................................146

Figure 7.16. Zero phase shifted data demonstrating the shift in the PI coupler due to effective coupling outside the defined coupling region, as compared to Figure 7.15
...........................................................................................................................................147

Figure 7.17. Modelling results of launching a Gaussian mode into the directional coupler for (a) TE and (b) TM polarisations
...........................................................................................................................................149

Figure 7.18. Bend loss results for a test chip from wafer W812
...........................................................................................................................................151

Figure 7.19. Results of the 180° bend loss experiment with 1μm wide waveguides
...........................................................................................................................................153

Figure 7.20. FP scans of a waveguide with 2-180° bends with 100μm radius. The scans show strong polarisation conversion for (a) TE input polarisation and (b) TM input polarisation. (The values A_e and A_c are used in defining equation 7.1 below)
...........................................................................................................................................154

Figure 7.21. FP scans of a straight waveguide for TE input polarised light
...........................................................................................................................................155

Figure 7.22. Results of the investigation of polarisation conversion in the 90° bend experiment with a waveguide width of approximately 1μm and a (a) bend radius of 300μm with an etch depth of approximately 0.73μm (b) bend radius of 300μm and
etch depth of approximately 0.93μm (c) bend radius 100μm and etch depth of 0.93μm

Figure 7.23. Spectral response of a racetrack resonator compared with a straight
waveguide. Both devices have uncoated facets resulting in an FP resonance ..........160
Figure 7.24. Comparison of the spectral response of a resonator to modelling..........160
Figure 7.25. Racetrack resonator spectral response demonstrating favourable polarisation
properties .......................................................................................................................162
Figure 7.26. Polarisation independent spectral response of a racetrack resonator .......162
Figure 7.27. Close-up of the resonance minimum at 1576.624nm from Figure 7.26.....163
Figure 7.28. Modelling results of the directional coupler in the PI resonator ..........164
Figure 7.29. Measurement of a racetrack resonator designed to have a PI response ....167
Figure 7.30. Sampling of the spectral response from the long scan study (1540-1560nm)
to determine the validity of the higher order mode hypothesis..............................169
Figure 7.31. The cross-polarised spectral response from the same device shown in
Figure 7.29 ....................................................................................................................171
Figure 7.32. Resonance separation implying polarisation conversion ....................172
Figure 7.33. FSR dependency on bend radius ............................................................174
Glossary of Terms

ARC Anti-Reflection Coating
AWG Arrayed Waveguide Grating
BESOI Bond and Etch-back SOI
BOX Buried OXide
BPM Beam Propagation Method
CAD Computer Aided Design
CL Coupler Length
CO Central Office
DOE Design of Experiment
DLF Diamond Lapping Film
DWDM Dense Wavelength Division Multiplexing
EIM Effective Index Method
ESEM Environmental Scanning Electron Microscope
FC/APC Ferrule Connector/Angled Physical Contact
FC/PC Ferrule Connector/Physical Contact
FOX Field OXide
FSR Free Spectral Range
FWHM Full Width at Half Maximum
HDTV High Definition TeleVision
MPEG2 Motion Picture Expert Group 2
NA Numerical Aperture
PDL Polarisation Dependent Loss
PI Polarisation Independent
PM Polarisation Maintaining
SEM Scanning Electron Microscope
SIMOX Separation by IMplanted Oxygen
SMC Single Mode Condition
SOI Silicon-On-Insulator
TE Transverse Electric
TEC ThermoElectric Cooler
TBM Transverse ElectroMagnetic
TIR Total Internal Reflection
TM Transverse Magnetic
ULSI Ultra Large Scale Integration
VOD Video-On-Demand
Chapter 1

1 Introduction

1.1 Impetus

The field of telecommunications has done reasonably well in keeping pace with the ever increasing consumer demand for information to date. However with the advances in technologies such as digital and High Definition TeleVision (HDTV), Video-On-Demand (VOD), and uncompressed data transfer, current telecommunication networks comprised of copper wire may begin to fall woefully short. Advances in copper network technologies such as ADSL 2+ (Asymmetric Digital Subscriber Line) bring the bandwidth limit to approximately 25 Mbps for those living within 2.5 km of a signal transmission node, or Central Office (CO) [1]. The bandwidth of a Motion Picture Expert Group second generation (MPEG2) compressed HDTV signal alone is approximately 20 Mbps. Coupled with bandwidth hungry applications such as VOD (~4 Mbps), or even multiple HDTV channels sent to a typical household, could bring current copper networks quickly to their bandwidth limits. Futuristic technologies such as F-ADSL (~174 Mbps @ 2.5 km from CO, down-stream data transfer rate, ~18 Mbps upstream), if they were to become commercially available, could potentially alleviate short-term demand issues [2, 3]. Optical networks have the ability to rise to the challenges of practically any level of future demand. Their signals are typically faster, and multiplexing techniques such as Dense Wavelength Division Multiplexing (DWDM) can push the optical network bandwidth into the terabit regime [4]. They are also less prone to environmental factors as electromagnetic interference as compared to their electronic counterparts. Optical networks tend to be much more secure as optical signals are well protected by the waveguide cladding. Large bandwidth signals on copper wires, however, cause the wires to act like antennas so that the signals are radiated and hence are prone to ‘electronic eavesdropping’.
One drawback, however, to fibre networks is cost. In addition to installation, component costs to build these networks traditionally have limited them to long haul applications such as intercontinental and city-to-city applications.

### 1.2 The ‘Superchip’

One solution to the component cost issue is to integrate as many of the necessary components onto one chip, such as Abstreitter’s vision of a ‘superchip’ [5]. The basic premise of a monolithic superchip is that it incorporates all of the necessary components to detect, route/reroute, convert, modulate, amplify, and create optical signals that could subsequently be interrogated by on-chip electrical circuitry. In Soref’s vision of such a chip (figure 1), optical signals input to and output from the chip were made possible by means of optical fibres butt-coupled to waveguides on the chip [6]. The fibres are supported by high-precision v-grooves etched into the chip substrate. Input optical signals would then either be detected by a photodetector for use in electronic interrogation, or passed onto either the output of the chip or other devices by means of waveguides for optical processing. Due to loss mechanisms in other parts of the system, an optical signal could also be amplified, or perhaps re-shaped and re-encoded via an optical modulator before re-transmission. Similarly, new electronic signals could be encoded onto the optical carrier signal using the same modulator.

![Figure 1.1. A fully integrated optical ‘superchip’ [6]](image-url)
With its decades of research and billions of pounds of investment, silicon would make a nearly ideal material with which to fabricate such a superchip. All of the electronic and nearly all of the optical components can be fabricated with the Ultra Large Scale Integration (ULSI) tools currently available. Silicon falls short of being the perfect material due to its indirect bandgap and centrosymmetric crystalline structure. As a result, a conventional semiconducting light emitter and a linear electro-optic effect for modulation are not possible. However, following recent work in Raman amplification and lasers [7, 8], as well as fast modulators [9-11] the probability of realizing a fully integrated silicon version of the superchip is now showing signs of feasibility. Optical and electronic integration is also proving to be a bottleneck as only very rudimentary integration has taken place thus far (e.g. [12]), and so remains a challenge. However, recent initiatives such as the Defence Advanced Research Projects Agency’s (DARPA) Electronic & Photonic Integrated Circuit (EPIC) programme is beginning to address this issue [13].

1.3 The Ring Resonator

A variety of optical devices will be necessary on a superchip in order to accommodate all possible contingencies that may arise during its use. An Arrayed Waveguide Grating (AWG) for instance may be employed as a multiplexer/demultiplexer. However, a much simpler device also suitable for this task is the ring resonator. By combining suitably designed rings and input/output waveguides, a ring resonator-based device can have the same functionality as an AWG. The benefit of such a device over the AWG is area. An AWG can typically consume areas of square millimetres. A single ring resonator can have an area of the order of tens of square microns. Therefore even if a multiplexer/demultiplexer designed with ring resonators required dozens of rings to achieve the same functionality as an AWG, its overall area would still be orders of magnitude smaller. Smaller areas allow for larger packing densities which may lead to a substantial cost savings in production. What makes ring resonators even more attractive is that they also have the ability to function as modulators, filters, and wavelength specific routers which are discussed further in the next chapter. Thus these devices could be quite useful in realizing a superchip or simply creating standalone optical devices.
Chapter 1: Introduction

The functionality of many if not all optical devices is dependent upon the polarisation state of the input signal. One potential solution to this issue is to design several devices each with an ability to function with a specific polarisation state. Several of these devices could then be placed either in series or in parallel with respect to the input signal. Thus if the polarisation state of the input beam is not ideal for a particular device it encounters, one of the designed devices will be. This assumes that each component functions with only the polarisation that it was designed for. The problem with using this method is that for each extra device, precious area is consumed. A better solution would be to design a device whose functionality is independent of the polarisation state of the input signal. This is the focus of the work herein. A ring resonator is broken down into its fundamental components. Each component is then modelled and analysed in order to obtain a polarisation independent response. The components are then recombined in order to realise a polarisation independent ring resonator.

Chapter two of this thesis is a review of the literature not only for the ring resonator, but also for the field of silicon photonics. Chapter three introduces and discusses the theory and modelling tools used to design a polarisation independent ring resonator. Initial modelling was carried out by Ansheng Liu of the Intel Corporation. However all subsequent modelling was carried out by the author. In order to validate the modelling, several test chips were designed by the author. Chapter four discusses the design of these test chips. The test chips were fabricated at an Intel fabrication plant in Jerusalem, Israel. Much of the initial sample preparation was developed and carried out by the author. The fabrication and sample preparation are discussed in chapter five. The experimental techniques developed and used by the author to examine the fabricated test chips are covered in chapter six. The results of the measurements made by the author and their comparisons to the theory and modelling are covered in chapter seven. The conclusions drawn from the results are discussed in chapter eight. This body of work is concluded by offering some insight into future work that could be undertaken to further optimise these devices.

This work has contributed to the field of silicon photonics in several ways. A polarisation independent ring resonator was designed, measured, and analysed by the author. The
resonance minima alignment is the best quoted in the literature. A world class Q-value for a resonator has also been measured and is currently the largest reported in the literature. A directional coupler experiment has been designed and measured by the author that is intended to validate the modelling of a single-mode rib waveguide. The results of this experiment have also demonstrated effects such as coupling outside the defined coupling region that will have an impact on functionality of directional couplers as well as ring resonators. Several hypotheses have been put forth by the author to explain the cause of a secondary resonance minima observed in the spectral response of several ring resonators. Preliminary results on polarisation conversion in waveguides have been presented and analysed by the author that will aid in the understanding of this effect. It can therefore either be utilised or overcome in future devices. Aspects of the design of a polarisation independent device have also appeared in several publications. These results, discussed throughout this thesis, have produced a better understanding of not only the ring resonator device, but also of the fundamental devices that comprise it. Hence, these results constitute a contribution to the field of silicon photonics.
1.4 References

1. *ADSL 2+: A New Era for Broadband*, 2004, from

2. Laclau, Y., *Free goes nuclear with North Korean strategy*, 25 November 2005,


11. Luxtera, 1819 Aston Avenue, Suite 102, Carlsbad, CA 92008, USA.


Chapter 2

2 Literature Review

This chapter sets the stage for the work undertaken in this project. Because the ring resonators studied in this work are fabricated in the Silicon-On-Insulator (SOI) material system, the chapter begins with a discussion of some of the key accomplishments in the field of silicon photonics. As silicon photonics has become a large field, emphasis is placed on the developments that would affect a ring resonator device, such as waveguides, the effects of strain caused by silicon dioxide, and modulators (for tuneable devices). The remainder of this chapter focuses on optical ring resonators discussed in the literature.

2.1 Silicon Photonics

The concerted efforts to investigate silicon as a photonic material began in the mid to late 1980's with the work of Soref and Bennett [1-5]. In one of their articles from this period, Soref makes the statement, “Silicon is a ‘new’ material in the context of integrated optics even though Si is the most thoroughly studied semiconductor in the world” [1]. He then goes on in this article to condense the relatively new knowledge of the optical properties of silicon in the optical telecommunications range of wavelengths from 1.3 to 1.6 μm. During the early years of this field (1985-1995), a reasonable amount was achieved in overcoming the issues surrounding the development of a monolithically integrated optical superchip, as presented in chapter one. Whilst informative, much of this work is beyond the scope of this chapter. However, a review paper highlighting the accomplishments of this era is referred to here for the interested reader [6].

One of the most important and fundamental devices in silicon photonics is the waveguide. It allows for the routing of confined light from one part of a chip to other parts. It is
especially important for the ring resonator as light is required to travel in a circular path in order for the device to function properly. The early work on silicon waveguides occurred in planar waveguides where the light is confined only in the vertical direction. The first single-crystal silicon planar waveguide was demonstrated by Soref et al. [1]. The authors used highly doped silicon substrates underneath an epitaxy of single-crystal silicon to confine the light. The doping creates a source of free carriers which lowers the index of refraction of the substrate. Light is then confined in the higher index epitaxy region due to total internal reflection (see section 3.2). The authors quote a, 'first try', measured propagation loss of 5-13dB/cm for their slab waveguides and 15-20dB/cm for their rib waveguides. A rib waveguide (defined in section 3.2.2) is a structure capable of confining light in two directions. The modelling of this important structure is discussed later on in this chapter.

SOI, whilst originally developed for the electronics industry to prevent latch-up in transistors [7], found an obvious use as an optical waveguiding material system. In the late eighties and early nineties, researchers were beginning to investigate waveguides patterned on SOI wafers fabricated using two main methods, Separation by IMplantated OXygen (SIMOX) and Bond and Etch-back SOI (BESOI) [8]. The SIMOX method uses oxygen ions implanted into a silicon wafer to create the buried silicon dioxide layer. This method was used to fabricate the SOI wafers in this work and is discussed further in section 5.1. A BESOI wafer is produced by taking two silicon wafers, each with an oxide grown on their top surfaces, and sandwiching them together. The pair of wafers is then heated so that the oxide layer from each wafer bonds to form a single layer. Then, one of the wafers is sacrificially polished back to the desired thickness. Because of the relative waste of one of the wafers, subsequent improvement of this method has been made and is discussed further in reference [8]. Whilst studies were made on waveguides patterned on BESOI waveguides [9, 10], focus is maintained on the results of the SIMOX material as it is the material used to fabricate the devices in this work.

In 1989, Soref et al. again was at the forefront by making some of the first waveguides in the SOI material system [2, 11]. Also in 1989, Davies et al. [12] measured a loss of 4 dB/cm for optical waveguides fabricated in SIMOX. Multiple layer waveguiding
structures using SIMOX technology were also demonstrated [13, 14]. Over the next several years other groups have verified and made improvements to these initial results. In 1991, Schmidtchen et al. demonstrated rib waveguides in SIMOX with propagation losses as low as 0.5dB/cm for rib heights of 7.4μm, etch depths (defined in section 3.2.2) of 2.2μm and widths of greater than 3μm for the free-space wavelengths λ=1.3μm and 1.55μm using horizontally polarised light (the electric field of the light is aligned parallel to the buried oxide layer) [15].

Here at the University of Surrey work on SIMOX waveguides was also underway at the time [16, 17]. Weiss et al. demonstrated planar optical waveguides on SIMOX with a guiding layer thickness of 0.5μm to 2.0μm for different wafers. They obtained a minimum loss for their devices of 8.0dB/cm for λ=1.15μm using horizontally polarised light. They attributed the loss to scattering from crystal lattice defects as well as surface roughness. Although their loss was higher than the previous value of 0.5dB/cm measured by Schmidtchen et al., their devices were more than three times smaller.

It was determined early on that the thickness of the oxide may contribute to the propagation loss of a waveguide. If the oxide is too thin, the optical field will couple to the substrate thereby increasing the propagation loss of the waveguide. Kurdi et al. predicted a loss of less than 1 dB/cm for a 0.2μm thick planar waveguide with a 0.5μm buried oxide thickness [18]. Planar waveguides with a thickness of 7.4μm were fabricated on SIMOX by Rickman et al. using various buried oxide thicknesses [19]. The results, shown in Figure 2.1, demonstrate the importance of the thickness of the buried oxide. These results are quite impressive as they were able to measure a propagation loss of 0.14±0.5dB/cm for a 400nm buried oxide thickness (λ=1.523μm, horizontally polarised light) which was the lowest recorded loss in single-crystal undoped SOI at the time. The uncertainty value was determined from the equipment used to make the measurement. This result implies that the propagation loss is negligible to within the stated uncertainty of the measurement.
The propagation loss value was further reduced, again by Rickman et al., for rib waveguides in SIMOX [20]. For a rib with a height of 4.32µm, a width of 3.72µm, and an etch depth of 1.7µm, they achieved a loss value of 0.0±0.5dB/cm for horizontally polarised light and 0.4±0.5dB/cm for vertically polarised light at λ=1.532 µm. These results imply that the waveguides have no propagation loss to within the stated uncertainty of the measurement. These are the best recorded propagation loss values in the literature to date for a rib waveguide in SIMOX.

One of the reasons that silicon photonics has continued to grow as a field is because of the propagation loss values given above. Propagation loss has a deleterious effect to the functionality of a ring resonator. Hence this value should be as low as possible.

In parallel to the experimental work carried out above, effort was also placed into waveguide modelling. For most practical applications, single mode propagation
(discussed in 3.2.1) is desired. In order to achieve single mode propagation in a planar waveguide, its thickness would need to be of the order of several hundred nanometres. In order to avoid complications such as coupling light to a waveguide of these dimensions, the concept of the rib waveguide was developed. One of the earliest efforts to determine the dimensions of a rib waveguide was made by Petermann et al. [21]. This work was subsequently refined by Soref et al. [4] by normalising the equations proposed by Petermann et al. to determine the dimensions of a single mode rib waveguide. They obtained the following relation:

\[
\frac{a}{b} \leq \alpha + \frac{r}{\sqrt{1-r^2}}; \quad 0.5 \leq r < 1.0, \alpha=0.3
\]

where \( \alpha \) is constant determined by the modelling, \( a \) and \( b \) are the waveguide cross-sectional dimensions, and \( r \) is a slab height scaling factor, all of which are defined in Figure 2.2(a). The variables \( n_0, n_1, n_2 \) are the indices of refraction for air, silicon, and silicon dioxide respectively and \( \lambda \) is the free-space wavelength of light. The authors then go on to determine the necessary dimensions of a single mode rib waveguide in terms of a ratio of the rib width to its height \((a/b)\) as a function of the rib height \((b)\), shown in Figure 2.2.

![Figure 2.2](image.png)

**Figure 2.2.** (a) Cross-sectional schematic of a single mode rib waveguide that defines the variables \(a, b, r\), and (b) a plot of the ratio of \(a/b\) as a function of \(b\) to determine values of a single mode waveguide for the SiO\(_2\)-Si-SiO\(_2\) material system [4].
Figure 2.2(b) for a SiO2-Si-SiO2 material system. The modelling results of an air-clad waveguide are also given in the paper. The results shown in Figure 2.2(b) are given here as they more closely resemble the ring resonator waveguides used in this work.

Several modifications to Equation 2.1 were attempted over the years, most notably to the constant \( \alpha \). Using the effective index method (discussed in section 3.2.2) Pogossian et al. [22] determined that \( \alpha=0 \) is a more accurate value to use. Experimental results were obtained by Rickman et al. [23] that agreed more favourably with this value of \( \alpha \) than that determined by Soref et al. However, results were presented that claimed the effective index method is not suitable for predicting higher order mode behaviour in rib waveguides [24]. In 2002, Powell investigated the single-mode condition for silicon rib waveguides using the beam propagation method (discussed in section 3.4.2) [25, 26]. His results were found to be in good agreement with the value \( \alpha=0.3 \), originally determined by Soref et al. He also investigated the single-mode condition for rib waveguides with angled sidewalls that give the top of the rib waveguide a trapezoidal appearance.

Unfortunately these results of Powell could not be used to determine the necessary waveguide dimensions for the waveguides used in this thesis. This is due to the constraint on the slab height to waveguide height ratio \( 0.5 \leq r \leq 1.0 \). The results of Powell and Soref are only valid for shallow etched waveguides. However, in order to obtain a polarisation independent rib waveguide, it was found that \( r \) needs to be less than 0.5 for the waveguides used in this thesis (discussed further in section 3.3).

In order to circumvent this issue, the waveguides investigated in this thesis were initially modelled for polarisation independence using similar methods proposed by Vivien et al. [27]. The resulting waveguide dimensions from the polarisation independent modelling were then checked for higher order mode propagation using the beam propagation method [28]. These results are discussed further in section 3.3.
A more comprehensive modelling study was carried out by Chan et al. on deep-etched ($r \leq 0.5$), single-mode, polarisation independent rib waveguides [29]. They used a combination of finite element and full-vectorial beam propagation methods to obtain their results. They investigated the single-mode and polarisation independent conditions for three waveguide heights, 1.00μm, 1.35μm, and 1.50μm as a function of waveguide width and etch depth. The results of their modelling are important, especially the results obtained for a 1.35μm height device. This is the same waveguide height used in the design of the polarisation independent ring resonator studied in this thesis. The results of their modelling for this waveguide height are shown in Figure 2.3. The conclusions of their work are consistent with the results obtained by Powell and Soref et al. for $r \geq 0.5$. For $r \leq 0.5$, the authors have presented approximate design rules, however they believe that best approach is the same as that taken to determine the polarisation independent waveguides used in this thesis.

The two red circles in Figure 2.3 illustrate the target dimensions of waveguides that were fabricated for study in this thesis. The polarisation independent results (labelled as 'ZBR'
in the legend) are consistent with those obtained in section 3.3. The Single Mode Condition (SMC) lines for horizontal (TE) and vertical (TM) polarisations pass very close to the two red circles. This indicates that for the top circle, the waveguide is borderline single-mode TE and multimode TM. For the lower circle, the modelling shows that waveguides with these dimensions will be single-mode in TE and borderline single-mode TM. One issue with the modelling is that an air cladding \((n=1)\) was used to obtain these results. Subsequent modelling by Dr. Chan was undertaken to investigate the effects of an oxide coating on the single-mode condition for TM polarisation [30]. His preliminary results demonstrated a small, downward shift parallel to the original SMC TM line. This result implies that waveguides having dimensions indicated by the lower circle may still maintain a single-mode for TE polarisation; it may now, however, allow higher order modes to propagate for TM. This result is important as it supports the claim of potential higher order mode behaviour observed in a directional coupler experiment discussed in section 7.2.2.

An effect that was not fully appreciated until the latter stages of this project is that the oxide layer covering the silicon waveguide causes unexpectedly high strain. A significant amount of the work undertaken to understand this effect was accomplished by researchers at the National Research Council (NRC) in Canada [31-34]. The stress on the waveguide is induced by the mismatch of the thermal coefficients of expansion for silicon \((3.6 \times 10^{-6} \text{ K}^{-1})\) and silicon dioxide \((5.4 \times 10^{-7} \text{ K}^{-1})\). Applying a stress to the silicon creates a change in the index of refraction due to the photoelastic effect. The researchers found that in the horizontal direction, the stress is compressive, whilst in the vertical direction it is creates a tensile strain on the waveguide. In several of their models they obtain stresses of the order of \(10^4\) MPa. The result of this stress/strain is two different indices of refraction for the waveguide. Vertically polarised light will travel at a different velocity in the waveguide than horizontally polarised light. A waveguide is defined as being birefringent if it has two different indices of refraction for the horizontal and vertical directions. For a corresponding strain of \(10^4\) MPa, the researchers observed a birefringence of the order of \(10^{-3}\).
Their approach to fabricating a polarisation independent waveguide is quite different from the method described in section 3.3. They first determine the birefringence of their waveguide as a result of its geometry. They then compensate for this birefringence by applying an oxide cladding to counteract the original birefringence, and hence realise a polarisation independent rib waveguide.

One of the shortcomings of silicon is that it doesn't have a strong linear electro-optic effect. However in 1987, Soref and Bennet determined that optical modulation could still be achieved through the use of the plasma dispersion effect [5]. Through an investigation of the literature they were able to ascertain a relationship between electroabsorption and a change in effective index (also known as the plasma dispersion effect) in silicon. For $\lambda=1550\text{nm}$, the authors determined [5]:

\begin{equation}
\Delta n = \Delta n_e + \Delta n_h = -[8.8 \times 10^{-22} \Delta N_e + 8.5 \times 10^{-18} (\Delta N_h)^{0.8}] \tag{2.2}
\end{equation}

\begin{equation}
\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = 8.5 \times 10^{-18} \Delta N_e + 6.0 \times 10^{-18} \Delta N_h \tag{2.3}
\end{equation}

where

- $\Delta n_e$ = change in refractive index resulting from a change in the free electron carrier concentrations.
- $\Delta n_h$ = change in refractive index resulting from a change in the free hole carrier concentrations.
- $\Delta \alpha_e$ = change in absorption resulting from a change in the free electron carrier concentrations.
- $\Delta \alpha_h$ = change in absorption resulting from a change in the free hole carrier concentrations.

This modulation of the index of refraction is not without its consequences. It is derived from a change in the absorption spectrum of silicon via the Kramers-Kronig relationship, and hence a change in refractive index must in optical absorption. Regardless, if the absorption region is kept small, a significant index of refraction change could still be possible [35].
Modulators are integral components in a telecommunications network. They allow for the conversion of electrical signals to optical ones. A ring resonator has the potential of acting as a modulator. If the resonator is tuned so that it resonates for a given input wavelength, no power will be observed at the output of the device. If the resonator is tuned so that the same input wavelength is off resonance, the input light will pass to the output. Therefore if the ring is oscillated on and off resonance, a modulated optical signal is created at the output of the device.

Many different varieties of optical modulators have been fabricated in silicon [3, 35-47]. However one particular modulator configuration may fit well into a racetrack resonator design. Png et al. proposed a three terminal p-i-n diode structure in a rib waveguide [35]. A cross-sectional image is shown in Figure 2.4. The diode structure was used to inject carriers into the rib region so that they have a strong interaction with a propagating mode. From the plasma dispersion effect, an index change in the rib is induced which results in a phase shift of the light propagating in the waveguide. If this modulator were placed into one arm of a Mach-Zehnder interferometer, the induced phase shift would yield an intensity modulation upon interference of the two arms. The results of their modelling demonstrate that for an injection current of approximately 1.5mA for the structure shown

![Cross-sectional schematic of a three terminal p-i-n diode structure incorporated into a rib waveguide](image-url)

Figure 2.4. Cross-sectional schematic of a three terminal p-i-n diode structure incorporated into a rib waveguide [35]
in Figure 2.4, gigahertz modulation can be achieved. Therefore if this type of structure was fabricated in the ring waveguide, it could be used to change the phase and hence the resonance conditions of the resonator. This would result in an electrically controlled modulator.

2.2 Ring Resonators

A directional coupler is created when two parallel waveguides are placed in close proximity to one another. An interesting result occurs when light is inserted into one of the waveguides. As light propagates along the waveguide, the power in the first waveguide begins to transfer to the second. This transfer of power continues until all of the power from the initial waveguide is transferred into the second waveguide. If the light is allowed to propagate further in this configuration, the power will begin to transfer back to the original waveguide. This oscillation of power will continue so long as the two waveguides are in close proximity (discussed further in section 3.4).

A ring resonator is created when the output of the second waveguide of a directional coupler is connected back to its input via a circular waveguide. Because of the straight waveguide section of the directional coupler, a ring resonator is sometimes referred to as a racetrack resonator in the literature (see p.46 for a further discussion). In the simplest of terms, light coupled to the ring waveguide whose wavelength is an integer multiple of the optical path around the ring, will resonate inside the ring. At resonance, ideally all of the light entering the ring stays in the ring for a single input/output resonator. A slight variation to the single input/output device is shown in Figure 2.5(a&b). This figure shows a schematic and Scanning Electron Micrograph (SEM) image of a dual input/output ring resonator. Figure 2.6 shows the corresponding spectral response (optical response of the resonator as a function of wavelength) of the resonator in Figure 2.5(b) [48]. For a single input/output device, the drop port waveguide is not connected.

Haavisto and Pajer demonstrated one of the first fabricated ring resonator devices in 1980 [49]. The structure was fabricated by the photopolymerisation of a doped polymethyl
methacrylate film on a quartz substrate. The radius of the ring was 4.5cm. They measured three important values for their device, total loss, finesse, and the coupling efficiency of their couplers. They defined the total loss of their device as the sum of the coupling, curvature-radiation, bulk-scattering, and fabrication losses. They obtained a value of 0.05±0.01dB/cm. Whilst this value appears small, it yields a loss of over 2dB in the ring alone. The finesse is a unitless figure of merit for a resonant device and is defined as the ratio of the Free Spectral Range (FSR) divided by the Full-Width at Half-Maximum (FWHM) amplitude of the resonance peak or dip. It gives an estimate of the quality of the device. The larger the finesse, the better quality the device. The FSR is defined as the distance between two consecutive resonance peaks or dips in a wavelength spectrum (discussed further in section 3.6). A large FSR is desirable in telecommunications, as the device should only act on one wavelength in the
telecommunications optical spectrum. Haavisto and Pajer measured a finesse value of 15.8±1.6. They did not, however, state a value for their FSR.

The coupling efficiency of the waveguide coupler is measure of how well the light couples from one waveguide to the other. For a coupling efficiency of one, all of the light in one waveguide is coupled to the other. They measured a coupling efficiency of 0.02. Thus, their input waveguide and ring do not appear to be very well coupled. This may be due to the fact that the distance between the two was 17.5µm with a waveguide width of 10µm. The coupling efficiency drops exponentially as a function of the distance between the waveguides. Therefore a distance of 17.5µm may have allowed for only very weak coupling between the waveguides.

Several years later, a report of a ring resonator made by silver ion-exchange in glass was presented [50]. Their ring radius of 500µm was decreased by almost an order of magnitude from the work discussed above. They also measured coupling efficiencies greater than 90% and finesse values of 15-20. The spacing of the waveguides in the coupling region is 1.5µm which may account for strong coupling efficiencies. They also measured a propagation loss of 2.3 dB/cm and an FSR of 84nm at λ=632.8nm.

In 1985, the first ring resonator made on an electro-optically tuneable material was realised. It was produced in lithium niobate by the method of proton exchange. The radius of the ring was 1.7mm and the waveguide separation in the coupler was approximately 2µm. A finesse of 6 was measured along with an FSR of 17nm at λ=632.8nm. No real improvement was obtained in terms of the figures of merit over previous resonator work, but since the device was fabricated in lithium niobate it could in theory be tuned.

Work continued slowly on ring resonators over the next ten years with rings being fabricated on phosphosilicate glass [51], silica [52], and GeO2 doped silica [53]. An improved ring resonator using silver ion exchange in glass was also produced that gave a finesse of 55, the largest value at that time [54].
Several interesting variations on the ring resonator began to emerge in the early to mid 1990's. Most notably were the double and multiple ring resonator devices [55-57]. Figure 2.7 demonstrates the concept of a multiple ring device [58]. The idea of multiple rings is that each subsequent ring couples with the previous one. The resonance condition is further restricted by the second (or more) rings as it must satisfy not only the conditions for the first ring but all the rings. Thus, any slight discrepancies in one of the rings, is filtered out by the conditions of the other rings. This would narrow the resonance peak and therefore increase the finesse of the device. Reference [55] reported a finesse of 138 for a two ring system. A drawback to this approach is that the rings must have almost the exact same optical path length. Processing variations may make this task difficult.

![Figure 2.7. SEM image of a three-ring resonator [58]](image)

In 1998, Little et al. published a paper that was very useful in understanding the fundamentals of a ring resonator [59]. In it, the authors discuss channel dropping filters on SOI material. The devices were fabricated on SOI material. Whilst the guiding layer was polysilicon, and not single crystal silicon, it nevertheless demonstrated the use of silicon processing technology to create these devices. They were able to fabricate rings with radii as small as 3µm thereby giving them an FSR of 24nm. Because their processing ability did not allow them the necessary 0.1-0.3µm waveguide separation in the coupling region, the result was that the straight waveguides and the ring fused together as shown in Figure 2.8. The spectral response at the throughput port for rings with radii of four and five microns is shown in Figure 2.9. Whilst they do not give a finesse value for the rings measured, they do determine the $Q$ value of the ring. The $Q$ value, or quality value, can be thought of in terms of the time averaged stored energy per optical cycle divided by the energy coupled to or scattered out of the resonator [60].
Therefore a device that loses light will have a low $Q$ value. The authors give a value of 250 for $Q$.

![SEM of a 3μm radius ring resonator in polysilicon](image1)

Figure 2.8. SEM of a 3μm radius ring resonator in polysilicon [59]

![Spectral response at the throughput port of the ring resonator](image2)

Figure 2.9. Spectral response at the throughput port of the ring resonator for rings with radii of 4 and 5 μm [59]

An estimate for the finesse can be made if the $Q$ value is known by using the following equation [61]:

$$Q = \frac{CN_gF}{\lambda}$$

(2.4)

where $N_g$ is the group index (defined in section 3.7), $C$ is the ring circumference, $F$ is the finesse, and $\lambda$ is the free-space wavelength of light. The determination of $N_g$ requires
modelling of the device. Therefore to determine an approximate value for the finesse, the refractive index of silicon is used instead. Rearranging the equation above, using $Q=250$, $R=3\mu m$, and $\lambda=1600nm$ gives a finesse of $\sim6.1$ [59].

As processing resolutions improve, more work is being done in strip waveguide resonators. Dumon et al. recently reported a ring resonator with waveguide height of 220nm and a width of 500nm. The bend radius is 5\(\mu\)m and the coupling length is 3\(\mu\)m leading to an FSR of 14nm, finesse of 28, and a Q value of 3000 [62]. Baher-Jones et al. also demonstrated a high-Q ring resonator composed of strip waveguides coated with PMMA that demonstrated Q values as large as 94,000 [63]. Their waveguides are 500nm wide by 120nm high, however, no other information pertaining to the dimensions or functionality of the device was given.

One of the largest Q-values to date on devices similar to those in this thesis is 119,000. This value was reported by Kiyat et al. [64]. The same authors also have obtained an FSR of 3nm using a 1\(\mu\)m high rib waveguide with a 0.5\(\mu\)m etch depth and bend radius of 20\(\mu\)m [65]. These results are important as they demonstrate that other researchers are interested in the methods used in this thesis. It also allows for a better comparison to the results obtained in this thesis with the results in the literature.

Another paper of interest demonstrated a thermally tuned ring resonator in Si$_3$N$_4$ on a silicon substrate [40]. By heating the ring, the thermooptic effect in silicon is employed to change the index of refraction of the ring, and hence its resonant wavelength. This is useful for making tuneable switches and filters for optical communication purposes. Whilst no quantities of the performance of ring were given, it demonstrated that efforts are underway to build a tuneable ring resonator. Figure 2.10 shows a schematic of the device.

A more impressive method of modulation was achieved in 2004. Almeida et al. demonstrated all-optical control of light in a ring resonator [66]. The authors use a 10ps
pump beam to induce two-photon absorption in the ring thereby generating free carriers. Two-photon absorption occurs when two photons, each with less than enough energy to bring an electron from the valance band to the conduction band of the semiconductor, arrive nearly simultaneously to a valence band electron. If the two photons arrive in phase, their wave amplitudes combine to effectively act like one photon with the correct energy to bring the electron from the valence band to the conduction band. The resulting free carriers in turn induce a change in the index of refraction due to the plasma dispersion effect. A probe beam with a wavelength that is resonant to the ring cavity is coupled to the device. The pump beam is also coupled to the device at another resonance of the device. Thus by pulsing the pump beam, modulation of the probe beam occurs. The authors were able to obtain a modulation depth (the measure of power at the output when the probe beam is resonant to when it is off resonance) of 94% and more importantly a response time of 100ps. This result demonstrates the enormous potential for racetrack resonators as modulator devices.

As stated previously, the spacing of the waveguides in the directional coupler is an important factor in creating a high quality resonator. This spacing determines the coupling efficiency of the resonator. To make an optical communications quality device this spacing needs to be on the order of 100nm [59]. This type of spacing is usually only achievable using e-beam lithography. Starting in the late nineties, a rather novel solution to this problem began to emerge; the vertically coupled ring resonator. Vertical coupling is achieved by placing the ring on top of the straight waveguides, as shown in Figure 2.11,
instead of next to them. The separation between the waveguide and the ring can then be controlled precisely by depositing a dielectric layer of desired thickness and then placing the ring on top. Such devices have been realised in the following material configurations: SiO$_2$-Ta$_2$O$_5$ [67-70], GaAs-AlGaAs [71, 72], and GaInAsP-InP [71] rings and waveguides. In [68], the authors measured an FSR of 10 nm and a $Q$ value of 800. Using equation 2.3, this translates to a finesse of 7.2 for $\lambda=1.55$ μm, $N=1.4508$, and $R=19\mu$m.

Reference [70] had a rather important impact in that it was one of the first recorded instances of a polarisation independent ring resonator. A device is polarisation independent if it functions regardless of the polarisation state of the input light. This is an important factor for telecommunication devices as fibres are typically degenerate. Thus, if the fibre were to be subjected to stresses, the initial polarisation state coupled to the fibre could be shifted into some other polarisation state.

On a final note, several other recent applications of ring resonators have been presented in the literature that are worthy of mention. The first is the use of optically active materials to fabricate ring resonators to create optical amplifiers [73], compact notch filters [74], wavelength converters [75], and tuneable lasers [76]. Ring resonators are also being employed as biochemical sensors to measure glucose concentrations, thus showing their utility in fields other than telecommunications [77].
2.3 References


Chapter 3

3 Theory, Modelling, and Device Design

The ring resonator is a rather complex device as it is comprised of two fundamental waveguiding components, the waveguide bend and the directional coupler (discussed in section 3.4). Making the device function as desired, regardless of the polarisation state of the light coupled to it, can make the study of the ring resonator even more complicated. However, by breaking the ring resonator down into its fundamental components and investigating the effect of polarisation on each, is a more pragmatic approach to the problem. This is the method used to attempt to investigate a Polarisation Independent (PI) ring resonator in this work. The investigation begins with the study of the rib waveguide in order to determine the cross-sectional dimensions necessary to yield a PI waveguide. Using these waveguide dimensions, the directional coupler is modelled to determine the necessary dimensions to realise a PI coupler. Finally, the waveguide bend is then modelled to determine its Polarisation Dependent Loss (PDL). Therefore if the bend has an equivalent loss for all polarisation states, the ring resonator as a whole should have the same functionality regardless of the input polarisation state.

This chapter begins with a brief discussion of the wave equation and the polarisation of light. Next, the rib waveguide is investigated. The directional coupler is then introduced and the methods to determine a polarisation independent coupler are discussed. This is followed by a discussion of the waveguide bend. An introductory formulation of a single input/output ring resonator has recently been described in the literature. The theory is reproduced herein as it has been found to be a useful tool in the analysis of fabricated devices. Whilst not directly related to the design of a ring resonator, this chapter concludes with a discussion of the Fabry-Perot resonance effect as it was used on several occasions to measure propagation loss in the waveguides.
3.1 The Wave Equation

One of the great successes of Maxwell’s equations is that they can be utilised to yield the electromagnetic wave equation [1]. In vacuum, the wave equation takes the following form:

\[
\nabla^2 \left( \frac{\vec{B}}{\vec{E}} \right) = \varepsilon_0 \mu_0 \frac{\partial^2}{\partial t^2} \left( \frac{\vec{B}}{\vec{E}} \right) \quad (3.1)
\]

where \( \varepsilon_0 \) and \( \mu_0 \) are the electric susceptibility and magnetic permeability of free space respectively, \( \vec{E} \) and \( \vec{B} \) are the electric and magnetic field vectors respectively that comprise the wave, and the Laplacian (\( \nabla^2 \)) in rectangular coordinates is defined as:

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (3.2)
\]

If one assumes a time dependent \((t)\) source of a plane electromagnetic wave [2]:

\[
\left[ \begin{array}{c} \vec{B} \\ \vec{E} \end{array} \right] (\vec{r}, t) = \left[ \begin{array}{c} B(\vec{r}) \\ E(\vec{r}) \end{array} \right] e^{i\omega t} \quad (3.3)
\]

where \( \omega \) is the oscillation frequency of the radiation, then equation 3.1 takes on the well-known Helmholtz equation form:

\[
\nabla^2 \left( \frac{B(\vec{r})}{E(\vec{r})} \right) + k_0^2 \left( \frac{B(\vec{r})}{E(\vec{r})} \right) = 0 \quad (3.4)
\]

where \( k_0^2 = \varepsilon_0 \mu_0 \omega^2 \). The variable, \( k_0 \), is defined as the free space propagation constant and is discussed further in section 3.2. For a plane wave there are no spatial variations in the transverse directions. Assuming propagation in the \( z \) direction, equation 3.4 can be written as [2]:

\[
\frac{d^2}{dz^2} \left( \frac{\vec{B}}{\vec{E}} \right) + k_0^2 \left( \frac{\vec{B}}{\vec{E}} \right) = 0 \quad (3.5)
\]

The solution to equation 3.5, assuming propagation in the positive \( z \) direction is:
\[ \begin{bmatrix} \bar{B}(z) \\ \bar{E}(z) \end{bmatrix} = \begin{bmatrix} \bar{B}_0 \\ \bar{E}_0 \end{bmatrix} e^{-jz} \tag{3.6} \]

As there are no known magnetic monopoles and in the absence of charge, from Maxwell's equations [2]:

\[ \nabla \cdot \left( \begin{bmatrix} \bar{B} \\ \bar{E} \end{bmatrix} \right) = 0 \tag{3.7} \]

where \( \nabla \) is defined as:

\[ \nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k} \tag{3.8} \]

applying this condition to equation 3.6, it is evident that:

\[ \nabla \cdot \left( \begin{bmatrix} \bar{B} \\ \bar{E} \end{bmatrix} \right) = 0 \tag{3.9} \]

where \( \bar{k} = k \hat{z} \) is defined as the propagation vector.

Thus \( \bar{E} \) and \( \bar{B} \) are transverse to the direction of propagation, which has been defined in this case as the \(+z\) direction. Again using Maxwell's equations one can determine that \( \bar{E} \) and \( \bar{B} \) are orthogonal to each other [2]. Hence, light is sometimes referred to as Transverse ElectroMagnetic (TEM) radiation [3].

When an electromagnetic wave impinges upon a material, a Fresnel reflection occurs [1]. The reflection coefficient is dependent not only upon the angle of incidence, but also upon the alignment of the electric field (or magnetic field) with respect to the material interface. The propagation vector, \( \bar{k} \), of the impinging light and material interface normal vector (\( \hat{n} \)) define a plane shown in Figure 3.1 as an orange rhombus. When the electric field vector (blue arrow) is aligned perpendicular to the \( \bar{k} - \hat{n} \) plane, the light is said to have a Transverse Electric (TE) polarisation, which is depicted in Figure 3.1. Similarly, when the magnetic field is aligned perpendicular to this plane, the light is said to have a Transverse Magnetic (TM) polarisation (not pictured).
The resultant Fresnel reflection coefficients for TE and TM polarisations that give rise to the reflected vector, $\vec{k'}$, are [3]:

$$r_{TE} = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2}$$  \hspace{1cm} (3.10)

$$r_{TM} = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_2}{n_2 \cos \theta_1 + n_1 \cos \theta_2}$$  \hspace{1cm} (3.11)

where $n_1$ is the index of refraction in which the light originates, $n_2$ is the index of refraction for the material which the light is incident upon, $\theta_1$ is the angle the propagation vector ($\vec{k}$) makes with respect to the interface normal vector, and $\theta_2$ is the angle the refracted propagation vector ($\vec{k'}$) makes with respect to the interface normal. These variables can be better visualised using Figure 3.2 where, for a slightly different representation than in Figure 3.1, the incident light is inside a material of higher index of refraction, and propagates into a material of lower index of refraction. This construction is particularly useful in the discussion of the waveguide.
3.2 The Waveguide

3.2.1 The Slab Waveguide

According to Snell's Law [1],

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  
(3.12)

Using Snell's Law, equations 3.10 and 3.11 can be re-written in terms of the incident angle and the indices of refraction to determine the amplitude of the reflected propagation vector \( \vec{k} \) [3]:

\[
r_{TE} = \frac{n_1 \cos \theta_1 - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_1 \cos \theta_1 + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}
\]
(3.13)

\[
r_{TM} = \frac{n_2 \cos \theta_1 - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_2 \cos \theta_1 + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}
\]
(3.14)

For \( \theta_2 = 90^\circ \) and \( n_1 > n_2 \), light incident in the medium with refractive index \( n_1 \), will undergo Total Internal Reflection (TIR) such that \( r_{TE} = r_{TM} = 1 \). The associated incident angle is defined as the critical angle:

\[
\theta_c = \sin^{-1} \left( \frac{n_2}{n_1} \right)
\]
(3.15)
It is interesting to note that for a Si/air \((n_{Si}=3.47/n_{air}=1.00)\) interface the critical angle is 16.7°. For a Si/SiO\(_2\) \((n_{SiO2}=1.44)\) interface, the critical angle is 24.5°. These small critical angles imply that silicon has strong optical confinement when surrounded by a material of a much lower index of refraction such as silicon dioxide or air.

For \(\theta > \theta_c\), light is still totally internally reflected. However, the square roots in equations 3.13 and 3.14 become imaginary so that the reflection coefficient becomes complex. The result is a phase shift of the reflected wave [3]:

\[
\phi_{TE} = 2 \tan^{-1} \sqrt{\frac{\sin^2 \theta_i - \left(\frac{n_2}{n_1}\right)^2}{\cos \theta_i}} \quad (3.16)
\]

\[
\phi_{TM} = 2 \tan^{-1} \frac{\left(\frac{n_1}{n_2}\right)^2 \sin^2 \theta_i - 1}{\frac{n_2}{n_1} \cos \theta_i} \quad (3.17)
\]

TIR becomes a useful property when an electromagnetic wave can be confined. By adding a second material interface above the first in Figure 3.2, light may be confined in the vertical direction, so long as the angle with which the wavevector strikes the interface is larger than the critical angle. Thus a one-dimensional slab waveguide is created. A silicon slab waveguide can be formed by placing a slab of silicon on top of a silicon dioxide layer so that the top interface of the slab is air/silicon and the bottom layer is silicon/SiO\(_2\) as shown in Figure 3.3. For many applications, the silicon slab thickness is of the order of 1 \(\mu\)m. To support a layer of this thickness, a thick silicon substrate is used. The silicon dioxide layer, therefore, is used to prevent light coupled into the slab from passing into the silicon substrate. This important material arrangement is defined as Silicon-On-Insulator (SOI) and is discussed further in section 5.1.

Because of the polarisation dependence of the phase change a wave experiences as it propagates in a waveguide, a TE polarised wave will in general propagate with a different velocity than a TM polarised wave. One of the primary goals in the investigation of a polarisation independent ring resonator is to determine a PI waveguide. For a waveguide
to be PI, a wave must propagate at the same velocity in the waveguide regardless of its polarisation state. A value used to quantify the rate of propagation of light in a waveguide is the propagation constant, $k$. This can be seen by investigating the phase factor ($\phi$) of equation 3.6. The spatial rate of change of $\phi$ in the $z$-direction is:

$$\frac{d\phi}{dz} = k$$

(3.18)

Hence the spatial rate of change of the phase in the propagation direction is simply the propagation constant. As defined earlier, the propagation constant in vacuum, $k_0$, can be rewritten as:

$$k_0 = \sqrt{\varepsilon_0 \mu_0} \omega = \frac{\omega}{c} = \frac{2\pi}{\lambda_0}$$

(3.19)

where $c (=1/\sqrt{\varepsilon_0 \mu_0})$ is the velocity of light in a vacuum and $\lambda_0$ is the wavelength of light in vacuum [1]. A similar propagation constant can be determined for a homogeneous, isotropic material with an electric susceptibility $\varepsilon_m$ and magnetic permeability $\mu_m$. The index of refraction of a material can be defined as the ratio of the speed of light in vacuum to the speed of light in a material [1]:

$$n = \frac{c}{v_p}$$

(3.20)

where $v_p (=1/\sqrt{\varepsilon_m \mu_m})$ is the propagation velocity of an electromagnetic wave in the material in question [3]. The propagation constant in a material can therefore be defined as:
Thus the propagation constant of an unconfined wave in a material can be determined simply by knowing the index of refraction of the material which the wave is propagating in and its wavelength in vacuum.

When light is confined, the wavevector propagates in a zig-zag fashion as shown in Figure 3.3. The wavevector \( \vec{k} \), whose amplitude is the propagation constant \( k_m \), can be decomposed into two orthogonal vectors whose propagation constants are [3]:

\[
k_x = n_s k_m \sin \theta_i
\]

\[
k_y = n_s k_m \cos \theta_i
\]

where \( k_y, k_z, \) and \( \theta_i \) are defined in Figure 3.3. From this decomposition, the propagation constant, \( k_y \), implies a wave reflecting back and forth from the top and bottom material interfaces. Equations 3.16 and 3.17 (depending on the polarisation of the light) state that a phase shift is applied to the reflected wave. As these equations are dependent upon the indices of refraction at the interface, the phase shift caused by silicon/air interface \( (\phi_s) \) will be different from the phase shift caused by the silicon/silicon dioxide interface \( (\phi_t) \).

For an implied wave travelling in the \( y \) direction, its total phase shift, \( \phi_i \), is given by [3]:

\[
\phi_i = 2h k_y - \phi_t - \phi_u
\]

where \( h \) is the height of the silicon slab. In order for this wave to be consistent, it must form a standing wave between the two interfaces so that [3]:

\[
2h k_y - \phi_t - \phi_u = 2m \pi, \text{ for } m=0, 1, 2, 3, \ldots
\]

This result implies that only certain wavevectors with discrete reflection angles \( (\theta_i) \) can be supported by the waveguide slab. Light that has a wavevector that satisfies equation 3.25 for a given index value, \( m \), is called a mode of the waveguide. The value \( m \) is also called the mode number. The mode for which \( m \) is zero is defined as the fundamental mode of the waveguide.
The preceding theory allows us to calculate the wave propagation rate in a waveguide. Inspection of equation 3.22 implies that this defined propagation constant, $k_z$, is the rate at which light propagates along the z-direction in the waveguide. Hence, by defining the effective index, $N$, as [3]:

$$N = n_s \sin \theta_1$$  \hspace{1cm} (3.26)

equation 3.21 becomes:

$$\frac{1}{q} = \frac{M}{c_0}$$  \hspace{1cm} (3.27)

Equation 3.27 is similar in form to equation 3.21 where the propagation constant of light in a material was determined by the index of refraction of the material and the propagation constant in vacuum. The constraint of confining light in a waveguide has altered the propagation constant such that if the light were travelling unconfined in a material with an index of refraction equivalent to $N$, it would effectively propagate with the same velocity as when it is confined in the waveguide. Thus by determining an effective index that is equivalent for both polarisation states, the waveguide will be PI.

Whilst on the topic of propagation constants, an alternative symbol, $\beta$, is often quoted in the literature for the propagation constant [3]. However this value is slightly different from the propagation constants defined above as it is a complex value which incorporates loss mechanisms encountered by the propagating wave. It is therefore defined as [3]:

$$\beta = \beta_r - j\frac{\alpha}{2}$$  \hspace{1cm} (3.28)

where $\beta_r = k_z$ and $\alpha$ is the loss coefficient. The discussion of loss and loss mechanisms brings little to the development of theories in this work. Therefore in order to avoid unnecessarily complicating this discussion with loss, $\alpha$ is neglected.

In order to determine the effective index of a waveguide, the reflection angle $\theta_1$ must first be determined. This can be achieved by applying either equation 3.16 or 3.17 to equation 3.25, depending on the polarisation state of the propagating wave. Using the material structure of Figure 3.3 and as an example the phase shift upon reflection for TE light, (equation 3.16) equation 3.25 takes the form:
The right side of equation 3.29 could be simplified by applying a silicon dioxide layer to the top of the silicon making it a symmetric structure. However, graphical or numerical methods techniques are required to solve for the reflection angle $\theta_i$, and hence the effective index of the waveguide. Because of equations 3.16 and 3.17, the effective index is dependent upon the polarisation state of the propagating light. Thus by finding an equivalent effective index for identical waveguide dimensions, the waveguide will be PI. An optical waveguide modelling software program can be used to determine the effective index of the waveguides and is used extensively in this work. It is discussed further in section 3.3.

### 3.2.2 Two-Dimensional Confinement

Planar waveguides have limited utility in most practical applications. By confining light in the $x$ and $y$ directions (assuming propagation in the $z$ direction), the waveguide becomes a much more practical tool in manipulating optical signals. Two-dimensional confinement of light can be achieved by etching two, slightly separated, parallel trenches into a slab waveguide. The result is a strip waveguide whose width is determined by the separation of the trenches (see Figure 3.4(a)). This type of waveguide, whilst potentially compact, can have several drawbacks. In order to make the waveguide propagate only a single optical mode, the waveguide’s cross-sectional dimensions need to be of the order of several hundred nanometres. As a typical single mode fibre at the telecommunications wavelength has a core of approximately 9$\mu$m, coupling to and from a waveguide may prove difficult [3]. Fabrication could potentially be more costly as high resolution photolithography would be needed to obtain the necessary submicron dimensions.

As introduced in section 2.1, a rib waveguide can be much larger than a strip waveguide and yet still maintain the single mode condition. Pictured in Figure 3.4(b), a rib
waveguide is created by only etching partial trenches into the silicon slab instead of etching completely down to the oxide as in the case of a strip waveguide. These shallow-etched slab regions (1 & 3 in Figure 3.4(b)) cause the light propagating in the waveguide (region 2) to be less confined in the lateral (x) direction as compared to regions where the silicon is etched to silicon dioxide layer. Less confinement allows the mode to have a larger mode field diameter. Thus by choosing the cross-sectional dimensions of the waveguide so that they satisfy the single-mode condition equation (equation 2.1 of chapter two), the waveguide can have dimensions of the order of micrometers and still be single mode. The single mode condition is important for the ring resonator device as higher order modes would have different resonance conditions which would degrade the overall performance of the device.

As discussed previously, the propagation velocity of a mode in a rib waveguide will be dependent upon its polarisation state. Because of the two-dimensional nature of these waveguides a slight modification to the definitions of the TE and TM polarisation states is required. A mode whose electric field lies parallel to the oxide layer is defined as being TE polarised. A mode whose electric field is perpendicular to the oxide layer is defined as being TM polarised (i.e. the magnetic field vector of the light lies parallel to the oxide layer).
3.3 Polarisation Independent Rib Waveguide Modelling

As discussed in section 3.2.1, the effective index can be used to determine the necessary waveguide dimensions to create a PI waveguide. For a rib waveguide, the determination of the effective index becomes even more complex. Not only must the effective index of region 2 in Figure 3.4(b) be calculated, but it must also be calculated for the slab regions of 1 and 3. Therefore in order to greatly simplify the calculations, the waveguide modelling software BeamPROP™ is used to calculate the effective index of the waveguides [4].

To aid in the sample preparation of fabricated devices, a silicon dioxide layer is placed on top of the waveguide. The modelling takes this into account. The index of refraction used in the program for the buried silicon dioxide layer and top layer is 1.444 [5]. The index of refraction for the silicon waveguiding layer is 3.476 for a free-space wavelength (wavelength of light in a vacuum) of 1550nm [5].

The method for determining the waveguide dimensions necessary to yield a PI rib waveguide is as follows. As a starting point, the waveguide height is 1.35µm and is kept constant throughout the study. This value is chosen from a fabrication standpoint and is discussed further in section 5.2. A waveguide width of 1µm is also kept constant throughout the study. For each polarisation state, the effective index is calculated for various rib etch depths (or similarly, slab heights). A cross-section profile of the rib waveguide used in the study is shown in Figure 3.5(a). For a given slab height, the effective index of TM polarised light is subtracted from the effective index of the TE polarised light. The difference ($\Delta N$) is then plotted as a function of the rib etch depth, as shown in Figure 3.5(b). For $\Delta N$ equal to zero, the corresponding rib etch depth is 0.828µm. This is the required etch depth to realise a PI rib waveguide for the pre-defined dimensions in Figure 3.5(a). For these dimensions, the waveguide was found to be near the single mode (only the fundamental (m=0) is confined in the waveguide) multimode boundary [6]. To start the project quickly, initial modelling was carried out by Dr. A. Liu of the Intel Corporation [5]. These results were subsequently verified by the author.
Figure 3.5. (a) Cross-section profile of the rib waveguide used to determine the PI waveguide dimensions. (b) Modelling of the effective index to determine the correct rib etch depth for a PI waveguide (modelling by A. Liu of the Intel Corporation).

Shown in Figure 3.6, subsequent modelling of the rib waveguide demonstrates that a single mode, PI rib waveguide, can also be realised for different waveguide widths but all with approximately the same etch depth. This result is important in terms of fabricating real devices. Processing tolerances may cause actual devices to have dimensions slightly different than expected. This result implies that a fabricated waveguide may function as desired even if the processing is slightly in error.

Figure 3.6. Single mode, PI rib waveguides for various waveguide widths (Modelling by A. Liu of the Intel Corporation)
3.4 The Directional Coupler

The previous discussion of a TEM wave propagating in a waveguide was given in the simplest of terms so that only the necessary concepts were introduced. One subtle but important concept was omitted from the discussion, the boundary conditions of the waveguide. The electric field and its first spatial derivative of a waveguide must be continuous across the boundary [3]. As a result, a portion of the electric field of the TEM wave resides outside the confines of the waveguide boundaries. This exponentially decaying field as a function of distance from the waveguide is referred to as the evanescent field.

If two identical, parallel waveguides are brought into close proximity so that for an optical mode propagating in the first waveguide has its evanescent field overlap the evanescent field profile of the second waveguide, an interesting result occurs. A mode propagating in the first waveguide will begin to transfer, or couple, to the second. This parallel waveguide device is known as a directional coupler. A schematic is shown in Figure 3.7. The power of the mode will continue to couple from the first waveguide to the second so long as the two waveguides maintain their proximity. The length of the coupler where the entire mode from the first waveguide is coupled to the second is defined as the coupling length, or $L_n$. If the proximity of the waveguides is maintained beyond $L_n$, the mode in second waveguide will couple back to the first. This sinusoidal coupling of power will continue so long as the proximity of the waveguides is maintained.

3.4.1 Mathematical Derivation of the Directional Coupler

Mathematically, the directional coupler can be presented in the following manner [7]. The electric field of the propagating mode inside one waveguide can be stated as:

$$\tilde{E}(x, y, z) = C(z)\tilde{E}(x, y)$$  \hspace{1cm} (3.30)

where $C(z)$ is the complex amplitude of the electric field and $\tilde{E}(x, y)$ is the normalised transverse field distribution of the mode in the waveguide. Assuming the waveguides are
symmetric, the following equations describe the change in amplitude of the mode as it propagates through the coupler [7]:

$$\frac{dC_1(z)}{dz} = -i\beta C_1(z) - i\kappa C_2(z)$$ \hspace{1cm} (3.31)

$$\frac{dC_2(z)}{dz} = -i\beta C_2(z) - i\kappa C_1(z)$$ \hspace{1cm} (3.32)

where the subscripts denote the waveguide number, $\kappa$ is the coupling constant of the waveguides, and $\beta$ is defined previously in equation 3.28.

If the following boundary conditions are used:

$$C_1(0) = 1$$ \hspace{1cm} (3.33)

$$C_2(0) = 0$$ \hspace{1cm} (3.34)

then the solutions to equations 3.31 and 3.32 respectively, are:

$$C_1(z) = \cos(\kappa z)e^{-i\beta z}$$ \hspace{1cm} (3.35)

$$C_2(z) = -i\sin(\kappa z)e^{-i\beta z}$$ \hspace{1cm} (3.36)

Neglecting loss ($\alpha=0$ in equation 3.28), the power flow in each of the waveguides is determined by squaring the amplitudes $C_1$ and $C_2$ which gives:

$$P_1(z) = \cos^2(\kappa z)$$ \hspace{1cm} (3.37)

$$P_2(z) = \sin^2(\kappa z)$$ \hspace{1cm} (3.38)

where the fact that

$$P_n(z) = |C_n(z)|^2 = C_n(z)C_n^*(z)$$ \hspace{1cm} (3.39)

is used. It can be seen that the total power in the coupler is conserved since:

$$P_1(z) + P_2(z) = \cos^2(\kappa z) + \sin^2(\kappa z) = 1$$ \hspace{1cm} (3.40)

Thus optical power transfers in a sinusoidal fashion between the waveguides as the mode propagates in the $+z$ direction. When $\kappa z=\pi/2$, all of the power from the first waveguide is
transferred into the second. This is the definition of coupling length of the coupler introduced previously so that:

\[ L_n = \frac{\pi}{2\kappa} \]  

(3.41)

A ring resonator can be formed by connecting the output of one of the coupler’s waveguides, by way of a circular or ‘ring’ waveguide, to its input. The other waveguide of the coupler is then defined as the input/output waveguide for the ring resonator device. The single input/output ring resonator is discussed further in section 3.6.

Because of the straight waveguide section of the directional coupler, a ring with a sizeable coupler length will take on an oval, or racetrack, appearance. In fact, to maintain the bend radius used in the bends, a straight length of waveguide is placed parallel to, but at the other ends of the 180° bends entering/exiting the coupling region (see Figure 4.6 of chapter four for an example). The term ‘racetrack resonator’ is used more commonly for rings with large directional couplers lengths. Hence the terms ‘ring’ and ‘racetrack’ are used interchangeably throughout this work.

The coupling coefficient, \( \kappa \), is a function of the free-space wavelength, the polarisation state of the light, the cross-sectional dimensions of the waveguides, and the separation of the waveguides [3]. As \( L_n \) is a function of the coupling coefficient, then so too must \( L_n \) be a function of all of these variables. Therefore in order to determine the \( L_n \) necessary for a PI device, the modelling program beamPROP is used to model the coupler.

3.4.2 The Beam Propagation Method

Indicative of its name, BeamPROP uses the Beam Propagation Method (BPM) to model waveguiding devices [4]. BPM is a method for approximating the rapidly varying wave equation for a monochromatic wave [8]. Assuming scalar fields, the Helmholtz equation (3.4) can be written as:
where \( k \) was previously defined in equation 3.21 but with the modification that the index of refraction, \( n \), is actually \( n(x,y,z) \) so that it defines the index of refraction distribution of the waveguiding structure thus taking into account the geometry of the waveguide.

For many guided-wave problems, it is the phase variation along the propagation direction that changes rapidly (the \( e^{j k z} \) factor in equation 3.6). The assumption of BPM is to remove this rapidly varying field by introducing a relatively slowly varying field, \( u \), so that:

\[
\phi(x, y, z) = u(x, y, z) e^{j \bar{k} z}
\]  

(3.43)

where \( \bar{k} \) is a constant chosen to represent the average phase variation of the field. Applying equation 3.43 to equation 3.42 yields:

\[
\frac{\partial^2 u}{\partial z^2} + 2i k \frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u = 0
\]  

(3.44)

The scalar Helmholtz equation has been rewritten in terms of the slowly varying field, \( u \). Assuming that the variation of \( u \) with \( z \) is sufficiently slow the first term can be neglected. Rearranging equation 3.44 gives the basic BPM equation in three dimensions:

\[
\frac{\partial u}{\partial z} = i \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u \right)
\]  

(3.45)

Thus by applying numerical methods to solve this equation, the BPM method can be used to model a waveguiding device. The RSoft Group, designers of the software program, have enhanced the scalar BPM discussed above by incorporating algorithms to allow for vector fields to be considered as well as reduced some of the restrictions of BPM such as the paraxial approximation (propagation of the wave occurs on an approximately straight path so that the partial differential equation in equation 3.45 remains valid). The program can therefore calculate polarisation dependent waveguide structures which is important for this work.
3.4.3 Modelling of a Polarisation Independent Directional Coupler

Building on the results of section 3.3, the cross-sectional dimensions of the PI rib waveguide are used as constraints in studying the directional coupler. The study of the coupler entails varying the length of the coupler and the waveguide separation. A cross-sectional schematic showing the constrained dimensions is shown in Figure 3.7.

![Cross-sectional view of a directional coupler](image)

Because of the numerous factors that influence the coupling constant, it is unlikely that a coupler length $L_x(TE) = L_x(TM)$ will be found as is necessary for a PI directional coupler using the PI rib waveguide dimensions as constraints. Nonetheless, a PI directional coupler can be realised by utilising the sinusoidal power flow between the waveguides. In Figure 3.8, a plan-view of a modelled directional coupler (coupler length of 1200μm, waveguide separation of 0.63μm, and free-space wavelength of 1550nm) for TE and TM polarisation states is shown. Light is initially coupled into the first waveguide. For TE polarisation, $L_x$ is achieved for a coupler length of approximately 340μm. For TM polarisation, however, $L_x$ is approximately 1030μm. A re-inspection of the TE data at 1030μm shows that the light has undergone three complete transitions in this length. As demonstrated by the black line in Figure 3.8, $3L_x(TE) \approx L_x(TM)$. Thus the directional coupler is effectively polarisation independent for a coupler length of 1030μm.
The result of Figure 3.8 was determined by plotting $L_n$ for TE and TM polarisation states as a function of waveguide separation, as shown in Figure 3.9. Also plotted are the $3L_n$ and $5L_n$ results. The $5L_n$ definition is analogous to the $3L_n$ definition described above in that five complete transfers of power have occurred between the waveguides for a given coupler length. Thus the dimensions of a PI directional coupler are determined where the TM and one of the TE data lines intersect. For the particular cross-sectional waveguide dimensions as shown in Figure 3.7, two PI directional couplers are determined. The first has a coupling length of approximately 1030µm and corresponding waveguide separation of approximately 0.62µm. The other has a coupling length of approximately 4841µm and a corresponding separation of approximately 0.95µm.

Figure 3.8. Plan-view of a modelled directional coupler for TE and TM polarisation states (Modelled by A. Liu of the Intel Corporation)
Using the same method described above, further modelling of the directional coupler was pursued by the author. Further along in the project, the opportunity arose to design a second set of test devices. According to the results of Figure 3.6, several waveguide widths have the ability to produce a PI rib waveguide. Hence a study of the directional coupler was carried out using various waveguide widths. For this study, the waveguide height and rib etch depth are maintained at 1.35μm and 0.82μm respectively. The results of the study are shown in Figure 3.10(a-c). This etch depth is the approximate average of the etch depths for the various PI waveguide widths in Figure 3.6. This value was used to significantly reduce the amount of modelling parameters especially since the processing accuracy of the rib etch is of the order of 20nm [9].

An interesting trend can be observed from the data in Figure 3.10. As the waveguide width decreases, the coupling length needed to design a PI directional coupler decreases. In fact, for a 0.8μm wide waveguide, the coupling length is approximately 310μm. This
is approximately a third of the length needed for a 1μm wide waveguide directional coupler.

Figure 3.10. Directional coupler modelling results for a waveguide width of (a) 0.7μm, (b) 0.8μm, and (c) 0.9μm. The waveguide height and rib etch depth were maintained at 1.35μm and 0.82μm respectively.
It is ideal to have as short a coupler as possible when designing a ring resonator. Not only is less space consumed, but one of the fundamental properties, the free spectral range (defined in section 3.6), is enhanced by having a short coupler. Thus the 0.7µm and 0.8µm waveguide width directional couplers are studied in the second set of fabricated test devices. The 0.7µm wide devices, however are expected to have some polarisation dependence due to the etch depth difference between the PI rib waveguide and the modelled directional coupler.

3.5 Waveguide Bends

The final component required to create a ring resonator device is the waveguide bend. Waveguide bends are necessary to connect the output of one of the arms of the directional coupler back to its input. Even though the waveguide bend is a rib waveguide and a rib waveguide can be made PI as discussed previously, the bend makes the polarisation issue slightly more complex. Figure 3.11(a) shows a modelled cross-sectional image of a TE mode in a waveguide bend (R=100µm) as compared to a mode propagating in a straight waveguide (Figure 3.11(b)). Both waveguides have the same cross-sectional dimensions as the PI rib waveguide with a width of 1.0µm.

The mode in Figure 3.11(a) is slightly pushed to the right (for a waveguide bending to the left), as can be seen by comparing the slab region of both modes in the figure. As the radius of the bend is decreased, more and more of the mode will leak out of the waveguide and into the slab. As optical confinement is dependent upon the polarisation state, each state will incur a different amount of loss as a function of bend radius [3]. This can be seen by the modelling of a TE and TM mode propagating in a bend with a 50µm bend radius. The cross-sectional dimensions are equivalent to those used in Figure 3.5(a) with an etch depth of 0.83µm. The TM (Figure 3.12(a)) mode shows almost no discernable perturbation due to the bend. The TE mode (Figure 3.12(b)), however, is showing a substantial amount of leakage into the slab. In fact the model was stopped only after a few microns into the bend to obtain Figure 3.12(b), as all of the light was lost by the end.
Chapter 3: Theory, Modelling, and Device Design

Figure 3.11. Cross-sectional image of a modelled waveguide with a confined TE mode (a) in a waveguide bend (R=100μm) and (b) a straight waveguide. Both waveguides have the same cross-sectional dimensions as the PI rib waveguide with a width of 1.0μm.

Loss that is dependent upon the polarisation state of the confined mode is known as Polarisation Dependent Loss (PDL). Discussed above, the waveguide bend has more loss due to slab leakage for TE polarisation than TM. As a result, the waveguide bend has PDL. A bend loss study was therefore conducted to find not only a reasonably small amount of loss for the waveguide bend but also to have a similar amount of loss for each polarisation state for a given bend radius. BeamPROP has the ability to model an 'effective' bend using BPM [8]. The program applies a coordinate transformation to a straight waveguide section to simulate the effects the bend has on the propagating mode.
The effective bend method is therefore used to model the bend loss of a 90° bend as a function of bend radius for both polarisation states. The dimensions of the 1μm wide PI rib waveguide are used in the study. The results of this study are shown in Figure 3.13. In the model, two small sections of straight waveguide are added before (approximately 10μm long) and after (approximately 100μm long) the effective bend waveguide section. This is done so that beforehand, the mode is correctly launched into the bend, and afterward, the mode is able to settle so that an accurate value of the loss can be made.

Figure 3.13. Modelled loss of a 90° waveguide bend as a function of bend radius (modelled by A. Liu of the Intel Corporation)

The modelling demonstrates that PDL becomes noticeable below 400μm. Even at this radius the loss for both polarisation states is very small. Other loss factors such as sidewall roughness of the rib waveguide may be considerable. BeamPROP does not take these other loss factors into account. Therefore as a conservative measure, the first fabricated ring resonators have a bend radius of 400μm.
3.6 Single Input/Output Ring Resonator Theory

A straightforward model of the functionality of a single input/output ring resonator was recently presented by Dr. A. Yariv and is summarised below [10]. This model is very useful in studying the fabricated ring resonators. The model can be used to fit the experimental results so that some of the parameters of the resonator can be determined. The model begins by considering the behaviour of the directional coupler. Two assumptions are made: 1) coupling is limited to waves travelling in only one direction (i.e. no reflections) and 2) there is no loss inherent in the coupler. With these two assumptions, the coupler can be described in terms of two coefficients via the unitary scattering matrix:

\[
\begin{pmatrix}
  b_1 \\
  b_2
\end{pmatrix} =
\begin{pmatrix}
  t & \kappa \\
  \kappa^* & -t^*
\end{pmatrix}
\begin{pmatrix}
  a_1 \\
  a_2
\end{pmatrix}
\]  

(3.46)

where \( a_1, a_2 \) are the coupler input amplitudes of the input waveguide and ring respectively, \( t \) is the transmission coefficient, \( \kappa \) is the coupling coefficient, and \( b_1, b_2 \) are the coupler output amplitudes of the output waveguide and ring respectively, as shown in Figure 3.15. The coefficients of the matrix are related by:

\[
|t|^2 + |\kappa|^2 = 1
\]  

(3.47)

Propagation around the ring is described by the equation:

\[
a_2 = b_2 K e^{i\theta}
\]  

(3.48)

where \( K \) describes the loss of the ring (\( K=0.95 \) means 95% transmission, 5% loss) and \( \theta \) is the phase shift induced per circulation around the ring. Combining equations 3.46-3.48, solving for \( b_2/a_1 \), and squaring the result yields the normalised power in the output waveguide:

\[
\left| b_2/a_1 \right|^2 = \frac{K^2 + |t|^2 - 2K|t|\cos(\theta + \varphi)}{1 + K^2|t|^2 - 2K|t|\cos(\theta + \varphi)}
\]  

(3.49)

where \( \varphi \) is the phase factor from \( t \), which is a complex value. Without loss of generality, the input power \( |a_1|^2 \) can be set to 1. The phase term in equation 3.49 can be stated in
terms of the free space wavelength, $\lambda$, the group index (defined in section 3.7), $N_g$, and the circumference of the ring, $L$:

$$\theta + \varphi = \frac{2\pi}{\lambda} N_g L$$

(3.50)

Inserting equation 3.50 into 3.49 yields an equation that can be used to model the results of a single input/output ring resonator:

$$|b_1|^2 = \frac{K^2 + |\epsilon|^2 - 2K|\epsilon|\cos\left(\frac{2\pi}{\lambda} N_g L\right)}{1 + K^2 |\epsilon|^2 - 2K|\epsilon|\cos\left(\frac{2\pi}{\lambda} N_g L\right)}$$

(3.51)

Figure 3.15 is a plot of equation 3.51 giving the spectral response of a single input/output ring resonator as a function of wavelength where $K=0.82$, $t=0.76$, $N_g=3.619$, $L=4.573\text{mm}$, and $\lambda=1550\text{ nm}$. These values were chosen to approximate fabricated devices.
Several important parameters can now be defined that quantify the functionality of the resonator. The first is the Free Spectral Range (FSR). The FSR is defined as the distance between the periodic resonance minima, as shown in Figure 3.15 [2]. Mathematically the FSR can be defined for a ring resonator as:

$$FSR = \frac{\lambda^2}{CN_g}$$

(3.52)

where $C$ is the circumference of the ring and $N_g$ is the group index (defined in section 3.7).

Another parameter that is used as a figure of merit is the finesse, $F$, of the resonator. It is defined as [10]:

$$F = \frac{FSR}{FWHM}$$

(3.53)

where the Full Width at Half Maximum (FWHM) is defined as the width of a resonant minimum measured half way up the resonance amplitude (see Figure 3.15). The finesse can be used to calculate yet another figure of merit, the quality, or $Q$, of a resonator. The value $Q$ is a measure of a resonator's wavelength selectivity as well as its ability to store energy. It can be defined as the time averaged energy stored in the ring per optical cycle divided by the power coupled (or scattered) out of the ring [11]. For completeness, $Q$ is restated here from chapter two. In terms of $F$, $Q$ can be defined as:

$$Q = \frac{CN_g F}{\lambda_0}$$

(3.54)

Thus if power is scattered from the ring, $Q$ will decrease. Since $Q$ is proportional to $F$, this implies that the FWHM increases for a lossy resonator. Hence the finesse can give a sense of the loss of the resonator as ideally it should be as large as possible, equating to minimum loss.

Another value of interest is the extinction ratio. This value is typically defined as the ratio of the power in the output waveguide when the resonator is off resonance to the power when the resonator is on resonance. Ideally this value should be as large as possible. This implies that the smallest amount of power should be passed to the output.
waveguide when the resonator is on resonance. This can be achieved by matching the power at the output of the ring with the power entering the ring from the input waveguide. If these two powers are matched when the resonator is on resonance, total destructive interference will occur, and hence no light will pass to the output waveguide. This condition is known as ‘critical coupling’ [10]. This concept is similar to the idea of matching the intensities of each arm in an interferometer to achieve a total destructive/constructive interference fringe pattern. Therefore in order to achieve critical coupling in the fabricated devices, it may be necessary to adjust the input power coupled to the device.

3.7 The Group Index

Several times in the previous section, the group index is used where typically the effective index (discussed in section 3.2.1) could be used. This is because the spectral response of a resonator is a function of the wavelength, and hence dispersion must also be considered. The spectral response of a device is achieved by measuring the transmitted power through the device for a series of wavelengths. If the device is dispersive then each wavelength will have a different propagation velocity and hence effective index. These wavelengths can be thought of as a group of wavelengths travelling in the device with a group velocity. Therefore by investigating the group velocity of the device a more accurate value of the index can be determined for the model. The index which accounts for dispersion is known as the group index. For a grouping of wavelengths in a dispersive material with propagation constant $k$ and angular frequency $\omega$, the group velocity, $v_g$, can be defined as [2]:

$$v_g = \frac{d\omega}{dk}.$$  (3.55)

Using the fact that $k = \omega n / c$, the group velocity can be written as:

$$v_g = \frac{c}{N_{eff} - \lambda \frac{dN_{eff}}{d\lambda}}.$$  (3.56)

The group index can therefore be defined as:
Geometric and material dispersion are the two that affect the response of a single mode racetrack resonator. Using the Sellmeier coefficients for silicon the Sellmeier equation can be used to determine the material dispersion [12]:

\[
\frac{n^2}{\lambda^2} = 11.6858 + \frac{0.939816}{\lambda^2} + \frac{0.009934}{\lambda^2 - 1.22567}
\]

(3.58)

where \(\lambda\) is the free space wavelength with units in micrometres. In Figure 3.16 the Sellmeier equation is plotted along with measured values of the index of refraction at various wavelengths from the literature [13]. The quoted values had no stated error so error bars were omitted. Regardless, most of the data points fall to within 0.3% of the Sellmeier equation line. Expanding the wavelength region from 1.5 to 1.6\(\mu\)m the slope of the Sellmeier equation line \((dn/d\lambda)\) was found to be -0.0759\(\mu\)m\(^{-1}\). Therefore for \(\lambda=1.55\mu\)m, the material dispersion contribution \((\lambda(dn/d\lambda))\) to the group index is -0.118 with the assumption that \(dn \approx dN_{\text{eff}}\).

---

Figure 3.16. Plot of the Sellmeier equation for silicon as compared with measured values of the index of refraction for silicon at various wavelengths
In order to determine the geometric dispersion, BeamPROP is used to calculate the effective index as a function of wavelength. Figure 3.17 shows a typical plot of the effective index as a function of wavelength for a 1μm wide rib waveguide with an etch depth of 0.83μm using TE polarised light. The slope of the data can then be used to determine the contribution of the geometric dispersion to the group index. Unlike the material dispersion, the geometric dispersion is dependent upon the cross-sectional dimensions of the waveguide and hence no 'standard value' of the geometric dispersion can be given. To facilitate a discussion on the effect of the dispersion on the accuracy of Yariv’s model, however, the geometric dispersion was calculated from the data in Figure 3.17. The slope of the data is -0.0002 which results in a contribution to the group index of -0.130 for λ=1550nm.

From Figure 3.17, the effective index of the waveguide at λ₀=1550nm is 3.371. Because of the minus sign in front of the dispersion contribution factor (λ(dNₑff/dλ)) in equation 3.57, the negative values obtained for the geometric (-0.130) and material (-0.118) dispersion add to the effective index so that the group index is 3.619. Thus the dispersion accounts for a 9% correction compared to simply using the effective index alone, when working with Yariv’s model.

![Figure 3.17. The effective index of a rib waveguide as a function of wavelength. The slope of the line is used to determine the dispersion due to the geometry of the waveguide.](image.png)

61
3.8 Measurement of Loss via Fabry-Perot Resonances

A Fresnel reflection occurs at the waveguide’s silicon/air interface, or facet, due to the index of refraction mismatch between the two materials. Assuming normal incidence, the reflection coefficient, \( R \), for either polarisation state is determined by equation 3.10 (or 3.11):

\[
R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}
\]  

(3.59)

where \( n_x \) is the index of refraction for a material in region \( x \). Using the indices for air \( (n_1=1.00) \) and silicon \( (n_2=3.47) \) the reflection coefficient is 31%. Thus an incident beam of light propagating in air coupled to a silicon waveguide will undergo an approximate 31% loss due to reflection at the waveguide facet. It should be noted that the reflection coefficient is not strictly dependent upon the Fresnel reflection coefficient alone but depends also upon the geometry of the waveguide. Therefore to obtain a more precise reflectance value, the waveguide should be investigated using a finite difference time domain modelling package or other suitable programme that can account for the backward propagation of light [6]. Thus, the ‘modal reflectivity’ can be determined.

Even potentially more detrimental is the 31% reflection of light that occurs as light inside the waveguide impinges upon the output facet. This light is not necessarily lost as in the case of the input facet. It can be guided backward within the waveguide to the input facet, undergoing another partial reflection. Depending on its phase, this second reflection can constructively/destructively interfere with the light coupled to the waveguide. This is the Fabry-Perot (FP) resonance effect. Even though each reflection depletes the amount of power in the resulting reflection (i.e. 31% of 31% etc.) the sum of all the reflections can be considerable. The resultant optical transmission, \( I_o \), through the waveguide can be determined by [3]:

\[
\frac{I_r}{I_o} = \frac{(1-R)^2 e^{-\alpha L}}{(1-\text{Re}^{-\alpha L})^2 + 4 \text{R} e^{-\alpha L} \sin^2(\phi/2)}
\]

(3.60)
where $\alpha$ is the propagation loss coefficient, $L$ is the distance between the waveguide facets, and $\phi$ is the phase difference between the incident beam, $I_0$, and the sum of all the reflections co-propagating with the incident beam. Applying equation 3.50 to the phase in equation 3.60, the normalised optical transmission as a function of wavelength can be plotted. Figure 3.18 is the result of equation 3.60 for various loss coefficients assuming a cavity length of 1.5cm and a reflection coefficient of 0.31.

![Figure 3.18. Spectral response of a waveguide due to the FP effect.](image)

The propagation loss coefficient $\alpha$ is typically an unknown value. By inspection of equation 3.60, a maximum can be achieved for $\phi = 2\pi m$ ($m=0, 1, 2, \ldots$) so that:

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

Likewise for $\phi = (2m+1)\pi$ ($m=0, 1, 2, \ldots$) a minimum is obtained:

$$I_{\text{min}} = \frac{(1-R)^2 e^{-\alpha L}}{(1-\Re e^{-\alpha L})^2}$$

Taking the ratio of equation 3.61 to 3.62 yields the maximum to minimum ratio, $\zeta$:

$$\zeta = \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{(1 + \Re e^{-\alpha L})^2}{(1 - \Re e^{-\alpha L})^2}$$

Solving equation 3.63 for $\alpha$ yields:
\[ \alpha = \frac{1}{L} \ln \left( \frac{1}{R} \frac{\sqrt{\xi} - 1}{\sqrt{\xi} + 1} \right) \]  

(3.64)

Whilst it was previously mentioned that modelling would be required to determine the modal reflectivity of the waveguide, equation 3.59 was used for the determination of \( R \) used in this work. It was determined that the resultant value of 0.31 using equation 3.59 is only a few percent different than that obtained by the modelled modal reflectivity for a device with similar cross sectional dimensions as those used in this work [6].

For the test chips designed to validate the theories discussed herein, rulers were added to the chips so that \( L \) could be determined relatively accurately (see section 4.4). Thus \( \alpha \) of a device can be determined. As the units of \( \alpha \) are cm\(^{-1}\), a logarithmic conversion to base 10 yields a more suitable statement of the loss in terms of dB.

\[ \text{Loss(dB)} = 10 \frac{\alpha L}{\ln(10)} \]  

(3.65)

Dividing by the length of the device gives the loss in a more commonly used set of units, dB/cm. Thus for \( \alpha = 0.5 \) plotted in Figure 3.18 for example, the corresponding loss is 2.2 dB/cm. Thus the loss determined from the FP method can be used to give general sense as to how well the test chips have been fabricated.
3.9 References


8. *BeamPROP™ 5.1.1 Users Guide*.


Chapter 4

4 Test Chip Design

The theory and modelling discussed in the previous chapters have demonstrated that a polarisation independent racetrack resonator is feasible. However, experiments are required to determine if the models adequately predict the functionality of the racetrack resonator. If the models are accurate then they become even more useful as they can be used to extrapolate the functionality of a more complex device. The focus of this chapter is to discuss the Design Of Experiments (DOE) used in deciding what to fabricate on a particular test chip. Each test chip contains several self-consistent experiments designed to investigate various aspects of the ring resonator. As the test chips are fabricated using photolithographic tools, the types of devices, dimensions, and skews to account for processing tolerances all need to be addressed within the DOE. This chapter begins with a brief discussion of the software used to design the photolithographic masks necessary to fabricate the devices. Subsequently a detailed discussion of the DOE for each test chip is given. Where pertinent, suggestions are given with respect to either the DOE or the mask design to aid future work.

4.1 Mask Design Software

Mr. D. Tran of the Intel Corporation drew the mask for the first test chip which was designed at the university by the author. Mr. Tran used a Computer Aided Design (CAD) software programme called Virtuoso® made by Cadence Design Systems, Inc. [1]. Subsequent masks were both designed and drawn here at the University of Surrey using a similar programme called L-Edit™ made by Tanner Research, Inc. [2] This programme was originally designed for creating masks used to fabricate Ultra Large Scale (ULSI) electronics. It allows the user to draw many different shapes with nanometre resolution. This programme is more than adequate for defining waveguides as the smallest dimension used in any part of the device design is of the order of several hundred nanometres.
A rib waveguide is defined by etching two parallel trenches to a desired depth into the surface of a wafer. The trenches are separated by the desired width of the waveguide. During the photolithographic process a positive photoresist is used. This means that whatever photoresist is exposed, that photoresist, and subsequently a controlled amount of silicon under the exposed photoresist, will be removed during the fabrication process. The mask therefore defines those areas that are to be exposed by light and those to be protected from it. Figure 4.1 demonstrates the design of a waveguide using the L-Edit programme. The red boxes indicate areas where the photoresist is to be exposed, thereby creating a rib waveguide. A layout is created by drawing a series of waveguide structures in a predetermined area. A test chip is defined by the waveguides contained in this area.

![Figure 4.1. L-Edit layout design of a rib waveguide](image)

A stepper is used in the photolithographic process to apply the optical pattern as defined by the mask to a photoresist-covered wafer. Each test chip is exposed individually. Thus after a test chip is exposed, the stepper moves an incremental amount (slightly more than the width of the test chip) and exposes the next test chip, hence the name. In order for the stepper to accurately step from one test chip to the next, a frame needs to be added to the
layout. This consists of a rectangle drawn around the layout which contains optical structures used by the stepper to align the mask as it steps. This frame is dependent upon the stepper used. The stepper used also defines the ultimate size of the layout. All of the frames used to fabricate the test chips in this project were designed by Mr. Tran.

Once all of the desired waveguide devices have been drawn, the layout is sent to a mask designer where the mask is fabricated. The mask consists of a rectangular plate of glass covered with chrome. The chrome is removed where red areas were drawn in the layout. This type of mask is known as a dark field mask in that chrome remains outside of the drawn region, or the field, so that those areas remain dark. All of the masks used in this project were fabricated by Compugraphics USA, Inc. [3].

Whilst L-Edit works well for drawing the layout it does have one major limitation. When drawing bends, the arcs are formed from polygonal shapes instead of a smooth bend as shown in Figure 4.2. This shape may perturb the optical mode as it travels around the bend thereby increasing the loss of the bend. This problem was also found in the Virtuoso programme.

One solution to this problem is to use the CAD layout in Rsoft's beam propagation (RSoft Design Group, Inc. [4] BeamPROP™) software. It has the ability to draw the arcs correctly. Once the arcs are drawn, the CAD layout of the arc is exported as a GDSII file.
Chapter 4: Test Chip Design

to L-Edit. The L-Edit programme uses layers to distinguish different materials drawn in the layout. As an example, metal lines will be drawn on one layer and polysilicon structures on another. Therefore when exporting the arc layout from the CAD software the programme prompts for a layer number. This layer number should match the layer upon which the waveguides are defined in the L-Edit programme. As the waveguides were drawn using the polysilicon layer in L-Edit (layer 46) this layer number was used in exporting the CAD designed arc.

4.2 First Test Chip Design

When designing a test chip, individual waveguides or waveguiding devices with similar dimensions are typically grouped together to form cells. These cells can then be easily duplicated and subsequently modified using the layout programme. A die is an area comprised of multiple cells suitably arranged so that the waveguide’s inputs/outputs lie on opposite sides of the die. The die area for the first test chip is 16.5mm x 16.5mm. For mass production purposes, dozens of die are fabricated on a wafer. A typical layout of die on a wafer is shown in Figure 4.14. A test chip is a die whose area is comprised of waveguides and waveguiding devices used to test a hypothesis of an experiment from the DOE for that test chip.

The first test chip was designed with the intention of investigating the properties of the individual components that comprise a ring resonator, namely the waveguide bend and the directional coupler. For the waveguide bends, modelling demonstrates that as the bend radius is decreased, loss increases. Therefore bend loss waveguides were designed to study the bend loss for various bend radii. Directional couplers with various coupler lengths and waveguide separations were designed to account for processing tolerances during fabrication. Single input/output ring resonators were also designed to determine how well these devices compared with the theory/modelling and how comparable a full device is to the sum of its individual components. The chip was therefore separated into three main sections: directional couplers, bends, and single input/output ring resonators.
4.2.1 Rib Waveguides

The same rib waveguide dimensions were used throughout this test chip layout. A cross-section schematic of the rib is given in Figure 4.3. The rib was defined by etching two 10 μm wide parallel trenches one micron apart. The removal of silicon only in the trench regions implies that the slab region in between the waveguides will have a rib-like profile. This slab region has two benefits. The first is that it helps to protect the rib waveguide during end-facet polishing after the wafer is diced into the individual test chips. The second is that for many of the waveguide configurations it is itself a large slab waveguide. This can be advantageous when initially optically aligning the chip using the free space setup. This is especially true for die with a deep rib trench. Small misalignments in the optics make it difficult to propagate any light through the chip. With the slab region, however, even misalignments of several microns of the input and output objective lenses can still allow an acceptable optical signal through the chip so that further refinements in the alignment can be made with a power meter. Then a small displacement of the chip in the lateral direction will yield an optical signal in the rib.

![Figure 4.3. Cross-section of a typical waveguide used in the first test chip layout](image)

4.2.2 Directional Couplers

From the modelling results of section 3.4.3, two couplers were predicted to have polarisation independent behaviour for each rib waveguide design. The first coupler had a Coupler Length (CL) 1030μm with a waveguide Separation (Sep.) of 0.62μm, and the other had CL of 4841μm with a Sep. of 0.95μm. It was felt that the coupler with a length
of 4841\(\mu\text{m}\) was too long and hence the shorter coupler was used. A cross-sectional schematic of the coupler is shown in Figure 4.4(a). S-bends were used to separate the waveguides outside the coupler region as shown in Figure 4.4(b). In this figure the red portions denote the rib trench, whilst the white line inside the red lines denotes the rib. S-bends were added to the directional coupler region so that the inputs/outputs were sufficiently separated to prevent cross-talk whilst being measured. The bends have a radius of 400\(\mu\text{m}\). This value was chosen because it was determined that the bend loss for this radius and waveguide dimensions was negligible [5]. At their furthest point, the waveguides have a separation of approximately 100\(\mu\text{m}\).

As this test chip was a first attempt at fabricating directional couplers, a set of variations on the length and width of the target coupler were chosen. A 5x5 grid of couplers (5 different coupling lengths and 5 different separations) was created around the target coupler’s dimensions (\(\text{CL}=1030\mu\text{m}\) with \(\text{Sep.}=0.62\mu\text{m}\)). The waveguide separations chosen were 0.62, 0.72, 0.82, 0.92, and 1.02\(\mu\text{m}\). The coupler lengths chosen were 1030, 1380, 1730, 2080, and 2430\(\mu\text{m}\). Therefore each waveguide separation was produced five times, each with one of the different coupler lengths, making a total of 25 directional couplers. It should be noted that these coupler dimensions are not the actual dimensions used in the mask layout. Because of skews that occur during processing these values were altered slightly on the mask so that the resultant couplers would have the desired dimensions listed above. A further discussion of processing skews is given in section 4.2.7.

![Figure 4.4](image.png)

(a) Cross-section of a directional coupler used in the first test chip layout (b) Plan view of a typical coupler showing the input/output waveguide configuration
4.2.3 Bend Loss Experiment

The FSR of a ring resonator is inversely proportional to the circumference of the ring. Since it is technically advantageous to have as large an FSR as possible, the ring circumference should therefore be as small as possible. A bend loss experiment was designed to investigate the bend loss as a function of bend radius in an attempt to eventually develop resonators with larger FSR’s.

The experiment was designed to investigate the loss of waveguides with 90° bends in them. Five waveguides, each having a different number of bends, but all having the same bend radius, were designed as shown in Figure 4.5 where each red line indicates a waveguide. Starting with two 90° bends, each subsequent waveguide has two more 90° bends than the previous one. Thus the final waveguide has a total of ten 90° bends. The power in each waveguide can then be measured and plotted as a function of the number of bends. The resulting slope of the data determines the amount of power lost per bend so that multiplying this value by four should give the approximate loss value for a ring resonator device. The data can also be normalised to the power in a straight waveguide. This normalisation removes the insertion loss factors common to both the straight and the bent waveguides with the supposition that both waveguides have the same cross-sectional dimensions. In order for this normalisation to be accurate however, a further assumption is made that the propagation loss difference between straight and bent waveguides is negligible so that the loss observed is due only to the bends.

![Figure 4.5. A cell of waveguides used in measuring loss due to bends. Each red line indicates a waveguide.](image)

The five bent waveguides are grouped together to form a cell. The waveguides were arranged within the cell to minimise the amount of area consumed. Each cell also contains two straight waveguides at the top and bottom of the cell for potential
normalisation and assessment purposes. The cell also contains two, single input/output racetrack resonators. The bottom resonator has a CL of 1030\(\mu\)m with a Sep. of 0.72\(\mu\)m. The upper resonator has a CL of 1030\(\mu\)m with a Sep. of 1.02\(\mu\)m. The bend radius for the rings is the same as that of the bent waveguides in the cell. The rings were added to maximise the space allocated by the bend loss cells as well as to investigate the effects of reducing the bend radius on fabricated resonators. The bend radii investigated on the test chip are 5, 10, 25, 50, 100, and 200\(\mu\)m. Thus there was a cell of waveguides/resonators for each of these radii.

### 4.2.4 Ring Resonator Devices

Due to space constraints only 12 of the 25 directional couplers discussed in section 4.2.2 have corresponding racetrack resonators. Four waveguide separations were chosen: 0.62, 0.72, 0.82, and 0.92 \(\mu\)m. For each separation, four resonators were fabricated each with the following coupling lengths: 500, 1030, 1380, and 1730\(\mu\)m. The 1.02\(\mu\)m separation couplers were excluded because it was felt that they would probably be polarisation dependent and therefore not very informative. The longer couplers, 2030 and 2480\(\mu\)m were excluded for the same reason. The 500\(\mu\)m coupling length was added to demonstrate a change in the FSR (by a factor of \(\sim\)2) over the ring with the next longest coupler. The bend radius for all of the racetrack resonators, barring those in the bend loss cells, is 400\(\mu\)m. This value was chosen because, according to modelling, it yielded the lowest equivalent amount of loss for both polarisation states [5].

![Figure 4.6. Layout of the single input/output racetrack resonators. Each red line denotes a waveguide](image)

73
In order to conserve space, the racetracks were laid out as shown in Figure 4.6. The red lines represent waveguides, however in reality they are actually the waveguide trenches as drawn in L-Edit and the waveguide, and hence the coupler is not shown. Labels indicating the particular coupler dimensions for each device were placed near the edges of the die, closest to the device to which it pertains. For every two racetracks, a straight waveguide is added for normalisation and assessment purposes.

4.2.5 Tapers

An initial concern of these first devices was that the cross-sectional area was small, making it difficult to couple light into them. Therefore horizontal tapers were added to the waveguide inputs to help collect as much of the incident light as possible. The tapers had a starting width of 10μm and tapered down to the final one micron width of the waveguide. The tapering occurred over 1000μm to minimise the loss due to mode conversion. The resultant taper angle is 0.7°. Figure 4.7 shows a plan-view schematic of the coupler and its dimensions. The trench around the coupler is the same as that of the rib waveguide trench.

![Figure 4.7. Plan-view of a horizontal waveguide taper schematic](image)

A 300μm long, 10μm wide area was added to the input of the taper as a buffer for wafer dicing and facet polishing. It was uncertain what effect the tapers would have on the performance of the devices. Therefore a ‘safety zone’ was kept between the start of the device and the end of the taper so that if the tapers proved to be detrimental to the
functionality of the device they could be polished off. The tapers were only added to the input (left side of the chip) of the waveguides as it was felt that no real benefit would be obtained by having them at the output, especially if they needed to be removed. Since this safety zone was not feasible with the bend loss experiment waveguides, tapers were not added to those waveguides.

4.2.6 Device Duplication

Each experiment discussed above was laid out so that they filled only one half of a chip, vertically, with the waveguides running horizontally. A mirror image of the left side of the chip was made, and placed in the right-hand side of the chip thereby creating duplicates of all the devices placed on the left side of the chip. This was done to minimise the risk of losing devices due to post-process handling of the chips. Also, processing variations across the wafer would cause each die near the centre of the wafer to have slightly different dimensions than those at the edge. Therefore by duplicating the experiment on the same die, these variations would be minimised. There are 43 full die per wafer, thereby making a total of 86 duplicate half-die on each wafer. However it is expected that the die near the edge of the wafer (27 in total) may suffer from large processing variations [6]. Therefore the centre 16 die (see Figure 4.11 for example) on the wafer are considered to be processed closest to the target specifications.

4.2.7 Print Bias Corrections to Waveguide/Coupler Dimensions

The photoresist used during the fabrication of the test chips is sensitive to the time it is exposed to light [6, 7]. Longer exposure times make the waveguide edges better defined. But the drawback of longer exposure times is that it tends to decrease the waveguide width thereby making it smaller than target. In a directional coupler, this is especially problematic because not only do the waveguides decrease in width, but coupler separation also increases. These variations are known as print bias errors.
The best method for correcting this error is to compensate for it on the mask. To determine the amount of bias, a test wafer is exposed (printed) using a mask containing parallel waveguides having various waveguide widths and spacings. Then the widths and spacings are measured and plotted as a function of the waveguide widths and spacings drawn on the mask. An example data set for the waveguide spacings is shown in Figure 4.8 [6]. The values in the legend are the photolithographic exposure times in milliseconds. The slope of the data determines the print bias error for the waveguide spacing. Using the 270ms data, a slope of 1.34 was determined.

![Figure 4.8. Data used to determine the print bias error for the first ring resonator test chip (Data taken by O. Cohen of the Intel Corporation)](image)

In order to obtain the expected waveguide separation values for the directional couplers and racetrack resonators presented in sections 4.2.2 and 4.2.4 respectively, the waveguide separations on the mask were redrawn using the calculated corrected separation value listed in Table 4.1. The corrected values were obtained by dividing the expected waveguide separation by the print bias error value of 1.34. It should be noted that the labels identifying their respective devices have the corrected separation value listed instead of the expected value. This was done to clarify what mask dimensions were used to fabricate the devices, as future test chips could be fabricated using a different exposure time which would lead to a different expected separation value.

**Table 4.1. Expected and Drawn Directional Coupler Waveguide Separations**

<table>
<thead>
<tr>
<th>Expected Separation (μm)</th>
<th>0.62</th>
<th>0.72</th>
<th>0.82</th>
<th>0.92</th>
<th>1.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Separation (μm)</td>
<td>0.46</td>
<td>0.54</td>
<td>0.62</td>
<td>0.69</td>
<td>0.76</td>
</tr>
</tbody>
</table>
The same method was used to determine the corrected waveguide width necessary to produce the desired one micron wide waveguides. The corrected value for the waveguide width was found to be 1.1 microns and hence the mask waveguide widths were drawn accordingly.

### 4.2.8 On-Wafer Exposure Time Skew

In order to determine the correct photolithographic exposure time to achieve the desired directional coupler dimensions a print bias study was made [7]. Figure 4.9 shows the result of the print bias study for a targeted 0.72μm (0.54μm drawn) waveguide spacing and 1.0μm (1.1μm drawn) waveguide width. The etch rate is dependent upon the number of devices in a given area. Therefore measurements were made in areas where a coupler was surrounded by a large number of waveguides (dense) and another region where only a few waveguides were present (sparse). This was done to determine the device dimension uniformity across the chip.

![Figure 4.9. Print test results to determine the proper exposure time to obtain the correct waveguide width and directional coupler waveguide spacing (Data taken by D. Hak of the Intel Corporation)]
From the data, it was determined that an exposure time of 330ms would yield dimensions closest to the target dimensions (0.73μm for the separation and 1.07μm for the waveguide width). However from Figure 4.10, we see that the sidewalls of the waveguides are sloped. This results in an ambiguity of where to make the separation measurement.

![Figure 4.10. Cross-sectional image of a directional coupler showing the sidewall slope (image taken by D. Hak of the Intel Corporation)](image)

Therefore an on-wafer exposure time skew was used to offset this issue. By exposing half of the wafer with at 330ms and the other half with 350ms, two variations on the dimensions could be obtained (see Figure 4.11). As there would be 16 optimal dies, including duplicates, for each of the exposure times, it was decided that the skew would make advantageous use of the wafer space. The 350ms value was chosen as it would result in a waveguide approximately 50nm smaller in width, along with a waveguide coupler separation approximately 50nm wider than the 330ms exposed couplers. The 50nm value was obtained from inspection of the exposure data in Figure 4.9.

### 4.3 Second Test Chip Design

An issue arose with the directional couplers fabricated on the target etched wafers for the first test chip. The directional couplers were found to have asymmetric waveguide
widths. This resulted in a poor phase match between the coupler waveguides and hence the couplers did not function. It was determined that the cause of the asymmetry arose from pushing the photolithographic stepper to its resolution limit.

The simplest solution to this problem was to move to a stepper with better resolution. However the mask designed for the first ring resonator test chip was incompatible with this new tool. It had an area of 16.5mm x 16.5mm. The stepper with better resolution required a mask area of 20.0mm x 20.0mm. Therefore a new mask had to be made. The original design could have been re-utilized but as a polarisation independent device was realised on a shallow etched wafer, the new test chip could be better served by investigating ways to improve upon the devices realised thus far. Therefore this new test chip had two roles. The first was to fabricate some of the old test structures to tie up the initial modelling with fabricated devices. The second role was to begin to optimize the polarisation independent device in terms of its critical parameters such as FSR, finesse, etc. The following discussion outlines the new mask design.

Figure 4.11. Die layout for the first ring resonator test chip. The dies with bold outlines are considered to have the targeted dimensions. The coloured boxes determine the exposure time used in the photolithographic process.
4.3.1 Recycled Experiments and General Modifications

Subsequent modelling of the directional coupler to that of the first test chip demonstrated that polarisation independent racetrack resonators could be realized using smaller, 0.8µm wide waveguides, as discussed in section 3.4.3. Therefore devices were added to the new design that utilized this new result. From the modelling it was determined that for 0.8µm wide waveguides, couplers with a CL of 210µm and 310µm, both with a Sep. of 0.54µm, would potentially yield a polarisation independent coupler. These devices were of particular interest because they would yield the larger FSR’s than any of the racetrack resonators on the previous test chip.

Because some the original modelled devices did not function due to the waveguide asymmetry in the couplers, the 1.0µm wide couplers with CL of 1030µm and Sep. of 0.62µm was retained to help validate the original modelling done for the first test chip. The coupler with a waveguide width of 1.0µm, a CL of 500µm, and a Sep. of 0.44µm was also recycled as it yielded a proven polarisation independent racetrack resonator on the first test chip (see section 7.4.2). These four couplers were drawn as stand alone couplers using the same cell configuration as that used in section 4.2.2.

The 90° bend loss cells from the first chip were also recycled. Two sets of cells were drawn to reflect the two waveguide widths (0.8 and 1.0µm) now being applied to this test chip. Both sets had the same bend radii cells of 300, 200, 100, 50, 25, and 10µm. The 300µm cell was added for consistency as 300µm bends are used in the dual input/output racetrack resonators (see section 4.3.3). The 5µm bend cell from the first test chip was dropped as most of the waveguides had too much loss to be of any value. For the 1.0µm wide waveguide cells, the bottom racetrack resonator had a coupler with a CL of 1030µm and Sep. of 0.62µm. The top racetrack had a coupler with a CL of 500µm and a Sep. of 0.44µm. For the 0.8µm wide waveguide cells, the bottom racetrack resonator had a coupler with a CL of 310µm and Sep. of 0.54µm. The top resonator had a coupler with a CL of 210µm and a Sep. of 0.54µm. Since these cells encompassed all of the variations
of racetrack resonators, no standalone sets of resonators such as those shown in Figure 4.6 were placed on this test chip.

Before discussing the new experimental additions made to the test chip, one final note needs to be made about the chip in general. All waveguides on this chip had the same tapers as in section 4.2.5 placed on their inputs and outputs. This was because preliminary experiments on devices using tapers showed no observable detrimental effects.

4.3.2 Directional Coupler Study

The directional coupler skew from the first test chip was abandoned as it offered no real benefit in terms of information. The space was used instead for a directional coupler study. The idea of the study is to map out the sinusoidal energy transfer as a function of the length of the coupler. Therefore 32 couplers, all with waveguide widths of 0.8μm and separations of 0.5μm but each with a different coupler length, were used to make up the study. The first and shortest coupler is 25μm long. Each subsequent coupler is an additional 25μm longer than the previous one, so that the 32nd coupler is 800μm long. The same input/output s-bend configuration that was used in section 4.2.2 was also used here.

4.3.3 Dual Input/Output Racetrack Resonator Devices

With the successful results of the single input/output racetrack resonators on the first test chip, it was felt that one of the next logical steps in understanding these devices was to add a second input/output waveguide to the racetracks. Shown in Figure 4.12, these devices have identical directional couplers on both sides of the device. In order to get the drop signal to exit the chip on the side opposite to the input signal, a 300μm 180° bend was added to the drop port of the racetrack resonator.
Four devices were fabricated in total, each with one of the four coupler dimensions discussed in section 4.3.1. To allow for comparison of the single input/output resonators on this chip the bend radius for all of these devices is 300μm. The 400μm bend radius used on the first test chip was abandoned because preliminary bend loss experiments demonstrated that the bend loss was negligible for bend radii of 200μm or larger.

4.3.4 180° S-Bend Experiment

One final experiment was designed for this test chip, the investigation of 180° bend structures. These waveguides (see Figure 4.13) were added because it was felt that the 90° bend structures may not be truly indicative of the bend losses inside of a racetrack resonator. In the 90° bend structures there is a straight waveguide section in between two bends. If loss occurs due to modal mismatch between the curved and straight waveguide sections, then a four 90° bend waveguide would have eight bend/straight waveguide interfaces. In a ring resonator with two 180° bends, however, there would only be four bend/straight waveguide interfaces and hence the latter is potentially lower loss than the equivalent waveguide with four 90° bends. Therefore the S-bend test cell was drawn with two 180° bend separated by a straight waveguide section of 1000μm to more closely mimic the racetrack resonator configuration. Each of the bend radii investigated in the 90° bend test cells were used here for completeness. Two cells of these bends were designed for each of the waveguide widths (0.8μm and 1.0μm) investigated on the chip.
4.3.5 Print Bias and On-Wafer Exposure Time Skew

The same method to determine the print bias that was discussed in section 4.2.7 was used on this test chip as well. It was determined that all of the couplers needed to be drawn 0.04\(\mu\)m smaller than target in order to obtain the expected waveguide separation in the coupler region. These changes are highlighted in Table 4.2. Because of the sidewall slope it was difficult to determine the true dimensions of waveguides. Thus no print bias offset was used when drawing the waveguides.

Table 4.2. Expected and Drawn Directional Coupler Waveguide Separations

<table>
<thead>
<tr>
<th>Expected Separation ((\mu)m)</th>
<th>CL=210&amp;310(\mu)m</th>
<th>CL=500(\mu)m</th>
<th>CL=1030(\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL=210&amp;310(\mu)m</td>
<td>0.54</td>
<td>0.44</td>
<td>0.62</td>
</tr>
<tr>
<td>Drawn Separation ((\mu)m)</td>
<td>0.50</td>
<td>0.40</td>
<td>0.58</td>
</tr>
</tbody>
</table>

For a greater variation in the cross-sectional dimensions of the devices, a five-way exposure time skew was made on the wafers, as shown in Figure 4.14. The targeted devices are in the middle (red) column so that a maximum of five repeated dies are fabricated. The lightly shaded dies are near the edge of the wafer and may suffer from
Chapter 4: Test Chip Design

large dimensional deviations due to processing tolerances. Therefore these dies are assumed not to be dimensionally repeatable with the other die in their respective columns. Technically there were seven different exposures carried out on the wafers. However only one die of the extreme exposure times were made and were not expected to be fabricated well due to their proximity to the edge of the wafer.

Figure 4.14. On-wafer exposure time split for the second test chip.

4.4 Dimension Calibration

For both experimental test chips, scale bars, or ‘rulers’ were added to the masks at the very top and bottom of the chip. Starting from the beginning of the waveguides along the vertical edge of the die, the rulers ran horizontally across the die from 0 to 1200μm in 25μm increments (see Figure 4.15). As every die is eventually cut into two smaller chips, rulers are also placed at the top and bottom of the die at the centre. The rulers serve several very important purposes. The first is that during the dicing of the chips, the rulers act as alignment marks when aligning the saw blade to the wafer. This is especially important for cuts through the centre of the die as there is little room for error.
Figure 4.15. (a) A ruler drawn just above a waveguide in the upper left hand corner of the die and (b) rulers at the bottom centre of the die indicating where the die should be diced in half vertically to make two separate test chips.

The rulers also aid in assessing the polish of the waveguide facets after dicing. They allow for the determination of how far the polishing has progressed into the chip. As there is only a 300μm buffer on the input of the tapered waveguides (section 4.2.5), it is important to monitor how much of the waveguide has been removed. During polishing, tilts across the die may form. As there are rulers at the top and bottom of the chip, they allow for any tilt to be determined so that steps may be taken to correct it if possible.

The Fabry-Perot loss measurement (see section 3.8) of a device requires the knowledge of the length of the Device Under Test (DUT). The initial width of the chip is known (8.25mm (16.5mm full die) for both test chips). Using the rulers, the amount of material removed from each side of the chip during polishing can be determined to ±25μm. Even with this error, the width of the chip can be known with an accuracy of approximately 3%.
4.5 References


3. Compugraphics USA, Inc., 120C Albright Way, Los Gatos, CA 95032, USA. www.cgi.co.uk.


Chapter 5

5 Wafer Fabrication and Device Preparation

With the test chip design complete, the next step is to fabricate the devices. As the test chips were fabricated in silicon-on-insulator, a brief discussion is given to start this chapter. This is followed by a discussion of the processing steps needed to fabricate the wafers. Once the wafers were completed, they then had to be prepared for testing by being diced into individual die. Because of the roughness of the saw cut, the waveguide facets at the edge of the die had to be polished. The facets were then covered with an anti-reflection coating to minimise the loss and other effects due to the silicon/air interface reflections. The remainder of this chapter discusses these sample preparation steps.

5.1 Silicon-On-Insulator (SOI)

An SOI wafer comprises an overlayer of single-crystal silicon on top of an insulating layer of silicon dioxide, or Buried OXide (BOX). Since these layers are of the order of a few microns thick, they are supported by a relatively thick, 750μm silicon substrate. A cross-sectional view of an SOI wafer is shown in Figure 5.1. SOI was originally created for the field of microelectronics to combat deleterious effects such as latch-up in transistors [1]. In photonic applications, the buried oxide allows for strong confinement of light in the vertical direction.

All of the wafers used in fabricating the test chips were produced by the IBIS Technology Corporation [2]. The wafers were 152.4mm in diameter, had a 1.5μm overlayer thickness, and a 375nm buried oxide thickness. Several methods are currently employed
Chapter 5: Wafer Fabrication and Device Preparation

to create SOI wafers [3]. However the method of Separation by Implanted Oxygen (SIMOX) was used to fabricate these particular wafers [4].

![Cross-section schematic of an SOI wafer](image)

The wafers are made in the following manner [3]. The surface of a generic silicon wafer is first implanted with highly energetic (~200keV) oxygen ions. The projected range of the ions is approximately 300nm below the surface of the substrate, forming a buried layer of ions approximately 500nm thick. Because of the damage created by the implantation and to allow the implanted oxygen to create silicon dioxide, the wafer is subsequently annealed at a temperature of approximately 1300°C for several hours. Upon annealing, the oxygen atoms coalesce with nearby silicon atoms to create an amorphous layer of silicon dioxide. The damage caused to the overlayer is mostly repaired. Hence the BOX layer is formed leaving a single crystal silicon overlayer. If the overlayer is not of the desired thickness, it may be made thicker by epitaxially growing more silicon on the surface to the desired thickness [5].

5.2 Device Fabrication

The fabrication of all the devices studied herein was carried out at one of the Intel Corporation's fabrication facilities located in Jerusalem, Israel [6] by Mr. D. Hak and Mr. O. Cohen [7, 8]. All of the devices were fabricated using the following generic recipe. Some of the processing details were omitted, however as they are proprietary information of the Intel Corporation.
Chapter 5: Wafer Fabrication and Device Preparation

The wafers are first loaded into a wet oxidisation oven. In this oven, the top surface of the silicon is oxidised to create a silicon dioxide, or Field OXide (FOX) layer. This oxidisation of the wafer surface is sacrificial in that as the surface is oxidised it consumes some of the silicon to make a silicon dioxide layer. The oxidisation consumes approximately 45nm of silicon for every 100nm of silicon dioxide created [7]. This oxide layer acts as a hard mask for defining the waveguides as it is more robust to the deep etches necessary to fabricate the waveguides than conventional photoresist. An oxide thickness of approximately 300nm was found to give good results [7]. This resulted in the consumption of approximately 150nm of the silicon overlayer, giving a final overlayer thickness of approximately 1.35μm. This is the waveguide height value used in the modelling of polarisation independent devices (section 3.3).

The next step of the fabrication process is to spin photoresist onto the top of the wafer. The photoresist is baked and the wafers are introduced into a stepper. The first test chip was fabricated with a stepper that had a 0.8μm resolution. As discussed in section 7.2.1, it was found that this resolution limit was too close to the designed device dimensions and therefore subsequent test chips were fabricated using a stepper with 0.5μm resolution. The resolution is defined as the smallest feature that can be correctly exposed when using a 50% duty cycle periodic line/space pattern.

As discussed in sections 4.2.8 and 4.3.5, several exposure times were used to expose the photoresist. This allowed for slight variations in the waveguide width, and in the case of the directional couplers the waveguide separation, to be fabricated on the same wafer using the same mask. Therefore if the targeted dimensions were slightly incorrect due to processing tolerances, one of the variations may result in the desired dimensions.

Once the photoresist on the wafers is exposed, the wafers are then placed in a chemical solution that develops and removes the exposed photoresist. The wafers are then subjected to an oxide plasma (also known as ashing) followed by immersion in a hot sulphuric acid bath to clean the unexposed resist.
The wafers are then loaded into a Reactive Ion Etcher (RIE) oxide etcher. The RIE works by placing the wafer into a chamber filled with a gas that reacts/bonds with the material to be etched. For the oxide etch the gas used is carbon tetraflouride (CF$_4$). The fluorine in the gas reacts with the exposed FOX layer. Highly energetic Argon (Ar$^+$) ions are then fired ballistically toward the wafer, striking the gas-silicon molecule, thereby transferring its momentum. The momentum transfer is significant enough to dislodge the molecule from the surface of the wafer thus allowing for a controlled etch of the surface. The etcher therefore removes the oxide not protected by the unexposed photoresist.

Once the FOX has been removed down to the silicon overlayer the wafers are placed into another RIE etcher whose etch is preferential to silicon. The reactive gas chemistry is chlorine mixed with hydrogen bromide (Cl$_2$/HBr).

Once the silicon has been etched to the desired thickness, the wafers are cleaned using a dilute HF wash and placed into an oxide deposition chamber. A Low Temperature Oxide (LTO) is deposited on the surface of the wafer. This layer has two purposes. Primarily, it creates a cover refractive index that is similar to the BOX refractive index. The second reason is that it gives the die a protective layer that is helpful during the sample preparation phase.

5.3 Sample Preparation

5.3.1 Wafer Dicing

Before the die can be tested, several additional preparation steps must be taken. The first of these is wafer dicing. Several different wafer saws were used to dice the wafers so a general outline of the dicing procedure is given instead of a detailed discussion about one particular tool. A wafer saw, such as those made by the Disco Corporation [9], is used to cut the wafer into the individual dies. The saw's blade width is of the order of tens of microns making it suitable for wafer dicing. Before dicing, the wafer is placed on a piece of Mylar® film that has a slightly tacky adhesive on one side. The wafer is then held
in place by the Van der Waals forces between the wafer and the film. It is in turn bonded to a steel ring. The ring is magnetically clamped onto the saw table, thereby securing the wafer and film to the table. A good adhesion of the wafer to the film is important during dicing. As a high pressure jet of water is sprayed onto the blade at the blade/wafer interface to remove debris, if the adhesion under the die is poor, or if there are air bubbles trapped between the film and a die there is a chance it will be washed away once the cut has been made. Therefore a rubberized roller is used to press the film onto the back of the wafer and ring. The roller also aids in removing trapped air bubbles.

The dicing saw's cut depth is set so that it just cuts through the wafer and gently scores the film. Chipping of the die sometimes occurs along the saw cut (see Figure 5.2). These chips can be of the order tens of microns wide. Therefore when the dicing occurs, the cuts are made several hundred microns from the beginning of the facets. When dicing individual die in half, as in the case of the first ring resonator test chip due to duplication (see section 4.2.6), this is not possible so a buffer region of several hundred microns is incorporated into the design of the test chip. Therefore if chipping should occur, they can be polished away if necessary, leaving the designed devices unaffected.

![Figure 5.2. Plan-view of a wafer showing chipping along the saw cut [9]](image)

**5.3.2 Facet Polishing**

As the saw cut is rough and chipping of the die may have occurred during dicing, polishing of the end facets is required before the die can be tested. A pictograph of the
polisher (Buehler [10] 95-2809) is shown in Figure 5.3. The tool consists of a variable speed rotating 8in. platen and a water jet to both lubricate the polishing pad and wash away the removed material. A polishing film is placed on the platen and held in place by a retaining ring. In order to accommodate our test chips, or samples, a dedicated sample holder was designed for use with this polisher. The sample holder is held in place by a retaining ring which is in turn connected to a cantilever arm (Buehler [10] 95-2600). To ensure contact between the samples and the polishing pad, a spring loaded sample holder clamp is used.

The sample holder, shown in Figure 5.4, consists of several parts. The sample holder itself is an aluminium block with two holes drilled through it. The holes serve as grip points for tweezers once the holder has been placed in the sample holder retaining ring. The sample holder sits upon a sample holder mount when the test chips are added to or removed from the sample holder. A groove was machined onto the top of the mount to match a groove placed in the bottom of the sample holder. This groove prevents the sample holder from sliding around whilst the test chips were attached to it. Loose strips
of aluminium are placed along the ridges machined into the mount so that the sample holder can accommodate a large range of chip widths.

![Sample holder diagram](image)

**Figure 5.4. Specially designed sample holder for use with the polisher**

The test chips are mounted to the sample holder using the following method. The sample holder, mount and height adjustment strips, assembled as shown in Figure 5.4, are placed on a hot plate and allowed to heat up to a temperature greater than 121°C. At this temperature, Crystalbond™ 509 (Buehler [10] 40-8150) clear wax begins to melt. A small piece of the wax is placed on a separate aluminium block and allowed to melt. Once this occurs, a toothpick is used to transfer the liquid wax to both of the long edges of the sample holder. The wax should be used sparingly as too much can cause the wax to leak in between the sample holder and sample holder mount, causing them to stick together once the wax has cooled.

Using either carbon tipped or plastic forceps, a test chip with its back toward the sample holder is set on edge on one of the height adjustment strips located on the sample mount holder. The test chip is then allowed to lean against the side of the sample holder. Using a cotton swab, the test chip is then gently pressed against the sample holder. Metal forceps may be used to push down on the top of the sample holder to prevent the holder/mount from moving whilst the test chip is being pressed against the side of the sample holder. This method is repeated on the other side of the holder. Two test chips must be polished at once with this sample holder. Should only one test chip need to be
polished, a piece of dummy silicon may be used on the other side. With both test chips in place, the sample holder/mount is removed from the hot plate and allowed to cool. Figure 5.5 shows the result of mounting two test chips to the sample holder.

![Sample holder with test chips mounted on each side](image)

For full die that have been diced in half vertically, it is recommended that the edges from the centre of the die be matched up so that they are polished simultaneously. This is because typically a small buffer area is left between the start of the waveguides and the outside edges of a full die. The cut made through the centre of the die has no such buffer and in fact removes 20-30μm of the waveguide from each die half when the cut is made. The outer edge of a full die therefore may require more removal of material in order to get to the start of the waveguide. The edges made from cutting the die in half do not require this removal. Hence if an inner edge and outer edge of a die were polished simultaneously, an unacceptable amount of the waveguide from the inner edge may be removed.

When the mount and holder are cool, the sample holder can be removed from the mount. If the sample holder is sticking to the mount, small force may be applied between the holder and the mount with forceps or a small screwdriver. If this method is unsuccessful, the mount/holder will have to be reheated, the test chips removed, and then the mount and holder can be separated. The individual pieces should then be allowed to cool down and subsequently cleaned with acetone before attempting to mount the test chips again. Thus
care should be taken when applying the wax to prevent it from penetrating the region between the sample holder and mount.

Prior to placing the sample holder on the polisher, a polishing film is placed on the platen and locked down with the polishing pad retaining ring. It is important to check the surface of the platen for debris prior to adding the film as even the smallest contaminants can push up on the film causing scratching on the facet surface. Thus the platen surface is usually rinsed with the water nozzle prior to adding the film. The film is then placed at the edge of the platen and slid on to not only displace any debris and water, but also remove any air bubbles trapped between the platen and film. The retaining ring is then pushed down along the rim of the platen, holding the film in place.

The sample holder is placed in one of the holes in the sample holder retaining ring as shown in Figure 5.6. The spring loaded pressure arm is then lowered onto the top of the sample holder. The arm has evenly spaced lines scribed around it. These lines act as a qualitative measure of the applied pressure. Typically the second line from the top of the arm is used. Therefore the clamp is pushed down until this line is level with the top of the pressure arm clamping ring that holds the arm in place, and locked into place using the allen head screw shown in Figure 5.6. To remove the sample holder, the above steps are carried out in reverse.
The water nozzle is then turned on and aligned so that it sprays toward the centre of the platen. The platen rotation is then turned on, starting the polishing sequence with the desired grit size film placed on the platen.

Because there are so many factors that affect the polishing quality, sample preparation is far from an exact science. Regardless, the following recipe is given as it has been found to be repeatable and has provided good facet quality. The recipe assumes that two ring resonator die are being polished, but is applicable to any type of die. Diamond Lapping Films (DLF) were usually used as they were found to give the best results in terms of the speed of removal of material as compared to a comparable aluminium oxide (AlO₂) film. However, the cost of the diamond films is significantly higher than the AlO₂ films and hence should be handled with care.

For initial polishing and for uses where large amounts of material removal are necessary, a 1µm (size of the diamond granules) diamond lapping film of is used (Buehler [10] 15-6802). The sample holder is placed in the polisher and the water nozzle is turned on as discussed above. The platen rotation is then turned on and set to a speed of approximately 100rpm. As the initial polish sets the stage for the future polishing steps, care should be taken to ensure that the sample holder is seated properly in the sample holder retaining ring and that the pressure arm is centred in the middle of the sample holder. As this first polishing pad is rather aggressive, a brown streak of removed silicon debris will stain the polishing pad. One sign that the sample holder is not properly seated in the sample holder retaining ring is that the streak width will be smaller than the width of the test chip being polished. If this is observed the platen should be stopped and the sample holder should be re-seated inside the retaining ring before continuing with the polish. After several minutes of polishing, the samples are removed and observed under a microscope. The front face of each of the test chips should be observed to see if the necessary amount of removal has occurred and that a significant angle is not being formed across the chip. An angle can be observed by using the rulers placed at the top and bottom of the test chip to see if the edge of the test chip is at the same position on the ruler at the top and bottom of the test chip. Should a considerable tilt be observed across the test chip, the test chip can be put back into the polisher and the pressure arm can be
pulled slightly to the side of the test chip that requires more material removal. Polishing with this first coarse film should also be continued until any chips caused by the dicing saw (see Figure 5.2) are removed that affect the waveguides so long as this continued polishing does not begin to damage other devices on the chip.

Once the desired material removal is achieved, the sample holder is removed from the polisher and turned over to polish the opposite facets. Even if very little or no material is required to be removed (such as the inner edges of a die cut in half) it is still a good idea to begin with the 1μm DLF. It quickly removes chips and scratches that may have occurred during the dicing and also helps to remove any tilts in the chip with respect to each other that may have occurred when the test chips were attached to the sample holder.

When the desired amount of material has been removed from both sides of the test chip, the 1μm film is removed from the polisher and replaced with a 0.5μm DLF (Buehler [10] 15-6796). Before starting to polish with this pad, the test chip, especially their facets, are cleaned with water and a cotton bud. As the removed material from the previous film is of the order of 1μm, it can contaminate the 0.5μm film. It was found that a speed of 75rpm or less gave the best results with this film. Material removal is no longer as much a concern as it was for the 1μm pad. The focus of the polishing from here forward is to reduce the depth of the scratches on the facets. Therefore when using this film, the scratch pattern on the edges of the chips should be observed. The scratches should all lie in the same direction. If they are not then the sample holder should be placed back on the polisher for a longer period of time. When all of the scratches lie in the same direction, it is an indication that the pad has uniformly polished the entire edge of the die. With this polishing film, the die edges should have a shiny metallic look when observed under a low magnification (40x) microscope. Both edges of each die should be polished with this pad before proceeding to the next pad. Polishing with this pad usually takes several minutes but the time is dependent on how long it takes to obtain a uniform scratch pattern on the edges.

Both test chips, especially the facets, are cleaned with a damp cotton swab before proceeding to the next polishing step. A 0.1μm DLF is used next (Buehler [10] 15-6792).
Chapter 5: Wafer Fabrication and Device Preparation

With this film the speed of the platen is set to 50rpm, the minimum speed of the wheel. The amount of material removed with this pad is minimal so longer polishing times are allowed. The edges of the dies should be checked every five minutes or so. Under a low magnification (40x) microscope the edges should start to take on a blackish appearance with no real observable scratch pattern. Both sides of the dies are polished with this pad before continuing to the final pad.

The dies are cleaned one final time before continuing with the final polishing film. As the smallest available granule size of the DLF is 0.1μm, a 0.05μm AlO₂ film is used as the final polishing film (Buehler [10] 69-3175). The optimal speed for this film was found to be 50rpm. The time taken on this film is the most variable of the films as it depends on the quality of the facets. After 10 minutes of polishing with this pad the individual facets are checked under a high power microscope (100–200x) for scratches. A trade-off is ultimately made during this polishing step between time and the facet quality. Also, the longer the facets are polished, the higher the risk a contaminant may be introduced during the polishing. Thus progress may be undone if debris greater than 50nm should contaminate the film. If there are an unacceptable number of scratches observed on the facets or if the quality of the facets decreases over time, the film should be replaced with a new one as these films are relatively inexpensive.

When an adequate polish has been achieved, the sample holder is placed back on the sample holder mount. Both are then placed back on the hot plate in order to melt the wax attaching the test chips to the sample holder. The height adjustment strips are not used for this step. After several minutes on the hot plate the test chips will begin slide downward. At this point a pair of forceps may be used to slide the test chip horizontally off of the sample holder, taking care not to touch the freshly polished edges. The dies are then placed on a tissue and allowed to cool. The sample holder and mount are then removed from the hot plate and allowed to cool.

Acetone soaked cotton swabs are used to remove any residual wax from the back of the test chips. When the backside of the test chip is clean, a fresh acetone soaked cotton swab is used to wipe down the polished edges. Only one swipe should be made with a single
swab to prevent further contamination of the facet area. The sample holder should also be cleaned to prevent the build-up of wax.

The DLF’s are expensive and therefore should be reused. The used films should be wiped off with a clean tissue and stored separately from the unused films. The 0.05μm AlO₂ films however are relatively inexpensive and therefore should be discarded after being used as the likelihood of contamination through multiple handlings is high.

The initial test chips obtained from the processed wafers were prepared using the sample preparation method discussed above. However for the test chips that required an anti-reflection coating (discussed below) they were polished in a slightly different manner. They were sent to an external vendor who had the ability to polish dozens of samples at a time [11]. The results were of a similar quality to those obtained using the method above.

5.3.3 Anti-Reflection (AR) Coating

Whilst the Fabry-Perot effect may be useful in determining the loss of a device such as a straight or bent waveguide, it may unacceptable when studying a device such as a ring resonator where large periodic power fluctuations may mask critical information about the device. A solution to this problem is to apply an Anti-Reflection Coating (ARC) to the facets of the waveguide. This coating can typically reduce the reflectance from 31% to less than 1% thereby reducing the Fabry-Perot resonances almost to an immeasurable level.

To create an ARC, two properties of the coating must be determined. The first is the thickness. An ARC works by creating two reflected waves, one from each of the coating surfaces, which are of the same amplitude but 180° out of phase. As shown in Figure 5.7, a wave (solid line) is incident from the left of the silicon. The resultant partially reflected waves are shown as dashed lines. The coating’s thickness determines the phase relationship between the two reflected waves. If the coating’s thickness, t, is a quarter of
the wavelength ($\lambda$) or an odd integer multiple thereof, the second reflected wave will have a half wave ($\pi$) phase shift when it returns to the air/coating interface with respect to the first reflected wave. The result is a destructive interference between the two reflected waves. In equation form this result states:

$$t = (2n + 1) \frac{\lambda}{4} \text{ for } n=0, 1, 2, 3, \ldots$$

(5.1)

The second property of the ARC to be determined is its index of refraction. The amplitude of the reflected wave is a function of the ratio of the indices of refraction of the materials from either side of the material interface. Therefore in order to get total destructive interference between the reflected waves they should have the same amplitudes,

$$\frac{n_{air}}{n_{coating}} = \frac{n_{coating}}{n_{Si}}$$

(5.2)

where $n$ is the index of a particular material region as shown in Figure 5.7. Solving for the coating index and assuming $n_{air}=1.0$ and $n_{Si}=3.5$, the coating's index of refraction needs to be:

$$n_{coating} = \sqrt{n_{Si}} = 1.9$$

(5.3)

Thus the coating should have an index of 1.9 and a thickness of 0.83\(\mu\)m to give total destructive interference at the facet interface for a free-space wavelength of 1.55\(\mu\)m. Hafnium oxide (HfO$_2$) has this index of refraction and was used as the ARC for all coated
devices used in this work. The coating was applied by Dominar, Inc. [12] using a thermal evaporator.

One final note should be made about the phases of the reflected light. A wave undergoes a \( \pi \)-phase shift upon reflection from a material of lower to higher refractive index interface. However as this shift occurs for the reflected wave from the air/coating (lower/higher index) interface and the reflected wave from the coating/silicon (lower/higher index) interface the resultant phase shift is inconsequential to the result.
5.4 References


6. Intel Corporation, Jerusalem 5 Office Building, S.B.I. Park Har Hotzvim, Jerusalem, 91031, IL,


10. Buehler, Saturn Building, 101 Lockhurst Lane, Coventry, CV6 5SF, UK. www.buehler.co.uk.

11. *Brand Laser Optics & MFG., 4515 Noris Road, Fremont, CA 94536, USA.*

6 Experimental Techniques

In order to study the fabricated devices discussed in the last chapter an experimental setup is required. This chapter focuses mainly on the equipment and configuration of this setup. In order to avoid any ambiguities in the polarisation state of an optical signal entering or exiting the test chip, the optical beam was allowed to propagate freely through space where possible. Hence a free-space experimental setup was developed as it provided flexibility in data acquisition and provided an optical signal whose polarisation state is well defined and maintained. This chapter begins with a discussion of this setup and the components that comprise it. The setup was designed to accommodate optical fibres as well so that a fibre/free-space hybrid setup could be for testing purposes. For completeness, the methods used to build the setup as well as a brief discussion of the automated scan programme are also given. As polarisation is of fundamental importance in the study of these devices, a discussion on the calibration of the polarisation components is given. This is followed in turn by an investigation of thermal effects that affect the measurements results. As the Scanning Electron Microscope (SEM) is an important piece of experimental equipment used to determine the dimensions of the fabricated devices, this chapter concludes with a brief discussion on its calibration.

6.1 The Free-Space Optical Test Setup

The outputs of many of the light sources in the laboratory are fibre coupled. Whilst it is possible to couple these sources directly to a waveguide on a test chip with the use of a pigtailed fibre, the ability to not only maintain, but control the polarisation state of the input light can be problematic. As the effect of polarised light on the devices is one of the fundamental aspects studied, the determination, control, and maintenance of the input light is of paramount importance. This can be achieved by using a free-space optical
input beam whose polarisation has been properly aligned and controlled using conventional free-space optics. Figure 6.1 is a pictograph of the experimental setup used to study the fabricated devices. To facilitate the discussion of the setup, the bold numbers in curved bold parenthesis in the text correspond to the boxed numbers in the figure.

The first piece of equipment used in the setup is the Lightwave Measurement System (1) (model # 8164A) manufactured by Agilent Technologies Inc. [1]. This system consists of a mainframe that controls and houses a tuneable laser (model # 81640A) and optical power detector interface module (model # 81618A). Connected to the interface module is the optical detector head (2) (model # 81624B). This head is sensitive to wavelengths in the range from 800 to 2400 nm which covers the operating range of the tuneable laser (1520 to 1620 nm). The measurement system can be used manually or controlled via a General Purpose Interface Bus (GPIB) cable and card that is attached to a computer (not shown in the figure).
Chapter 6: Experimental Techniques

A Polarisation Maintaining (PM) fibre is used to connect the tuneable laser to the fibre-to-free-space optics patchcord (OZ Optics, Inc. [2] PMJ-3A3S-1550-8/125-3-1-1). One end of the fibre has an FC/APC (Ferrule Connector/Angled Physical Contact) connector to match the output connection of the tuneable laser. The other end has an FC/PC (Ferrule Connector/Physical Contact) connector whose output facet is perpendicular to the fibre’s optical axis. The laser has a low noise (output one) and a high power (output two) output. The low noise output is also low power and as power is typically the main concern in measurements, the optical fibre is connected to output two. A 3-axis stage (3) (Melles Griot [3] 17 AMB 003/MD) is used to fine tune the x-y-z spacing between the FC/PC connector and the free-space collimating objective lens. The objective lens is held by an objective lens holder which is designed to attach to the stage (Melles Griot [3] 17 HMO 001). The effective Numerical Aperature (NA) of the PM fibre patchcord is 0.40. According to the manufacturer’s suggested collimation procedure, an objective lens with an NA of approximately 50% greater than that of the fibre should be used. A 40x objective lens (Melles Griot [3] 04 OAS 01) with an NA of 0.65 was used. The end of the fibre is held by an FC connector fibre chuck (Melles Griot [3] 17 HFB 003) that can be clamped to the top plate of the stage. It is designed to hold a patchcord with an FC/PC connector. The fibre chuck and objective holder have been designed so that when the two are placed on the stage they have approximately the same optic axis. The objective lens was attached to a fixed platform bracket (Melles Griot [3] 17 AMA 009). This bracket is attached to the side of the stage so that when the stage platform is adjusted, this bracket remains stationary. Thus the fibre can be adjusted with respect to the objective lens which stays fixed.

With the optical beam from the fibre now in free-space, it is sent through a broadband polarising cube beamsplitter (4) (Newport Corp. [4] 10FC16PB.9) that is mounted inside a cube beamsplitter holder (Newport Corp. [4] CH-1). The beamsplitter has two functions. Firstly it defines the polarisation state of the free-space beam. The cube is aligned so that the light exiting the cube in the forward direction is in the TE polarisation state (parallel to the optical table). Secondly it is used as a filter to remove any TM polarisation components that are inherent within the beam. These filtered components are transmitted perpendicular to the transmitted beam where they are then absorbed by a beam block.
A half-wave plate (5) (CVI Corp. [5] QWPO-1550-10-2-R/5) is then placed in the beam path. This allows for the linear polarisation state of the input beam to be converted from TE to TM or vice versa.

Figure 6.2 gives a close-up view of items 6, 7, and 8 from figure 6.1. A 3-axis central stage (6) (Newport Corp. [4] M-562) is used to hold the test chip. A platform (6a) was machined out of aluminium to hold the test chip. The platform was designed so that it is the same width or just slightly smaller than the test chips. This was done so that when the objective lenses were brought in near the chip, the platform would not interfere with them getting close enough to the waveguide facets on the test chip. The platform was attached to the central stage (6) by using a modified bracket (Melles Griot [3] 17 AMA 009). The bracket was modified by having the vertical face shortened by half its original height. Two parallel vertical notches were also cut into the vertical face so that it could be attached to the central stage with two M6 screws.

The free-space beam is focused onto the input facet of a waveguide by a 63x objective (7a) (Melles Griot [3] 04 OAS 018). This lens was chosen as its spot size is of the order of a micron. The lens was held in place by a holder identical to the one used in the free-space collimation setup (3).
Light emerging from a waveguide is normally collected and collimated with a 40x objective (8a) (Melles Griot [3] 04 OAS 016/IR). This objective was chosen as it gave the best image on the infrared imaging camera as well as the fact that it did an acceptable job of collecting and collimating the light exiting waveguide. The objective lens holder and associated stage are identical to the ones used on the input stage.

The typical waveguide cross-section is of the order of a square micron. Therefore high precision stages (7 & 8) (Melles Griot [3] 17 MAX 101) are needed to properly align the objective lenses to the test chip. These 3-axis stages are micrometer driven for coarse alignment (Melles Griot [3] 17 DRV 002). The micrometers have a manufacturer specified 50nm resolution. Fine tuning is then accomplished by using built-in piezoelectric drives. The drives are powered and tuned with piezoelectric controllers (Melles Griot [3] 17 PCZ 013) shown in Figure 6.3. These controllers have feedback so that the position of the objective lens, and hence the beam, can be manipulated with a manufacturer specified resolution of 5 nm.

A linear polarizer (9) (Thorlabs, Inc. [6] LPNIR050) that is housed in a one degree incremented rotation mount (Thorlabs, Inc. [6] RSP05/M) is also sometimes placed in the beam path. The polarizer is used to investigate and filter the output light from a device under test. It has a transmittance of ~90% and an extinction ratio of >100,000 at 1550nm.
Using an aluminium mirror (Thorlabs, Inc. [6] PF10-3-G01) held by a Flipper™ mirror mount (New Focus [7] 9891) the output beam from the test chip can then be directed either to an infrared camera (11), or allowed to pass onto the detector head (2) for measurement of the optical power. The infrared camera (Electrophysics [8] 7290A) is a vital piece of equipment for the free-space setup. As the light is infrared, it allows visual confirmation that the light coupled into the waveguide is emerging from the correct waveguide. Figure 6.4(a) shows an image of the output facet of a tapered waveguide. Figure 6.4(b) demonstrates what a typical output beam looks like when coupled to the waveguide. Since the focal length of the imaging optics is wavelength dependent, the output mode is blurry. By changing the focus of the output objective lens, the light can be focused to give a clean image of the output mode, shown in Figure 6.4(c).

![Figure 6.4](image.png)

(a) Image of the output waveguide (b) with unfocused light (c) and focused light

A standard colour CCD (JVC TK-1280E) camera and variable zoom imaging tube (12) situated above the test chip is used to image the top of the test chip. This camera aids in the alignment of the input/output optics (see Figure 6.6 for an example image from this camera). The output of the camera is sent to a colour video monitor. The camera and imaging tube are connected to two 1-axis stages (Thor Labs, Inc. [6] PT1/M) by way of a cylindrical mount (Newport Corp. [4] ULM) that clamps the imaging tube in place, as shown in Figure 6.5. The first stage is used to aid in focusing the camera/tube system. The second stage is connected so that the camera/tube assembly can be translated between the input and output sides of the chip. The stages are attached to a bracket (Newport Corp. [4] M370-RC) that also clamps to a vertical bar (Newport Corp. [4] 70). In order to move the stage in the third direction (perpendicular to the waveguides), the bar is connected at its base to a universal construction bracket (Newport Corp. [4] CB-2-M). This bracket is then held to the optical table by clamps that are only hand tightened.
These clamps are connected to construction brackets that are locked down to the optical table (see the bottom of Figure 6.5).

The same type of imaging tube is connected to the infrared camera. Thus the visible light source (Schott North America, Inc. [9] KL1500) (located next to the infrared camera in Figure 6.1) can be used for either camera, depending on which is desired. The light source connects to the imaging tubes via an optical fibre bundle.

The optical power of the beam coming from the tuneable laser is approximately 1mW. With devices that have a relatively large loss, this level of power may make it difficult to initially align the optics. A broadband light source can be used in these situations (13) (Thor Labs, Inc. [6] ASE-FL7002). It has an output power of approximately 20mW. This light source is also APC fibre coupled so that the PM fibre used to connect the tuneable laser to the setup can also be used with it. As this light source has a random polarisation state, the polarising beamsplitter is removed from the optical path so that none of the power is lost as a result of its placement in the beam path.

![Figure 6.5. Overhead imaging assembly](image)
With this setup configuration, most of the measurements made to characterise the optical racetrack resonators were made. A list of the all the major components used in the setup are given at the end of this chapter. Whilst this setup does allow for the greatest degree of experimental freedom, it does have a tendency to be difficult in the initial alignment of the input/output alignment objective lenses. When polarisation control is not an issue, a hybrid version of the free-space setup is usually used.

6.2 Hybrid Fibre-Free Space Setup

The setup in section 6.1 can be modified by using optical pigtail (fibres whose core and cladding are exposed at one and either have a connector or are permanently connected at the other) fibres in place of the objective lenses. The fibres are useful for several reasons. The first is that the fibre tip can aid in the initial alignment of the fibre to the waveguide. Two types of fibre ends are typically used in the setups, a flat-faced faced fibre or a lensed fibre. The flat faced fibre is used to butt-couple the fibre directly to the waveguide (see Figure 6.6(a)). Lensed fibres (Figure 6.6(b)) have a conical tip which helps focus the beam onto the waveguide facet (or helps collect the light emerging from a waveguide). The fibres are secured to the stages with tapered fibre chucks (Melles Griot [3] 17 HFV 002).

Figure 6.6. (a) Plan view of a flat-faced fibre and a (b) lensed fibre coupled to a waveguide.
The reason that fibres are not typically used is because of the issues of polarisation control and determination. Because fibre modes are degenerate, if the fibres were to be anisotropically strained or heated, the input polarisation state may change. This problem may be overcome by the use of Polarisation Maintaining (PM) fibre, however for pigtailed fibres the polarisation state of light coming out of the fibre is still an issue. Typical patchcords have keys on the connectors that define the polarisation state of the output of a fibre with respect to the input. Pigtailed fibres have no such alignment determination and hence need to be calibrated prior to use. As these fibres are typically held in place by magnets these fibres may rotate in the holders over time. Thus the polarisation state of the fibre would need to be determined every time any experiment is done to ensure that the output polarisation state is known. Also, many of the same components such as polarizers and half wave plates would need to be installed in the fibre’s path. These are typically more expensive than their free space counterparts. Regardless, there are instances when the polarisation state of the input light is unimportant and hence fibre coupling can allow for relatively easier coupling as compared to the fully free-space configuration.

6.3 Calibration of the Polarisation Components

Determination and control of the input polarisation state is of critical importance in many of the measurements made in this work. Thus great care was taken in ensuring that the input polarisation state is accurately known. The output of the tuneable laser, after the collimating optics, was analysed and was found to be primarily in the TE state. Regardless, a polarising cube beamsplitter (4) was placed in the beam path that had a 500:1 extinction ratio at 1550 nm. The cube is made by gluing two triangular pieces of glass together at their hypotenuses thereby creating a plane along the diagonal of the cube. The splitting of the beam into TE and TM components occurs at this plane. The cube was aligned in its holder so that the plane was vertical with respect to the table (see Figure 6.7). Thus filtered TE polarised light is passed to a half wave plate (5) and any TM components are reflected perpendicular to the TE beam and subsequently ‘dumped’ into a beam block.
When the polarizer (6) was purchased, it was not installed in a rotary mount. Therefore once it was inserted into the mount, it had to be calibrated in order to account for any misalignment during insertion. This was accomplished by passing the filtered free-space optical beam through it and into the detector head. The polarizer was rotated until a maximum optical signal was measured on the detector. The corresponding rotary mount angle was 17°. This defines the TE state of the polarizer. Power measurements were then taken as a function of angle. Figure 6.8 shows the results of these measurements. The results demonstrate a sinusoidal behaviour with the minima occurring 90° from the initial maximum and subsequent maximum occurring 180° from the initial maximum. The red data points indicate those that were re-measured to verify the maxima and minima of the polarizer. Fluctuations and repeatability of the data were found to be less than one percent and as a result no error bars are given.
Chapter 6: Experimental Techniques

The half-wave plate (5) was also purchased separately from its rotation mount and therefore required calibration as well. The calibrated polarizer was placed just in front of the optical detector and set so that it fully passed TE light. The uncalibrated half-wave plate was placed at the output of the polarising cube beamsplitter. The optical power as a function of the rotated angle of the half-wave plate was then measured. The result is given in Figure 6.9. The red data points are the maxima and minima that were re-measured after the initial measurements were taken to ensure the validity of the measurements. For experiments, the angle of 357° was used for launching TE light and 42° for TM. The fluctuations in the data were again very small (<1%), therefore error bars were omitted to avoid cluttering the graph.

![Figure 6.9. Calibration data of the half-wave plate used in the experimental setup](image)

**6.4 Alignment of the Free-Space Experimental Setup**

As the cross-sectional dimensions of a typical waveguide are only of the order of a few microns, great care was taken in the alignment of the components in the free-space setup. The following steps in the alignment process are given in order, as it was found that this procedure yielded the most reproducible results.

The first and probably most important of the alignments is the placement of the stage containing the fibre-to-free-space collimating optics (3). This stage was securely fastened to the table as any slight misalignments would potentially create large beam path deviations further into the setup. The beam was centred with respect to the objective lens
in the $x$ (horizontal to the table) and $y$ (vertical to the table) planes in the following way. An IR card (Newport Corp. [4] F-IRC-2) was used to image the output beam coming from the objective lens. The beam was adjusted by moving the x-axis micrometer, for instance, until it clipped the side of the objective lens (see Figure 6.10). The value of the micrometer was noted and the micrometer was adjusted in the other direction until it again clipped the objective lens sidewall and the value of the micrometer was again noted. The average of the micrometer readings is expected to give the centre point beam with respect to the output of the objective lens. The same method was used to determine the y-axis centre point.

![Figure 6.10. Plan-view of collimation stage showing the centring of the beam in the objective lens](image)

The heights of two adjustable irises (Thorlabs, Inc. [6] ID12/M) were set by placing them just in front of the objective lens output. The irises were closed as much as possible to minimise their aperture, and their heights adjusted until light passed through the iris aperture. The collimation stage was then loosely attached to the table and aligned so that the output beam approximately followed a line of screws holes in the table. One of the irises was placed just in front of the output objective whilst the second was placed on the opposite side of the table, but in line with the screw holes to which the output beam is approximately aligned. The collimation stage was then adjusted by moving the entire stage until the output beam passed through the irises at each side of the table. The IR card was used on the opposite side of the far pinhole to image the beam passing through it. The collimation stage was then clamped down tightly to the table. The z-axis (fibre/lens separation) was then adjusted to give an approximately collimated beam. This was accomplished by using the IR card to image the beam diameter at several points...
along the beam as it propagated along the table. The y-axis was also adjusted slightly for fine alignment of the beam in the vertical direction.

Next, the piezoelectric stages (7 & 8) were placed in the beam path. It was found that the approximate median travel of the x- and y- axes is 4mm. The micrometers for both x- and y- axes of both stages were set to this value. The stages were then approximately placed as shown in Figure 6.2. The slots in the adjustable top plate of these stages were used to approximately align the stages to the beam path as this slot lies parallel to the optical axis for the optics that are attached to the stage. The adjustable irises were then removed from their holders and placed inside the objective lens holders. The irises can be pressed into the holders for a snug fit. The lens holders were then attached to the stages as they would if they were holding objective lenses as shown in Figure 6.2. As the holes in the base of the stage are slotted, the stage could be adjusted to allow the beam from the collimating optics to pass through the iris. Once the light could pass through the iris, the stage was clamped down firmly.

The power detector head (2) was then placed in the beam path. It was adjusted so that the maximum amount of power passing through the pinholes was obtained. The collimating and piezoelectric stages were then adjusted slightly in an attempt to fine tune the alignment, by optimising the throughput power.

The central stage and aluminium platform were then added to the setup. The platform and stage were placed approximately half way between the two piezoelectric stages. The central stage was then adjusted so that the top of the platform lay just below the optical beam passing through the irises. This was done by adjusting the height of the platform until a slight decrease in power is observed with the power meter. Thus the central stage is at approximately the right height with respect to the optical beam.

The overhead camera (12) was then placed into the setup aligned to image the top of the platform. The 1-axis stages used to adjust the camera were centred with respect to their respective travel prior to aligning the camera. The clamp on the support rod was adjusted
so that the stage was approximately in focus. The support rod attached to the universal bracket was then loosely clamped to the table with the camera image approximately centred on the middle of the platform.

A test chip containing a straight waveguide was placed on the platform. The focus of the overhead camera was adjusted so that the top of the chip could be imaged. The overhead camera was translated to image the output side of the chip. The irises were removed from the objective lens holders and replaced with the appropriate objective lenses. The IR camera (11) at the output was placed at a 90° angle with respect to the optical beam path as shown in Figure 6.1. A Flipper™ mirror was then placed in the beam path to direct the image of the output facet to the IR camera (see Figure 6.4(a) for example).

Two benefits are obtained by connecting the fibre optic light source to the IR camera’s imaging tube. The first is that the output facet of the waveguide can be imaged. The second is that the light projected onto the chip, as shown in Figure 6.11(a), aids in aligning the output optics to the chip. This light can then be imaged using the overhead imaging camera (Figure 6.11(b)), to approximately determine which waveguides are being observed with the IR camera. Using this method, the centre stage was used to align a straight waveguide to the output optics.

![Figure 6.11](image)

**Figure 6.11.** (a) Light from the IR camera imaging tube projected onto the output of the chip (b) Plan-view image of the projected light as observed with the overhead camera
The alignment of the input objective lens is more difficult than the output objective as the input facet is not imaged. However an analogous method can be used by taking the unconnected end of the fibre from the fibre light source and shining it into the input objective lens as shown in Figure 6.12. As the input objective is divergent, this method only produces a qualitative reference between the input objective and the desired waveguide input facet.

As it is unlikely that the test chip is perfectly aligned with the optic axis of the setup when it is placed on the aluminium platform, some movement of the input objective’s stage will usually be necessary. Once light is observed passing through the desired waveguide, the Flipper™ mirror is lowered so that the light from the waveguide is passed onto the detector. Slight adjustments to the micrometers, and subsequently the piezoelectric controllers (Figure 6.3) are made to both stages to optimise the light passing through the waveguide. Small adjustments may also be made to the collimating stage although this is not recommended as gross misalignment may result.

Finally, the polarising cube beamsplitter and half-wave plate are placed in the beam path just after the collimating optics. They are adjusted so that the optical beam runs approximately through the centre of their respective apertures. They are also swivelled back and forth in an attempt to maintain the maximum amount of power passing through the system as measured by the detector to ensure they are positioned normal to the beam.
path. This is done so that the refraction of the beam due to these components is minimised.

6.5 Automated Measurement Control Programme

The spectral response of a racetrack resonator device is one of its most important measurements carried out in this work. From this response, many of the characteristics of the device such as the FSR, finesse, and quality factor can be determined (see section 3.6 for definitions of these characteristics). Such a measurement could be made manually by measuring the corresponding output power for a range of wavelengths. As a high resolution scan could have, of the order of a thousand data points, manual measurements would simply be too tedious and would suffer from potential thermal drift of the device over the extended time required to make the measurements. Therefore an automation programme was written by a former summer student, Miss I. Huille, using LabVIEW™ [10] software that interfaces a computer with the lightwave measurement system (1). The programme incrementally adjusts the tuneable laser’s wavelength whilst obtaining the optical power as measured by the optical detector head. The interface of the programme, programme2.vi, is shown in Figure 6.13. The coloured rectangles in the diagram are used to facilitate the following discussion highlighting the main aspects of the interface.

Figure 6.13. Interface of the automated scan programme used to measure the spectral response of the fabricated racetrack resonators
The controls in the red, solid-lined box are used to initialize the lightwave measurement system. The square ‘initialize’ button is used initially to setup communications between the computer and the system. Once communication has been established, this button is turned off and only needs to be enabled again if either the programme is closed or the system has been switched off. Below this button is a vertical slide bar labelled ‘Laser Output’. This control driver was downloaded from the LabVIEW [10] website. As this is a generic driver for several Agilent systems, only two of the settings, ‘High Power’ and ‘Low SSE’ are actually connected. Output two of the laser is the high power output. This output is used for all experiments in this work. Output one is the Low Source Spontaneous Emission output (Low SSE) which is typically used for measurements of DWDM devices where a low optical noise output is necessary to characterise the device. However the drawback with this output is that is has a very low amount of output power and as a result is not useful for most of the device applications used. The ‘Laser State’ button enables the output for whichever mode was chosen on the slide bar above. The ‘Save’ button is used to toggle the save data prompt (on or off) that appears after a wavelength scan has occurred. Turning the save button off can be useful if a quick scan is desired and it has been predetermined that the data will not be saved or if the programme is used to simply tune the laser to a desired wavelength.

The controls in the double-lined orange box are used to set the power level of the laser. The ‘Power Selection’ slide bar allows the user to set the output level of the laser to its maximum, minimum, or a default power output. If a specific output power value is desired it can be typed into the ‘Manual Power’ box. The desired units of the output power can also be set using the slide bar located next to the power selection bar.

The controls in the solid-lined green box are used to set the wavelength characteristics of the laser. If the user wishes to tune the laser using the programme the red toggle switch is switched down and the desired wavelength is entered in the ‘Manual Wavelength’ box. If the programme is used to measure the detected power as a function of wavelength, the red toggle switch is switched upward. There are two methods for setting the start and finish wavelength values of the scan. The first is to move the green (start) and red (stop) sliders on the bar located just above the red toggle switch. The second is to type the desired start
wavelength in the left-hand box and the stop wavelength in the right-hand box located just above slider bar. The 'Step Size' determines the step in nanometres which the laser is incrementally tuned during the scan. The 'Step Delay' box is used to adjust the amount of time the programme waits before obtaining the power reading from the system. This parameter was introduced into the programme to account for the time averaging the system does whilst acquiring the power reading. The default value of 200ms was determined through trial and error to give the smoothest data whilst acquiring the data at an acceptable rate. For values less than 200ms, the detector will not be allowed to average properly and the resulting data will have large fluctuations especially in regions where adjacent data points have relatively large differences in their measured power such as along a slope of a resonance dip.

The solid-lined yellow box is where a graphical presentation of the acquired data is plotted as it is taken. The default values of the axes are the detector power in microwatts as a function of wavelength in nanometres. Should the user desire to modify the scales or turn off/on the auto ranging capabilities of the plotter these controls can be found in the drop down menus located just above the blue box.

The dashed-line black box is the tabular representation of the data being plotted in the dark blue box. This table is particularly useful if a quick determination of a power or wavelength is desired without having to analyse the entire data set to determine the desired values.

The red error indicator in the double-lined yellow box lets the user know when an error is encountered with the programme such as an initialization failure between the computer and the system. Should an error occur, a diagnostic box can be found by scrolling down on the interface screen to determine the potential cause of the error. The stop button can be pressed should the user wish to halt the programme whilst it is in a data acquisition loop.
A subroutine was subsequently added to the programme that would aid in calculating the loss of a waveguide using the Fabry-Perot method (see section 3.8). Thus the dialogue boxes in the upper right-hand corner of the yellow box labelled 'R' and 'L(cm)' are used to enter the reflectance of the waveguide facet and the length of the device in centimetres respectively. The programme is then used to obtain a wavelength spectrum of a waveguide. The programme can then calculate the maxima and minima from the data (and 'R' and 'L' values) and thereby determine the loss of the structure.

6.6 Investigation of Thermal Effects on Measurement Accuracy

Silicon’s thermooptic coefficient \( \frac{dn}{dT} \) is \( 1.86 \times 10^{-4} \, ^\circ C \) [11]. Whilst this value may seem small, its impact on the spectral response of a racetrack resonator device can be considerable. The change in phase, \( \Delta \phi \), of a resonator is given as:

\[
\Delta \phi = \frac{2\pi \Delta NL}{\lambda}
\]  

(6.1)

where \( \Delta N \) is the change in the effective index of refraction, \( L \) is the circumference of the racetrack, and \( \lambda \) is the free-space wavelength of light. As the phase between two consecutive resonant dips is \( 2\pi \), a proportionate change in the phase can be written in terms of a proportionate change in the FSR or:

\[
\frac{x}{\Delta \phi} = \frac{FSR}{2\pi}
\]  

(6.2)

where \( x \) is the spatial separation of two resonance dips as a result of a phase shift as shown in Figure 6.14 along with the FSR. Combining equations 6.1, 6.2, using the thermooptic coefficient, and using the assumption \( \Delta n = \Delta N \), a change in temperature as a function of the phase shift of the spectral response of a device can be written as:

\[
\Delta T = \frac{\lambda x}{L(FSR)(1.86 \times 10^{-4} \, ^\circ C)}
\]  

(6.3)

To quantify the sensitivity of these devices, a resonator with \( L=2884.96\mu m \), \( FSR=225\)pm at \( \lambda=1549.71\)nm was used to calculate the temperature change expected for a given phase
shift. The result is that the temperature necessary to shift the phase by 1pm is only 0.01°C.

The resonator chip was placed on a ThermoElectric Cooler (TEC) (Thorlabs, Inc. [6] TE3-6) and driven by an ILX (ILX Lightwave Corp. [12] LDT-5910B) TEC controller. Thermal feedback was achieved by using a 10kΩ thermistor (Thorlabs, Inc. [6] TH10K) that has an accuracy of ±1°C @ 25°C. The controller has a resolution of ±0.1°C. A handheld multimeter (Omega Engineering, Inc. [13] HHM290) with a built-in type K thermocouple was used to monitor the temperature reading given by the TEC controller. It has an accuracy of ±1°C and a resolution of ±0.2°C. The setup is shown in Figure 6.15. A specially designed aluminium device holder was fabricated so that the TEC could be accommodated. The TEC was attached to the aluminium device holder with thermal epoxy. An aluminium block was epoxied to the top of the TEC to hold the chip. The thermistor was applied to the top side of the TEC instead of to the side of the aluminium block. It was found that this configuration gave the best stability of the controller. Thermal grease was applied between the thermistor and the top of the TEC to improve the thermal contact.

Initially the controller was set to approximately room temperature (22.0°C) and allowed to stabilise using the auto tuning feature on the controller. Spectral scans were then taken.

Figure 6.14. Phase shift of a racetrack resonator’s spectral response due to heating
throughout the day to determine the stability of the system. Figure 6.16 is a plot demonstrating the thermal drift of the device over time even with TEC stabilization. The “10min” data is used as the reference point as it was felt that the system was not at a steady state initially because the overhead imaging light, which may have been heating the chip, was turned off just prior to the taking of the “0hr” data.

Thus the experimental setup with thermal stabilization has an approximate ±2pm stability over a five hour period. This result (and the use of equation 6.3) would imply that the
Chapter 6: Experimental Techniques

system is accurate to ±0.02°C over the five hour period. To measure the validity of the calculated temperature drift of the system (0.01°C/pm) the temperature of the TEC controller was changed from 22°C to 23°C by 0.1°C increments with a wavelength scan made at each increment. The shift of the minima with respect to the 22.0°C minima at 1549.707nm as a function of temperature is given in Figure 6.17. The horizontal error bars are from the minimum resolution of the controller. The vertical error bars are a result of the time dependent thermal drift of the system. The theoretical shift was calculated from the expected drift of 0.01°C/pm. Considering the relatively poor accuracy and sensitivity of the system, the results are in support of the calculated drift. Whilst this result may seem troublesome for silicon, it does have a positive significance in that these devices could be used as very sensitive integrated temperature sensors. Also, TEC’s could be packaged with silicon optoelectronic devices should a device require some sort of thermal control.

![Figure 6.17. Shift in the resonance minima of a racetrack resonator due to heating](image)

Since much of the data was taken without thermal stabilisation, an attempt to determine the drift in these conditions was made. Several scans were made throughout the day using the standard free-space configuration, are plotted in Figure 6.18. A typical scan over a 1nm range takes approximately 12 minutes to complete. A common data set
investigating the response of a racetrack resonator comprises four scans (the two polarisation states and the two cross-polarisation states). Thus a scan was made of the chip after 50 minutes had elapsed from the initial scan to determine what sort of drift could be expected in a typical data set. The results show that a 5pm drift occurred in this time frame. A scan was taken several hours later to determine the long term drift of the setup. The results show a 29pm drift with respect to the initial measurement. The overhead light was then turned on and allowed to heat the chip for approximately five minutes. A scan was then made to determine the drift caused by the light. The additional drift due to the light was only about 2pm. Whilst this is only a limited data set, the results of this experiment show that drifts observed in data sets discussed in the next chapter are probably caused by thermal drift.

![Graph showing thermal drift of a racetrack resonator minimum over time without attempting to thermally stabilize the chip](image)

**Figure 6.18.** Thermal drift of a racetrack resonator minimum over time without attempting to thermally stabilize the chip

### 6.7 Calibration of the Scanning Electron Microscope

The Scanning Electron Microscope (SEM) is a very important instrument in determining the dimensions of the fabricated devices. Due to processing tolerances, the fabricated devices will most likely be different than what was modelled. As the modelling and device performance is heavily dependent upon the device dimensions, they need to be known accurately. Thus any deviations from the expected dimensions can be remodelled to determine how well the modelling results match the experimental results.
Several SEM’s were used during the study of the fabricated devices. However an Environmental SEM (ESEM) (FEI Company [14] Quanta 200F) operating in low-vacuum mode was used to measure most of the more recently studied and imaged samples. The major benefit of this mode is that allows for the measurement of dielectric samples without the issue of charging that usually occurs with most high-vacuum SEM systems.

Regardless of which SEM was used to measure the dimensions of devices, all of the microscopes were calibrated using the same method although with slightly different working conditions. A Sira certified SEM calibration standard (Agar Scientific, Ltd. [15] part no. S170C spec. no. A925) was used to determine the measurement error for a typical measurement. The standard comprises a grid of scribed lines uniformly spaced so that it has 2160 lines/mm, which corresponds to a line spacing of 463 nm. The standard was placed 11.22 mm from the tip of the electron gun. The chamber was set to a pressure of 0.9 mbar. The electron beam had a spot size setting of 3.0, a 20 kV accelerating voltage, and an emission of 1.88 μA. These are the working conditions used when using the ESEM.

The resulting image of the standard is shown in Figure 6.19. The line spacing was measured using the post-process image analysis software package bundled with the ESEM. For the horizontal lines, a value of 465 ± 2 nm was obtained for the line separation. A separation of 472 ± 2 nm was obtained for the vertical lines. The horizontal value is in excellent agreement with the expected value of 463 nm. The vertical measurements have a 2% discrepancy from the expected value. To determine the resolution of the SEM at this magnification, a ruler was used to measure the measurement bar located in the bottom right hand corner of the image in Figure 6.19. The bar was found to be 20 ± 1 mm long. Using 1 mm as the minimum achievable accurate measurement using the ruler, a value of 25 nm was determined as the resolution of the SEM for this particular magnification. The 2% discrepancy determined in the y-value measurement is well within the determined resolution. The calibration standard does demonstrate, therefore, that the SEM is calibrated to within the resolution of the SEM for the stated working conditions.
Figure 6.19. Image of the calibration standard as viewed with an ESEM. The measurement bars were subsequently added with analysis software

6.8 Table of Components Used in the Free-Space Experimental Setup

The following table is a list of the manufacturers, part numbers and, where possible, the serial numbers of the components used to build to free-space setup.

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer</th>
<th>Part #</th>
<th>Serial #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightwave Measurement System</td>
<td>Agilent</td>
<td>8164A</td>
<td>DE40705155</td>
</tr>
<tr>
<td>Tuneable Laser</td>
<td>Agilent</td>
<td>81640A</td>
<td>DE39401637</td>
</tr>
<tr>
<td>Power Detector Interface Module</td>
<td>Agilent</td>
<td>81618A</td>
<td></td>
</tr>
<tr>
<td>Optical Power Detector Head</td>
<td>Agilent</td>
<td>81624B</td>
<td>DE38200649</td>
</tr>
<tr>
<td>PM fibre patchcord (APC-PC)</td>
<td>Oz Optics</td>
<td>PMJ-3A3S-1550-8/125-3-1-1</td>
<td>T719091-04</td>
</tr>
<tr>
<td>Top-down imaging camera</td>
<td>JVC</td>
<td>TK-1280E</td>
<td>15015369</td>
</tr>
</tbody>
</table>
## Chapter 6: Experimental Techniques

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer</th>
<th>Part #</th>
<th>Serial #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric stage controllers (input)</td>
<td>Melles Griot</td>
<td>17 PCZ 013</td>
<td>801017 (inp.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>801052 (out.)</td>
</tr>
<tr>
<td>Objective lens holder</td>
<td>Melles Griot</td>
<td>17 HMO 001</td>
<td></td>
</tr>
<tr>
<td>Imaging light source</td>
<td>Schott</td>
<td>KL1500</td>
<td>02147</td>
</tr>
<tr>
<td>Infrared camera</td>
<td>Electrophysics</td>
<td>7290A</td>
<td></td>
</tr>
<tr>
<td>Centre 3-axis stage</td>
<td>Newport</td>
<td>M-562</td>
<td></td>
</tr>
<tr>
<td>Collimating stage</td>
<td>Melles Griot</td>
<td>17 AMB 003/MD</td>
<td></td>
</tr>
<tr>
<td>40x objective lens</td>
<td>Melles Griot</td>
<td>04 OAS 016</td>
<td></td>
</tr>
<tr>
<td>40x objective lens IR coated</td>
<td>Melles Griot</td>
<td>04 OAS 016/IR</td>
<td></td>
</tr>
<tr>
<td>63x objective lens</td>
<td>Melles Griot</td>
<td>04 OAS 018</td>
<td></td>
</tr>
<tr>
<td>FC connector fibre chuck</td>
<td>Melles Griot</td>
<td>17 HFB 003</td>
<td></td>
</tr>
<tr>
<td>Polarising cube beamsplitter</td>
<td>Newport</td>
<td>10FC16PB. 9</td>
<td></td>
</tr>
<tr>
<td>Cube beamsplitter holder</td>
<td>Newport</td>
<td>CH-1</td>
<td></td>
</tr>
<tr>
<td>Half-wave plate</td>
<td>CVI</td>
<td>QWPO-1550-10-2-R/5</td>
<td></td>
</tr>
<tr>
<td>High precision piezo. stages</td>
<td>Melles Griot</td>
<td>17 DRV 002</td>
<td></td>
</tr>
<tr>
<td>Linear polarizer</td>
<td>Thorlabs</td>
<td>LPNIR050</td>
<td></td>
</tr>
<tr>
<td>Linear polarizer rotation mount</td>
<td>Thorlabs</td>
<td>RSP05/M</td>
<td></td>
</tr>
<tr>
<td>Aluminium mirror</td>
<td>Thorlabs</td>
<td>PF10-3-G01</td>
<td></td>
</tr>
<tr>
<td>Flipper mirror mount</td>
<td>New Focus</td>
<td>9891</td>
<td></td>
</tr>
</tbody>
</table>
## Chapter 6: Experimental Techniques

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer</th>
<th>Part #</th>
<th>Serial #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical mount</td>
<td>Newport</td>
<td>ULM</td>
<td></td>
</tr>
<tr>
<td>Bar clamp</td>
<td>Newport</td>
<td>M370-RC</td>
<td></td>
</tr>
<tr>
<td>Vertical bar</td>
<td>Newport</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Universal construction bracket</td>
<td>Newport</td>
<td>CB-2-M</td>
<td></td>
</tr>
<tr>
<td>Tapered fibre chuck</td>
<td>Melles Griot</td>
<td>17 HFV 002</td>
<td></td>
</tr>
<tr>
<td>IR card</td>
<td>Newport</td>
<td>F-IRC-2</td>
<td></td>
</tr>
<tr>
<td>Adjustable iris</td>
<td>Thorlabs</td>
<td>ID12/M</td>
<td></td>
</tr>
</tbody>
</table>
6.9 References

12. ILX Lightwave Corp., P.O. Box 6310, Bozeman, MT 59771, USA. www.ilxlightwave.com.
15. Agar Scientific, Ltd., 66a Cambridge Road, Stnasted, Essex, CM24 8DA, UK. www.agar.co.uk.
This chapter discusses the results obtained from two fabricated test chips. The results are, in general, grouped so that the results of the two test chips can be discussed together. The chapter begins with an investigation of the propagation loss as determined by the Fabry-Perot method. One of the reasons for designing a second test chip was that some of the directional couplers on the first test chip were found to have an issue with waveguide asymmetry. This is discussed next. However, a polarisation independent racetrack resonator was found in the first set of test chips, but on a wafer with an etch depth slightly shallower than the target etched wafer. The polarisation independent device is discussed and is compared to the single input/output model presented in chapter three. To take full advantage of the second test chip design, the waveguide bend test structures were investigated and their results are discussed next. This chapter concludes with the discussion of the results and issues associated with the racetrack resonators on the second test chip.

### 7.1 Waveguide Propagation Loss

#### 7.1.1 The First Test Chip Design

From the first test chip design, a wafer was fabricated with the designation W812. Devices on this wafer were fabricated to have the targeted Polarisation Independent (PI) rib waveguide cross-sectional dimensions: 1.0μm waveguide width, 0.83μm etch depth, and 1.35μm waveguide height. Figure 7.1 shows a cross-sectional image of a waveguide from this wafer taken with a Scanning Electron Microscope (SEM). From the image, the actual height of the waveguide as determined from the scaling bar is 1.3μm. The etch depth is 0.5μm. Because of the sidewall slope, the waveguide width is difficult to state
definitively. A measure of the width is made at the top of the waveguide (1.0μm), just under the hard mask, and at the bottom of the rib trench (1.4μm). An average of these two values is 1.2μm. From the width measurements, the sidewall is sloped approximately 27° as measured from the vertical axis of the waveguide. After this image was taken, it was found that the SEM used to make the measurements had a calibration error in the software program that defined the scaling bar. Similar devices were later measured with a different calibration software program. Those results revealed that the values quoted above have an error of approximately 10%. Thus all of the values, except for the waveguide width, are within target when this error is accounted for.

![SEM cross-sectional image of a fabricated straight rib waveguide.](image)

To obtain an initial sense of the quality of a fabricated test chip, a measurement of the propagation loss of a straight waveguide was made. This value is commonly stated in the literature and is a useful figure of merit for comparison of similar devices [1]. One of the simplest methods of determining the propagation loss is to use the Fabry-Perot (FP) method as discussed in section 3.8. In Figure 7.2, a typical FP spectrum is shown for both polarisation states. By measuring the maximum and minimum power of the sinusoidal-like resonance, the propagation loss of the waveguide can be determined as outlined in section 3.8.
Chapter 7: Experimental Results

Figure 7.2. Typical FP response of a straight waveguide

Intermixed with the racetrack resonators on the first test chip, are eight straight waveguides. The loss of these waveguides was measured using the FP method. The propagation loss for TE polarised light is $3.4 \pm 0.3\,\text{dB/cm}$ whilst for TM polarised light it is $5.8 \pm 0.2\,\text{dB/cm}$. The uncertainty is determined from the variation in the measurements of the eight waveguides as these waveguides are expected to be identical.

These results demonstrate that the waveguides from wafer W812 have a substantial Polarisation Dependent Loss (PDL). The cause of the PDL is unknown, however a hypothesis is presented. Shown in Figure 7.3, the fundamental TE and TM modes were modelled using BeamPROP with the dimensions obtained from the SEM image in Figure 7.1. A free-space wavelength of 1550nm is used. By close inspection of the sidewalls of each mode in Figure 7.3, the TM mode appears to have more of its mode field amplitude in contact with the sidewall than the TE mode. Therefore if the sidewalls are rough, the TM mode would incur more scattering loss than the TE mode. Hence the PDL may be caused by sidewall roughness as the modelling suggests.

A two-exposure time split was made on each wafer using the first test chip design (see section 4.2.7). Die from the left side of a wafer have a slightly shorter exposure time than on those on the right. The result of this exposure time difference is that the die on the left
should have slightly wider waveguides than those on the right. A die from the right hand side of W812 was also measured to determine whether the exposure time has an impact on the waveguide loss. The propagation loss values for a chip from the right side of wafer are 3.1±0.5dB/cm and 5.1±0.5dB/cm for TE and TM polarisations respectively. The results demonstrate that the propagation loss values as determined from the left and right-hand sides of the wafer are indistinguishable within experimental uncertainty.

7.1.2 The Second Test Chip Design

As there are two waveguide widths being investigated on the second test chip, as opposed to a single width on the first test chip, SEM cross-sections of both waveguide widths are given in Figure 7.4. The wafer with the targeted PI waveguide dimensions is designated W4. All of the target dimensions for the first test chip are the same for this second test chip, with the exception of the additional 0.8μm wide waveguides. The slab height of the fabricated devices is 0.534±0.025μm, which is within the target of 0.52μm. The waveguide height is 1.304±0.025μm. For the 1.0μm target width waveguides, the top of the waveguide has a width of 0.99±0.025μm, whilst the width measured at the bottom of the rib trench is 1.099±0.025μm. These widths yield a sidewall slope of approximately 8° from perpendicular. For the 0.8μm target width waveguides, the top of the waveguide

Figure 7.3. Modelled (a) TE and (b) TM modes using the dimensions of the fabricated rib waveguide shown in Figure 7.1
has a width of $0.990\pm 0.025\mu m$, whilst the width measured at the bottom of the rib trench is $0.840\pm 0.025\mu m$. These waveguides also have a slope of approximately $8^\circ$ from perpendicular. The uncertainty of these measurements was determined by using a calibration sample, as discussed in section 6.7.

Figure 7.4. Cross-sectional SEM images of the targeted PI rib waveguides using the second test chip design.
As different processing equipment was used to fabricate the first and second test chip, differences in the waveguide dimensions can be expected. One interesting difference noticed is the shape of the sidewalls. For the first test chip, the sidewall has a curved profile. For the second test chip, however, the sidewall has more of an hourglass shape. The effect of the sidewall slope is discussed further in section 7.3.2.

The FP method was again used to determine the propagation loss of the waveguides on the second test chip. For the target width 1μm wide waveguides, the propagation loss is 2.14±0.15dB/cm and 3.86±0.15dB/cm for TE and TM polarisations respectively. For the 0.8μm wide waveguides, the propagation loss is 3.21±0.08dB/cm and 4.23±0.16dB/cm for TE and TM polarisations respectively. In comparison to the propagation loss on the first test chip, the 1μm wide waveguides on the second test chip have approximately 30% lower loss for both polarisation states. The stated uncertainty is also better as the loss across various, identical waveguides is more uniform for the second test chip than the first. However, one factor that has remained nearly constant for both test chips is the TE to TM loss ratio. As the waveguides are nearly identical for both test chips, the hypothesis of the sidewall roughness may hold for the second test chip as well. There may be less roughness for the second test chip’s sidewalls thereby giving a proportionately smaller loss.

7.2 Directional Couplers

To aid in the discussion of the results obtained from the fabricated directional couplers, several definitions are given first. In Figure 7.5, a plan-view schematic of a directional coupler is shown. The definitions of the ‘pass-state’ and ‘cross-state’ are best defined by using an example. For an optical mode launched into input one, for example, the portion of the mode’s power that passes to output 1 is power that is in the pass-state of the coupler. For the remainder of the mode power that has coupled to the second waveguide and is emitted at output 2, is power that is in the cross-state.
7.2.1 The First Test Chip Design

A cross-sectional SEM of a directional coupler from wafer W812 is shown in Figure 7.6. The waveguide height and etch depth are the same as the waveguide in Figure 7.1. The waveguide separation, measured between the two sidewalls of the waveguides at a vertical point lying half-way between the top of the waveguide and the rib trench, is $0.60 \pm 0.05 \mu m$. The target separation for this particular coupler is $0.82 \mu m$. Measuring the separation at the top of the waveguides gives a value of $0.79 \pm 0.05 \mu m$. The uncertainty on the measurement therefore includes the target separation. The waveguide separation, also measured at the same vertical point as the initial waveguide widths value stated, is $1.10 \pm 0.05 \mu m$ for the left waveguide and $0.90 \pm 0.05 \mu m$ for the right. The uncertainty of these values is determined by the measuring the dimensions using a ruler with an assumed resolution of $\pm 0.5 mm$. Using the calibration bar at the bottom of the image, $0.5 mm$ corresponds to approximately $0.05 \mu m$.

Initial power measurements on the directional couplers of wafer W812 showed that nearly all of the power passing through the coupler was found in the pass state. A small amount of power, of the order of a few percent, was found in the cross state. All of the couplers investigated, regardless of their waveguide separations and coupler lengths exhibited this...
Figure 7.6. Cross-sectional SEM view of a directional coupler from wafer W812

behaviour. In order to determine if the lack of functionality of the couplers was wavelength dependent, a spectral scan, shown in Figure 7.7, was taken on a coupler whose target length is 1730μm and waveguide separation is 0.69μm. Since the propagation constant and hence the coupling coefficient of the coupler is dependent upon the wavelength (see section 3.4), the coupler should have a wavelength dependent response. The results show that nearly all of the power remains in the pass-state. A slight amount of power is observed in the cross-state for some wavelengths. The spectral

Figure 7.7. Spectral response of a directional coupler from wafer W812
response of a straight waveguide next to the coupler is also plotted. This was done to show that whatever the source of the resonance observed on the pass-state data is most likely not a result of the functionality of the coupler.

The cause of the non-functional directional couplers on wafer W812 is the waveguide width asymmetry mentioned in the discussion of Figure 7.6. This coupler was modelled using BeamPROP. The results, shown in Figure 7.8, demonstrate that very little coupling occurs from the first waveguide (WG 1) to the second (WG 2), regardless of the polarisation state of the optical mode launched.

![Diagram of directional coupler](image)

*Figure 7.8. Modelling results of the directional coupler in Figure 7.6 with asymmetric waveguide widths*

This result makes sense from the standpoint of the need to phase match the waveguides. The propagation constant of a waveguide is dependent upon the effective index (see section 3.2.1). The effective index is, in turn, dependent upon the geometry of the waveguide. Therefore, if the waveguides have different geometries (i.e. waveguide
Chapter 7: Experimental Results

widths), then they will have different propagation velocities. The solutions to the
directional coupler equation discussed in section 3.4.1 require that the waveguides
maintain a constant 90° phase shift between them. Hence if the waveguides have
different propagation constants, this phase criteria will not be met and therefore coupling
between the waveguides will not occur.

It is likely that the waveguide width asymmetry is caused by attempting to fabricate
devices that have dimensions, such as the waveguide spacing, smaller than the resolution
of the photolithography tools used to fabricate the devices [2]. As discussed in section
5.2, the resolution of the stepper used to photolithographically define the waveguide
spacing is 0.8µm. All of the waveguide separations drawn on the mask are smaller than
this resolution. Waveguide spacings that were smaller than the stated resolution of the
stepper were successfully fabricated on test structures similar to a directional coupler
configuration. Hence the stepper was used to fabricate the actual die in this project. What
was not obvious, however, was the impact of the stepper on the waveguide widths.

In an effort to further understand the sensitivity of the waveguide width asymmetry in the
directional coupler, a small modelling study was carried out. Both waveguides in the
model have a height of 1.35µm. The slab height is 0.52µm. The width of the launch
waveguide is held constant at 1.0µm. The width of the second waveguide was varied
from 0.8 to 1.2µm. The indices of refraction and coupler structure are the same as that of
section 3.4.3. The results of the modelling, shown in Figure 7.10, were determined by
investigating the modelled sinusoidal power transfer as a function of distance. An
example is shown in Figure 7.9 where the width of the second waveguide is 1% smaller
than the first, and TE polarised light is used. The blue line indicates the normalised
power in the pass state of the coupler. The green line is the normalised power in the
second waveguide of the coupler. The ‘% Power Transfer’ in Figure 7.9 is the amplitude
of the green line. For the result shown in Figure 7.9, a 90% power transfer occurs
between the waveguides.
Chapter 7: Experimental Results

Figure 7.9. Sinusoidal power transfer between two asymmetric waveguides in a directional coupler as a function of distance into the coupling region.

Figure 7.10. Modelling results of a directional coupler comprised of waveguides with asymmetric widths.

The results shown in Figure 7.10 demonstrate that a 1% difference in the widths of the waveguides comprising the directional coupler defined above results in a 10% drop in the amount of power transferred for TE polarised light and approximately 35% for TM. For a 2% width discrepancy, nearly 30% of TE polarised light will not couple and almost
70% of the TM polarised light remains uncoupled. Thus for the coupler shown in Figure 7.6, only 10% of TE light is expected to couple to the second waveguide and only a few percent for TM. This model appears to support the conclusion that the waveguide width asymmetry is the cause for the non-functional directional couplers on wafer W812. The modelling also indicates that for asymmetric waveguides, the amount of coupled light is strongly dependent on its polarisation state. Still another disadvantage of asymmetric waveguides is that the coupling length $L_n$ (defined in section 3.4) is also altered. For symmetric waveguides, $L_n$ is 230μm for TE polarised light. For the data shown in Figure 7.9, the effective $L_n$ for the coupler decreases to 215μm. The term 'effective' is used because total power transfer does not occur when the pass state has reached a minimum, which is one of the criteria in the definition of $L_n$.

Another wafer, designated W712, was patterned using the same mask that was used to fabricate W812. The devices on this wafer, however, have an etch depth of 0.69±0.03μm. A cross-sectional SEM image of a directional coupler from wafer W712 is shown in Figure 7.11. The waveguide height is 1.34±0.03μm. From a rib waveguide from the same chip, the slope of the sidewall was determined. The width at the top of the waveguide is 0.72±0.03μm and 0.94±0.03μm at the bottom of the rib trench. These widths yield a sidewall angle value of 20.3° as measured from the vertical axis of the

Figure 7.11. Cross-sectional SEM image of a directional coupler from the shallow-etched wafer W712
waveguide. The width of the left waveguide is $0.88 \pm 0.03 \mu m$. The right waveguide has a width of $0.85 \pm 0.03 \mu m$. These widths were measured half-way between the top of the waveguide, just under the oxide hard mask, and the bottom of the rib trench. The waveguide separation at this point is $0.69 \pm 0.03 \mu m$. Neglecting the uncertainty, the waveguides have a 3% width difference. Incorporating the uncertainty, the potential separation can be anywhere from 0% to 10%. It appears that the severity of the waveguide asymmetry is etch depth dependent.

The spectral response of a directional coupler from this wafer, with a coupling length of 1730\( \mu m \) and waveguide target width of 0.69\( \mu m \), is shown in Figure 7.12. These are the same coupler dimensions that were used to study the non-functional coupler on wafer W812, shown in Figure 7.7. The facets of the waveguide were Anti-Reflection (AR) coated and TE polarised light was used. This result demonstrates that the couplers on wafer W712 are functional. Because of the limited wavelength range of the tuneable laser used to make the measurement (see section 6.1), only a small portion of the sinusoidal response of the coupler can be determined. Therefore very little information can be gleaned from the standalone directional couplers of the first test chip. This issue was rectified on the second test chip.

Figure 7.12. Spectral response of a functioning directional coupler from wafer W712
7.2.2 The Second Test Chip Design

As discussed in section 4.3.2, a more in-depth directional coupler experiment was designed to study the coupler. The results from the first test chip were found to be inadequate due to the limitations of the tuneable laser used to measure the couplers. Instead of using a spectrum of wavelengths to study the coupler, a series of couplers were designed, each having a different coupler length. Thus the measured output power of the pass state and cross state of each coupler can be plotted as a function of the length of the coupler.

A cross-sectional SEM of one of the couplers used in the experiment is shown in Figure 7.13. The target waveguide width of all the couplers is 0.8μm. The left waveguide has a width of 0.809±0.025μm. The right waveguide has a width of 0.820±0.025μm. These width values were measured at the bottom of the rib trench. The waveguide separation at this point is 0.452±0.025μm. The uncertainty value applied to these measurements was determined using a SEM calibration sample as discussed in section 6.7.

Figure 7.13. Cross-section SEM of a directional coupler used in the directional coupler experiment
Chapter 7: Experimental Results

The results of the directional coupler experiment for the coupler discussed above is shown in Figure 7.14 for both TE and TM polarisation states. A straight waveguide is placed next to each coupler. The power transmitted through the waveguide is used to normalise the power transmitted from the coupler. In some instances the straight waveguide was damaged so the power from the next nearest straight waveguide was used for the

![Figure 7.14. Directional coupler experimental results for (a) TE and (b) TM polarisation states](image)

Figure 7.14. Directional coupler experimental results for (a) TE and (b) TM polarisation states
normalisation. Because the experiment consumes a large portion of the chip surface, this method of normalisation was used because it helped to reduce the effects of regional irregularities in the waveguide facets such as poor AR coating adhesion, or scratches. As there are two pass and cross states for each coupler, the data was filtered by comparing both of the pass state (cross states) power values. For values that were clearly wrong, such as from a damaged waveguide, they were replaced with the value from the identical state of the other arm. As these preliminary results were obtained only recently, the solid curves in Figure 7.14 are sine waves that were fitted empirically to the data so that an approximate value of the coupling length, $L_n$, can be determined. For TE polarisation, $L_n$ is 80µm. For TM polarisation $L_n$ is 190µm.

The curves used to fit the pass state data from each polarisation state are plotted together in Figure 7.15. This was done to highlight an important aspect of the data. In order to obtain a proper fit to the data, a phase shift had to be introduced to the fit curve. No coupling should occur for a coupler length of zero and yet the results demonstrate that approximately 25% of the light in the pass state has already coupled to the cross-state at this point. The start of the coupler is defined as the point where the two waveguides, which are brought together using gradual waveguide bends (radius of 400µm), are parallel to each other. It is clear that coupling between the waveguides occurs

![Figure 7.15. Comparison of the curves used to fit the pass state data in Figure 7.14](image-url)
prior to, and after the defined region of the coupler length. The phase shift can be used to calculate the 'effective' length added to the coupler due to coupling outside of the defined coupler region. For TE polarisation, the effective length is 25μm whilst for TM polarisation it is 80μm. This 'effective coupling' is a considerable effect as it is equivalent to approximately 30% of $L_\pi$.

A further consequence of effective coupling is its effect on the modelling of a PI directional coupler. According to Figure 7.15, a very nearly PI directional coupler can be realised for a coupler with a length of approximately 510μm. However by neglecting the effects of effective coupling, as shown in Figure 7.16, the necessary coupler length to obtain a PI directional coupler would be approximately 560μm. Hence, effective coupling can be a significant effect when determining the dimensions necessary to realise a PI directional coupler.

![Graph demonstrating the shift in the PI coupler due to effective coupling outside the defined coupling region](image)

**Figure 7.16.** Zero phase shifted data demonstrating the shift in the PI coupler due to effective coupling outside the defined coupling region, as compared to Figure 7.15

Using the approximate measured dimensions of the coupler in Figure 7.13, the coupler was modelled to determine the theoretical TE and TM coupling lengths. The dimensions used in the model are 0.81μm waveguide width (for both waveguides), 1.29μm waveguide height, a slab thickness of 0.56μm, and a waveguide separation of 0.45μm.
For TE polarisation, the expected $L_\pi$ is 74\(\mu\)m whilst for TM it is 157\(\mu\)m. This corresponds to a difference between the measured and expected values of 7% and 17% for TE and TM respectively. This result seems reasonable considering the non-uniform waveguide sidewalls and the fact that the data was fit empirically.

One final point needs to be made about the data in Figure 7.14. The TM data (Figure 7.14(b)) is a rather 'noisy' data set. One possible explanation is that some of the couplers are potentially damaged. However, the TE data (Figure 7.14(a)) has no such noise. As the devices used to measure the TE and TM data sets are the same, the hypothesis of damaged waveguides is highly unlikely.

Another potential explanation is that the noise is caused by a higher order mode interfering with the fundamental. This hypothesis is tested by launching a Gaussian mode into the modelled directional coupler used to model the theoretical $L_\pi$. The results are shown in Figure 7.17. The standard sinusoidal power transfer between the two waveguides is evident for both polarisation states. Both states also have an initial, secondary oscillation, on the primary sinusoid. For the TE data, the secondary oscillation disappears after several oscillations of the primary sinusoid. The secondary oscillation remains, however, for the TM polarisation data. This result is consistent with a recent modelling study of the SOI rib waveguide [3]. According to the study, a rib waveguide with the approximate cross sectional dimensions was modelled to determine the single mode condition for TE and TM polarisation states. The results of the study indicate that for TE polarisation, the waveguide is single mode. However for TM polarisation, the waveguide dimensions could allow for higher order modes to propagate. It should be noted that the modelling uses a waveguide height of 1.35\(\mu\)m where the coupler waveguides have a height of approximately 1.29\(\mu\)m so that an exact comparison cannot be made. Regardless, the results shown in Figure 7.17, appear to support the hypothesis that the secondary oscillation, or noise, in the TM data in Figure 7.14(b) is the result of a higher order mode interfering with the fundamental.

The secondary oscillation in Figure 7.17(a) that disappears several hundred microns into the coupler supports the statement that for TE polarisation, the waveguide is single mode.
If the waveguide is single mode, then a higher order mode generated at the input would radiate away as it propagates, which appears to be the case in Figure 7.17(a). This result is also consistent with the experimental findings shown in Figure 7.14(a).

Figure 7.17. Modelling results of launching a Gaussian mode into the directional coupler for (a) TE and (b) TM polarisations
7.3 Waveguide Bend Loss

7.3.1 The First Test Chip

Because of the directional coupler waveguide width asymmetry issue (see section 7.2.1), the bend loss experiment on the first test chip was investigated only briefly. The main reason for studying these devices was to determine which bend radii would be useful to investigate on the second test chip. Of 10 die tested from the target etched wafer, W812, only one was found to give the expected trend of increasing loss as a function of the number of bends and decreasing bend radius. It was determined that the reason most of the die failed to yield the correct trend is because their facets were damaged. The waveguides comprising the bend loss experiment do not have tapers on them. From the author’s experience, waveguides with tapers tend to be more resilient to the stresses of sample preparation than those without.

Another issue encountered with the bend loss experiment is that of the propagation loss. As discussed in section 7.1.1, the propagation loss is of the order of 2-4 dB/cm. One of the assumptions made when designing the experiment was that the propagation loss would be negligible so that each waveguide bend could be normalised to a straight waveguide. This would allow for the elimination of other loss factors such as those due to coupling which should be identical for identical waveguide cross-sections. However, the longest waveguide (R=200μm width 10 bends) in the experiment is approximately 1.7mm longer than a straight waveguide. This would correspond to a worst case systematic uncertainty on the loss per bend for a radius of 200μm to be of the order of 0.7dB, for example.

The results of the bend loss measurements for a test chip from wafer W812 are shown in Figure 7.18. Because the facets of this particular die were uncoated at the time of the measurement, a broadband light source was used to make the measurements in order to prevent the FP effect from affecting the results. The loss of the 200μm and 100μm waveguide bends is negligible and hence the data is omitted to prevent cluttering the graph. The results demonstrate that even for a 50μm bend radius, the loss per 90° bend,
as determined by the slope of the data, is approximately 0.09dB. Therefore for a racetrack resonator comprised of four, 50μm radius 90° bends, the loss in the racetrack waveguide due to the bends would be just under 0.5dB. As the circumference of a typical resonator studied in this work is of the order of several millimetres, the expected propagation loss in the ring would be approximately 0.6-1.2 dB (assuming 3-6dB/cm of propagation loss). Hence, even for a bend radius of only 50μm, the measured bend loss value is comparable to the propagation loss of the waveguide.

![Graph](image)

**Figure 7.18. Bend loss results for a test chip from wafer W812**

As expected, the loss per bend increases as the bend radius decreases. The loss due to a 25μm bend radius used to make a racetrack resonator waveguide would result in approximately 1.3dB of loss. Whilst several assumptions were made in determining the loss values determined in Figure 7.18, the objective of the measurements was to obtain a general sense of the loss that could be expected from resonators fabricated with these bend radii. Hence these test structures were added to the second test chip for further study. The waveguide bends with a radius of 5μm demonstrated no real sense of optical guiding and therefore were not added to the second test chip. The result that the 200μm bend waveguides demonstrated no measurable bend loss aided in the decision to reduce the bend radius from 400μm to 300μm for all of the dual input/output racetrack resonators, discussed in section 4.3.3. This reduction provided a substantial space savings when designing the second test chip.
7.3.2 The Second Test Chip

The first bend loss experiments to be conducted from devices on the second test chip were on the 180° bend waveguides as discussed in section 4.3.4. In common with the first test chip, the propagation loss of a straight waveguide on the second chip is not negligible (see section 7.1.2). Therefore the additional loss must be compensated for in order to determine the bend loss. The FP method, used to determine the propagation loss, was also used to determine the loss of the 180° waveguide bend devices. The determined loss value will be a combination of the propagation and bend losses in the waveguide, assuming other loss mechanism such as scattering or absorption are negligible. The propagation loss was determined in section 7.1.2 and is quoted in units of dB/cm. By multiplying the total length of the waveguide bend devices by the propagation loss of the straight waveguide, the propagation loss of the waveguide bend device can be determined. Subtracting this value from the total loss value obtained from the FP measurement yields the loss due to the bends in the waveguide.

An unexpected result was obtained from the measurement of the 180° waveguide bend experiment on a die from the target etched wafer, W4. Contrary to expectations, the output power was found to increase as a function of decreasing bend radius. It was initially expected that since the waveguides with smaller bend radii were shorter than the waveguide than the longest waveguide with a 300µm bend radius, the propagation loss could be causing these unexpected results. This would be a correct assumption if the propagation loss is larger than the bend loss, then a waveguide with a smaller bend radius would be shorter and thus have less overall loss than a longer one.

The method for determining the bend loss, described above, was attempted on the 180° bend loss experiment for a waveguide width of 1µm. The results are shown in Figure 7.19. The uncertainty values were determined from the stated measurement uncertainty of the equipment combined with the uncertainty in the propagation loss measurement of a straight waveguide. The results demonstrate that the bend loss actually decreases as a function of bend radius until 50µm when it begins to increase. One particular value stands out from the rest. The TM polarisation loss of the 100µm bend radius waveguide
is not only statistically lower than the other measurements, but is negative even if the uncertainty on the measurement is taken into account. This result and the overall trend of the data contradict the modelling of a waveguide bend as demonstrated in Figure 3.13 of chapter 3. The results of this data imply that either the assumed method of removing the propagation loss from the total loss as measured using the FP method may be incorrect, or that there is an issue with this particular die. The trend shown in Figure 7.19, however, was observed on other die as well. As an accurate determination of the bend loss is important in obtaining a critically coupled racetrack resonator (see section 3.6), the abnormality of these results was investigated further.

As the results appeared to be somewhat polarisation specific, an assessment of polarisation state of the light exiting the waveguide was made. This was done by placing a polarizer between the output of the waveguide and the power metre, discussed further in section 6.1. FP scans were taken with the polarizer in the beam path. Two scans were taken for each input polarisation state. For the first scan, the polarizer was aligned to pass light in the same polarisation state as that coupled to the waveguide. This is defined as the 'parallel' state in the data shown in Figure 7.20. For the second scan, the polarizer was rotated by 90° so that only light cross-polarised to the input polarisation was allowed to pass. This is shown as the ‘X-pol’ data in Figure 7.20. The scans showed a surprising result. For the 300, 200, and 100μm bend radius waveguides, the amount of light coming...
out of a waveguide in the cross-polarised state increased as the bend radius decreased. In fact, for the 100μm bend waveguide, more light was observed in the cross-polarised state than in the parallel state for both polarisations. The FP scans of this waveguide are shown in Figure 7.20. Because the straight waveguide contained within the experiment showed almost no light in the cross-polarised state (see Figure 7.21, the input light is TE polarised), it appears that the bends are causing the conversion of a portion of the input polarisation state to the cross-polarised state. For the 50 and 25μm bend radius waveguides, only a small amount of conversion was observed.

Figure 7.20. FP scans of a waveguide with 2-180° bends with 100μm radius. The scans show strong polarisation conversion for (a) TE input polarisation and (b) TM input polarisation. (The values $A_u$ and $A_c$ are used in defining equation 7.1 below)
In light of the polarisation conversion observed in the waveguide bend experiment, the method discussed previously for obtaining the bend loss by subtracting out the propagation loss cannot be used. The PDL of the waveguides, as determined in section 7.1.2, is significant. Because of polarisation conversion, it is not possible to simply subtract the corresponding propagation loss from the total loss determined for the waveguide bend device. For example, light initially coupled to the waveguide that is TM polarised will have a larger amount of propagation loss than if it was TE polarised. As a portion of the TM light is converted as it propagates through the waveguide to TE, the converted light will incur the TE propagation loss. This would result in a lower total loss in the waveguide than if conversion would not have occurred. Therefore, in the case of the 100\(\mu\)m bend waveguide with a TM polarised input, simply subtracting the effects of the TM propagation loss from the total loss would result in an erroneously small bend loss value.

As stated previously, the amount of conversion increases as the bend radius decrease, but only until the 50\(\mu\)m bend radius waveguide. This result reinforces the hypothesis that it is the bends that are causing conversion. More specifically it is likely that the waveguide sidewall angle, in conjunction with the bend, breaks the symmetry of the waveguide and hence causes conversion [4]. Therefore a mode propagating in a bend will have a stronger sidewall interaction for a small bend radius than a large one and thus cause greater conversion of the mode. According to the literature, however, the amount of
conversion is also dependent upon several other factors such as the waveguide’s cross-sectional dimensions, the angle of the sidewall, and the length of waveguide bend region [5].

As the polarisation conversion in the waveguide bend experiment was discovered towards the end of the work, a model describing the behaviour of the conversion was not effectively developed. However a preliminary experiment was undertaken in an attempt to further understand the aspects of polarisation conversion in the waveguides. Because of the greater number of bends in the 90° bend loss experiment (and hence a longer waveguide bend region), these structures were used instead of the structures in the 180° bend experiment.

The following definition of the percentage of polarisation conversion is introduced in order to quantify the conversion observed in the waveguides:

\[
\%\text{Conversion} = 100 \left( \frac{\bar{P}_c}{\bar{P}_c + \bar{P}_n} \right)
\]  

(7.1)

where \(\bar{P}_c\) is the mean output power of the FP resonance of the converted (cross-polarised) light and \(\bar{P}_n\) is the mean output power of the FP resonance of the unconverted (parallel) light. The definitions are shown graphically in Figure 7.20(a). The percent conversion is defined in this way because at the time of measurement, the chips had no AR coating. Therefore in order to eliminate the effects of the FP, the mean height of the resonance (or DC offset) is taken to determine the desired power value. The FP response is useful in a qualitative sense. In order to obtain an FP resonance, the light must be coherent. Hence if the cross-polarised data shows an FP resonance, then the cross-polarised light is also coherent.

Two hypotheses were proposed prior to taking the data. The first is that if it is the sidewall angle is a source of the conversion, then a shallow etched waveguide (smaller sidewall, less modal interaction) would have less conversion than a deep etched waveguide (larger sidewall, more modal interaction) in a bend. The second hypothesis
made is that amount of conversion should increase with decreasing bend radius due to stronger sidewall interaction.

To test the first hypothesis, the waveguides comprising the 90° bend experiment with a waveguide width of 1μm and bend radius of 300μm were measured using the FP method for both polarisation states and both polarizer positions (parallel and x-pol). The measurements were made on two different die each with a different etch depth. One die has an approximate etch depth of 0.73μm and the other 0.93μm. The second hypothesis was tested using the 90° bend experiment with a waveguide width of approximately 1μm and bend radius of 100μm on the 0.93μm etch depth die. Therefore a comparison between the 300μm and 100μm bend results can be made. The results are shown in Figure 7.22(a)-(c).

The data obtained from the shallow etched die (Figure 7.22(a)) appears to validate the first hypothesis that a waveguide with a shallower etch depth will have less conversion than a deep etched one (Figure 7.22(b)). The data for ‘0 bends’ indicates the results for a straight waveguide contained within the experiment. The results of Figure 7.22(a) are slightly surprising in that the amount of conversion appears to be independent of the number of bends.

The results of Figure 7.22(b) are somewhat unexpected as well. Whilst the conversion is approximately five times greater than for the shallow etched data, it too has no real trend as a function of the number of bends. Also, the % conversion of TM light in a straight waveguide is substantial. However this value is somewhat suspect. Whilst the FP scan for this particular waveguide does show a reasonable amount of power in the cross-polarised state, the FP amplitude is very small. This would indicate that the power in the cross-polarised state is not coherent and may be a result of scattering. It should be noted that the ‘6 bend’ waveguide was damaged and hence no measurement could be obtained.

Comparing the results of Figure 7.22(b) with those of Figure 7.22(c) indicate that the second hypothesis, a decrease in the bend radius will increase the amount of conversion,
Figure 7.22. Results of the investigation of polarisation conversion in the 90° bend experiment with a waveguide width of approximately 1μm and a (a) bend radius of 300μm with an etch depth of approximately 0.73μm (b) bend radius of 300μm and etch depth of approximately 0.93μm (c) bend radius 100μm and etch depth of 0.93μm
appears to be valid as well. The comparison of bend radii was made on the deep etched wafer to ensure adequate confinement for the smaller bend radius. The results of Figure 7.22(c) are again surprising from the standpoint of conversion as a function of the number of bends. Nearly 50% conversion was observed for the 6 bend waveguide. For the waveguides with a greater number of bends the conversion decreases. A review of the literature determined that polarisation conversion in a waveguide bend behaves much the same as a directional coupler in that power is transferred in a sinusoidal fashion between the polarisation states [5]. Therefore it is plausible that the data shown in Figure 7.22(c) is mimicking a sinusoidal response. Due to a small set of data points it is not possible to sufficiently determine the functional form of the data. An accurate model of the conversion would be required to properly fit the data. However as this result was obtained only recently, a model has not yet been determined and hence requires further study as discussed in the future work section 9.2.

7.4 The Racetrack Resonator

7.4.1 Comparison of Data vs. Modelling

With the observation of functional directional couplers on the shallow etched wafer, W712, of the first test chip, effort was immediately turned to the study of the racetrack resonators. A single input/output resonator, without AR coated facets, was initially measured; as at the time coated die were unavailable. The result of the measurement is shown in Figure 7.23. The main purpose of showing this result is to demonstrate the significant clutter in the data caused by the FP effect. The spectral response of a straight waveguide showing a comparable FP resonance is also plotted. The dips in the resonator data are therefore the resonances of the resonator. Figure 7.23 is also useful in demonstrating that the output power of the resonator, off resonance, is similar to a straight waveguide.

The spectral response of a racetrack resonator with AR coated facets is shown in Figure 7.24. To quantify the loss of the racetrack waveguide, the model proposed by A. Yariv (discussed in section 3.6) for a single input/output resonator was used to fit the results.
Chapter 7: Experimental Results

Figure 7.23. Spectral response of a racetrack resonator compared with a straight waveguide. Both devices have uncoated facets resulting in an FP resonance.

Figure 7.24. Comparison of the spectral response of a resonator to modelling.
Chapter 7: Experimental Results

The data was fitted by varying the values of the transmission coefficient, t, and the variable \( K \) that is proportional to the roundtrip loss in the racetrack waveguide (where for \( K=1 \), the waveguide is lossless), until a good fit is achieved. The resulting values of \( K \) and \( t \) for this particular device are 0.82 and 0.76 respectively. Since \( K=1 \) implies a lossless racetrack waveguide, subtracting it from one would imply that:

\[
\alpha L = 1 - K
\]  
(7.2)

where \( \alpha \) is the propagation loss coefficient and \( L \) is the circumference of the racetrack. Using equation 3.65 from chapter 3 gives the loss in dB. Hence for a value of 0.82, the roundtrip loss of the waveguide is 0.78dB. Dividing this value by the circumference of this particular racetrack (\( L=4.573\text{mm} \)) gives a loss value of approximately 1.7dB/cm.

Another important use of the model is to verify the value of the group index obtained in section 3.7 from modelling the effective index of the waveguide. As the FSR of the resonator is a function of the group index (chapter 3, equation 3.52), by varying the group index, the FSR can also be varied. However, the value obtained in section 3.7 was used as a constraint in the model. The fit of the model to the data in Figure 7.24 shows that the group index value determined by modelling is in good agreement with the experiment.

### 7.4.2 The Polarisation Independent Racetrack Resonator

Because the dimensions of the waveguides on the shallow etched wafer are significantly different than those of the PI waveguide target dimensions, a systematic study of the racetrack resonators was made. One device in particular demonstrated favourable polarisation properties. Its spectral response is shown in Figure 7.25. In order to remove the polarisation effects of the waveguides from the results of Figure 7.25, the data of each polarisation state was normalised with a corresponding polarisation dependent wavelength scan of a straight waveguide located near the resonator. The results are shown in Figure 7.26. The results show a polarisation independent spectral response of the racetrack resonator. The minima of both polarisation states at 1576.624nm align to within 1pm. A close-up of this minimum in Figure 7.27 better demonstrates this fact. Because this data was taken without any sort of thermal stabilisation, the precision of the
alignment of the minima can be stated only to within approximately 5 pm due to the potential for thermal drift of the minima whilst the data was being collected. Nonetheless the result demonstrates that a polarisation independent racetrack resonator is feasible.

Figure 7.25. Racetrack resonator spectral response demonstrating favourable polarisation properties

Figure 7.26. Polarisation independent spectral response of a racetrack resonator
Prior to normalisation, the data of Figure 7.25 was fit with the model to determine the loss of the waveguide for both polarisation states. The loss was determined to be 1.97±0.12 and 1.85±0.12 dB/cm for TE and TM respectively. These results indicate that the roundtrip loss of the racetrack waveguide is the same for both TE and TM polarisations. This conclusion seems plausible as the waveguide etch is shallow so that potential loss mechanisms such as sidewall roughness are less of an effect than they would be for a deeper etched waveguide. Also, the waveguide bends in the racetrack have a bend radius of 400µm for this particular device. According to the result of Figure 3.42 of chapter three, the bend loss at this radius should be negligible for both polarisation states and hence should not be a factor for the roundtrip loss of the racetrack waveguide.

An attempt was made to model the directional coupler of this resonator to determine how well the coupler model compares with the measured result. Determined from a SEM image, the directional coupler has the following dimensions: 1.34µm waveguide height, 0.88µm waveguide width (used for both waveguides in the modelling), 0.67µm waveguide etch depth (0.67µm slab height), 0.65µm waveguide separation, and 500µm coupler length. These are the dimensions that are used in the beamPROP model. In order
to simulate the results of Figure 7.26, the free-space wavelength of 1576nm was used in the modelling. The model used here is slightly different than that used in section 3.4 of chapter three. Because of the significant amount of effective coupling observed in the directional coupler experiments of section 7.2.2, 400μm bends were added to the cross state arm of the coupler. These bends mimic the bends of the racetrack waveguide entering/exiting the coupling region. The results of the modelling are shown in Figure 7.28. The normalised output of the pass states for each polarisation are plotted as a function of the length of the coupler. The coupler length does not start at zero due to the 400μm bend region added to the input of the coupler. The bends are drawn so that at the furthest point of separation, the waveguide bend is approximately 10μm from the straight waveguide. This resulted in the coupler starting approximately 90μm into the coupler length plotted on the x-axis and defined as the green shaded region in Figure 7.28. The red shaded regions define where effective coupling is taking place.

![Figure 7.28. Modelling results of the directional coupler in the PI resonator](image)

The results of the modelling in Figure 7.28 indicate that approximately 80% of the light input into the input waveguide of the resonator is coupled into the racetrack resonator waveguide. When the experimental data was normalised in order to model the roundtrip loss of the racetrack waveguide, it was noticed that the resonance minima had amplitudes of approximately 90%. This implies that 10% of the light passing through the resonator is passed onto the waveguide output. Thus the modelling result of Figure 7.28 appears to be
in error by approximately 10%. There are several factors that could potentially explain this discrepancy. The first, and most likely cause, is that the model is not accurate enough in its description of the real device. The non-linear, angled sidewalls make it difficult to determine the true waveguide width and coupler separation. Several iterations of the model were run with slight variations (~2%) in the waveguide width and separation to observe the sensitivity of these parameters. The measurement variations are within the measurement uncertainty as determined from the SEM image of the coupler. The results of these variations demonstrated significant changes in the outcome of the model. The results shown in Figure 7.28 were determined to be the most representative of the experimental results. Hence, in order to obtain a more accurate description of a real device, the model may need to incorporate all of the small geometric irregularities of the waveguide.

Another potential cause of the modelling discrepancy is the oxide covering the coupler. As discussed in chapter two, recent results published in the literature have demonstrated that the oxide layer can strain the silicon, thereby inducing a change in its index of refraction due to the elastooptic effect [6]. A change in the index of refraction affects the effective index of the waveguide as well as the coupling coefficient of the directional coupler. If the strain is directional, this would cause the waveguides to become birefringent. The modelling program used here does not take this strain into account. As it appears that the oxide strain may affect the polarisation properties of these devices, it should be investigated further. Potential future experiments are discussed in chapter nine.

Several other characteristics of the resonator were determined directly from Figure 7.26 and Figure 7.27. These are the FSR, Finesse, and Quality (Q) of the resonator. The results are tabulated in Table 7.1 along with the roundtrip loss of the resonator waveguide. To minimize the issues associated with small waveguide cross-sections, the waveguides used in this work are large. The result is a relatively small FSR for the resonators. However, as this work began with a focused dimensional study with several constraints, it may be possible to increase the FSR through further dimensional modelling of the waveguides. These methods are discussed further in chapter nine.
Chapter 7: Experimental Results

The full-width at half maximum of the resonance in Figure 7.27 is 16pm and is used to determine the Finesse of the resonator. The value $Q$ is determined from the Finesse which is calculated using equation 3.53 of chapter three. It is a figure of merit that provides one with a sense of the quality of the resonator such that the larger the $Q$, the better. Recent literature articles have quoted $Q$ values of approximately 57,000 and as high as 119,000 for ring resonator fabricated in SOI [7, 8]. With an approximate value of 95,000, the PI resonator is of comparable quality to those in the literature.

| Table 7.1. Characteristics of the PI racetrack resonator shown in Figure 7.26 |
|------------------|------------------|------------------|
|                  | TE               | TM               |
| FSR (pm)         | 190±4            | 188±4            |
| Finesse          | 11.9             | 11.8             |
| Loss (dB/cm)     | 1.97±0.12        | 1.85±0.12        |
| $Q$              | ~95,000          |                  |

One noticeable attribute of the data in Figure 7.26 is that the resonance occurs at approximately 1576nm instead of near the telecommunications wavelength of 1550nm. The most plausible reason for this discrepancy is due to the difference in the FSR as shown in Table 7.1. The difference in the FSR’s suggests that the propagation constants are not the same for TE and TM polarisation states. This is to be expected as the etch depth of this racetrack resonator is shallower than what is required for a PI rib waveguide. As the phase of the light propagating in the racetrack waveguide is a function of the propagation constant, a mismatch in the propagation constants would induce a mismatch in the relative phases of the polarisation states in the ring. The result would be a vernier-type effect such that polarisation independence would be achieved only when the phase of one polarisation state is an integer multiple of the other. For this particular device, the phases aligned at approximately 1576nm. If the target etched devices functioned properly, it is expected that the propagation would be identical as predicted by the modelling and hence yield a PI result closer to 1550nm where the modelling was carried out.
7.5 The Second Test Chip Design

With the positive result of the directional couplers functioning at the target etch depth for a PI device, it was anticipated that the racetrack resonators should function as designed. However when the devices were measured, an anomaly was observed. Shown in Figure 7.29, secondary resonance minima appear in the data. This result is not an isolated incident as it has been observed to some degree on other die from the target etched wafer as well as other wafers.

![Figure 7.29. Measurement of a racetrack resonator designed to have a PI response](image)

It is uncertain what is causing this secondary resonance, however two competing theories have emerged as candidates: higher order modes and polarisation conversion. The hypothesis that a higher order mode or modes is the cause comes from the following argument. According to a recent modelling study of rib waveguides, the dimensions of the 1μm wide PI rib waveguide place it slightly to the multimode side of the single mode/multimode boundary for TE polarised modes and is considered multimode for TM modes [3]. Hence the waveguide has the ability to support higher order modes. If a higher order mode were launched into the resonator, it would resonate, analogous to the fundamental mode. The effective index would probably have a different propagation constant, especially if the waveguide dimensions cause it to be near the multimode cut-off...
point. As the phase of the mode in the racetrack is dependent upon the effective index which is, in turn, dependent upon the propagation constant, the fundamental and higher order mode would have different phases and hence resonate at different wavelengths. This would result in two different resonance minima observed in a spectral scan of the resonator. As mentioned in the previous section, the strain of the oxide could also be adding complications. Any phase difference occurring naturally due to the waveguide dimensions could be exacerbated by birefringence potentially induced by the oxide strain. This possibility puts further emphasis on the need to study the effects of the oxide.

A subsequent hypothesis was made in an attempt to invalidate the higher order mode theory as the cause of the secondary resonance. If the fundamental and higher order modes do have different effective indices, then it would be expected that they would have different group indices, and hence different FSR’s. This would result in a movement of one of the minima with respect to the other as a function of wavelength. To test this hypothesis, two long scans (TE and TM polarisations) were made on a single input/output racetrack resonator with PI target waveguide dimensions (1μm waveguide width), a bend radius of 300μm, and coupler length of 500μm. The scans covered 20nm, from 1540nm to 1560nm, in 0.001nm steps. The FSR’s and separations of the minima from the TM spectrum were recorded at 1540nm, 1550nm, and 1560nm and are shown in Table 7.2. The spectral response of this data for both polarisation states is shown in Figure 7.30. All of the data has ±4pm uncertainty associated with it. This value was determined by measuring the FSR of several sets of minima around each of the three main wavelengths. It is assumed the uncertainty is due to thermal drift as the scan took several hours to complete. This uncertainty is then combined with the typical relative wavelength accuracy of the laser (±3pm) to obtain the value above.

| Table 7.2. FSR and minima separation measurements from long spectral scan |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | $\lambda=1540\text{nm}$ | $\lambda=1550\text{nm}$ | $\lambda=1560\text{nm}$ |
| $\text{FSR}_{\text{large}}$ (pm) | 219              | 228              | 232              |
| $\text{FSR}_{\text{small}}$ (pm)  | 220              | 228              | 232              |
| Minima separation (pm)          | 90               | 95               | 105              |
These results are surprising in that the FSR of the large amplitude resonances is identical to the FSR of the small amplitude resonances shown in Figure 7.30. The group index of the fundamental and first order TM modes was modelled using the method described in section 3.7 of chapter three for the three wavelengths in the table above. A comparison of the modelled and experimental results is shown in Table 7.3. Because of the experimental uncertainty, the comparison demonstrates that the modelling and experimental results are identical with the exception of the modelled result of the first order mode at 1560nm.

The modelled results are quite surprising as the effective index of the fundamental is 0.08 larger than the first order mode. However the first order mode has greater dispersion than the fundamental which nearly negates the effective index difference. Thus, the hypothesis that the large and small amplitude resonance minima should have different FSR’s and hence move relative to one another as a function of wavelength cannot be validated nor dismissed with these results. Hence the theory that the secondary resonance observed is due to a higher order mode remains valid.
### Table 7.3. Comparison of Experimental and Modelled FSR values (modelled by B. Timotijevic of the University of Surrey)

<table>
<thead>
<tr>
<th>$\lambda_0$ (nm)</th>
<th>Experimental FSR (pm)</th>
<th>Modelling FSR (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large resonance</td>
<td>Small resonance</td>
</tr>
<tr>
<td>1540</td>
<td>219</td>
<td>220</td>
</tr>
<tr>
<td>1550</td>
<td>228</td>
<td>228</td>
</tr>
<tr>
<td>1560</td>
<td>232</td>
<td>232</td>
</tr>
</tbody>
</table>

The second theory that may explain the secondary resonance is polarisation conversion. Because of the conversion observed in the bend loss experiments, discussed in section 7.3.2, it is reasonable to assume that the bends in the racetrack waveguide may also be causing conversion. Similar to the experiments of section 7.3.2, a polarizer was placed in the output beam coming from the die under test. The scans shown in Figure 7.29 are a result of the parallel alignment of the polariser, continuing with the definition of the polarizer states defined in section 7.3.2. The cross-polarised scans are shown in Figure 7.31. In the legend, the term ‘TE X-Pol’ for example, states that TE light is initially coupled to the resonator and the polariser is set to pass only cross-polarised (TM) light.

The scans of Figure 7.31 show that a strong amount of conversion is observed at the resonances. In fact the percent conversions at a resonance are 29% and 35% for TE and TM polarisations respectively. It is hypothesized that a portion of the light in the input polarisation state is converted to the orthogonal polarisation state as it propagates around the bends in the racetrack waveguide. The converted light will then take on all the characteristics of the orthogonal polarisation state. For example, if the propagation constants are different for each polarisation state, then the converted light and the unconverted light will resonate at different wavelengths. This is the same argument used in the discussion of the higher order modes. In order for the converted light to actually resonate, it would have to convert back to the original polarisation state so that it can effectively interfere with the light from the input waveguide. This re-converted light will still be phase shifted relative to the unconverted light due to the time it spent propagating in the orthogonal polarisation state. Any of the converted light not converted back before
the racetrack waveguide returns to the coupler will be pass onto the output waveguide as cross-polarised light as shown in Figure 7.31. As the conversion is occurring in the resonator, even small amounts of conversion may be enhanced by the resonance effect of the device.

![Figure 7.31. The cross-polarised spectral response from the same device shown in Figure 7.29](image)

The argument given above is supported by the results of Figure 7.30. The secondary resonance in the TM data aligns well with the TE resonance. Thus if a portion of the TM polarised is converted to TE, then the TE converted light would obtain the same resonance characterisations of the unconverted TE polarised light. By close inspection of the TE polarisation spectrum in Figure 7.30, small minima in the off resonance noise of the spectrum are observed to align with the large resonances of the TM polarisation spectrum.

One further argument in favour of polarisation conversion can be observed in Figure 7.32. This spectral scan was taken on a device from the target etched wafer with a coupler length of 500\(\mu\)m. According to the theory behind the design of the waveguides on the target etched wafer, the propagation constants should be identical for TE and TM polarisations. This would imply that they have the same phase in the ring. If this is the case, then converted light will have the same propagation constant, and hence phase, as the unconverted light. Therefore only one resonance minima should be observed according to the argument given above regarding how a secondary set of minima could be
realised through polarisation conversion. As this is not the case, according the results of Figure 7.29 and Figure 7.32, another explanation is required in order to maintain the polarisation conversion theory. According to the literature, optical power coupling between the two orthogonal polarisation states is sinusoidal as a function of the distance a mode has travelled in a waveguide bend [5, 9]. This sinusoidal power coupling is similar in nature to the coupling of a typical directional coupler. Hence, it is plausible that this 'polarisation coupler' would have other similarities to a directional coupler. One of these potential similarities is the relative phase between the solutions of the coupler. According to the mathematical discussion of the directional coupler in section 3.4.1, the solutions that satisfy the differential equation describing the coupler have a $\pi/2$ phase difference between them. Therefore if the 'polarisation coupler' has a similar solution, then a $\pi/2$ phase shift would be imparted to the converted light with respect to the unconverted light.

![Figure 7.32. Resonance separation implying polarisation conversion](image)

In order to determine the phase relationship between the two resonances, the FSR (221±3pm) of one of the resonances is defined as $2\pi$, as shown in Figure 7.32. The distance between the first and second minima at approximately 1549.5nm is 44±3pm. A phase shift $\pi/2$ would correspond to a distance of 55±1pm. This corresponds to a percentage difference of 20±7% from the expected phase shift of $\pi/2$. Whilst this difference is considerable, other factors such as slight differences in the propagation...
Chapter 7: Experimental Results

constants of the polarisation states may have an additional contribution to the phase. This result implies that polarisation conversion is still a reasonable theory to describe the existence of a secondary resonance minima observed on many die from the second test chip design. Because of the complexity of the conversion, in conjunction with the complexity of the resonator, modelling will be needed to more accurately describe the conversion occurring in the ring.

Unfortunately the effect of the secondary resonance in the spectral measurements of the racetrack resonators was discovered only towards the end of the project and hence understanding this phenomenon has met with only reasonable success. Whilst this effect is deleterious to the functionality of the resonator, it is an interesting result from an academic perspective. Experiments to investigate this effect further are therefore discussed in the future work section 9.2.

Several resonators were found to have a single minima spectral response. One in particular has the following target dimensions: 0.8μm waveguide width, 1.35μm waveguide height, 0.88μm etch depth (0.47μm slab height), 0.54μm waveguide separation in the coupling region, and a coupler length of 310μm. This particular resonator is contained within the 90° bend loss experiment (section 4.2.2 but with 0.8μm wide waveguides). Therefore the resonator has been fabricated five times, but each with a different bend radius (300, 200, 100, 50, and 25μm). The spectral scan results of these devices are shown in Figure 7.33. The 100μm data has been omitted as it demonstrated strong secondary resonance behaviour. A minimum from each scan is used as a reference point. These references are then plotted together to emphasize the effects of the radius on the FSR.

As expected, the FSR increases as the bend radius, and hence circumference of the racetrack resonator, decreases. Another interesting result of the data is that the resonances begin to broaden as a function of decreasing bend radius. This is expected as the bend loss will be greater for smaller radii and hence cause a decrease in the $Q$ of the
Chapter 7: Experimental Results

resonator. Some of the key figures of merit of the data in Figure 7.33 are tabulated in Table 7.4.

![Figure 7.33. FSR dependency on bend radius](image)

**Table 7.4. Figures of merit for the FSR study in Figure 7.33**

<table>
<thead>
<tr>
<th>Circum. (µm)</th>
<th>2505</th>
<th>1877</th>
<th>934</th>
<th>777</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSR (pm)</td>
<td>256±4</td>
<td>335±4</td>
<td>695±4</td>
<td>819±4</td>
</tr>
<tr>
<td>Finesse</td>
<td>28±4</td>
<td>10.8±0.5</td>
<td>14±1</td>
<td>10.1±0.5</td>
</tr>
<tr>
<td>Q</td>
<td>170,000±21,000</td>
<td>50,000±1,500</td>
<td>30,000±2,000</td>
<td>19,200±600</td>
</tr>
</tbody>
</table>

A direct comparison between the results of the PI resonator results of the last section and those in Figure 7.33 cannot be made. The differences in most of the cross-sectional dimensions between the two resonators are considerable. However, several general comparisons can be made. The first and probably most impressive is the difference in value of $Q$. The $Q$ value for the 300µm device is nearly twice as large as that calculated for the PI device. It is also larger than any value in the literature known to the author for similar devices. The 25µm device has an FSR more than four times that of the PI device whilst maintaining a comparable Finesse value. The amplitudes of the resonances in
Figure 7.33 are also typically 6dB larger than those of the PI device. Hence the devices of the second chip appear to be of better overall quality than those of the first test chip. It may be difficult to pinpoint the exact reason why this is so as there are several key differences between them. One possible cause is the different fabrication tools used. It is therefore likely that not only did moving to a higher resolution photolithographic stepper improve the directional coupler issues and decrease the sidewall angle of the waveguides, but it also may have led to better quality devices. Therefore, even though the newer processing methods may have led to the introduction or enhancement of polarisation conversion, significant benefits to the overall quality of the fabricated devices were still obtained.
Chapter 7: Experimental Results

7.6 References


Chapter 8

8 Conclusions

This project has been beneficial both academically to the author and to the field of silicon photonics. The results obtained from the study of optical ring resonators in SOI have produced more than a dozen publications over the last three years. It has also been an interesting project from the evolution of the fundamental concepts necessary to design the device, to the experimental considerations for properly investigating the characteristics of the fabricated devices. Also, with the unexpected results such as asymmetric waveguides in a directional coupler and polarisation conversion in waveguide bends, a more fundamental level of understanding of these devices has been obtained by the author. The aim of this chapter is to discuss the key findings of this research and the conclusions that may be drawn from them.

It is impressive that the photolithographic tools used to create nanometre scale electronics can also be used to fabricate photonic devices that are orders of magnitude larger. However, with this change of purpose come some potentially undesirable side effects. The first set of experimental test structures were fabricated using a photolithographic tool that has a resolution limit of 0.8μm. The waveguide separations of the designed directional couplers vary from 0.6 to 1.0μm. Preliminary fabrication tests were conducted to determine the prospects of surpassing the stated resolution of the tool. The results of these tests demonstrated that the desired waveguide widths and separations could indeed be achieved. What was not noticed, however, was a small difference in the widths of the waveguides. For the wafer targeted to have Polarisation Independent (PI) rib waveguides, the width asymmetry was found to be approximately 15-20%. A modelling study (section 7.2.1) was subsequently undertaken to investigate the effects of waveguide width asymmetry in the directional coupler. The modelling revealed that a 1% asymmetry results in a 10% drop in the amount of power transferred for TE polarised light and approximately 35% for TM. For a 2% width discrepancy, nearly 30% and 70%
Chapter 8: Conclusions

of TE and TM polarised light respectively will not transfer to the second waveguide in the coupler. It was concluded that the cause of the width discrepancy is a result of surpassing the resolution of the photolithographic tool.

The modelling results are somewhat disheartening as they imply that a photolithographic tool with a resolution of 10nm (1% of 1μm) would be necessary to achieve the necessary dimensions for 100% coupling between the two waveguides. However, this implication appears to be invalid as the second test chip has symmetric waveguides, within measurement resolution (section 7.2.2). The second test chip was fabricated using a photolithographic tool that has a resolution of 0.5μm. All of the fabricated devices had waveguide separations greater than this resolution. Thus, whilst there is the benefit of using older generation tools to fabricate photonic devices, care should be taken to ascertain all the effects of using them.

Whilst moving to a photolithographic tool with better resolution not only solved the waveguide asymmetry issue but it appears to have improved the overall quality as compared to the first batch of test chips. For the first test chip, the propagation loss in a straight waveguide with PI target dimensions was found to be 3.4±0.3 and 5.8±0.2 dB/cm for TE and TM polarisation states respectively (section 7.1.1). For a waveguide with similar dimensions on the second test chip, the loss values decreased to 2.14±0.15 and 3.86±0.15 dB/cm for TE and TM polarisation states respectively. This is an approximately 33% improvement in the propagation loss from the first test chip to the second. Whilst these loss figures are relatively high as compared to devices in the literature, this is probably due to some coupling to the substrate due to an inadequate thickness of the buried oxide layer.

Further evidence of device improvement was found when comparing the quality factor, Q, of the racetrack resonators of the first batch of test chips with the second. A resonator fabricated using the better resolution tool was found to have approximately twice the quality factor, Q, as that calculated for the PI resonator (~95,000). In fact, to the author's knowledge, the Q value of 170,000±21,000 on a racetrack resonator of this or similar
design is better than any value quoted in the literature. Using tools of higher resolution may therefore have significant benefits to the functionality of fabricated devices.

The experiments designed to investigate the properties of the racetrack resonator and its individual components, were successful in general. One experiment in particular, however, was found to have issues. Measurements of the waveguides in the 90° bend loss experiment (section 4.2.2) on the first test chip yielded values of approximately 0.09, 0.33, and 1.15dB/bend for 50, 25, and 10μm bend radii respectively. Therefore a racetrack resonator waveguide consisting of four 50μm 90° bends would have an approximate bend loss of 0.3dB. These results are somewhat suspect because the assumption that the propagation loss is negligible is questionable. The idea behind this experiment was to separate the effects of other loss mechanisms such as coupling and propagation loss from the bend loss by normalising the bend loss measurement to a straight waveguide. The propagation loss measurements on straight waveguides yielded loss values of several dB/cm. As the length of the longest waveguide in the 50μm bend test cell is only 10% longer than a straight waveguide, normalisation using a straight waveguide was deemed appropriate. These results were only intended to be an approximate measure of the bend loss to determine if devices with these smaller bend radii were useful to be placed on the second test chip. Consequently it was deemed necessary to compensate for the additional propagation loss in order to correctly obtain the true bend loss of the waveguides.

The 180° bend loss experiment (section 4.3.4) on the second test chip also had minor issues, as it provided an unexpected result. To overcome the normalisation issues confronted with in the first test chip, the Fabry Perot (FP) method (section 3.8) to determine the bend loss was used. The results showed that from 300μm down to 100μm, the bend loss decreased as the bend radius decreased. In fact, for TM polarised light in a waveguide with bends having a 100μm bend radius, the loss value obtained was negative. As this result is not possible, a search for the cause was undertaken. The cause of the problem is that light propagating in the bends partially converted to the orthogonal polarisation state. If the orthogonal polarisation state has less propagation loss then the overall loss measurement will be lower than if conversion was not occurring. Thus the
method of removing the propagation loss by knowing the propagation loss in a straight waveguide and using it to subtract it out from the total loss as determined by the FP method is invalid. Whilst polarisation conversion effectively invalidated the results of the bend experiment, it did bring to light the effect of polarisation conversion in waveguide bends.

The effects of polarisation conversion were investigated further using the 90° bend loss experiment. The results of this investigation appeared to support two hypotheses made in regards to the conversion: 1) if the conversion is caused by the waveguide sidewalls, a deeper-etched sidewall will cause more conversion than a shallow-etched one and 2) a bend with a smaller radius will cause more conversion than a bend with a larger one. In fact for the second hypothesis, polarisation conversion of the order of 45% was observed for a smaller bend radius (100μm) waveguide where only 15% was observed in a waveguide with a larger (300μm) one. It was surprising to find that the amount of conversion did not increase as a function of the number of bends. As this effect was discovered late in the project, only a small number of results were obtained. However from these preliminary results, it is likely that not only are the bends the cause of conversion, but also the sidewall angle of the waveguides affects the degree of conversion. It also appears that due to the complexity of the conversion and the limited number of data points available from the bend loss experiment, an accurate model of the waveguide and the effects of the bend must be obtained.

The directional coupler experiment (section 4.3.2) on the second test chip was found to be very beneficial. Not only did it help to understand the behaviour of the coupler, but it also showed promise in the study of higher order modes as well as the effects of coupling outside the defined directional coupling region. The results of the experiment on die with PI target dimensions showed a coupling length \( (L_d) \) of 80 and 190μm for TE and TM polarisations respectively. These values are only approximate as the fit to the data was determined empirically. The device was modelled using the dimensions taken from a cross-sectional SEM from a similar die. The modelling showed a 7% and 17% discrepancy in \( L_{\pi} \) between experiment and the model for TE and TM polarisations respectively. This discrepancy appears to be reasonable as potential factors such the
waveguide sidewall angle, uncertainty in the SEM measurements, and strain effects due to the cover oxide would all lead to inaccuracies in the modelling results. This discrepancy, however, is compounded by the method used to determine a PI directional coupler (see section 3.4.3). The goal of the modelling is to determine the coupler length and waveguide separation necessary to match one TM $L_\pi$ to multiple TE $L_\pi$. As the coupling of power between the two waveguides is sinusoidal, the discrepancy will increase for subsequent $L_\pi$. For the PI directional coupler $L_\pi(TM) = 3L_\pi(TE)$. Therefore a discrepancy of $7\%$ would compound to $21\%$ for $3L_\pi(TE)$. For the PI racetrack resonator in section 7.4.1, the modelling of the coupler in this device showed that $3L_\pi(TM) = 5L_\pi(TE)$. The compounded discrepancy for this device would be substantial. The dimensions of the modelled directional coupler of the PI resonator were varied within the error on the dimensions to better fit the experimental results and hence reduce the discrepancy. If modelling is used to predict the dimensions of a PI coupler, however, the potential discrepancy between the modelled and fabricated device could be substantial. These results imply that a more accurate model is necessary to incorporate all of the known effects affecting the coupler. This model could then be use not only to determine the necessary dimensions for a PI coupler, but also determine the effects of processing tolerances on the functionality of the coupler.

Both modelling and a recent theory paper in the literature indicate that the 0.8μm wide waveguides on die with targeted PI dimensions are multimodal for TM polarised modes but borderline single mode for TE polarised modes. The results of the directional coupler experiment showed a small, secondary oscillation on top of the expected sinusoidal power transfer between the waveguides as a function of the length of the coupler for the TM data. This oscillation was not observed on the TE data, however. This result implies that the directional coupler experiment has the potential to investigate effects other than what it was primarily intended. In this particular case it was used to detect potential higher order modes propagating in the coupler.

The directional coupler experiment also was useful in investigating the effects of coupling between the waveguides outside of the defined coupling region. The coupling region is defined as the area where the two waveguides comprising the coupler are parallel and in
close proximity to one another. S-bends are therefore placed at the inputs and outputs of the waveguides to separate the waveguides outside the defined coupling region. However, the bends used to separate the waveguides have a bend radius of 400μm. It was determined during the investigation of the directional coupler experiment that coupling was occurring between the two waveguides in the bend region just outside the defined coupler region. This ‘effective’ coupling is actually quite significant. It was found to cause a shift in the sinusoidal power transfer as a function of the length of the coupler by approximately 30% of $L_n$ for both polarisation states.

This effect is likely to be larger for racetrack resonators with large bend radii. The racetrack waveguide bends slowly toward and away from a straight waveguide where for the coupler experiment, both waveguides are bending toward and away from each other. Hence the directional coupler experiment has a greater waveguide separation, and therefore weaker coupling, in the regions just outside the coupler region. This argument assumes that the bend radius of the racetrack waveguides and the S-bends are the same. These results indicate that the effects of effective coupling outside the coupling region need to be incorporated into the coupling model whilst attempting to determine the dimensions necessary for a PI directional coupler.

Whilst not a designed experiment, the investigation of thermal effects on racetrack resonators was undertaken in chapter 6 as they have been a source of concern throughout this project. An impressive result was obtained on the alignment of TE and TM polarisation minima in the spectral response of a racetrack resonator. According to the data, this particular device demonstrated alignment of a TE and TM polarisation minimum to 1pm. Combined with the nearly identical TE and TM resonance amplitudes, this device is considered to be a PI racetrack resonator, one of the main goals of this project. Whilst quantifying the impact of thermal effects on a resonator, it was found that in the time necessary to complete the spectral scans necessary to characterize the device, the resonance had drifted by as much as 5pm. A more in-depth analysis of the drift in minima separation was also carried out whilst analysing the scan results from other resonators. It was determined that the typical drift between subsequent minima in a
scan, thought to be caused by thermal effects, is ±4 pm. The unfortunate result is that an
impressive result is diminished slightly to account for potential thermal drift in the data.

Whilst thermal effects can be considered detrimental if left uncontrolled, one potential
device may benefit from them. It was determined in chapter 6 that a thermally induced
drift in a resonance minimum would hypothetically correspond to a temperature change
of 0.01 °C/pm. A racetrack resonator could then be used as a sensitive temperature sensor.
The FWHM of the PI resonator minimum discussed in chapter 7 is approximately 16 pm.
A drift of 1 pm off the minimum would correspond to 1 dB power transfer from the ring to
the output waveguide. The resonator, in combination with a monolithically integrated
detector could be used as a feedback circuit to thermally stabilize a monolithic
telecommunications superchip as discussed in chapter 1.

Whilst it is unfortunate that a polarisation independent racetrack resonator that was
designed using the methods of chapter 3 was not realised, it is believed that the methods
are still valid. One of the main conclusions made from this project is that more accurate
modelling is required that encompasses many of the factors that are currently omitted
such as oxide loading, sidewall angles, polarisation conversion, and effective coupling to
name a few. This modelling could then be used to investigate the possibility designing a
resonator that is not only PI, but also more insensitive to processing tolerances than the
current design. A PI racetrack resonator has been achieved in the course of this project
with respectable figures of merit (i.e. Q ~ 95,000). Whilst the second attempt to fabricate
the desired device proved unsuccessful, it did yield resonators whose figures of merit (i.e.
Q ~ 170,000) are world class when compared to similar devices in the literature. It also
provided insight into several phenomena such as polarisation conversion in bends, and
higher order modes in directional couplers. It is possible that the second test chip could
have a PI racetrack resonator, but that the issues of higher order modes or polarisation
conversion could be masking it. Regardless of this result, it is believed by the author that
this project has provided valuable insight into the complexities of the polarisation
independent racetrack resonator, whose success can be measured by the number of
publications to which these results have contributed.
Chapter 9

9 Future Work

Notwithstanding the positive results obtained in chapter seven of this work, there are many aspects of the research that should still be investigated. The purpose of this chapter is to highlight the main areas where future work would be beneficial in the study of a Polarisation Independent (PI) racetrack resonator. The five main areas which the author believes should be investigated further are: oxide loading, polarisation conversion, the further investigation of fabricated devices, device enhancements, and finally tuneable devices. These areas are discussed in turn below.

9.1 Oxide Loading

As discussed in chapter two and briefly in chapter seven, the oxide covering the waveguides is far from innocuous. The photoelastic strain induced by the coefficient of expansion mismatch between silicon and silicon dioxide cannot be ignored. Discussed in chapter two, several authors were able to use the strain, or loading, of the oxide to convert a polarisation dependent waveguide into a polarisation independent one. It is likely that the strain induced by the oxide may be processing dependent. Therefore a study of the strain induced by the oxide should be carried out using the same fabrication tools used to fabricate the devices in this work.

It is envisaged that an experiment similar to the directional coupler experiment discussed in section 4.3.2 could be used to investigate the change in the effective index caused by the oxide. A change in the effective index results in a change of the propagation and coupling constants of the coupler. Several versions of the coupler experiment could be placed on a test chip to determine the effects on different coupler geometries. Several
sets of test chips could then be fabricated, each with a different etch depth, so that the effects that the oxide has on various amounts of sidewall interaction could be studied. Another test chip experiment could also be run, that uses the same etch depth for all the wafers, but with a different oxide thickness on each. This way the strain as a function of oxide thickness can be determined.

In conjunction with the experiments discussed above, accurate modelling methods would need to be pursued either through collaborative efforts or in-house. Thus, the effects of oxide strain can be accounted for in future devices. The investigation of oxide loading would be of practical importance not only to the fabrication of PI racetrack resonators, but to any device fabricated with the same tools used in the oxide study.

9.2 Polarisation Conversion

Discussed in section 7.3.2, polarisation conversion was observed in waveguides from the waveguide bend experiment. It is uncertain as to the exact cause; however it is likely that it may be due to a combination of the bend and the sidewall angle. As this conversion may be causing the deleterious effect of the secondary resonance in the racetrack resonators (see section 7.4.2), understanding the cause is very important.

It is proposed that two studies be undertaken to better understand the conversion and hopefully determine its cause. Both studies would use experiments similar to the waveguide bend loss experiment discussed in section 4.2.2. The first study requires developing the silicon etch recipe used to define the waveguides. It is this recipe that is primarily responsible for the angled sidewalls. By determining a recipe that yields vertical sidewalls, a comparison of vertical sidewall waveguides could be made with those having angled sidewalls. A die from each wafer could then be measured for polarisation conversion. The results would aid in determining how much of a factor the angled sidewall is in causing the conversion. If possible, several different sidewall angles could be fabricated so that, if the angled sidewall is indeed a strong contributor to the conversion, then its effect as a function of angle can be determined.
Chapter 9: Future Work

The second study that should be undertaken is the investigation of the amount of conversion for various waveguide widths and etch depths. The experiments of section 7.3.2 indicate that the conversion is due to a relatively strong sidewall interaction in the bend region of the waveguide. Waveguides with different dimensions would have different degrees of modal confinement and hence different amounts of sidewall interaction. The amount of conversion could then be determined for many of the typical waveguide cross-sectional parameters.

These results, in conjunction with the results obtained in the sidewall angle study should allow for the development and verification of a model. Several models of polarisation conversion exist in the literature for rib-like waveguide structures. One of these models could be applied to the particular dimensions of our waveguides so that future device designs can account for this conversion. This may result in the ability to remove the effect or intentionally develop polarisation conversion devices.

Another study that could be undertaken using devices from the variation in waveguide width and etch depth study, is the investigation of the secondary resonance. The waveguide bend loss experiment includes two single input/output racetrack resonators. By increasing the waveguide width, for instance, a waveguide can be created that will propagate higher order modes. As one of the potential explanations for the secondary resonance observed in the spectral response of a racetrack resonator (section 7.4.2) is that it is a higher order mode, it would be interesting to fabricate a racetrack resonator that has the ability to propagate distinctly higher order modes for both polarisation states. The spectral response of this type of device can then be compared to the response of a device that should be strictly single mode. This result may aid in revealing the cause of the secondary resonance observed in the current devices.

9.3 Further Investigation of Fabricated Devices

In an effort to account for processing tolerances during fabrication of the devices studied in this work, several on-wafer photolithographic exposure time skews were carried out.
Each exposure time will result in small variations in the waveguide width and for directional couplers, waveguide separation. Several wafers, each with a different etch depth, were also fabricated. The result is a large number of fabricated test die (~200) each with slight variations in their dimensions. A comprehensive study of the experiments on one die would take approximately 40 hours to complete. In order to complete the project in a timely manner, experiments were prioritised as to their impact to the project. Therefore a significant amount of die or experiments on partially tested die remain untested.

As discussed in the previous section, a study of the waveguide bend loss experiment as a function of waveguide width and etch depth may prove valuable. The second test chip has two waveguide widths (0.8μm and 1.0μm) for each full test die. With five exposure time variations on each wafer and five wafers each with a different etch depth, further study could yield a reasonable amount of information on the polarisation conversion issue. Using a broadband light source to avoid the conversion issue, an involved study of the bend loss could also be undertaken.

The directional coupler experiment could be used to study the functionality of a directional coupler as a function of etch depth, and to some degree waveguide width and separation as well. In conjunction with section 7.1, a more extensive experiment could be undertaken where the couplers are measured, the cover oxide etched in a controlled manner, and the couplers retested. This method could be used to study the oxide effects if future device fabrication is not feasible.

A beam expander could be built and used to expand the output beam of a straight waveguide. Then, by imaging the expanded beam, the modal properties of a straight waveguide can be investigate as a function of the two waveguide widths on the second test chip. To a limited degree, the modal properties could also be investigated as a function of waveguide width by studying die that were exposed using different exposure times. However, as the waveguides have tapers on their inputs/outputs this may complicate the findings.
These are just some of the potential experiments, most of which are on the second test chip, that could provide useful information on the functionality of some of the more fundamental components used in silicon photonics. They may also provide a useful starting point for the investigation of the issues discussed in the previous two sections.

9.4 Device Enhancements

The rib waveguide height of 1.35\(\mu m\) used in the study of a PI racetrack resonator, discussed in chapter three, was chosen primarily as a matter of convenience. The Intel Corporation, who fabricated the devices in this work, had previous experience with this waveguide height. As this project needed several constraints on which to build, it seemed logical to use this height. However, the methods used in chapter three to design a PI resonator can be attempted on a large range of waveguide heights.

The ring resonators fabricated from strip waveguides, as discussed in chapter two, have Free Spectral Ranges (FSRs) of the order of tens of nanometres. Their waveguide dimensions are of the order of several hundred nanometres. As the devices fabricated in this project have FSRs of the order of several hundred picometres, it is believed that smaller waveguide heights should be investigated to improve the FSR. One of the drawbacks of a smaller waveguide height is increased coupling losses. It is expected, however, that there is an optimum set of device dimensions that yield a PI resonator with a relatively large cross-sectional area whilst approximating the large FSR of a strip waveguide device. To determine these optimal dimensions would require a large modelling study that incorporates the modelling methods discussed in chapter three, but for a variety of waveguide heights. This resultant device could have far reaching applications. Not only would it have the benefits of a strip waveguide device, but the slab region may allow for easier contacting to doped regions of an electrically tuneable device, as discussed in the next section.
9.5 Tuneable Devices

One final area that is worth investigating is that of tuneable devices. The devices fabricated in this project are passive in that the resonances at which they resonate are based solely upon the dimensions with which they were fabricated. By means of the thermooptic or electro-optic effects (introduced in chapter two), these passive devices can be made tuneable such that by applying heat or injecting a current into the rib area, the wavelengths at which the device resonates can be shifted. Making a racetrack resonator tuneable allows for the realisation of several new types of devices such as, tuneable filters, tuneable add/drop multiplexers, and optical switches. By quickly tuning and detuning a resonator, an optical modulator can be realised.

To realise a PI tuneable device, however, would require an extensive amount of modelling. The thermooptic and electro-optic effects work by altering the index of refraction via heating or current injection respectively. A change in the index of refraction induces a change in the effective index of the waveguide. These changes may alter the PI conditions of the originally designed devices. As discussed in chapter two, current injection devices have several loss mechanisms which need to be considered. This requires separate modelling of the electrical properties of the device. Regardless of these difficulties, the result of realising a tuneable PI racetrack resonator may well be worth the effort. With their potential for being compact and PI, multiple tuneable racetrack resonators could provide nearly all of the functions necessary to realise an optical superchip as discussed in chapter one.