Silicon Photonic Devices for Sensing, Switching, Polarization and Mode Control

by

Yule Xiong, B. Eng., M.Sc.

A dissertation submitted to the
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in partial fulfillment of the requirements for the degree of

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Department of Electronics
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The undersigned hereby recommends to the
Faculty of Graduate and Postdoctoral Affairs
acceptance of the dissertation

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Professor Niall Tait, Chairman,
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Abstract

Silicon photonics has emerged as a promising platform for optical sensing, optical interconnect and telecommunication due to the availability of the low cost complementary metal-oxide semiconductor (CMOS) processing technology. This thesis starts with an investigation of the local oxidation of silicon (LOCOS) technique to fabricate submicron-size photonic waveguides. A cut-back method with a serpentine pattern was used to examine the fabrication feasibility by directly measuring the propagation loss and the bending loss of the fabricated waveguides. Lesson and knowledge learned from the experience is the fabrication tolerance, which provided the guidance on the following device design.

Next, the thesis shifts the focus theme from fabrication technology to device designs. The fabrication tolerance is the key design consideration in the designing process. The first class of silicon devices that was investigated in this thesis is microring resonator (MRR)-based devices, two of which are targeted for label-free evanescent field sensing. We presented a vertically coupled double-ring sensor design to allow temperature-insensitive sensing. The vertical stack is designed for the ease of fabrication as the coupling gap is simply controlled by the deposition. Then a multimode interference (MMI) coupled slotted microring resonator (MRR) was proposed and investigated for sensing applications with high sensitivity. The MMI coupler is introduced to relax the fabrication tolerance of the coupling region. These sensors have the potential for inexpensive mass production and for enabling real time measurements and fast sample preparation, as well as detecting extremely-low analyte quantities. Combining with a microfluidic setup, thousands of silicon photonic sensors can be arranged in compact arrays for parallel sensing within just a few square millimeters. The last MRR-based device proposed is an all-optical switch using a ring-assisted Mach-Zehnder interferometer (RAMZI), which is the essential building block for on-chip silicon photonic circuits. The RAMZI structure is designed to improve the fabrication tolerance as the critical coupling condition is not required to

achieve a high performance.

One significant issue in all silicon devices is polarization management as the intrinsic high-index property of silicon induces large polarization dependence in silicon waveguides, affecting the performance of all waveguides and waveguides-based devices. Polarization management components include polarization splitters, rotators and polarizers. The polarization splitters and rotators (PSRs) are the key elements in polarization diversity circuits and polarization multiplexing systems; while polarizers are satisfactory for many practical situations as they eliminate the undesired polarization state. The second class of silicon photonic devices investigated in this thesis is subwavelength grating (SWG) structures for polarization management. The SWG structure features the unique engineering capability of the waveguide effective index. The first SWG-based PSR device presented in the thesis shows a significant enhancement in fabrication tolerance, while the second SWG-based TE-pass polarizer is compact and broadband.

The third class of silicon photonic devices investigated in this thesis is taper-based devices. The taper-based devices are first applied in polarization management. One design is a polarization rotator (PR) using a tapered amorphous silicon layer, which can effectively reduce the insertion loss; while the second design is a PSR based on a taper-etched directional coupler (DC). The taper-etched feature significantly relaxes the fabrication tolerance in DCs. Inspired by the study of the DC-based PSR, the tapered design is then used to implement a mode (de)multiplexer. Mode (de)multiplexers offer an alternative way for optimizing optical interconnect, by increasing waveguide channel numbers using multimodes and by enabling high data transmission bandwidths through a single wavelength carrier. The thesis presented a two-mode (de)multiplexer using a simple taper-etched DC, where the fabrication tolerance was greatly improved by the tapered design.

All the devices mentioned above were thoroughly examined through numerical simulations. A selective set of devices were fabricated experimentally. For example, the LOCOS wire waveguides were fabricated at the Carleton University MicroFabrication Facility; the MMI coupled slotted MRRs and the TE-pass polarizer based on SWG waveguides have been fabricated using deep ultraviolet (DUV) lithography by the OpSIS and IMEC foundry services through the CMC Microsystems.

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Preface

This thesis is based on the Author's research output from 2010 to 2014 as journal and conference publications.

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[1] **Yule Xiong**, Marc Ibrahim, and Winnie N. Ye, "Impact of LOCOS techniques on photonic wire waveguides," *Applied Optics*, 51(29), pp. 7089-7093 (2012).

[2] **Yule Xiong**, and Winnie N. Ye, "All-optical switching of a single wavelength in a silicon-based ring-assisted Mach-Zehnder interferometer," *Applied Optics*, 51(32), pp. 7788-7793 (2012).

[3] **Yule Xiong**, and Winnie N. Ye, "Silicon MMI-Coupled slotted conventional and MZI racetrack microring resonators," *IEEE Photonics Technology Letters*, 25(19), pp. 1885-1888 (2013).

[4] **Yule Xiong**, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, "Robust silicon waveguide polarization rotator with an amorphous silicon overlayer," *IEEE Photonics Journal*, 6(2), pp. 2200308.1-8 (2014).

[5] **Yule Xiong**, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, "Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler," *Optics Express*, 22(14), pp. 17458-17465 (2014).

[6] **Yule Xiong**, J. Gonzalo Wangüemert-Pérez, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, and Winnie N. Ye, "Polarization splitter and rotator with subwavelength grating for enhanced fabrication tolerance," *Optics Letters*, doc. ID 223256 (posted 15 November 2014, in press).

[7] Winnie N. Ye, and **Yule Xiong**, “Review of silicon photonics: history and recent advances,” *Journal of Modern Optics*, 60(16), pp. 1299-1320 (2013).

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[1] **Yule Xiong**, and Winnie N. Ye, “Vertically coupled Si-based athermal double-ring biosensor,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8007, pp. 80070L1-6, Photonics North 2011, Ottawa, Canada, May 2011.

[2] **Yule Xiong**, and Winnie N. Ye, “Low-loss photonic wires defined by local oxidation of silicon (LOCOS),” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8265, pp. 82650D1-6, Photonics West 2012, San Francisco, USA, Jan. 2012.

[3] **Yule Xiong**, and Winnie N. Ye, “Temperature-independent vertically coupled double-ring sensor,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8266, pp. 826603_1-6, Photonics West 2012, San Francisco, USA, Jan. 2012.

[4] **Yule Xiong**, and Winnie N. Ye, “All-optical single resonance control using a silicon-based ring-assisted Mach-Zehnder interferometer,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8629, pp. 86291D1-6, Photonics West 2013, San Francisco, USA, Jan. 2013.

[5] **Yule Xiong**, and Winnie N. Ye, “Slotted silicon microring resonators with multimode interferometer couplers,” *Group IV Photonics (GFP), IEEE 10th International Conference on*, pp. 118-119 (2013).

[6] **Yule Xiong**, and Winnie N. Ye, “Silicon Mach-Zehnder interferometer race-track microring for sensing,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8990, pp. 89901H1-6, Photonics West 2014, San Francisco, USA, Feb. 2014.

[7] **Yule Xiong**, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, “Broadband two-mode multiplexer with taper-etched directional coupler on SOI platform,” *Group IV Photonics (GFP), IEEE 11th International Conference on*, pp. 39-40 (2014).

This integrated thesis consists of ten articles in the above list that have been published or accepted (with one submitted) to refereed journals and international conferences:

1. Yule Xiong, Marc Ibrahim, and Winnie N. Ye, “Impact of LOCOS techniques on photonic wire waveguides,” *Applied Optics*, 51(29), pp. 7089-7093 (2012)
2. Yule Xiong, and Winnie N. Ye, “Temperature-independent vertically coupled double-ring sensor,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8266, pp. 826603_1-6, Photonics West 2012, San Francisco, USA, Jan. 2012.
3. Yule Xiong, and Winnie N. Ye, “Silicon MMI-Coupled slotted conventional and MZI racetrack microring resonators,” *IEEE Photonics Technology Letters*, 25(19), pp. 1885-1888 (2013).
4. Yule Xiong, and Winnie N. Ye, “Silicon Mach-Zehnder interferometer racetrack microring for sensing,” in *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 8990, pp. 89901H1-6, Photonics West 2014, San Francisco, USA, Feb. 2014.
5. Yule Xiong, and Winnie N. Ye, “All-optical switching of a single wavelength in a silicon-based ring-assisted Mach-Zehnder interferometer,” *Applied Optics*, 51(32), pp. 7788-7793 (2012).
6. Yule Xiong, J. Gonzalo Wangüemert-Pérez, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, and Winnie N. Ye, “Polarization splitter and rotator with subwavelength grating for enhanced fabrication tolerance,” *Optics Letters*, doc. ID 223256 (posted 15 November 2014, in press)
7. Yule Xiong, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, and Winnie N. Ye, “Compact and broadband silicon TE-pass polarizer with subwavelength grating,” submitted to *Optics Express* in December 2014.
8. Yule Xiong, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, “Robust silicon waveguide polarization rotator

with an amorphous silicon overlayer,” *IEEE Photonics Journal*, 6(2), pp. 2200308_1-8 (2014).

9. Yule Xiong, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, “Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler,” *Optics Express*, 22(14), pp. 17458-17465 (2014).

10. Yule Xiong, Dan-Xia Xu, Jens H. Schmid, Pavel Cheben, Siegfried Janz, and Winnie N. Ye, “Broadband two-mode multiplexer with taper-etched directional coupler on SOI platform,” *Group IV Photonics (GFP), IEEE 11th International Conference on*, pp. 39-40 (2014).

Yule Xiong is the principal author in the all ten articles. The ten articles are included in their entirety, while the numbering of equations, figures, tables, and references are changed to maintain consistency throughout the thesis. Except Article 7, permissions from the SPIE, IEEE, and OSA to reproduce other articles with minor edits are included in supporting documents. In reference to the IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of Carleton University’s products or services. Internal or personal use of this material is permitted. Copyright for Article 7 is held by the authors since it has not yet been published.

The suggested citing method of work from this thesis is to directly reference the published articles if possible, while citing this thesis is allowed only when an available citation in the included articles cannot be found.

Student Statement Regarding Student Involvement

I, Yule Xiong, was fully involved and responsible for designing and simulating devices, partially fabricating devices, measuring the fabricated devices, analyzing data and writing the first drafts of the work presented in the accompanying thesis.

Yule Xiong

Supervisor Statement Regarding Student Involvement

The student, Yule Xiong, was fully involved and responsible for designing and simulating devices, partially fabricating devices, measuring the fabricated devices, analyzing data and writing the first drafts of the work presented in the accompanying thesis.

Winnie N. Ye

Table of Contents

Abstract	iii
Acknowledgments	v
Preface	vi
Table of Contents	xi
List of Tables	xviii
List of Figures	xix
Nomenclature	xxx
1 Introduction	1
1.1 Background on Silicon Photonics	1
1.2 Silicon Photonic Structures	2
1.2.1 Waveguides	2
1.2.2 Tapered Structures	5

1.2.3	Directional Couplers	6
1.2.4	Multimode Interference Couplers	10
1.2.5	Microring Resonators	11
1.3	Silicon Photonics Applications	14
1.3.1	Optical Sensing	14
1.3.2	Polarization Management	16
1.3.3	Mode Division Multiplexing	19
1.4	Thesis Objectives	21
1.5	Thesis Organization	22
	List of References	24
2	Methods	31
2.1	Thermal Oxidation Model	31
2.2	Maxwell's Equations	34
2.2.1	Plane Waves	35
2.2.2	Boundary Conditions	36
2.2.3	Slab Waveguides	37
2.2.4	Finite Difference Method (FDM)	41
2.2.5	Finite Element Method (FEM)	42
2.2.6	Eigenmode Expansion (EME) Method	43
2.2.7	Finite Difference Time Domain (FDTD) Method	44
2.3	Fabrication Process	46

2.3.1	Lithography	46
2.3.2	Etching	47
2.3.3	Deposition	48
2.3.4	Fabrication Foundries	49
2.4	Fiber-to-Waveguide Couplers	50
2.5	Measurement Setups	52
	List of References	54
3	Waveguide Fabrication Using the Local Oxidation of Silicon (LOCOS)	57
3.1	Abstract	58
3.2	Introduction	58
3.3	Fabrication	59
3.4	Optical Losses	62
3.5	Polarization Conversions	65
3.6	Conclusion	67
	List of References	67
4	Microring Resonator (MRR)-Based Devices	70
4.1	Vertically Coupled Double-Ring	70
4.1.1	Abstract	71
4.1.2	Introduction	72
4.1.3	Design and Analysis	73

4.1.4	Athermal Characteristics	75
4.1.5	Summary	78
4.2	Slotted Microring Resonator	79
4.2.1	Abstract	80
4.2.2	Introduction	81
4.2.3	MMI-Coupled Slotted Microring Resonator	81
4.2.4	Fabrication and Measurements of Slotted MRR	83
4.2.5	Slotted MZI Racetrack Microrings	86
4.2.6	Conclusion	87
4.3	Mach-Zehnder Interferometer Racetrack Microring For Sensing	89
4.3.1	Abstract	90
4.3.2	Introduction	91
4.3.3	MZI racetrack microring	92
4.3.4	Bulk refractive index sensing	96
4.3.5	Conclusion	98
4.4	Ring-Assisted Mach-Zehnder interferometer	99
4.4.1	Abstract	100
4.4.2	Introduction	100
4.4.3	Design and Theory	101
4.4.4	Simulation and Analysis	104
4.4.5	Comparison of RAMZI and MRR Switches	109

4.4.6	Conclusion	110
	List of References	110
5	Subwavelength Grating (SWG)-Based Devices	115
5.1	Polarization splitter and rotator with subwavelength grating	115
5.1.1	Abstract	116
5.1.2	Introduction	117
5.1.3	Structure Design and Operation Principle	118
5.1.4	Fabrication Tolerances	123
5.1.5	Conclusion	125
5.2	Polarizer with subwavelength grating	126
5.2.1	Abstract	127
5.2.2	Introduction	128
5.2.3	TE-pass Polarizer Design	129
5.2.4	Fabrication and Experimental Results	133
5.2.5	Conclusion	134
	List of References	135
6	Taper-Based Devices	140
6.1	Polarization Rotator with an Amorphous Silicon Overlayer	140
6.1.1	Abstract	141
6.1.2	Introduction	142

6.1.3	Structure Design and Operation Principle	143
6.1.4	Fabrication Tolerances	147
6.1.5	Conclusion	151
6.2	Polarization Splitter and Rotator with Taper-etched Directional Coupler	152
6.2.1	Abstract	153
6.2.2	Introduction	154
6.2.3	Structure Design and Operation Principle	155
6.2.4	Fabrication Tolerances	159
6.2.5	Comparison with Literature Results	162
6.2.6	Conclusion	163
6.3	Two-Mode Multiplexer with Taper-etched Directional Coupler	165
6.3.1	Abstract	166
6.3.2	Introduction	166
6.3.3	Structure Design and Operation Principle	167
6.3.4	Fabrication Tolerances	169
6.3.5	Conclusion	171
	List of References	171
7	Conclusions	175
8	Future Work	178
	List of References	179

Appendix A Derivation of Transmission on Microring Resonators	181
Appendix B Mask Layout Design	183

List of Tables

5.1	Performance of the PSR at phase-matching conditions, for waveguide width $W_A=450$ nm and gap $D=100$ nm	124
6.1	Optimized parameters of the rotator structures for $H=220$ nm and $H=260$ nm by assuming a TE input	147
6.2	Calculated tolerances of the polarization rotator structures for $PRE>90\%$ a TE input	148
6.3	Optimized parameters of the polarization splitter and rotator calculated using the EME method	159
6.4	Calculated tolerance of the polarization splitter and rotator for $CE_{TM-TE} > -0.5$ dB and a TM-like input mode	161
6.5	Performance of the polarization splitter and rotator for the S, C and L bands (the wavelength range from 1460 nm to 1625 nm)	162
6.6	Comparison of directional coupler based polarization splitter and rotator	163

List of Figures

1.1	Silicon (a) rib, (b) strip and (c) buried waveguides.	3
1.2	(a) Schematic of a slot waveguide, (b) Simulated electric field distribution of the slot waveguide, (c) electric field profile across the center line, 'AB'. The cladding is SiO ₂	4
1.3	Schematic of a subwavelength grating (SWG) waveguide.	4
1.4	Schematics of lateral tapers: a symmetrical taper (a) 3D view, (b) Top view; and an asymmetrical taper (c) 3D view, (d) Top view.	6
1.5	Cross-sections of silicon (a) symmetrical and (b) asymmetrical directional couplers.	7
1.6	The first two E_x mode profiles and profiles across the center line, 'AB', of (a) and (c) symmetrical, (b) and (d) asymmetrical TE-like modes in a symmetrical directional coupler using 450 nm $\times$ 220 nm Si waveguides with a gap of 200 nm.	8
1.7	The E_x mode profiles and profiles across the center line, 'AB', of (a) and (c) second, (b) and (d) third eigenmode modes in an asymmetrical directional coupler for TE ₀ -TE ₁ coupling. The dimension of the wide waveguide is 930 nm $\times$ 220 nm, while the narrow waveguide has a dimension of 450 nm $\times$ 220 nm, and the coupling gap is 200 nm. . . .	9
1.8	(a) Schematic of a 2 $\times$ 2 MMI coupler and (b) Field profiles of the four lowest order modes in the MMI coupler.	11

1.9	Schematic of an all-pass ring resonator.	12
1.10	Normalized transmission of an all-pass ring resonator.	13
1.11	(a) Schematic diagram illustrating the principle of microring resonator (MRR) biosensing: as the sensing molecular target binds to the MRR, the resonant wavelength shifts with $\Delta\lambda$ shown in a representative transmission spectrum. (b) Top-view scanning electron micrograph image of a microring resonator [42].	16
1.12	Schematic of a TE-pass polarizer. Only TE mode passes through the device while the TM mode is blocked.	17
1.13	Schematic of a polarization diversity scheme. Arrows represent the orientation of the electric field, i.e., TE and TM polarizations [51]. . .	18
1.14	Schematic configuration of a multimode division multiplexing system link with two polarizations.	20
2.1	Oxidant flux (F) from the gas phase to the silicon surface during thermal oxidation [1].	33
2.2	(a) Slab waveguide; (b) refractive index profile of slab waveguide. . .	37
2.3	Electric field distribution for the first four TE modes in a slab waveguide.	40
2.4	Scattering matrix for the join of waveguides. $a^{(+)}, a^{(-)}, b^{(+)}, b^{(-)}$ are mode coefficients at the join, S_J is a scattering matrix for the join [4].	44
2.5	Standard Cartesian Yee cell used for FDTD, about which electric and magnetic field vector components are distributed. The electric field components form the edges of the cube, and the magnetic field components form the normals to the faces of the cube.	45
2.6	Lithography process.	47

2.7	Isotropy and selectivity of the etching process of a SOI waveguide. (a) A perfectly anisotropic and highly selective etching process produces vertical sidewalls and leaves the underlying SiO ₂ substrate unharmed; (b) an isotropic etching produces round sidewalls; (c) a poorly selective etching over-etches the underlying SiO ₂ substrate.	48
2.8	Comparison of relative sizes of two optical fiber Modal Field Diameters (MFDs) and the cross-section of a typical silicon waveguide.	51
2.9	A lensed fiber from OZ Optics Ltd.	51
2.10	An inverse-taper coupler. (a) Schematic of the coupler. (b) Fabricated inverse coupler.	52
2.11	Schematic of a grating coupler.	52
2.12	Schematic of the measurement system	53
2.13	Fiber array measurement setup	53
2.14	Cross-section of the fiber array containing three TE polarization maintaining (PM) fibers and three TM PM fibers	54
3.1	Fabrication process flow of (a) Type A LOCOS waveguide (a stack of pad oxide and silicon nitride layers as the mask), (b) Type B LOCOS waveguide (a single silicon nitride layer as the mask). (1) and (5) Silicon on insulator wafer. (2) and (6) Depositing silicon nitride and/or pad oxide layers. (3) and (7) Patterning of silicon nitride. (4) and (8) Wet Oxidation.	60
3.2	Cross-section of the LOCOS wire waveguides. (a) Simulated shape for Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask). (b) Simulated shape for Type B waveguides (a single silicon nitride layer as the mask). (c). SEM image of Type A waveguides. (d) SEM image of Type B waveguides.	62

3.3	Simulated quasi-TE polarization profiles of the fabricated LOCOS wire waveguide. (a) Type A waveguides ((a stack of pad oxide and silicon nitride layers as the mask). (b) Type B waveguides (a single silicon nitride layer as the mask).	63
3.4	Waveguide paperclip structure for cut-back measurements of the propagation loss.	64
3.5	Propagation loss for the LOCOS wire waveguide for the quasi-TE polarization. (a) Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask) (b) Type B waveguides (a single silicon nitride layer as the mask).	64
3.6	Waveguide serpentine pattern for measurements of the bending loss. .	65
3.7	Bending loss for the LOCOS wire waveguide for the quasi-TE polarization. (a) Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask) (b) Type B waveguides (a single silicon nitride layer as the mask).	66
3.8	Output power of quasi-TE and quasi-TM polarizations for Type B waveguides when TE polarization was launched.	66
4.1	Schematic of a vertically coupled double-ring resonator: (a) 3D view (b) side view.	73
4.2	Simulated transmission spectra of the silicon-based vertically coupled double-ring resonator structure with radii 6 μm and 8 μm for the reference and sensing rings, respectively. Inset: the configuration of the double-ring resonator (Sensing: Sensing microring waveguide, Ref. Reference microring waveguide).	74
4.3	Simulated resonance wavelength shifts with temperature change at $n_c=1$.	76
4.4	Simulated resonance wavelength shifts with both temperature and cladding index induced effects.	77

4.5	(a) Schematic of a MMI-coupled slotted microring resonator (MRR). (b) Microscopic image of the fabricated device.	82
4.6	(a) Simulated fundamental TE mode profile (E field primarily parallel to the wafer surface) of the fabricated slot waveguide. (b) Optical field distribution of the fabricated MMI coupler by FDTD simulation. . . .	84
4.7	(a) Measured transmission spectrum of the MMI-coupled slotted MRR with a radius of 20 μm . The wavelength scan step is 1 pm. (b) Magnified transmission spectrum near 1510 nm.	85
4.8	Schematic of the MMI-coupled slotted MZI racetrack microring. . . .	86
4.9	(a) Microscopic image of the fabricated MMI-coupled slotted MZI racetrack microring. (b) Measured transmission spectra of the MMI-coupled slotted MZI racetrack microring with a radius of 20 μm . The wavelength scan step is 1 pm.	87
4.10	Schematic of the MZI racetrack microring with MMI couplers.	93
4.11	Schematics, optical microscope pictures and measured transmission responses of the designed the MMI-coupled MZI racetrack microrings with (a)-(c) wire waveguides; and (d)-(f) slot waveguides.	96
4.12	The major resonance wavelength λ_r shifts as the concentration of the sucrose solution varies. (Inset: Measured transmission responses of the MZI racetrack microring covered by the sucrose solution with difference concentrations): (a) MZI racetrack microring using wire waveguides; (b) MZI racetrack microring using slot waveguides.	97
4.13	Schematic of an all-optical switch based on a ring-assisted MZI (RAMZI) with control light and anti-Stokes signal.	102
4.14	(a) Transmission spectrum of the RAMZI switch. (b) Transmission at the anti-Stokes resonance for several control light pulse energies. . . .	105

4.15	(a) Transmission from Arm 1 of the RAMZI for the side-coupled MRR resonance. (b) Transmission at the anti-Stokes resonance for several control light pulse energies.	106
4.16	(a) Transmission spectrum of the RAMZI switch. (b) Transmission at the anti-Stokes resonance for the control light pulse energy of 20 pJ (Resonances next to the anti-Stokes wavelength are disturbed). Inset: transmission spectrum around the anti-Stokes wavelength for the control light pulse energy of 0.4 pJ.	107
4.17	(a) Transmission as a function of the control light pulse energy. Switching is most efficient for transmission values below -3 dB. (b) Required control light pulse energy at the roll-off point (3 dB transmission) for various finesses (F) of the side-coupled MRR.	108
4.18	Simulated time response of the anti-Stokes signal with 200 ps control pulse of 20 pJ.	108
4.19	Simulated ER as a function of the coupling coefficients t_1 , t_2 and the microring intrinsic loss a_0 with 200 ps control pulse of 20 pJ: (a) and (b) are for a standalone MRR switch, and (c) and (d) are for a RAMZI switch, where the blue indicates $ER > 5\text{dB}$, while the green, yellow, brown are for $ER > 10\text{ dB}$, $> 15\text{ dB}$, $> 20\text{ dB}$, respectively. In (a) and (c), $a_0 = 2\text{ dB/cm}$	110
5.1	Schematics of the polarization splitter and rotator based on an asymmetrical directional coupler with a subwavelength grating (SWG) waveguide. (a) Top view, (b) 3D view, and (c) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index n_B	119
5.2	Effective indices of the fundamental TE and/or TM modes of (a) the wire waveguide A and (b) the SWG waveguide B with different equivalent refractive indices $n_B = 3.476, 2.525, 2.4$, and 2.3 , as a function of the waveguide widths W_A and W_B . Red curves represent the phase matching condition where the width W_A is set to 450 nm.	120

5.3	Light propagation along the polarization splitter and rotator (top view) for (a) TE mode and (b) TM mode injected at the input (the left port). Calculated by the 3D-FDTD method with the grid sizes $\Delta x=15$ nm, $\Delta y=15$ nm, and $\Delta z=20$ nm.	122
5.4	Wavelength dependence of the polarization splitter and rotator, calculated by 3D-FDTD simulations. (a) TE mode insertion loss and TM-TE polarization conversion loss; (b) Polarization crosstalk XT_{TE} and XT_{TM} . Waveguide parameters: $W_A = 450$ nm, $H = 220$ nm, $W_B = 685$ nm, $\eta=0.5$, $D = 100$ nm, and $L = 25$ μ m.	123
5.5	Dependence of the TM-TE polarization conversion loss PCL on the width variation δW of both the wire waveguide A and the SWG waveguide B, (a) for $n_B=3.476, 2.525, 2.4, 2.3$ (duty ratios $\eta=1, 0.6, 0.5$ and 0.4), as calculated by an EME method; (b) confirmation by the 3D-FDTD method for $\eta=0.5$	125
5.6	Schematics of the TE-pass polarizer based on a subwavelength grating (SWG) waveguide with an air top cladding. (a) Top view, (b) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index n_{SWG} ; and (c) effective indices of the TE and TM modes of the SWG waveguide as a function of the engineered refractive index n_{SWG} when $W=1100$ nm, $H=220$ nm: (i) cut-off region with no mode supported; (ii) TE only (on TM); (iii) TE and TM modes region.	130
5.7	Light intensity (input from the left port) propagates along the proposed SWG TE-pass polarizer, as simulated by a 3D-FDTD method. With a TE input, the TE mode field distribution along the x-z plane (a), and along the y-z plane (b). With a TM input, the TM mode field distribution along the x-z plane (c), and along the y-z plane (d). $W=1100$ nm, $L=50$ μ m, $L_t=5$ μ m, $\Lambda=300$ nm, $\eta=0.5$, $\lambda_0=1550$ nm	131
5.8	Simulated wavelength dependence of transmission [$T_{TE}(\lambda)$ and $T_{TM}(\lambda)$] and reflection [$R_{TE}(\lambda)$ and $R_{TM}(\lambda)$] for the proposed TE-pass polarizer. $W=1100$ nm, $H=220$ nm, $L=50$ nm, $\eta=0.5$	132

5.9	Calculated transmission of the TE-pass polarizer as a function the SWG waveguide length L for different SWG waveguide width. $H=220$ nm, $\eta=0.5$	133
5.10	(a) Schematic of the mask layout; microscopic pictures of (b) the fabricated polarizer; (c) the enlarged view.	134
5.11	Measured results of the fabricated polarizer and the reference waveguide: (a) transmission of TE and TM in the SWG-polarizer compared to the straight wire reference waveguide;(b) reflection of TE and TM in the SWG-polarizer.	135
6.1	(a) Schematic of the polarization rotator with a-Si overlayer. (b) Waveguide cross-section with asymmetric a-Si loading and SiO_2 upper cladding.	143
6.2	Electric field components (a) E_x and (b) E_y evolution along the polarization rotator (top view), as calculated by a 3D-FDTD method. (c) Transverse electric field distributions at the corresponding positions along the polarization rotator.	145
6.3	(a) Polarization Rotation Efficiency (PRE) as a function of the a-Si strip width W_R for access waveguide width $W=430$ nm; $H=H_R=260$ nm. (b) Length of the rotation section L_R and the corresponding W_R as a function of tilt angle θ for two different heights H (220 nm and 260 nm) of the access waveguide; two heights (220nm and 260nm) of the access wire waveguide.	146
6.4	(a) Polarization rotation efficiency as a function of the access waveguide width W for different thickness H_R of a-Si overlayer. (b) Possible combinations of the width of the access waveguide W and the height of the a-Si layer H_R for a PRE of $>99\%$. Grey area: $H=220$ nm; hatched area: $H=260$ nm.	147

6.5	Dependence of the polarization rotation efficiency (PRE) on structure geometrical tolerances calculated with fully vectorial EME simulations for: (a) Width of the access waveguide, ΔW ; (b) height of the access waveguide, ΔH ; (c) width of the a-Si patch, ΔW_R ; (d) height of the a-Si patch, ΔH_R , (e) angle between the a-Si layer and the access waveguide, $\Delta\theta$; and (f) tip width of the a-Si layer, D_t . The optimal parameters are listed in Table 6.1; For $H=220$ nm: $H_R=220$ nm, $W=430$ nm, $W_R=386$ nm, and $\theta=2.4^\circ$; For $H=260$ nm: $H_R=260$ nm, $W=430$ nm, $W_R=386$ nm, and $\theta=1.7^\circ$	149
6.6	Waveguide width tolerances for different widths of the access waveguide, calculated by fully vectorial EME simulations. Dash curve: $W=400$ nm, $H=H_R=260$ nm, $W_R=860$ nm, $\theta=3^\circ$; Solid curve: $W=430$ nm, $H=H_R=260$ nm, $W_R=386$ nm, $\theta=1.7^\circ$	150
6.7	Wavelength dependence of polarization rotation for TE polarized input calculated by 3D-FDTD and fully vectorial EME simulations. (a) $H=H_R=220$ nm, $W=390$ nm, $W_R=343$ nm and $\theta=2.4^\circ$; (b) $H=H_R=260$ nm, $W=430$ nm, $W_R=386$ nm and $\theta=1.7^\circ$	150
6.8	(a) Schematic of the polarization splitter and rotator based on the taper-etched directional coupler. For clarity, the SiO_2 upper cladding is not shown. (b) Effective index of the TE-like mode of the taper-etched waveguide B as a function of the ridge width W_e for a post-etch height $H_e=110$ nm, $W_t=350$ nm, and $H=220$ nm. Effective indices of the TM-like mode of the access waveguide A ($H=220$ nm) are shown for different widths W of the access waveguide A (black lines). Red circles indicate the phase matching condition.	155
6.9	Light intensity (Light input from the left port) of (a) TE-like mode input and (b) TM-like mode input evolution along the polarization splitter and rotator (top views), as calculated by a 3D-FDTD method. (c) Transverse electric field distributions at the corresponding positions along the polarization splitter and rotator when launching TM-like mode as input.	157

6.10	(a) Effective index of the TE-like mode of the taper-etched waveguide B as a function of a width ratio W_e/W_t , for three different post-etch slab heights ($H_e=70$ nm, 110 nm and 150 nm). The corresponding width W_t is 410 nm, 350 nm and 310 nm, for the phase matching near the position $W_e/W_t=0.5$. Effective index of the TM-like mode of the access waveguide A ($H=220$ nm) are shown for a waveguide width range $W=450\pm50$ nm (shadow region). (b) Polarization conversion efficiency CE_{TM-TE} as a function of coupling length L_{DC} for post-etch slab heights $H_e=70$ nm, 110 nm, and 150 nm.	158
6.11	Dependence of the polarization conversion efficiency CE_{TM-TE} on structure geometrical tolerances. Calculated using the full-vectorial EME simulations for (a) post-etch slab height, ΔH_e , and (b) tip width D_t . The optimized parameters are listed in Table 6.3.	160
6.12	Wavelength dependence of the polarization splitter and rotator as calculated by the full-vectorial EME simulations. (a) TE-like mode insertion loss and TM-to-TE polarization conversion loss; (b) Crosstalk XT_{TE} and XT_{TM} . $W=450$ nm, $H=220$ nm, $W_t=350$ nm, $H_e=110$ nm, $D_{gap}=200$ nm, and $L_{DC}=200$ μm	161
6.13	(a) Schematic of the TE_0/TE_1 mode multiplexer with a taper-etched directional coupler; (b) Calculated electric field for the TE_0 - TE_1 coupling, obtained by the eigenmode expansion method (EME).	168
6.14	(a) Effective TE_0 mode index in the taper-etched waveguide as a function of the ridge width W_e for a post-etch height $H_e=150$ nm. Effective indices of the TE_1 mode of the wire waveguide ($H=220$ nm) are shown for different waveguide widths W (red lines); (b) Calculated TE_0 - TE_1 coupling efficiency and mode crosstalk $T_{TE_0-TE_0}$ as a function of wavelength for $W=840$ nm, $H=220$ nm, $W_t=490$ nm, $H_e=150$ nm, $D_{gap}=200$ nm and $L_{DC}=330$ μm	169

6.15	Dependence of the TE_0 - TE_1 mode coupling efficiency on the following parameters: (a) error in width ΔW and (b) height ΔH of the multimode wire waveguide, (c) error in width of the taper-etched waveguide ΔW_t , (d) slab height error ΔH_e , (e) coupling gap error ΔD_{gap} , and (f) tip width error ΔD_t of the etched taper. Other parameters are specified in Fig. 6.14(b).	170
A.1	Schematic of an all-pass ring resonator.	182
B.1	Mask layout of the LOCOS waveguide. Both the paper-clip pattern for the propagation loss and the serpentine pattern for the bending loss are included. The target waveguide lengths range from 0.48 cm to 1.92 cm, while the bending radius are $5 \mu\text{m}$ to $50 \mu\text{m}$	184
B.2	Mask layout of microring resonators and MZI racetrack microring resonators. 42 microring resonators with a radius ranging from $5 \mu\text{m}$ to $20 \mu\text{m}$. Both MMIs and DCs are used for light coupling.	184
B.3	Mask layout of the polarization splitter and rotator (PSR) with the taper-etched directional coupler. The target gap is 200 nm while the PSR length is $80 \mu\text{m}$	185
B.4	Mask layout of the two-mode (de)multiplexer with the taper-etched directional coupler. The length of the (de)multiplexer is $313 \mu\text{m}$, and the gap is 200 nm.	186

Nomenclature

a-Si - amorphous silicon
CMC - Canadian Microelectronics Corporation
CMOS - Complimentary Metal-Oxide Semiconductor
CVD - Chemical Vapor Deposition
DC - Directional Coupler
DUV - Deep Ultraviolet
e-beam - Electron Beam
EME - Eigenmode Expansion
ER - Extinction Ratio
FCA - Free Carrier Absorption
FCR - Free Carrier Refraction FDM - Finite Difference Method
FDTD - Finite Difference Time Domain
FEM - Finite Element Method
FSR - Free Spectral Range
FWHM - Full-Width Half-Maximum
IRS - Inverse Raman Scattering
IME - Institute of Microelectronics
IMEC - Interuniversity Microelectronics Centre
LOCOS - Local Oxidation of Silicon
MDM - Mode Division Multiplexing
MFD - Mode Field Diameter
MMI - Multimode Interference
MRR - Microring Resonator
MZI - Mach-Zehnder Interferometer
MZIRM - Mach-Zehnder Interferometer Racetrack Microring

NRC Canada - National Research Council Canada
OpSIS - Optoelectronic Systems Integration in Silicon
PBS - polarization Beam Splitter
PECVD - Plasma Enhanced Chemical Vapor Deposition
PR - Polarization Rotator
PSR - Polarization Splitter and Rotator
PVD - Physical Vapor Deposition
Q-factor - quality factor
RAMZI - Ring-assisted Mach-Zehnder Interferometer
RIE - Reactive Ion Etching
SMF - Single Mode Fiber
SOI - Silicon-on-insulator
SWG - Subwavelength Grating
TO - Thermo-Optical
TPA - Two-photon Absorption
TE mode - Transverse electric mode
TM mode - Transverse magnetic mode
UV- Ultraviolet

Chapter 1

Introduction

1.1 Background on Silicon Photonics

Silicon photonics is a promising technology in optoelectronic integration for computing, communication and sensing [1–3]. Silicon-on-insulator (SOI) wafers are an important platform for silicon photonics [4]. In the late 1980s and mid-1990s, SOI substrates were applied to the microelectronics industry to reduce the parasitic capacitances in the electronic integrated circuits. By leveraging on the continuous development of a well-established and standardized microelectronic industry, namely, the CMOS technology [4], silicon photonic circuits can be massively produced with low cost. Furthermore, silicon’s high-quality native oxide, silicon dioxide (SiO_2), offers one important advantage for silicon photonic circuit integration: the high refractive index contrast between silicon and SiO_2 enables high confinement of light and hence a dense circuit integration.

Pioneered by Soref et al. [5] in the mid-1980s, silicon photonics has expanded rapidly. Various active and passive devices are demonstrated as building blocks of silicon photonics, including low-loss waveguides [6], high-performance modulators [7–9] and detectors [10, 11]. Due to the intrinsic indirect band gap, silicon is not an ideal choice for lasing. Much effort has put towards integrating III-V lasers onto silicon [12]. The first silicon Raman laser was finally demonstrated by using stimulated Raman scattering in 2004 [13].

Section 1.2 discusses fundamental silicon photonic structures used in this thesis, including waveguides, tapers, directional couplers, multimode interference couplers, microring resonators and so on. Section 1.3 introduces the basics of the three target applications of the designed devices in the thesis, i.e., optical sensing, polarization management, and mode division multiplexing. The objective and organization of the thesis are given in Sections 1.4 and 1.5, respectively.

1.2 Silicon Photonic Structures

1.2.1 Waveguides

Waveguides are the most fundamental building block in silicon photonic circuits. There are three main types of waveguide structures: rib, strip, and buried [14], as illustrated in Fig. 1.1. Strip and buried waveguides are also called wire waveguides in the literature. Limited by fabrication challenges, the early research on silicon photonics focused on the rib waveguides, which can meet the single-mode condition with cross-section dimensions on the order of several microns. For dense photonic circuit integration, the deeply etched rib waveguides is required to reduce the waveguide dimension. The rib waveguide is popular in designing active devices such as silicon Raman laser [13, 15] and modulators [16, 17] as the slab region in the rib waveguide is suitable for the doping. Due to the asymmetrical geometry, the rib waveguide is desired for a mode conversion between the fundamental TM mode and the higher-order TE mode [18], which has been used for the polarization rotation. On the other hand, such a mode conversion of the rib waveguide in the taper section will introduce a significant excess loss. The high index contrast between silicon ($n=3.476$) and SiO_2 ($n=1.444$) in a SOI platform enables a high confinement of light in ultra-small waveguide dimensions. In recent years, strip waveguides have gained popularity due to their ability to support the single mode propagation within submicron dimensions [6]. In addition, the fabrication of the strip waveguide requires only one-step etching process.

Shrinking the waveguide dimension down to a few hundred nanometers significantly increases the propagation loss induced by the sidewall roughness. The relation between scattering loss and the sidewall roughness can be modeled by the analytical

approach [19, 20]. The approach relates the attenuation coefficient to the standard deviation and the autocorrelation length of the sidewall roughness. In 2000, the effect of the sidewall roughness on the propagation loss in a Si/SiO₂ was confirmed experimentally [21]. In order to reduce the scattering loss from the sidewall roughness, an oxidation process is often used to smooth the waveguide sidewall roughness [22]. Various oxidation processes have been proposed to define silicon waveguides, such as the wet chemical oxidation technique [23] and the selective oxidation process [24, 25] where etchless buried waveguides can be defined. As shown in Fig. 1.1(c), a buried waveguide formed by an oxidation process has intrinsically smooth sidewalls, hence, achieving low propagation loss. This thesis explores the use of the local oxidation of silicon (LOCOS) technique to achieve an etch-less buried waveguide.

Figure 1.1: Silicon (a) rib, (b) strip and (c) buried waveguides.

Recently, two new types of silicon waveguides have been developed. One is slot waveguides [26], consisting of a low-refractive-index submicron slot between two adjacent silicon waveguide segments. In slot waveguides, a large portion of the optical mode propagates through the low index slot region, as shown in Fig. 1.2. The large optical field enhancement in the submicron slot region [Figs. 1.2 (b) and (c)] can greatly enhance the interaction between light and matter, significantly improving the efficiency in sensing applications.

The second new type of waveguides is subwavelength grating (SWG) waveguides [27], where the waveguide core is a composite medium formed by periodically interlacing silicon segments with a material of a lower refractive index at the subwavelength scale, as shown in Fig. 1.3. SWG waveguides have a unique property where the waveguide's effective index can be engineered by the choice of the cladding material or by selecting a specific duty cycle of the grating. In a SWG waveguide, light excites a Bloch mode, which can theoretically propagate losslessly without diffraction

into radiative or cladding modes. In addition, the mode delocalized in the SWG core reduces the scattering efficiency at the core-cladding interface. SWGs offer the design freedom of index engineering in silicon integrated optics. Furthermore, the SWG structures can be used to engineer the dispersive property of silicon photonic devices.

Figure 1.2: (a) Schematic of a slot waveguide, (b) Simulated electric field distribution of the slot waveguide, (c) electric field profile across the center line, 'AB'. The cladding is SiO₂.

Figure 1.3: Schematic of a subwavelength grating (SWG) waveguide.

Two parameters used to evaluate waveguide performance include: propagation loss and bending loss. When light propagates through a silicon waveguide, it experiences

propagation loss. The output power simply decays exponentially; that is, with a factor of $\exp(-\alpha L)$, where α is the attenuation coefficient and L is the propagation distance in the silicon waveguide. The propagation loss is often specified in dB/cm. For silicon wire waveguides, the attenuation coefficient α is mainly related to sidewall scattering at the silicon and SiO₂ interface from the etching process [24, 28]. The typical propagation loss of a silicon wire waveguide is around 2 dB/cm, with the minimum reported loss of 0.3 dB/cm [28].

In order to achieve dense silicon photonic integration, bending or folding of waveguides is necessary. However, additional propagation loss may occur. Typically the bending loss rises very quickly once the bending radius approaches below the critical radius. Due to the high index contrast between silicon and SiO₂, the critical bending radius of a silicon waveguide can be as small as 1 μm . The bending loss is usually specified in dB/90°, i.e., loss per a 90° bend, with a typically low value of 0.01 dB/90°.

1.2.2 Tapered Structures

Tapered structures with an adiabatic mode transition between different waveguide sections are important in designing various silicon devices. Tapered designs [29] are either lateral or vertical. The tapered angle in the transition region must be sufficiently small to prevent additional transition loss in the tapered region. In a laterally tapered device, the width of the guiding layer is varied, which can be defined by standard processing techniques. In a vertical taper, the thickness of the guiding layer varies along the device, which requires special growth and etching techniques. Only lateral tapers, which can be fabricated in public commercial fabrication foundries, are discussed here.

The fabrication of a lateral taper is rather straightforward and can generally be done using a standard lithography step followed by a single wet or dry etching process. Two typical lateral tapered designs are shown in Fig. 1.4. One is a symmetrical taper, in which the center points of both the large and small facets are collinear [Figs. 1.4(a) and 1.4(b)]. The symmetrical lateral taper has been commonly used to realize compact fiber-to-waveguide edge coupling. An asymmetrical taper, as shown in Figs. 1.4(c) and 1.4(d), has non-collinear center points of the large and small facets.

Due to the asymmetry in geometry, the asymmetrical tapers have been often used to achieve polarization rotation in silicon photonics [30]. Tapered structures can also provide a certain degree of freedom in designing devices such as directional couplers, which has proven to be useful for achieving fabrication-tolerance in devices [31].

Figure 1.4: Schematics of lateral tapers: a symmetrical taper (a) 3D view, (b) Top view; and an asymmetrical taper (c) 3D view, (d) Top view.

1.2.3 Directional Couplers

A widely used passive device configuration is a directional coupler (DC). A DC consists of two waveguides in close proximity, where the light coupling between the two waveguides occurs via the evanescent field. Silicon DCs can be either symmetrical or asymmetrical, as shown in Fig. 1.5. The widths of the two waveguides in a symmetrical DC are the same while the two waveguides in an asymmetrical DC have different widths. Although both types of DCs have been used for power and polarization splitting, asymmetrical DCs attracted more attention due to their capability in achieving mode-division multiplexing [32], as well as in obtaining polarization rotation and splitting simultaneously [33].

Figure 1.5: Cross-sections of silicon (a) symmetrical and (b) asymmetrical directional couplers.

In order to efficiently transfer the optical power from one mode in the first waveguide to another mode in the second waveguide, the effective indices of the two modes in the two waveguides of a DC should be the same, satisfying the phase-matching condition. For a symmetrical DC, the phase-matching condition happens only for the same mode since the two waveguides are identical. For an asymmetrical DC, the fundamental TE mode of waveguide 1 can be coupled to other modes of waveguide 2 by selecting specific waveguide widths, which is useful for mode division multiplexing. Based on the coupled mode theory [34], the fraction of the light coupled from waveguide 1 to waveguide 2, κ^2 , can be described as:

$$\kappa^2 = \frac{I_2}{I_{in}} = \sin^2(C \cdot L) \quad (1.1)$$

where I_{in} is the input light intensity from waveguide 1, while I_2 is the intensity coupled across waveguide 2, L is the coupling length, and C is the coupling coefficient.

Assuming a lossless DC, the fraction of the intensity passing through the original waveguide 1, t^2 , is:

$$t^2 = \frac{I_1}{I_{in}} = \cos^2(C \cdot L) \quad (1.2)$$

where I_1 is the light intensity passing through the waveguide 1.

Figure 1.6: The first two E_x mode profiles and profiles across the center line, 'AB', of (a) and (c) symmetrical, (b) and (d) asymmetrical TE-like modes in a symmetrical directional coupler using $450 \text{ nm} \times 220 \text{ nm}$ Si waveguides with a gap of 200 nm .

The coupling coefficient is related to the effective indices of the two supermodes in the DC region. For a symmetrical DC, the two supermodes are called the symmetric and antisymmetric modes. The TE-like symmetric and antisymmetric modes are the first two eigenmodes of the DC, as shown in Fig. 1.6. Similarly, for an asymmetrical DC realizing TE_0 to TE_1 mode coupling, the two supermodes are the second and third eigenmodes of the DC, as shown in Fig. 1.7. The coupling coefficient is expressed as

$$C = \frac{\pi \Delta n}{\lambda} \quad (1.3)$$

where Δn is the index difference of the two supermodes ($n_1 - n_2$).

Combining Eqs. 1.1-1.3, we can obtain that, the required coupling length to couple the light to the cross waveguide completely is

$$L_c = \frac{\lambda}{2\Delta n} \quad (1.4)$$

Figure 1.7: The E_x mode profiles and profiles across the center line, 'AB', of (a) and (c) second, (b) and (d) third eigenmode modes in an asymmetrical directional coupler for TE_0 - TE_1 coupling. The dimension of the wide waveguide is $930 \text{ nm} \times 220 \text{ nm}$, while the narrow waveguide has a dimension of $450 \text{ nm} \times 220 \text{ nm}$, and the coupling gap is 200 nm .

To intuitively understand Eq. 1.4, we first express the phase difference induced by the propagation difference of the two supermodes:

$$\Delta\phi = (\beta_1 - \beta_2)L \quad (1.5)$$

where $\beta_1 = 2\pi n_1/\lambda$ and $\beta_2 = 2\pi n_2/\lambda$ are the propagation constants of the two supermodes. After a $\Delta\phi = \pi$ phase shift, a complete coupling can be achieved, where L_c satisfies Eq. 1.4.

By using a deep ultraviolet (DUV) or e-beam lithography step, the DCs can be very short if the coupling gap is 100 nm or less. However, very small features are sensitive to fabrication imperfections, such as sidewall roughness, making tight fabrication tolerances. Taper-etched DCs have been proposed in this thesis to compensate for the fabrication variations, making the DC fabrication more tolerant. The design will be discussed in detail in Chapter 6.

The key parameters to evaluate the performance of a DC include insertion loss,

fabrication tolerance and bandwidth. DC devices usually have low insertion loss and are compact in size. However, they are sensitive to fabrication inaccuracies and has a narrow operating bandwidth.

1.2.4 Multimode Interference Couplers

Multimode interference (MMI) coupler employing the self-imaging principle in multimode waveguides is another common component in silicon integrated circuits [35]. Compared to DCs, MMI devices exhibit low polarization dependence with large fabrication tolerances. The multimode waveguide in the MMI coupler supports a large number of guided modes. Fig. 1.8(a) shows schematically a 2×2 MMI coupler with 2 input and 2 output waveguides connected to a multimode section with a dimension of W (width) $\times$ L (length). A set of guided modes in the multimode section are excited by a fundamental mode from one of the input ports. For a perfect self-imaging by which an input mode profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the multimode section, the propagation constants follow the relation:

$$\Delta\beta_m = \beta_0 - \beta_m = \frac{m(m+2)\pi}{3L_\pi} \quad (1.6)$$

where β_m is the propagation constant of the m -th mode, and L_π refers to the beat length between the two lowest order modes. The parameter L_π specifies the minimum length for the output to reproduce itself, i.e., $L_\pi = \pi/(\beta_0 - \beta_1)$. When a MMI of width W and core refractive index n_c is excited from either input port, the beat length can also be expressed as [36]

$$L_\pi = \frac{4n_c W^2}{3\lambda} \quad (1.7)$$

where the phase difference between the even and odd modes at the end of the multimode region is π . At a distance one beat length and a half $3L_\pi/2$, the MMI produces a pair of identical images, making the MMI a 3 dB coupler, as shown in Fig. 1.8(b).

Figure 1.8: (a) Schematic of a 2×2 MMI coupler and (b) Field profiles of the four lowest order modes in the MMI coupler.

1.2.5 Microring Resonators

Another promising building block for silicon photonics is a microring resonator (MRR), which consists of a circular waveguide coupled to one or two separate straight waveguides, as shown in Fig. 1.9. The key advantages of a MRR include small device footprint, its ability to obtain narrow linewidths and high Q performance, and the potential for large-scale monolithic integration. MRRs have been used almost everywhere in photonics for applications ranging from optical sensing to optical communication [37]. Both DCs and MMI couplers [38] can be used to achieve the coupling between the ring waveguide and the straight bus waveguides. In comparison, DCs introduce a lower insertion loss to MRR, which is useful to achieve very high quality (Q) factors in optical sensing and nonlinear optics applications. However, the fabrication requirement of DC-coupled MRRs is strict, which is the main bottleneck to achieve an accurate operation. Since MMI couplers may induce a relatively large insertion loss, the bandwidth of MMI-coupled MRRs is wide while the Q factor of MMI-coupled MRRs is moderate. MMI-coupled MRRs are compatible to applications for high speed signal processing and optical delay lines.

Assuming the DC or MMI coupler has an insertion loss with a transmission coefficient α_C , the ratio of the output and input field in the straight bus waveguide can be obtained by a generalization of the MRR equations [39] (see Appendix A for the detailed derivation):

$$\frac{E_{out}}{E_{in}} = \alpha_C e^{i(\pi+\phi)} \frac{\alpha - t e^{-i\phi}}{1 - \alpha t e^{i\phi}} \quad (1.8)$$

Figure 1.9: Schematic of an all-pass ring resonator.

where $\phi = \beta L$ is the total round-trip phase accumulation, L is the round-trip length and β is the propagation constant of the circulating mode. $\alpha = \alpha_C \cdot \alpha_R$ is the total power amplitude transmission coefficient, including both the ring propagation loss (α_R) and the coupler loss (α_C). t is the self-coupling coefficient, while κ is the cross-coupling coefficient. $|t|^2$ and $|\kappa|^2$ represent the power splitting ratios of the coupler, and $|t|^2 + |\kappa|^2 = |\alpha_C|^2$, which means the total transmitted power through the coupling region is $|\alpha_C|^2$.

By squaring Eq. 1.8, the power transmission T can be obtained as

$$T = \frac{|E_{out}|^2}{|E_{in}|^2} = \frac{P_{out}}{P_{in}} = \alpha_C^2 \frac{\alpha^2 - 2t\alpha \cos(\phi) + t^2}{1 - 2t\alpha \cos(\phi) + (t\alpha)^2} \quad (1.9)$$

A sample plot of the transmission spectrum as a function of the wavelength of a typical MRR is shown in Fig. 1.10. The power transmission spectrum has periodic dips at resonance frequencies determined by $\phi = 2m\pi$. At resonances, the transmission magnitude is given by

$$T = \frac{P_{out}}{P_{in}} = \alpha_C^2 \frac{(\alpha - t)^2}{(1 - t\alpha)^2} \quad (1.10)$$

As shown in Fig. 1.10, several parameters can be used to describe the characteristics of MRRs, including the free spectral range (FSR), the full width at half maximum (FWHM) (or the 3 dB bandwidth of the resonance), and the quality factor (Q factor).

The FSR can be expressed as [37]

$$FSR \approx \frac{\lambda^2}{n_g L} \quad (1.11)$$

where λ is the wavelength in vacuum, L is the ring cavity length, n_g is the ring waveguide group index.

Figure 1.10: Normalized transmission of an all-pass ring resonator.

The corresponding Q is given by

$$Q = \frac{\lambda}{FWHM} \approx \frac{\pi n_g L}{\lambda} \frac{\sqrt{\alpha}}{1 - \alpha t} \quad (1.12)$$

Both Q and FSR are related to the total length of the ring cavity, as well as the operating wavelength.

1.3 Silicon Photonics Applications

1.3.1 Optical Sensing

Followed by the investigation of numerous photonics device designs, this thesis identifies the potential applications of the devices. The first application is the label-free evanescent field sensing. Because of the high refractive index of silicon, the optical modal field is strongly localized near the waveguide surface, resulting in a high response to surface perturbations.

The sensing principle of the silicon waveguide-based sensors is illustrated in Fig. 1.11, where surface responses can be translated to a shift in the resonant wavelength. Such a shift can be a result of either the surface covering of the sensing media or the bulk index change. The cumulative optical phase delay $\Delta\theta$ in the waveguide is proportional to the waveguide effective index perturbation Δn_{eff} caused by the sensing media, and the interaction length L_w between the sensing media and the waveguide [40]. The phase delay can be expressed as:

$$\Delta\theta = \frac{2\pi}{\lambda} \Delta n_{eff} L_w \quad (1.13)$$

where λ is the wavelength in vacuum.

For the ease of characterization, the optical phase delay of waveguides is typically converted to the resonance wavelength shift $\Delta\lambda$, as shown in Fig. 1.11:

$$\Delta\lambda = \frac{L_r}{m} \Delta n_{eff} \quad (1.14)$$

where L_r is the round trip length and m is the cavity mode order. A change of the refractive index of the cavity's environment shifts the resonance spectrum.

Highly compact SOI sensor arrays are readily manufacturable using standard CMOS processing. In 2006, Densmore et al. [5] demonstrated the first SOI evanescent field sensor using wire waveguide. In this design, an MZI sensor was fabricated on a unibond SOI wafer with a silicon core thickness of 260 nm and a buried silicon dioxide of 2 μm . A single-mode photonic wire waveguide of 260 nm $\times$ 450 nm was

used as the sensing waveguide. In 2007, De Vos *et al.* [41] reported a biosensor based on an MRR structure. Thanks to the high Q-factor of the MRR, this device can sense low amounts of analyte through the resonance wavelength shift induced by the surrounding changes of the cavity. In order to further improve the sensitivity of the silicon photonic sensor, Xu *et al.* [40] illustrated folded waveguide ring resonators for biomolecular sensing. The folded spiral path geometry effectively increases the ring cavity length to 1.2 mm within a 150 μm diameter sensor area, thus further enhancing the detection sensitivity.

The sensitivity of the silicon waveguide-based sensors is typically evaluated by two factors: the bulk sensing sensitivity S_b and the surface sensing sensitivity S_s :

$$S_b = \frac{\partial n_{eff}}{\partial n_c} \quad (1.15)$$

$$S_s = \frac{\partial n_{eff}}{\partial t} \quad (1.16)$$

where n_c is the refractive index of the sensing medium, and t is the thickness of the adsorbed molecular layer [43]. In order to enhance the waveguide bulk and surface sensing sensitivities S_b and S_s , slot waveguides and SWG waveguides are recently proposed [43]. However, temperature dependence of silicon waveguides is one obstacle to the development of viable commercial integrated photonic circuits for sensing applications. The temperature dependence is caused by the comparatively high thermo-optical (TO) material coefficient of silicon [44]. In order to cancel the effect of sensor temperature fluctuations, a double-ring configuration has been proposed [45]. The sensing ring is exposed to the biomaterial under test, while a reference ring provides a temperature-insensitive reference to the sensing measurements. In this thesis, temperature-insensitive (or athermal) configuration using double-ring resonators with a vertically coupled structure will be discussed in Chapter 4.

Figure 1.11: (a) Schematic diagram illustrating the principle of microring resonator (MRR) biosensing: as the sensing molecular target binds to the MRR, the resonant wavelength shifts with $\Delta\lambda$ shown in a representative transmission spectrum. (b) Top-view scanning electron micrograph image of a microring resonator [42].

1.3.2 Polarization Management

Besides the sensing application mentioned in the above Section 1.3.1, silicon photonics is ideal for optical communication applications. To achieve long-haul and high-speed optical communication, polarization management is very important for silicon photonic integrated circuits [46], due to the large difference in the effective indices of the fundamental TE and TM modes in a typical silicon waveguide. For example, the index difference is nearly 0.7 for a silicon waveguide with a dimension of 450 nm $\times$ 220 nm. Various polarization handling components have been reported including polarizers, polarization beam splitters (PBSs) and polarization rotators (PRs).

Polarizers (Fig. 1.12), blocking all unwanted polarization while passing one single

polarization, are a simple yet satisfactory approach to circumvent the polarization dependence of silicon waveguides. Various TE-pass or TM-pass polarizers have been reported by using photonic crystal structures [47], pure silicon waveguides [48, 49] and hybrid plasmonic waveguides [50], to name a few.

Figure 1.12: Schematic of a TE-pass polarizer. Only TE mode passes through the device while the TM mode is blocked.

Polarization-diversity technology, combining PBSs and PRs, is another attractive solution to eliminate the polarization sensitivity in silicon photonic wire waveguides [51]. A PBS enables polarization splitting while a PR provides rotation of a given polarization. As shown in Fig. 1.13, the basic principle of a polarization diversity circuit is that any arbitrary input polarization light is first split into the two orthogonal polarizations (i.e., TE and TM modes) by a PBS, followed by rotating polarization (e.g., TM mode) 90° by using a PR. After being processed by two identical photonic integrated circuits (PICs), the two identical output polarizations are expected. One of the polarizations is then rotated 90° by using a second PR. Finally, the two orthogonal polarizations are then combined by a PBS. PBSs and PRs are the essential elements in a polarization diversity circuit. In addition, as shown in the following Section 1.3.3, they can be used for polarization division multiplexing.

Typically, polarization beam splitting can be achieved by MMI couplers, DCs, and MZIs. The length of the MMI-based PBS is chosen to be a common integer multiple of the self-imaging lengths for the TE and TM polarizations, which is usually long on the order of millimeters because the self-imaging length difference between the two polarizations in the MMI section is small. In this aspect, DCs are a better choice for PBSs because of its simplicity and compact size.

Figure 1.13: Schematic of a polarization diversity scheme. Arrows represent the orientation of the electric field, i.e., TE and TM polarizations [51].

Polarization rotation is realized only when the optical axis of the silicon waveguide is rotated. In the past, the rotation has been achieved by introducing geometrical anisotropy in the silicon waveguide structure. There are two types of basic polarization rotation principles: mode-coupling [52] and mode-evolution [53, 54]. Mode-coupling structures require phase matching and precisely tuned coupling, which are sensitive to fabrication variations and are wavelength dependent. Mode-evolution structures, on the other hand, rotate the principal axis of the structure and the polarization state of the fundamental mode in unison along the transition, allowing more relaxed fabrication and broader bandwidth performance.

A polarization splitter-rotator (PSR), enabling polarization splitting and rotation simultaneously, is promising for ultra-compact polarization diversity circuits. PSRs based on asymmetrical directional couplers have been proposed [33]. Another interesting PSR design combines one adiabatic tapered TM_0 -to- TE_1 polarization converter and one TE_1 -to- TE_0 mode converter [55–57].

Key performance parameters of the polarizer, the PR or the PSR are insertion loss, extinction ratio, and bandwidth. It is also necessary to take into account the device footprint and fabrication tolerances. In addition, polarization conversion efficiency

(PCE) is a crucial performance parameter to evaluate the efficiency of the polarization rotation in the PR or the PSR. For the TM-to-TE conversion, the polarization conversion efficiency can be defined as:

$$PCE = 10\log_{10}\left(\frac{P_{TE}^{out}}{P_{TM}^{in}}\right), \quad (1.17)$$

while the extinction ratio can be expressed as:

$$ER = 10\log_{10}\left(\frac{P_{TE}^{out}}{P_{TM}^{out}}\right), \quad (1.18)$$

where P_{TM}^{in} , P_{TM}^{out} and P_{TE}^{out} are the power of the input TM mode, the output TM mode and the output TE, respectively, given a TM input. Usually, the better PCE is, the higher ER is.

1.3.3 Mode Division Multiplexing

Polarizers and polarization diversity approach presented in Section 1.3.2 are crucial for managing the polarization dependence in a circuit that supports only single mode propagation. With the use of multimode waveguides or fibers, mode division multiplexing (MDM) technology is an alternative to improve the optical link capacity [58], attracting applications for long-haul fiber communications. Multimode waveguides enable modulation into different modes by using a single wavelength. Combining with other multiplexing schemes, such as wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) [59], the MDM technology can further improve the total optical capacity up to Peta-bit/s [60]. Figure 1.14 illustrates a simple MDM system where light from an on-chip (or off-chip) laser diode is split into $2N$ channels by a power splitter. Two orthogonal polarizations can be used simultaneously in combination with a polarization rotator array. In each channel, light carries signals independently through a modulator. Finally, the $2N$ channels are combined by the mode multiplexer to the multimode bus waveguide, which supports $2N$ modes (N TE modes and N TM modes). At the receiver end, the $2N$ modes get distributed to $2N$ separate single channels by mode demultiplexers, and received by

$2N$ photodetectors.

Figure 1.14: Schematic configuration of a multimode division multiplexing system link with two polarizations.

In a MDM system, the design of mode (de)multiplexers to handle higher-order modes is critical. Various mode (de)multiplexers designs have been proposed, such as asymmetrical directional couplers (ADCs), adiabatic couplers, asymmetrical Y-splitters and MMI couplers. Although the ADC using a parallel DC structure in [61] is compact, the fabrication tolerance is tight and the ADC has a limited operation bandwidth. ADC-based mode (de)multiplexers using tapered DC structures are more broadband and the fabrication tolerance is relieved at the expense of footprint [62]. Mode (de)multiplexers using asymmetrical Y-splitters in [63] have low crosstalk (< -30 dB), the drawback is the large footprint and the limited fabrication tolerance. The mode (de)multiplexer based on an MMI structure in [64] is broadband and relatively fabrication tolerant; however, it suffers from the inability to multiplex more than two modes. To date, new designs of mode (de)multiplexers is still of great interest to the optical research community. In this thesis, a taper-etched DC design is proposed to implement a two-mode (de)multiplexer, which is described in detail in Chapter 6.

Similar to the performance parameters for a PSR/PR/polarizer, figures of merit of mode (de)multiplexers are insertion loss, mode conversion efficiency, modal crosstalk, and bandwidth. Footprint and fabrication tolerance are also considered in the design. An ideal mode (de)multiplexer has a high mode conversion efficiency, low modal crosstalk, low insertion loss, broad bandwidth, small footprint and large fabrication tolerance.

1.4 Thesis Objectives

As mentioned above, silicon photonics is a promising candidate for photonic circuit integration. Several milestones in silicon photonics have been reached, namely, efficient fiber-to-chip coupling, low loss waveguide, silicon-based lasers, modulators and detectors. However, optimization of the existing photonic components and expansion of photonic functionalities are necessary for the ultimate commercialization of silicon photonics. The goal of the thesis is to design various novel silicon devices with different techniques and structures. The key design consideration is the fabrication tolerance. By using novel structures, the fabrication tolerances of the designed devices are improved. Some of the designed devices are fabricated for experimental verification using services from commercial silicon photonics foundries. The designed silicon photonic devices are targeted to sensing applications, as well as polarization and mode manipulations in optical communication applications.

In particular, this thesis explores the following silicon photonic devices and technologies:

1. Use of the LOCal Oxidation of Silicon (LOCOS) lithography technique to define submicron silicon wire straight and bent waveguides.
2. Vertically coupled double-ring sensors to provide temperature-insensitive measurements for sensing applications. The vertical stack is designed for the ease of fabrication as the coupling gap can be simply controlled by the deposition.
3. MMI-coupled slot microring resonator (MRR) and Mach-Zehnder interferometer (MZI) racetrack microring sensors. MMI coupler is designed to relax the fabrication tolerance for the coupling region of the slot MRR.
4. Polarization splitter and rotators (PSRs) using subwavelength grating (SWG) waveguides. The SWG waveguide is introduced to improve the fabrication tolerance of the waveguide widths.
5. TE-pass polarizers using SWG waveguides. By adjusting the equivalent material index of the SWG waveguide, the polarizer is compact and fabrication tolerant.

6. Polarization rotators (PRs) using asymmetric amorphous silicon overlayers. The asymmetric amorphous silicon overlayer is designed to relax the high-precision lithographic alignment as well as to achieve a fabrication tolerant design.

7. Polarization splitter and rotators (PSRs) using taper-etched directional couplers. The taper-etched structure is designed to improve the fabrication tolerance of the PSR.

8. Two-mode (de)multiplexers using taper-etched directional couplers. Inspired by the above PSR, the taper-etched structure is designed to improve the fabrication tolerance of the (de)multiplexer as well.

1.5 Thesis Organization

The thesis is organized as follows:

Chapter 2 introduces numerical and experimental methods employed in the design, fabrication and measurements of the silicon devices. The wave equations derived from Maxwell's equations provide basic guidelines in designing silicon photonic devices. However, it is almost impossible to obtain analytical solutions to the wave equations for devices of practical interest. Therefore, numerical methods such as the finite element method (FEM) and the finite difference method (FDM) are used to calculate the effective indices and the electromagnetic profiles of the propagating eigenmodes, while the eigenmode expansion (EME) and the finite difference time domain (FDTD) methods are used to examine the propagation performance of the eigenmodes in the designed silicon devices. Standard CMOS techniques are used to fabricate a selective collection of devices. LOCOS, deep ultraviolet (DUV) and electron beam (e-beam) lithographies are applied to define submicron silicon waveguides and devices in this thesis. All measurements are done by using in-house experimental setups.

Chapter 3 demonstrates the fabrication of submicron silicon wire waveguides, in both the straight and bent configuration, using the CMOS-compatible LOCOS technique. The LOCOS method utilizes a protective stack, consisting of a thin thermal pad oxide layer overlaid by a thicker silicon nitride, to mask the waveguides during

the growth process of the field oxide. Here, we use the cut-back method to directly measure the propagation loss, and the serpentine pattern to measure the bending loss of the LOCOS wire waveguides. Unlike most of the submicron-sized waveguides reported in literature, LOCOS uses only the basic optical lithography technique to pattern the waveguides, to save fabrication time and cost. A comprehensive study of the propagation loss and bending loss will be presented.

Chapter 4 discusses several MRR-based designs. The first device is a vertically coupled double-ring structure, where the temperature fluctuations in sensing application can be effectively eliminated by the resonant wavelength shift correction provided by the reference ring. The second device is a silicon slot MRR employing MMI couplers. The novelty lies on the use of the MMI couplers for the slotted ring and bus waveguides. Next, a slotted MZI-coupled MRR is discussed, where the device consists of a ring and a feedback line that connects the two access waveguides to form one MZI arm. The coupling ratio can be adjusted by changing the length difference between the two MZI arms. The MZI-coupled MRR has only one major resonance wavelength in a large wavelength span, which is useful for large measurement range covering the refractive index change of various gases or liquids. The last device is an all-optical Raman switch using a ring-assisted MZI (RAMZI) optical structure. In this Raman switch, the optical loss induced by the inverse Raman scattering (IRS) at the anti-Stokes wavelength has a bandwidth much narrower than the free spectral range (FSR) of a typical ring cavity, but wider than the resonance linewidth. Such a narrow bandwidth allows an independent modulation of a specific single resonance while leaving adjacent resonances undisturbed by simply changing the control light wavelength. The RAMZI switch works as long as the coupling between the MRR and the MZI arm is over-coupled.

Chapter 5 proposes SWG-based photonic devices. SWG is formed by submicron-sized silicon segments spaced periodically at a pitch substantially smaller than the wavelength of light propagating through the structure. SWG waveguides have the unique ability to engineer their modal effective indices. The SWG is first applied to the design of a PSR. The tuning of the effective index of the SWG waveguide significantly improve the width fabrication tolerance of a PSR. Next, the SWG is applied to realize a compact TE-pass polarizer experimentally, where the mode cut-off condition of the SWG waveguide is again manipulated by adjusting the effective

index of the SWG waveguide.

In Chapter 6, tapered structures are used to provide polarization and mode management. Firstly, a PR based on the mode evolution principle is discussed, utilizing an amorphous silicon (a-Si) overlayer. The a-Si layer is etched to obtain a strip of a constant width, aligned at a tilted angle relative to the silicon access waveguide. The varying a-Si width intercepting the access waveguide will efficiently rotate the polarization axis of the waveguide mode. Secondly, a taper-etched DC is designed to achieve polarization splitting and rotating simultaneously. The taper-etched waveguide can break both the horizontal and vertical symmetries of the waveguide, allowing for a high polarization conversion efficiency. Inspired by the versatility of the taper-etched DC, the structure is utilized to realize a fabrication tolerant and broadband two-mode (de)multiplexer.

Chapter 7 summarizes the significant contributions of the thesis including the design and experimental demonstration of various silicon waveguide-based devices.

Chapter 8 presents future work in the sensing, polarization management, and mode division multiplexing.

List of References

- [1] R. Soref, “The past, present, and future of silicon photonics,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 6, pp. 1678–1687, 2006.
- [2] M. Paniccia and N. Photonics, “Integrating silicon photonics,” *Nature Photonics*, vol. 4, pp. 498–499, Aug. 2010.
- [3] W. N. Ye and Y. Xiong, “Review of silicon photonics: history and recent advances,” *Journal of Modern Optics*, vol. 60, pp. 1299–1320, Sept. 2013.
- [4] W. Bogaerts, R. Baets, and P. Dumon, “Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology,” *Journal of Lightwave Technology*, vol. 23, no. 1, pp. 401–412, 2005.
- [5] A. Densmore, D. Xu, P. Waldron, S. Janz, P. Cheben, J. Lapointe, A. Delâge, B. Lamontagne, J. H. Schmid, and E. Post, “A silicon-on-insulator photonic wire based evanescent field sensor,” *IEEE Photonics Technology Letters*, vol. 18, no. 23, pp. 2520–2522, 2006.
- [6] Y. Vlasov and S. McNab, “Losses in single-mode silicon-on-insulator strip waveguides and bends,” *Optics Express*, vol. 12, pp. 1622–1631, Apr. 2004.
- [7] D. J. Thomson, F. Y. Gardes, J.-M. Fedeli, S. Zlatanovic, Y. Hu, B. Ping, P. Kuo, S. Member, E. Myslivets, A. Member, N. Alic, S. Radic, S. Member, G. Z. Mashanovich, and G. T. Reed, “50-Gb/s silicon optical modulator,” *IEEE Photonics Technology Letters*, vol. 24, no. 4, pp. 234–236, 2012.
- [8] T. Baba, S. Akiyama, M. Imai, N. Hirayama, H. Takahashi, Y. Noguchi, T. Horikawa, and T. Usuki, “50-Gb/s ring-resonator-based silicon modulator,” *Optics Express*, vol. 21, no. 10, pp. 11869–11876, 2013.
- [9] X. Tu, T.-y. Liow, J. Song, X. Luo, Q. Fang, M. Yu, and G.-q. Lo, “50-Gb/s silicon optical modulator with traveling-wave electrodes,” *Optics Express*, vol. 21, no. 10, pp. 12776–12782, 2013.
- [10] J. Michel, J. Liu, and L. Kimerling, “High-performance Ge-on-Si photodetectors,” *Nature Photonics*, vol. 4, no. 8, pp. 527–534, 2010.

- [11] L. Vivien, A. Polzer, D. Marris-Morini, J. Osmond, J. M. Hartmann, P. Crozat, E. Cassan, C. Kopp, H. Zimmermann, and J. M. Fédéli, “Zero-bias 40Gbit/s germanium waveguide photodetector on silicon,” *Optics Express*, vol. 20, pp. 1096–1101, Jan. 2012.
- [12] J. Justice, C. Bower, and M. Meitl, “Wafer-scale integration of group III-V lasers on silicon using transfer printing of epitaxial layers,” *Nature Photonics*, vol. 6, pp. 610–614, 2012.
- [13] H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang, and M. Paniccia, “A continuous-wave Raman silicon laser,” *Nature*, vol. 433, pp. 725–728, Feb. 2005.
- [14] G. Z. Mashanovich, G. T. Reed, B. D. Timotijevic, and S. P. Chan, “Silicon photonic waveguides,” in *Silicon Photonics . The State of the Art* (G. T. Reed, ed.), Wiley, 2008.
- [15] O. Boyraz and B. Jalali, “Demonstration of a silicon Raman laser,” *Optics Express*, vol. 12, pp. 5269–5273, Oct. 2004.
- [16] C. A. Barrios, V. R. Almeida, S. Member, S. Member, and R. Panepucci, “Electrooptic modulation of silicon-on-insulator submicrometer-size waveguide devices,” *Journal of Lightwave Technology*, vol. 21, no. 10, pp. 2332–2339, 2003.
- [17] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, “Micrometre-scale silicon electro-optic modulator,” *Nature*, vol. 435, pp. 325–327, May 2005.
- [18] D. Dai, Y. Tang, and J. E. Bowers, “Mode conversion in tapered submicron silicon ridge optical waveguides,” *Optics Express*, vol. 20, pp. 13425–13439, June 2012.
- [19] F. P. Payne and J. P. R. Lacey, “A theoretical analysis of scattering loss from planar optical waveguides,” *Optical and Quantum Electronics*, vol. 26, pp. 977–986, 1994.
- [20] T. Barwicz, H. A. Haus, and L. Fellow, “Three-dimensional analysis of scattering losses due to sidewall roughness in microphotonic waveguides,” *Journal of Lightwave Technology*, vol. 23, no. 9, pp. 2719–2732, 2005.
- [21] K. K. Lee, D. R. Lim, H.-C. Luan, A. Agarwal, J. Foresi, and L. C. Kimerling, “Effect of size and roughness on light transmission in a Si/SiO₂ waveguide: Experiments and model,” *Applied Physics Letters*, vol. 77, no. 11, p. 1617, 2000.
- [22] K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin, and F. Cerrina, “Fabrication of ultralow-loss Si/SiO₂ waveguides by roughness reduction,” *Optics Letters*, vol. 26, pp. 1888–1890, Dec. 2001.
- [23] D. Sparacin, S. Spector, and L. Kimerling, “Silicon waveguide sidewall smoothing by wet chemical oxidation,” *Journal of Lightwave Technology*, vol. 23, pp. 2455–2461, Aug. 2005.
- [24] J. Cardenas, C. B. Poitras, J. T. Robinson, K. Preston, L. Chen, and M. Lipson, “Low loss etchless silicon photonic waveguides,” *Optics Express*, vol. 17, pp. 4752–4757, Mar. 2009.

- [25] N. Sherwood-Droz, A. Gondarenko, and M. Lipson, "Oxidized silicon-on-insulator (OxSOI) from bulk silicon: a new photonic platform," *Optics Express*, vol. 18, pp. 5785–5790, Mar. 2010.
- [26] V. R. Almeida, Q. Xu, C. A. Barrios, and M. Lipson, "Guiding and confining light in void nanostructure," *Optics Letters*, vol. 29, pp. 1209–1211, June 2004.
- [27] P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Delge, S. Janz, G. C. Aers, D.-x. Xu, A. Densmore, and T. J. Hall, "Subwavelength grating periodic structures in silicon-on-insulator : a new type of microphotonic waveguide," *Optics Express*, vol. 18, no. 19, pp. 20251–20262, 2010.
- [28] K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin, and F. Cerrina, "Fabrication of ultralow-loss Si/SiO(2) waveguides by roughness reduction," *Optics Letters*, vol. 26, pp. 1888–1890, Dec. 2001.
- [29] I. Moerman, P. P. V. Daele, and P. M. Demeester, "A Review on fabrication technologies for the monolithic integration of tapers with III-V semiconductor devices," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, no. 6, pp. 1308–1320, 1997.
- [30] H. Zhang, S. Das, Y. Huang, C. Li, S. Chen, H. Zhou, M. Yu, P. Guo-Qiang Lo, and J. T. L. Thong, "Efficient and broadband polarization rotator using horizontal slot waveguide for silicon photonics," *Applied Physics Letters*, vol. 101, no. 2, p. 021105, 2012.
- [31] Y. Ding, L. Liu, C. Peucheret, and H. Ou, "Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler," *Optics Express*, vol. 20, pp. 20021–20027, Aug. 2012.
- [32] D. Dai, J. Wang, and Y. Shi, "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," *Optics Letters*, vol. 38, pp. 1422–1424, May 2013.
- [33] L. Liu, Y. Ding, K. Yvind, and J. M. Hvam, "Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits," *Optics Express*, vol. 19, pp. 12646–12651, June 2011.
- [34] L. Chrostowski and M. Hochberg, "Fundamental building blocks," in *Silicon Photonics Design*, pp. 68–68, Cambridge University Press, 2014.
- [35] L. Soldano and E. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications," *Journal of Lightwave Technology*, vol. 13, pp. 615–627, Apr. 1995.
- [36] A. Ortega-Monux, C. Alonso-Ramos, A. Maese-Novo, R. Halir, L. Zavargo-Peche, D. Prez-Galacho, I. n. Molina-Fernndez, J. G. Wanguemert-Perez, P. Cheben, J. H. Schmid, J. Lapointe, D.-X. Xu, and S. Janz, "An ultra-compact multimode interference coupler with a subwavelength grating slot," *Laser and Photonics Reviews*, vol. 7, no. 2, pp. L12–L15, 2013.

- [37] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. Van Thourhout, and R. Baets, "Silicon microring resonators," *Laser and Photonics Reviews*, vol. 6, pp. 47–73, Jan. 2012.
- [38] D.-X. Xu, A. Densmore, P. Waldron, J. Lapointe, E. Post, A. Delâge, S. Janz, P. Cheben, J. H. Schmid, and B. Lamontagne, "High bandwidth SOI photonic wire ring resonators using MMI couplers," *Optics Express*, vol. 15, no. 6, pp. 3149–3155, 2007.
- [39] A. Yariv, "Critical coupling and its control in optical waveguide-ring resonator systems," *IEEE Photonics Technology Letters*, vol. 14, no. 4, pp. 483–485, 2002.
- [40] D. X. Xu, A. Densmore, A. Delâge, P. Waldron, R. McKinnon, S. Janz, J. Lapointe, G. Lopinski, T. Mischki, E. Post, P. Cheben, and J. H. Schmid, "Folded cavity SOI microring sensors for high sensitivity and real time measurement of biomolecular binding," *Optics Express*, vol. 16, pp. 15137–15148, Sept. 2008.
- [41] K. De Vos, I. Bartolozzi, E. Schacht, P. Bienstman, and R. Baets, "Silicon-on-Insulator microring resonator for sensitive and label-free biosensing," *Optics Express*, vol. 15, pp. 7610–7615, June 2007.
- [42] A. L. Washburn, L. C. Gunn, and R. C. Bailey, "Label-free quantitation of a cancer biomarker in complex media using silicon photonic microring resonators," *Analytical chemistry*, vol. 81, pp. 9499–9506, Nov. 2009.
- [43] J. Gonzalo Wangüemert-Pérez, P. Cheben, A. Ortega-Moñux, C. Alonso-Ramos, D. Pérez-Galacho, R. Halir, I. n. Molina-Fernández, D.-X. Xu, and J. H. Schmid, "Evanescent field waveguide sensing with subwavelength grating structures in silicon-on-insulator," *Optics Letters*, vol. 39, pp. 4442–4425, Aug. 2014.
- [44] W. N. Ye, J. Michel, and L. C. Kimerling, "Athermal high-index-contrast waveguide design," *IEEE Photonics Technology Letters*, vol. 20, pp. 885–887, June 2008.
- [45] D.-X. Xu, M. Vachon, A. Densmore, R. Ma, S. Janz, A. Delâge, J. Lapointe, P. Cheben, J. H. Schmid, E. Post, S. Messaoudène, and J.-M. Fédéli, "Real-time cancellation of temperature induced resonance shifts in SOI wire waveguide ring resonator label-free biosensor arrays," *Optics Express*, vol. 18, pp. 22867–22879, Oct. 2010.
- [46] D. Dai, L. Liu, S. Gao, D.-X. Xu, and S. He, "Polarization management for silicon photonic integrated circuits," *Laser and Photonics Reviews*, vol. 7, pp. 303–328, May 2013.
- [47] Y. Cui, Q. Wu, E. Schonbrun, M. Tinker, J. Lee, and S. Member, "Silicon-based 2-D slab photonic crystal TM polarizer at telecommunication wavelength," *IEEE Photonics Technology Letters*, vol. 20, no. 8, pp. 641–643, 2008.
- [48] Q. Wang, "Ultracompact TM-Pass Silicon Nanophotonic Waveguide Polarizer and Design," *IEEE Photonics Journal*, vol. 2, pp. 49–56, Feb. 2010.

- [49] D. Dai, Z. Wang, N. Julian, and J. E. Bowers, "Compact broadband polarizer based on shallowly-etched silicon-on-insulator ridge optical waveguides," *Optics Express*, vol. 18, no. 26, pp. 27404–27415, 2010.
- [50] M. Z. Alam, J. S. Aitchison, and M. Mojahedi, "Compact and silicon-on-insulator-compatible hybrid plasmonic TE-pass polarizer," *Optics Letters*, vol. 37, pp. 55–57, Jan. 2012.
- [51] T. Barwicz, M. R. Watts, M. A. Popović, P. T. Rakich, L. Socci, F. X. Kärtner, E. P. Ippen, and H. I. Smith, "Polarization-transparent microphotonic devices in the strong confinement limit," *Nature Photonics*, vol. 1, pp. 57–60, Jan. 2007.
- [52] L. Liu, Y. Ding, K. Yvind, and J. r. M. Hvam, "Efficient and compact TE-TM polarization converter built on silicon-on-insulator platform with a simple fabrication process," *Optics Letters*, vol. 36, pp. 1059–1061, Apr. 2011.
- [53] H. Fukuda, K. Yamada, T. Tsuchizawa, T. Watanabe, H. Shinojima, and S.-i. Itabashi, "Polarization rotator based on silicon wire waveguides," *Optics Express*, vol. 16, pp. 2628–2635, Feb. 2008.
- [54] L. Chen, C. R. Doerr, and Y.-K. Chen, "Compact polarization rotator on silicon for polarization-diversified circuits," *Optics Letters*, vol. 36, pp. 469–471, Feb. 2011.
- [55] Y. Ding, H. Ou, and C. Peucheret, "Wideband polarization splitter and rotator with large fabrication tolerance and simple fabrication process," *Optics Letters*, vol. 38, pp. 1227–1229, Apr. 2013.
- [56] J. Wang, B. Niu, Z. Sheng, A. Wu, W. Li, X. Wang, S. Zou, M. Qi, and F. Gan, "Novel ultra-broadband polarization splitter-rotator based on mode-evolution tapers and a mode-sorting asymmetric Y-junction," *Optics Express*, vol. 22, no. 11, pp. 13565–13571, 2014.
- [57] W. D. Sacher, T. Barwicz, B. J. F. Taylor, and J. K. S. Poon, "Polarization rotator-splitters in standard active silicon photonics platforms," *Optics Express*, vol. 22, pp. 3777–3786, Feb. 2014.
- [58] P. J. Winzer, "Energy-Efficient Optical Transport Capacity Scaling Through Spatial Multiplexing," *IEEE Photonics Technology Letters*, vol. 23, no. 13, pp. 851–853, 2011.
- [59] J. Wang, S. He, and D. Dai, "On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode- and polarization-division-multiplexing," *Laser Photonics Reviews*, vol. 8, pp. L18–L22, Mar. 2014.
- [60] D. Dai, J. Wang, and Y. Shi, "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," *Optics Letters*, vol. 38, pp. 1422–1424, May 2013.
- [61] D. Dai, J. Wang, and Y. Shi, "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," *Optics Letters*, vol. 38, pp. 1422–1424, May 2013.

- [62] Y. Ding, J. Xu, F. D. Ros, B. Huang, H. Ou, and C. Peucheret, “On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer,” *Optics Express*, vol. 21, no. 8, pp. 10376–10382, 2013.
- [63] S. Martínez-Garaot, S.-Y. Tseng, and J. G. Muga, “Compact and high conversion efficiency mode-sorting asymmetric Y junction using shortcuts to adiabaticity,” *Optics Letters*, vol. 39, pp. 2306–2309, Apr. 2014.
- [64] Y. Li, C. Li, B. Cheng, and C. Xue, “Compact two-mode (de) multiplexer based on symmetric Y-junction and Multimode interference waveguides,” *Optics Express*, vol. 22, no. 5, pp. 5781–5786, 2014.

Chapter 2

Methods

In order to design silicon photonic devices, we first need numerical calculations and simulations based on mathematical models for analysis and optimization. For simulations predicting the outcome of a fabrication process, a thermal oxidation model was used to simulate the cross-section profiles of a silicon waveguide using the local oxidation of silicon (LOCOS) technique. For device-level simulations, Maxwell's equations and corresponding Helmholtz wave equations are the basis to analyze the optical performance of the designed devices. The details about numerical models and calculations are discussed in Sections 2.1 and 2.2.

The LOCOS waveguides were fabricated at the Carleton University MicroFabrication Facility; while the OpSIS and IME foundry services as well as the Fabrication Facility at the National Research Council (NRC) Canada were used to fabricate silicon devices with the feature size on the scale of hundreds of nanometers. Section 2.3 describes the fabrication processes in detail. Finally, fiber-to-waveguide couplers and measurement setups are shown in Sections 2.4 and 2.5.

2.1 Thermal Oxidation Model

Oxidation is a process which converts silicon into silicon dioxide. The chemical reaction of silicon and oxygen starts at room temperature but stops after a very thin

native oxide film (~ 15 nm). In order to form high quality silicon oxide with a specific thickness, a wafer must be sent to a furnace with oxygen or water vapor at an elevated temperature. The ability of silicon to form high quality silicon dioxide is an important reason that silicon is still the dominating material in integrated circuits fabrication.

It has been proven by a number of experiments that thermal oxidation of silicon can be described by diffusion of the oxidant through the growing oxide. The oxidation reaction itself takes place at the oxide-silicon interface. During oxidation, the oxide-silicon interface moves into the silicon material as the silicon is oxidized. Considering the densities of silicon and SiO_2 , a part of the oxide layer grows into the silicon substrate. The remaining part grows on top of the silicon, resulting in a non-planar surface if oxidation is localized.

The general linear parabolic model (often referred to as the Deal-Grove model) to simulate the thermal oxidation process was developed by Deal and Grove [1]. The oxide grows by indiffusion of the oxidant species to the oxide/silicon interface where simple chemical reactions happen as follows:

There are three sequential steps in the oxidation process. The first represents the transport of the oxidant in the gas phase to the oxide surface. This adsorption of oxidant can be described as

$$F_1 = h(C^* - C_0) \quad (2.3)$$

where h is the gas-phase transport coefficient, C^* is the equilibrium concentration of the oxidants in the surrounding gas atmosphere, C_0 the concentration of oxidants at the oxide surface, and $(C^* - C_0)$ is the oxidant concentration difference between the main gas flow and the oxide surface. The process represented by F_1 is the gas phase

diffusion of the oxidant species through the boundary to a solid object placed in a gas.

Flux F_2 represents the diffusion of the oxidant through the oxide to the Si/SiO₂ interface, and can be expressed as

$$F_2 = D \left(\frac{C_0 - C_S}{x_0} \right) \quad (2.4)$$

where D is the oxidant diffusivity in the oxide, C_0 and C_S are the concentrations at the two interfaces, and x_0 is the oxide thickness. The oxidant concentration falls off linearly through the oxide.

Figure 2.1: Oxidant flux (F) from the gas phase to the silicon surface during thermal oxidation [1].

The third part of the oxidation process is the reaction at the Si/SiO₂ interface, and can be described as

$$F_3 = k_S C_S \quad (2.5)$$

The rate at which this reaction takes place should be proportional to the oxidant

concentration at the interface C_S . K_S is the interface reaction rate constant. Under steady-state conditions, $F_1 = F_2 = F_3$. The central idea of the Deal-Grove model is graphically illustrated in Fig. 2.1, while the Deal-Grove model in the commercial software package TSUPREM-4 was used in this thesis to simulate the cross-section profiles of the waveguide using thermal oxidation.

2.2 Maxwell's Equations

In the area of photonics, Maxwell's equations (2.6)-(2.9) are an accurate model to describe the electromagnetic behaviors.

$$\nabla \cdot \vec{D} = \rho \quad (2.6)$$

$$\nabla \cdot \vec{B} = 0 \quad (2.7)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2.8)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (2.9)$$

Here, ρ is the charge density, $\vec{J}$ is the current density, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic induction, $\vec{D}$ is the electric displacement field, and $\vec{H}$ is the applied magnetic field.

In photonic application, we assume a source-free medium, i.e., $\rho = 0$ and $\vec{J} = 0$. The constitutive relations of linear and homogeneous materials are

$$\vec{D} = \epsilon \vec{E} \quad (2.10)$$

$$\vec{B} = \mu \vec{H} \quad (2.11)$$

where ε is the electric permittivity of the medium, μ is the magnetic permeability of the medium.

Combining Eqs.(2.6)-(2.11), we can construct the Helmholtz wave equations for $\vec{E}$ and $\vec{H}$.

$$\nabla^2 \vec{E} - \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (2.12)$$

$$\nabla^2 \vec{H} - \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0 \quad (2.13)$$

2.2.1 Plane Waves

In the homogeneous medium, the solutions of the wave equations (2.12)-(2.13) are simply plane waves, which can taking the following form:

$$\vec{E}(\vec{r}, t) = \vec{E}_0 e^{i(\omega t - \vec{k} \cdot \vec{r})} \quad (2.14)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_0 e^{i(\omega t - \vec{k} \cdot \vec{r})} \quad (2.15)$$

where $|\vec{E}_0|$ and $|\vec{H}_0|$ are the amplitudes of the electric and magnetic fields, respectively. The magnitude k of the wavevector $\vec{k}$ is related to the angular frequency ω by

$$k = \omega \sqrt{\mu\varepsilon} = \omega \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} k_0 = n k_0 \quad (2.16)$$

where ε_0 and μ_0 are the electric permittivity and the magnetic permeability in the free space. n is the refractive index of the medium expressed by

$$n = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} \quad (2.17)$$

Most transparent media in optics are nonmagnetic and have a magnetic permeability μ_0 . So, the refractive index of the medium can be simplified as

$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \quad (2.18)$$

2.2.2 Boundary Conditions

In order to confine the light propagation in a specific domain, the waveguide consisting of media with different refractive indices are required. The characteristics of the light propagation and the corresponding electric and magnetic fields are determined by the boundary between media with different refractive indices. In optics, we assume that there is no surface charge and surface currents. The reflection and transmission of light at a boundary is governed by the boundary conditions for $\vec{E}$ and $\vec{H}$, given by

$$\hat{n} \cdot (\varepsilon_2 \vec{E}_2 - \varepsilon_1 \vec{E}_1) = 0 \quad (2.19)$$

$$\hat{n} \times (\vec{E}_2 - \vec{E}_1) = 0 \quad (2.20)$$

$$\hat{n} \cdot (\mu_2 \vec{H}_2 - \mu_1 \vec{H}_1) = 0 \quad (2.21)$$

$$\hat{n} \times (\vec{H}_2 - \vec{H}_1) = 0 \quad (2.22)$$

where $\hat{n}$ is the normal vector from medium 2 to medium 1.

From Eqs. (2.19) and (2.21), the normal components of the electric and magnetic fields $\vec{E}$ and $\vec{H}$ conserve the following relationships:

$$\varepsilon_1 E_{1\perp} = \varepsilon_2 E_{2\perp} \quad (2.23)$$

$$\mu_1 H_{1\perp} = \mu_2 H_{2\perp} \quad (2.24)$$

From Eqs. (2.20) and (2.22), the tangential components of the electric and magnetic fields $\vec{E}$ and $\vec{H}$ conserve the following relationships:

$$E_{1\parallel} = E_{2\parallel} \quad (2.25)$$

$$H_{1\parallel} = H_{2\parallel} \quad (2.26)$$

Therefore, in optics, normal components of $\vec{D}$ ($\vec{D} = \epsilon\vec{E}$) and $\vec{B}$ ($\vec{B} = \mu\vec{H}$) are continuous across the interface while the tangential components of $\vec{E}$ and $\vec{H}$ are continuous across the surface.

2.2.3 Slab Waveguides

In the simplest slab waveguide consisting of a thin dielectric layer sandwiched by two semi-infinite bounding media (clad), the analytical solutions of the wave equations (2.12)-(2.13) can still be obtained.

As shown in Fig. 2.2, the step-index slab waveguide consists of a thin dielectric layer with thickness h and index n_2 sandwiched by two semi-infinite bounding media with indices n_1 and n_3 . In addition, we assume that $n_2 > n_3 > n_1$. The slab waveguide introduces one-dimensional confinement of light along the x-axis.

Figure 2.2: (a) Slab waveguide; (b) refractive index profile of slab waveguide.

Since the solutions of the wave equations (2.12)-(2.13) are plane waves in homogeneous media, the solutions for the slab waveguide combines the plane wave solutions for each segment with the boundary conditions Eqs. (2.19)-(2.22) at the interfaces

to ensure the continuity of the wavefunction. Since the whole structure is homogeneous along the z axis (the propagation direction), solutions to the wave equations (2.12)-(2.13) in the slab waveguide can be taken as

$$\vec{E}(\vec{r}, t) = \vec{E}_m(x, y)e^{i(\omega t - \beta z)} \quad (2.27)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_m(x, y)e^{i(\omega t - \beta z)} \quad (2.28)$$

where β is the z component of the wavevector $\vec{k}$ or the propagation constant, and $\vec{E}_m(x, y)$ and $\vec{H}_m(x, y)$ are wavefunctions of the guided modes, with the mode number m .

By substituting Eqs. (2.27)-(2.28) into the wave equations (2.12)-(2.13), we obtain the wave equation for the transverse electric (TE) and the transverse magnetic (TM) modes in the slab waveguide as

$$\frac{d^2 E_y}{dx^2} + (k_0^2 n^2 - \beta^2) E_y = 0 \quad (2.29)$$

$$\frac{d^2 H_y}{dx^2} + (k_0^2 n^2 - \beta^2) H_y = 0 \quad (2.30)$$

For the TE mode, $\vec{E}_m(x, y) = E_y \vec{u}_y = E_m(x) \vec{u}_y$, where $\vec{u}_y$ is unity vector parallel with y -axis; for the TM mode, $\vec{H}_m(x, y) = H_y \vec{u}_y = H_m(x) \vec{u}_y$.

We now discuss the solution to the wave equation of the TE mode in the slab waveguide. The process is similar for the TM mode.

By using the boundary conditions Eqs. (2.19) and (2.20), the eigenfunction $E_m(x)$ can be expressed as

$$E_m(x) = Ae^{-qx}, x \geq 0 \quad (2.31)$$

$$E_m(x) = A[\cos(tx) - \frac{q}{t} \sin(tx)], 0 \geq x \geq -h \quad (2.32)$$

$$E_m(x) = A[\cos(th) + \frac{q}{t} \sin(th)]e^{p(x+h)}, -h \geq x \quad (2.33)$$

where A is the coefficient related to the power carried in the waveguide. The coefficients t , p and q are related to the propagation constant β by

$$t^2 = k_0^2 n_2^2 - \beta^2 \quad (2.34)$$

$$q^2 = \beta^2 - k_0^2 n_1^2 \quad (2.35)$$

$$p^2 = \beta^2 - k_0^2 n_3^2 \quad (2.36)$$

In addition, the mode condition determining the propagation constant β (the eigenvalue) is

$$\tan(th) = \frac{t(p+q)}{t^2 - pq} \quad (2.37)$$

Eq. (2.37) has only a finite number of solutions. Therefore, the spectrum of β for guided mode is discrete. For a sufficiently large thickness h , Eq. (2.37) has several solutions and the slab waveguide is multimode. The electric field distributions for the first four TE modes in a slab waveguide is illustrated in Fig. 2.3. For the TE _{m} mode, the m is the mode number. By decreasing the thickness h , the slab waveguide may support only one mode, the slab waveguide is a single mode waveguide. If the thickness h still decreases, there is a certain value of h for which firstly the coefficient $p = 0$ since $n_3 > n_1$. Therefore, the slab waveguide reaches the mode cut-off condition. When the thickness h further decreases, there is no guided mode in the slab waveguide. Under this circumstance, the radiation modes in the waveguide will leak away into

the upper and lower clads. These radiation modes are called leaky modes as well. There exists an infinite and continuous number of solutions for leaky modes to Eq. (2.37).

Figure 2.3: Electric field distribution for the first four TE modes in a slab waveguide.

For more complex waveguides such as rib, strip and buried waveguides, as mentioned in Section 1.2.1, there is no analytical solutions to the wave equations directly. A variety of numerical methods have been developed to approximate Maxwell's equations and wave equations. The finite element, finite difference, finite difference time domain and eigenmode expansion methods have been used in this thesis. Each method has its own advantages and disadvantages. The finite difference method (FDM) and the finite element method (FEM) were mainly used to simulate mode profiles (eigenfunctions) of the waveguide cross-section and to calculate the corresponding effective indices (eigenvalues) of modes. Generally, the FEM and FDM have comparable accuracy and the choice mainly depends on personal preferences and the availability of the software packages. Both the eigenmode expansion (EME) and the finite difference time domain (FDTD) methods were used to simulate the light propagation in silicon

devices. The EME method is more efficient for long waveguides while the FDTD method is more accurate (but time consuming) for complicated photonic structures.

2.2.4 Finite Difference Method (FDM)

The FDM uses finite difference equations to approximate derivatives of the Maxwell's equations. For a given, arbitrary waveguide structure with an index distribution $n(x, y)$, the guided wave has the same form as Eqs (2.27) and (2.28) since the whole structure is homogeneous along the z axis. By substituting Eqs. (2.27)-(2.28) into the wave equations (2.12)-(2.13), we obtain the wave equations for the electric and magnetic fields (mode profiles) in the given, arbitrary waveguide as

$$\left(\frac{\partial^2 E_m(x, y)}{\partial x^2} + \frac{\partial^2 E_m(x, y)}{\partial y^2}\right) + (k_0^2 n(x, y)^2 - \beta_m^2) E_m(x, y) = 0 \quad (2.38)$$

$$\left(\frac{\partial^2 H_m(x, y)}{\partial x^2} + \frac{\partial^2 H_m(x, y)}{\partial y^2}\right) + (k_0^2 n(x, y)^2 - \beta_m^2) H_m(x, y) = 0 \quad (2.39)$$

where $E_m(x, y)$ and $H_m(x, y)$ are the eigenfunctions for the electric and magnetic fields, respectively with the mode number m . The propagation constant β_m is the corresponding eigenvalue.

The wave equations (2.38) and (2.39) in combination with the boundary conditions Eqs. (2.19)-(2.26) are the basis of the FDM and the finite element method (FEM).

The FDM combines function values at a finite grid of points to approximate the derivatives in the wave equations (2.38) and (2.39) [2]. The function values at each grid point are approximated from the neighboring values by using the Taylor's series. The FDM uses a topologically square network of lines to construct the discretization of the wave equations. This is a potential bottleneck of the method when handling complex geometries in multiple dimensions.

In this thesis, the FDM in the commercial software FIMMWAVE was used to analyze the mode profiles and effective index of simple silicon waveguides. The

FDM Solver in the FIMMWAVE implements a full-vectorial finite-difference technique and can accurately model waveguides with abrupt refractive index changes, slanting/curved interfaces and gradient profiles.

The mode profiles of the slot waveguide in the Section 4.2, the effective index profiles for the subwavelength grating (SWG)-based structures in Chapter 5, the mode and effective index profiles for the taper-based devices in Chapter 6 were simulated by the FDM.

2.2.5 Finite Element Method (FEM)

The FEM uses variational methods to minimize the error function and produces a stable solution to the integral form of the wave equations (2.38) and (2.39) [3]. The FEM is generally advantageous for complex geometries with high index contrast materials, e.g. silicon waveguides on a SOI platform. Instead of finding an expansion basis over the entire domain, which is almost impossible in general, the FEM subdivides the domain into a collection of elements, for which a simple basis can be defined. The subdivision of the whole domain into a collection of elements has several advantages: 1) accurate representation of a complex geometry, 2) inclusion of dissimilar material properties, 3) easy representation of the total solution, 4) capturing of local effects.

The FEM method involves (1) dividing the domain of the problem into a collection of subdomains, with each subdomain represented by a set of element equations to the original problem, followed by (2) systematically recombining all sets of element equations into a global system of equations for the final calculation.

In this thesis, the commercial software package RSoft FemSIM module has been used to calculate waveguide modes. The output of simulations by the FEM includes the effective index and field distribution of the mode, which is useful in the modal analysis of a single waveguide. The RSoft FemSIM module can generate a collection of conformal subdomains, which adjusts the spacing between grid points. Grid points can be increased at important boundaries, and users can further increase the density of the grid points if necessary. Therefore, less computational time is required while keeping the required accuracy. The mode profiles and the corresponding effective indices of the LOCOS wire waveguide in Chapter 3 were calculated by the FEM.

2.2.6 Eigenmode Expansion (EME) Method

The EME method is a rigorous technique to simulate electromagnetic propagation which relies on the decomposition of the electromagnetic fields into a basis set of local eigenmodes that exists in the cross-section of the device. The eigenmodes are found by solving the wave equations (2.38) and (2.39) using the FDM or FEM in each local cross-section. The method can be fully vectorial provided that the mode solvers themselves are fully vectorial. Many problems can be simplified by considering only a modest number of modes, which makes EME a very powerful method [4].

In a typical waveguide, there are a few guided modes and an infinite number of radiation modes. The guided and radiation modes together form a complete basis set. In the EME method, the solution of the Maxwell's equations (2.6)-(2.9) can be expressed as the superposition of the forward and backward propagation modes:

$$\vec{E}(x, y, z) = \sum_{k=1}^M (a_k e^{i\beta_k z} + b_k e^{-i\beta_k z}) \vec{E}_k(x, y) \quad (2.40)$$

$$\vec{H}(x, y, z) = \sum_{k=1}^M (a_k e^{i\beta_k z} + b_k e^{-i\beta_k z}) \vec{H}_k(x, y) \quad (2.41)$$

where $\vec{E}_k(x, y)$ and $\vec{H}_k(x, y)$ are the mode profiles, which can be calculated by the FDM or FEM. β_k is the corresponding propagation constant. a_k and b_k are the forward and backward amplitudes.

The EME method uses the scattering matrix (S-matrix) technique to join different sections of the waveguide or to model non-uniform structures, as illustrated in Fig. 2.4. The S-matrix approach in the EME method provides a flexible calculation framework, potentially allowing users to only re-calculate modified parts of the structure when performing parameter scans. It is an excellent technique to model long devices or devices composed of metals. In addition, only one simulation is required to obtain the result for all input modes and polarizations.

Figure 2.4: Scattering matrix for the join of waveguides. $a^{(+)}$, $a^{(-)}$, $b^{(+)}$, $b^{(-)}$ are mode coefficients at the join, S_J is a scattering matrix for the join [4].

The EME, however, is limited to linear problems. Nonlinear problems may be modelled using iterative techniques. In addition, the EME may be inefficient to model structures requiring a very large number of modes, which limits the size of the cross-section for three-dimensional simulations.

In this thesis, the EME method in the commercial software FIMMWAVE was used to analyze the light propagation in the simple silicon waveguide. The fabrication tolerance analysis for the polarization splitter and rotator using the SWG in Section 5.1 and the taper-based devices in Chapter 6 were simulated by the EME method.

2.2.7 Finite Difference Time Domain (FDTD) Method

The FDTD method is a numerical analysis technique used for modeling computational electrodynamics (i.e., finding approximate solutions to the associated system of differential equations). Since it is a time-domain method, FDTD solutions can cover a wide frequency range in a single simulation run, and treat nonlinear material properties in a natural way. To implement an FDTD solution of the Maxwell's equations (2.8) and (2.9), computational domain must first be established to define the physical region over which the simulation will be performed. The most famous computational domain is the Yee cell [5], which spatially staggers the vector component of the electric field and magnetic field together with explicit leapfrog time updates in rectangular unit cells of a Cartesian computational grid, as illustrated in Fig. 2.5.

Figure 2.5: Standard Cartesian Yee cell used for FDTD, about which electric and magnetic field vector components are distributed. The electric field components form the edges of the cube, and the magnetic field components form the normals to the faces of the cube.

The electrical and magnetic fields are determined at every point in the Yee cell. Using the leapfrog time updates, the Maxwell's equations (2.8) and (2.9) can be expressed as

$$\vec{H}(x, y, z)^{k+1/2} = \vec{H}(x, y, z)^{k-1/2} - \frac{\Delta t}{\mu} \nabla \times \vec{E}(x, y, z)^n \quad (2.42)$$

$$\vec{E}(x, y, z)^{k+1} = \vec{E}(x, y, z)^k - \frac{\Delta t}{\varepsilon} \nabla \times \vec{H}(x, y, z)^{n+1/2} \quad (2.43)$$

where Δt is the discretized time size.

The material of each cell within the computational domain must be specified. Typically, the material is either free-space (air), metal, or dielectric. Any material can be used as long as the permeability, permittivity, and conductivity are defined. Once the computational domain and the grid materials are established, a source is specified.

The FDTD is a time-domain technique, and when a broadband pulse (such as a Gaussian pulse) is used as the source, the response of the system over a wide range of frequencies can be obtained in a single simulation. This is useful in applications where

resonant frequencies are not exactly known, or that a broadband performance is desired. The FDTD technique allows the user to specify the material at all points within the computational domain. A wide variety of linear and nonlinear dielectric and magnetic materials can be naturally and easily modeled. However, FDTD requires that the entire computational domain be gridded, and the grid spatial discretization must be sufficiently fine to resolve both the smallest electromagnetic wavelength and the smallest geometrical feature in the model. As a result, very large computational domains require large computational resources and long simulation time.

In this thesis, the FDTD method in the commercial software Lumerical FDTD Solutions was employed to analyze the light propagation and the output transmission in the designed devices. The transmission spectra of the vertically coupled double-ring in Section 4.1, and the wavelength dependence of the polarization splitter and rotator using the SWG in Section 5.1, the performance of the SWG-based polarizer in Section 5.2, the wavelength dependence of the polarization rotator using a tapered amorphous silicon layer in Section 6.1 were demonstrated by the FDTD method.

2.3 Fabrication Process

Silicon photonic devices can be fabricated using standard CMOS fabrication techniques. In general, a full fabrication process include the oxidation process (as mentioned in Section 2.1), lithography, etching, and deposition.

2.3.1 Lithography

Lithography is the process of transferring a pattern from a mask to the surface of the wafer [6], as shown in Fig. 2.6. The pattern information is recorded on a layer of photoresist which is applied on the top of the wafer. The photoresist changes its physical properties when exposed to light (often ultraviolet) or another source of illumination (e.g. E-beam and X-ray). The photoresist is either developed by (wet or dry) etching or by conversion to volatile compounds through the exposure itself. The pattern defined by the mask is either removed or remained after development,

depending on the type of resist (positive or negative).

Figure 2.6: Lithography process.

2.3.2 Etching

Etching is used to remove material selectively in order to create patterns to obtain the desired device or interconnect geometry. The pattern is defined by an etching mask, where desired parts are protected in selective regions. The undesired material can be removed either by wet (chemical) or dry (physical) etching. An ideal etching process is anisotropic and selective, as shown in Fig. 2.7(a). Wet etching is usually isotropic [Fig. 2.7(b)] which limits its application and the etching time can be difficult to control. Because of the so-called “under-etch effect”, wet etching is not suited to transfer patterns with sub-micron feature size. However, wet etching has a high selectivity as the etch rate is specific to the material. On the other hand, dry etching is highly anisotropic but less selective with a possibility of over-etching [Fig. 2.7(c)]. However, with careful process control, dry etching is more capable for transferring small structures.

One popular dry etching technique is the reactive ion etching (RIE), which provides high anisotropy by bombarding ions onto the surface. The main advantage of the RIE is its enhanced directionality compared to wet etching. RIE becomes increasingly important as device feature size further decreases and deeper etching in the vertical direction is required without affecting adjacent features [7].

Figure 2.7: Isotropy and selectivity of the etching process of a SOI waveguide. (a) A perfectly anisotropic and highly selective etching process produces vertical sidewalls and leaves the underlying SiO_2 substrate unharmed; (b) an isotropic etching produces round sidewalls; (c) a poorly selective etching over-etches the underlying SiO_2 substrate.

2.3.3 Deposition

A multiple of layers of different materials must be deposited during the silicon photonic fabrication process. The two common deposition methods are the physical vapor deposition (PVD) and the chemical vapor deposition (CVD). During a PVD, accelerated gas ions from a sputter target are deposited to a substrate surface under low pressure. The principle of CVD is a chemical reaction of a gas mixture on a substrate surface at high temperature. The need of high temperatures is the most restricting factor for applying CVD. This problem can be avoided by using the plasma enhanced chemical vapor deposition (PECVD), where the chemical reaction is enhanced by

radio frequencies instead of high temperature [8]. Semiconductor materials that can be deposited by CVD processes are silicon dioxide, amorphous silicon, silicon nitride, tungsten, copper, titanium nitride, and aluminum. One of the most important factors during the deposition of materials is the conformality, i.e., same layer thickness around all positions on the device surface. Due to a better conformality deposition property, the CVD is usually preferred over the PVD.

2.3.4 Fabrication Foundries

The LOCOS waveguides were fabricated by the ultraviolet lithography at the Carleton University MicroFabrication Facility. The minimum feature size is 800 nm by using a positive photoresist, which is larger than the typical dimension of a single-mode silicon wire waveguide. 340 nm thick SOI wafers were used in the fabrication run, where a thermal oxidation setup was used to define the wire waveguide with a targeted feature size less than 800 nm. Tapered waveguides were designed to couple light in and out the chip.

All the microring resonator-based structures were fabricated by the OpSIS/IMEC foundry process through CMC Microsystems. The fabrication run was done on a 220 nm SOI wafer using a 248 nm deep ultraviolet (DUV) photolithography step. The minimum feature size was set to 200 nm. A full 220 nm etch was used to define the silicon wire waveguides and the inverse-taper edge couplers. The width of the inverse taper tip is set to the minimum 200 nm.

The taper-based structures were fabricated by the IMEC foundry process through CMC Microsystems. The fabrication run was also done on a 220 nm SOI platform using a 193 nm DUV photolithography step, while the minimum feature size was 130 nm. A full 220 nm etch was used to define wire waveguides while the fiber-to-waveguide grating structure couplers and the taper-etched directional couplers were realized by combining the full 220 nm with a partial 70 nm etching step. The inverse-taper edge couplers and the grating surface couplers for the fiber-to-waveguide coupling will be discussed in detail in the next section.

The subwavelength grating (SWG)-based TE-pass polarizer was fabricated by the the Fabrication Facility at the NRC Canada. The fabrication run was done on a 220

nm SOI wafer using an e-beam lithography step with the minimum feature size of 100 nm. A full 220 etch was used to define the SWG waveguide and the inverse-taper edge couplers. The width of the inverse taper tip is 300 nm to support both TE and TM modes.

2.4 Fiber-to-Waveguide Couplers

The coupling efficiency between silicon waveguides and fibers is limited by the mode mismatch because the ratio of the cross-sectional area of a single mode silicon waveguide to the modal area of a single-mode fiber (SMF) can be as low as 10^{-3} :1. For a typical Gaussian power distribution, the mode field diameter (MFD) is defined as the diameter where the electric field is reduced to a factor of $1/e$, (i.e., the corresponding optical power is reduced by $1/e^2$ of the maximum value). Fig. 2.8 illustrates the relative MFDs of a SMF and a lensed fiber used to measure waveguides in this thesis, as well as the cross-sectional areas of a typical single-mode silicon waveguide.

Fiber-to-waveguide coupling can be improved in two ways: 1) reducing the fiber MFD and 2) using efficient waveguide I/O couplers. A lensed fiber is often used to reduce the fiber MFD of the I/O fibers. Lensed fibers are available commercially. Fig. 2.9 illustrates a commercial lensed fiber from OZ Optics Ltd. with a MFD as low as 2 μm . Inverse taper edge couplers and vertical grating couplers have also been used to improve the fiber-to-waveguide coupling efficiency. In an inverse-taper edge coupler [9], the waveguide width is tapered in, to nearly a point or to the minimum feature dimension, as shown in Fig. 2.10. The advantages of inverting the taper are threefold. Firstly, reducing the waveguide core size induces the waveguide mode to expand, enabling better mode matching to the input fiber. Secondly, expanding the mode into the silicon dioxide cladding results in effective index matching of the waveguide and fiber modes and reduces the facet reflection coefficient, further reducing the coupling loss. Thirdly, the inverse-taper edge coupler can operate in a broadband wavelength range. Coupling loss values of an inverse-taper coupler have been reported as low as 1 dB for silicon [10]. The key parameter to a low loss inverse taper edge coupler is the width of the taper tip. In this thesis, the width of the taper tip is 200 nm due to fabrication limitation.

Figure 2.8: Comparison of relative sizes of two optical fiber Modal Field Diameters (MFDs) and the cross-section of a typical silicon waveguide.

Figure 2.9: A lensed fiber from OZ Optics Ltd.

A vertical grating coupler is another critical waveguide I/O coupler in silicon photonic circuits [11], as shown in Fig. 2.11. Vertical coupling eliminates the need for the wafer dicing and offers an easier geometry to package a fiber pigtail. This allows simultaneous electrical and optical measurements from a single automated probe station, which is useful for electronic and photonic integrated circuits. The drawback of grating couplers is polarization and wavelength sensitivity, as the grating teeth only vary the permittivity and not permeability in real space. The grating coupler is also sensitive to the input fiber angle and wavelength. Coupling losses of less than 2 dB at $\lambda=1550$ nm have been reported [12]. Due to the availability from different foundries, both inverse-taper edge couplers and grating couplers have been used in this thesis.

Figure 2.10: An inverse-taper coupler. (a) Schematic of the coupler. (b) Fabricated inverse coupler.

Figure 2.11: Schematic of a grating coupler.

2.5 Measurement Setups

The chip measurement system in the NRC Canada was used to measure the performance of the fabricated chips with inverse-taper edge couplers. The schematic of the measurement system is shown in Fig. 2.12.

Light from a tunable laser is guided in a SMF after passing through a polarizer to the edge coupler of the chip. The fiber output is aligned using a 3-axis stepper motor to the waveguide facet, by means of a lensed fiber, with a MFD of $2\ \mu\text{m}$. The output

light from the waveguide chip is collected, focused and collimated by a microscope objective to the detector. To increase the detection precision, an optical chopper has been used to distinguish the signal light from other light sources that may be detected in the free space detector. Power versus wavelength measurements are collected and controlled by a computer using the commercial Labview software. Alignment of the measurement system is implemented by visual imaging of the output with a mirror and an infrared camera placed in the beam path between the lens and detector.

Figure 2.12: Schematic of the measurement system

Figure 2.13: Fiber array measurement setup

For chips with grating couplers, the measurement setup in the Micro/NanoPhotonics Lab of Carleton University was used, as shown in Fig. 2.13. Both the TE and TM light were supplied and collected from the grating couplers using a fiber array, which hold six polarization maintaining SMFs positioned in a silica casing, $127\text{ }\mu\text{m}$ apart from each other. As the cross-section of the fiber array shown in Fig. 2.14, there are 3 TE and 3 TM polarization maintaining fibers, of which some can be used as an input, while others used as outputs. The fiber array can simplify the measurement alignment since only one alignment is required per device, rather than once for each input and output fiber. The light from the tunable laser is guided by one SMF of the fiber array to the input grating coupler. The output light of the device under test is coupled to another fiber of the same fiber array, allowing the Luna Optical Vector Analyzer for data measurements and analysis.

Figure 2.14: Cross-section of the fiber array containing three TE polarization maintaining (PM) fibers and three TM PM fibers

List of References

- [1] B. E. Deal and A. S. Grove, "General relationship for the thermal oxidation of silicon," *Journal of Applied Physics*, vol. 36, no. 12, pp. 3770–3778, 1965.
- [2] Z. Zhu and T. Brown, "Full-vectorial finite-difference analysis of microstructured optical fibers," *Optics Express*, vol. 10, pp. 853–864, Aug. 2002.
- [3] J. Jin, *The Finite-Element Method in Electromagnetics*, vol. 376. New York: Wiley, 1993.
- [4] D. F. G. Gallagher and T. P. Felici, "Eigenmode Expansion Methods for Photonics - Pros and Cons," in *Proc. SPIE 4987* (Y. S. Sidorin and A. Tervonen, eds.), pp. 69–82, 2003.
- [5] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Transactions on Antennas and Propagation*, vol. 14, no. 3, pp. 302–307, 1966.
- [6] M. D. Levenson, N. S. Viswanathan, and R. A. Simpson, "Improving resolution in photolithography with a phase-shifting mask," *IEEE Transactions on Electron Devices*, vol. ED-29, no. 12, pp. 1828–1836, 1982.
- [7] E. H. Klaassen, K. Petersen, J. Logan, N. I. Maluf, J. Brown, C. Storment, W. McCulley, and G. T. A. Kovacs, "Silicon fusion bonding and deep reactive ion etching : a new technology for microstructures," *Sensors and Actuators A*, vol. 52, pp. 132–139, 1996.
- [8] M. L. Hitchman and K. F. Jensen, *Chemical vapor deposition: principles and applications*. No. November, London: Academic Press, 1993.
- [9] V. R. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," *Optics Letters*, vol. 28, pp. 1302–1304, Aug. 2003.
- [10] G. Ren, S. Chen, Y. Cheng, and Y. Zhai, "Study on inverse taper based mode transformer for low loss coupling between silicon wire waveguide and lensed fiber," *Optics Communications*, vol. 284, pp. 4782–4788, Sept. 2011.
- [11] D. Taillaert, F. Van Laere, M. Ayre, W. Bogaerts, D. Van Thourhout, P. Bienstman, and R. Baets, "Grating couplers for coupling between optical fibers and nanophotonic waveguides," *Japanese Journal of Applied Physics*, vol. 45, pp. 6071–6077, Aug. 2006.

- [12] R. Halir, P. Cheben, S. Janz, D.-X. Xu, I. n. Molina-Fernández, and J. G. Wangüemert-Pérez, “Waveguide grating coupler with subwavelength microstructures,” *Optics Letters*, vol. 34, p. 1408, Apr. 2009.

Chapter 3

Waveguide Fabrication Using the Local Oxidation of Silicon (LOCOS)

In this chapter, a fabrication technique, the LOCal Oxidation of Silicon (LOCOS), is used to fabricate submicron-sized silicon waveguides.

The following article, “Impact of LOCOS techniques on photonic wire waveguides,” provides details on the characteristics of the silicon wire waveguide defined by the LOCOS technique. This article includes the fabrication design and process, as well as the assessment and evaluation of the fabrication method. The AutoCAD mask used to define the waveguides is shown in Appendix [B](#).

Yule Xiong performed the waveguide design, all simulations, analysis of the data, partially fabricated the waveguides and wrote this article. The LOCOS waveguides were fabricated at the Carleton University MicroFabrication Facility and tested using the measurement setup in the group of Information and Communication Technologies at the National Research Council (NRC) Canada. The article was published in Applied Optics, volume 51, issue 29, on pages 7089-7093 in 2012.

Impact of LOCOS techniques on photonic wire waveguides

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3.1 Abstract

We use the LOCal Oxidation of Silicon (LOCOS) method as a fabrication technique to define submicron photonic waveguides. We attempted fabricating the wire waveguides with two different masking processes, one with a stack of pad oxide and silicon nitride layers, and the other with a single silicon nitride layer. The smallest waveguide we achieved had a cross-section profile of $280\text{ nm} \times 650\text{ nm}$. The propagation loss of the waveguides was measured by the cut-back method; and the bending loss was measured by employing the serpentine pattern. The minimum propagation loss achieved was 8.78 dB/cm and the bending loss was $0.0089\text{ dB/90}^\circ$ bend for a $5\text{ }\mu\text{m}$ bending radius.

3.2 Introduction

Silicon photonics has attracted tremendous attention as a promising technology for optical telecommunications and for optoelectronics integrations in the past decade [1]. Owing to the high refractive index contrast between silicon and silica, the silicon-on-insulator (SOI) technology used for fabrication of planar photonic circuits in the

silicon photonic field, further down-scales the device footprint, promotes a greater integration density, thus leading to improvement in both performance and cost. Photonic wire waveguides based on the SOI technology are attractive for monolithic electronic-photonic integration because the photonic submicron core dimensions and micron bending sections match the scale of their counterpart electronics [2, 3]. Recently, the Local Oxidation of Silicon (LOCOS) technique using various mask materials based on the SOI platform has been reported to make rib [4–7] and wire channel waveguides [8, 9]. The LOCOS technique, used for transistor insulation in the complementary metal-oxide-semiconductor (CMOS) process for three decades, is able to combine the CMOS integration with silicon photonic devices. Instead of etching the silicon layer directly, the waveguide is defined by oxidizing selected areas of the silicon layer. Therefore, due to the smooth sidewall produced by the oxidation, the resulting photonic waveguides can achieve low loss. The estimated propagation loss of the waveguides fabricated by the LOCOS technique ranges from 0.3 dB/cm to 9 dB/cm [4–9], with a minimum dimension of 300 nm (FWHM) $\times$ 85 nm (height) [6]. However, there has been no direct measurement reported in literature on the bending loss of LOCOS photonic wire waveguides. Here, we use the cut-back method to directly measure the propagation loss, as well as using the serpentine pattern to directly measure the bending loss of photonic wire waveguides fabricated by the LOCOS technique. We utilize two types of protective masks, one consisting of a thermal pad oxide overlaid by a silicon nitride, and the other consisting of only a single layer silicon nitride. Unlike most of the LOCOS waveguides reported in literature, we utilized basic optical lithography method to define the waveguides, and to save fabrication time and cost.

3.3 Fabrication

The fabrication process of the waveguides using a pad oxide layer as a stress-relief buffer (Type A) has been reported previously [10], as illustrated in Fig. 3.1(a). A 30 nm thick pad oxide layer grown over the entire silicon surface relieves the stresses from the thermal expansion mismatch between the silicon nitride masking layer and the underneath silicon core layer. The fabrication process used to define the LOCOS waveguides without a pad oxide layer (Type B) is shown in Fig. 3.1(b). An 80 nm

thick silicon nitride mask layer is directly deposited atop the silicon layer, without a pad oxide layer between the silicon core and the nitride layer.

Figure 3.1: Fabrication process flow of (a) Type A LOCOS waveguide (a stack of pad oxide and silicon nitride layers as the mask), (b) Type B LOCOS waveguide (a single silicon nitride layer as the mask). (1) and (5) Silicon on insulator wafer. (2) and (6) Depositing silicon nitride and/or pad oxide layers. (3) and (7) Patterning of silicon nitride. (4) and (8) Wet Oxidation.

The fabrication details are as follows: an N-type $\langle 100 \rangle$ SOI wafer (SOITEC) with an initial silicon layer of 340 nm and a buried oxide layer of 1 μm was employed to fabricate both the Type A and Type B waveguides. For Type A waveguides, a 30 nm thermal pad oxide layer was first grown on the top of the silicon layer by a 6-minute dry thermal oxidation step at 1100 $^{\circ}\text{C}$. Then for both Types A and B waveguides,

an 80 nm thick silicon nitride mask layer was deposited at 820 °C by an 11-minute low pressure chemical vapor deposition (LPCVD) step. After that, we spun-coated a layer of negative photoresist (IC-28), followed by a ultraviolet (UV) exposure step, a photoresist development and a hard bake to define waveguide patterns of 1 μm in width. Next, the waveguide patterns were transferred onto the silicon nitride layer by using a 5-minute reactive ion etching (RIE), completed by a 2-minute wet etching. After stripping off the IC-28 photoresist, we performed a 100-minute wet oxidation LOCOS step at 1100 °C to create submicron waveguide features directly from the 1 μm waveguide patterns, using only the standard optical lithography. Finally, the silicon nitride layer was removed by using a wet etching process. To evaluate and optimize the LOCOS wire waveguide profile, we first simulated the fabrication process using a commercial software TSUPREM-4. The simulated cross-section profiles under the two types of processes are demonstrated in Figs. 3.2 (a) and (b). The simulated cross section of the Type A LOCOS waveguides shows a full-width half-maximum (FWHM) of 700 nm, and a height of 230 nm. The simulated cross section of Type B waveguides, on the other hand, has a trapezoidal shape, with a dimension of 1.3 μm (FWHM) $\times$ 300 nm (height). Figures 3.2 (c) and (d) illustrate the scanning electron microscope (SEM) images of the two types of fabricated waveguide cross-sections. The FWHM of the fabricated type A waveguide is approximately 650 nm with a height of 280 nm, while the FWHM of the type B waveguide is approximately 1.4 μm with a height of 280 nm. The slight differences between the simulation and fabrication results are due to the fact that the parameters, such as the Young's modulus of the silicon nitride and mask dimensions, used in the simulations may not represent the true values in the fabrication processes. As demonstrated in Fig. 3.2, even though the fabrication parameters were set to be the same, the cross section of the Type A waveguides appeared smaller than that of the Type B waveguides. The pad oxide involved in the Type A process induced the side growth of the excess oxide. Although the pad oxide layer relieves the thermal stress, the oxidation process restricts the shape of the waveguide. In contrast, Type B waveguides has more vertical sidewalls at the upper section of the waveguide. The FWHM of Type B waveguides can be controlled by depositing a silicon nitride layer with a desirable width.

Figure 3.2: Cross-section of the LOCOS wire waveguides. (a) Simulated shape for Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask). (b) Simulated shape for Type B waveguides (a single silicon nitride layer as the mask). (c). SEM image of Type A waveguides. (d) SEM image of Type B waveguides.

3.4 Optical Losses

Before measuring the propagation loss and bending loss of the fabricated waveguides, we first compute the modal profiles and the effective refractive index of the two waveguides by using a commercial software RSoft. The simulated fundamental quasi-TE polarization profiles of the two waveguides are shown in Fig. 3.3. The calculated effective refractive indices of the fundamental quasi-TE polarizations are 2.79 and 2.93 for the Type A and Type B waveguides, respectively. While the Type A waveguide only supports a single-mode operation, the Type B waveguide is a multimode waveguide due to its large width.

To measure the propagation loss of the LOCOS photonic wire waveguides, we used the cut-back method. The waveguide paperclip structure for cut-back measurements of the propagation loss is shown in Fig. 3.4. A 10-mW output of a broadband light source with a wavelength centered at 1550 nm was coupled into the waveguide via a single mode lensed fiber. Lateral taper coupling was used, while the signal polarization was controlled by an in-line polarization controller. The estimated system loss

Figure 3.3: Simulated quasi-TE polarization profiles of the fabricated LOCOS wire waveguide. (a) Type A waveguides ((a stack of pad oxide and silicon nitride layers as the mask). (b) Type B waveguides (a single silicon nitride layer as the mask).

is around 10 dB. In our experiments, only quasi-TE polarization can be detected by the photodetector for Type A waveguides, while no quasi-TM polarization can be measured experimentally. Fig. 3.5 illustrates the measured propagation losses of the waveguides operating in the quasi-TE polarization. The propagation loss of the Type A waveguides was measured to be 8.78 dB/cm, while the Type B waveguides had a loss of 9.83 dB/cm. The propagation losses for both the Type A and B waveguides are high because the basic optical lithography may induce the silicon nitride pattern with a rough sidewall, which potentially has a negative impact on the performance of the waveguides. The advanced lithography such as the e-beam and deep ultra-violet (DUV) lithographies may reduce the roughness of the silicon pattern and the propagation loss of the waveguides.

The propagation losses of all our fabricated devices are consistent, with linear slopes as shown in Figs. 3.5 (a) and (b). The origin of the propagation loss of photonic wire waveguides is mainly the surface roughness of the waveguide core. As direct measurement of waveguide sidewall roughness is difficult, the random surface roughness cannot be simulated by the available software. However, the propagation loss due to the surface roughness can be described from the attenuation coefficient α as follow [11].

$$\alpha = \frac{\sigma^2 \kappa}{k_0 \omega^4 n_{eff}} \quad (3.1)$$

Figure 3.4: Waveguide paperclip structure for cut-back measurements of the propagation loss.

Figure 3.5: Propagation loss for the LOCOS wire waveguide for the quasi-TE polarization. (a) Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask) (b) Type B waveguides (a single silicon nitride layer as the mask).

where k_0 , ω and n_{eff} are the wavevector of the light in vacuum, the half-width of the waveguide core, and the effective index of a silicon slab with the same thickness as the waveguide core, respectively. σ is the root-mean square (RMS) surface roughness; κ is the statistical distribution of the roughness, which depends on the waveguide geometry [12]. Normally, κ is around 1 for practical waveguides. The propagation loss is inversely proportional to the fourth power of ω . Thus, making waveguides with smaller feature size is more susceptible to large losses. Give a $650 \text{ nm} \times 280 \text{ nm}$ photonic wire waveguide, the estimated propagation loss using Eq. 3.1 is around 7 dB/cm.

Bending loss is another important parameter for waveguides. The serpentine

pattern used for the measurement of the bending loss is illustrated in Fig. 3.6. To measure the waveguide bending loss, two types of waveguides with 4 bends, 12 bends, and 20 bends folded in the serpentine pattern were designed. As shown in Fig. 3.7, the measured bending loss for the Type A waveguides with the bending radius of $R=5\text{ }\mu\text{m}$ is 0.0089 dB/90° bend for the quasi-TE polarization, while for the Type B waveguides, we have 0.0417 dB/90° bend.

The bending loss includes the inherent radiation loss and the modal transition loss. Since the radiation loss depends on the waveguide confinement at a fixed bending radius, a larger width means a lower radiation loss for a bending waveguide [13]. However, with a larger width, the waveguide is at risk to support multimodes which induce a large modal transition loss. In our experiment, the Type B waveguides are multimode waveguides, and the measured bending loss is almost 5 times higher than that of the Type A waveguides.

Figure 3.6: Waveguide serpentine pattern for measurements of the bending loss.

3.5 Polarization Conversions

A serious challenge in silicon photonic waveguides is their polarization dependence. A perfect dielectric waveguide can transmit any of its guided modes without conversion energy to any of the other possible guided modes or to the continuous spectrum. However, any imperfection on the waveguide, such as the structural deformations, will couple the particular guided mode to all other guided modes, as well as to all the modes of the unguided continuum [14].

Figure 3.7: Bending loss for the LOCOS wire waveguide for the quasi-TE polarization. (a) Type A waveguides (a stack of pad oxide and silicon nitride layers as the mask) (b) Type B waveguides (a single silicon nitride layer as the mask).

Figure 3.8: Output power of quasi-TE and quasi-TM polarizations for Type B waveguides when TE polarization was launched.

Here, when the TE polarization was coupled into the waveguide, the polarization conversion can be estimated by the TE to TM output ratio:

$$T_{pol} = 10 \log_{10} \frac{P_{TE}}{P_{TM}} \quad (3.2)$$

where P_{TE} and P_{TM} are the output power at the end of the waveguide for quasi-TE polarization and quasi-TM polarization, respectively. As shown in Fig. 3.8, when TE polarization was launched, we measured the TE to TM output ratio $T_{pol} = 6$ dB for the Type B waveguides. Since the quasi-TM polarization cannot be observed easily

in the Type A waveguides, the TE to TM output ratio $T_{pol} > 13$ dB was estimated for the Type A waveguides.

3.6 Conclusion

We fabricate two types of photonic wire waveguides using the LOCOS techniques. The pad oxide layer can significantly affect the cross-section profile of the LOCOS waveguides. The protective mask consisting of a single layer of the silicon nitride enables the steeper sidewalls for the LOCOS waveguides. We have experimentally measured the propagation loss and the bending loss of the wire waveguides from the two LOCOS processes (Type A and Type B). The measured propagation losses are 8.78 dB/cm and 9.83 dB/cm for the Type A (with a pad oxide layer) and Type B (without a pad oxide layer) waveguides, respectively; while the bending losses are 0.0089 dB/90° bend (Type A) and 0.0417 dB/90° bend (Type B). Our experiments show that the LOCOS photonic wire waveguides can achieve bending radius much smaller than 5 μm , thus enabling the photonic integrated circuits.

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List of References

- [1] R. Soref, “The past, present, and future of silicon photonics,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 6, pp. 1678–1687, 2006.
- [2] Y. Vlasov and S. McNab, “Losses in single-mode silicon-on-insulator strip waveguides and bends,” *Optics Express*, vol. 12, pp. 1622–1631, Apr. 2004.
- [3] G. T. Reed, W. R. Headley, G. Z. Mashanovich, F. Y. Gardes, D. J. Thomson, and M. M. Milosevic, “Silicon photonics-the evolution of integration,” in *Silicon Photonics for Telecommunication and Biomedicine* (S. Fathpour and B. Jalali, eds.), pp. 7–8, CRC Press, 2011.
- [4] L. K. Rowe, M. Elsey, N. G. Tarr, A. P. Knights, and E. Post, “CMOS-compatible optical rib waveguides defined by local oxidation of silicon,” *Electronics Letters*, vol. 43, no. 7, pp. 392–393, 2007.
- [5] F. Y. Gardes, G. T. Reed, a. P. Knights, G. Mashanovich, P. E. Jessop, L. Rowe, S. McFaul, D. Bruce, and N. G. Tarr, “Sub-micron optical waveguides for silicon photonics formed via the Local Oxidation of Silicon (LOCOS),” in *Proc. of SPIE 6898* (J. A. Kubby and G. T. Reed, eds.), p. 68980R, Feb. 2008.
- [6] M. P. Nezhad, O. Bondarenko, M. Khajavikhan, A. Simic, and Y. Fainman, “Etch-free low loss silicon waveguides using hydrogen silsesquioxane oxidation masks,” *Optics Express*, vol. 19, pp. 18827–18832, Sept. 2011.
- [7] J. Cardenas, C. B. Poitras, J. T. Robinson, K. Preston, L. Chen, and M. Lipson, “Low loss etchless silicon photonic waveguides,” *Optics Express*, vol. 17, pp. 4752–4757, Mar. 2009.
- [8] B. Desiatov, I. Goykhman, and U. Levy, “Demonstration of submicron square-like silicon waveguide using optimized LOCOS process,” *Optics Express*, vol. 18, pp. 18592–18597, Aug. 2010.
- [9] A. W. Tam, M. Ibrahim, B. Lamontagne, N. G. T. Member, W. N. Ye, S. J. Member, and D. Xu, “Deep submicron LOCOS- defined SOI photonic wire waveguides,” in *8th IEEE International Conference on Group IV Photonics*, pp. 249–251, 2011.
- [10] Y. Xiong, M. Ibrahim, and W. N. Ye, “Low-loss photonic wires defined by Local Oxidation of Silicon (LOCOS),” in *Proc. of SPIE 8265* (L. A. Eldada and E.-H. Lee, eds.), vol. 8265, p. 82650D, Feb. 2012.

- [11] K. Yamada, “Silicon photonic wire waveguides: fundamentals and applications,” in *Silicon Photonics II* (D. J. Lockwood and L. Pavesi, eds.), vol. 119 of *Topics in Applied Physics*, ch. 1, pp. 7–13, Berlin, Heidelberg: Springer Berlin Heidelberg, 2011.
- [12] F. P. Payne and J. P. R. Lacey, “A theoretical analysis of scattering loss from planar optical waveguides,” *Optical and Quantum Electronics*, vol. 26, pp. 977–986, 1994.
- [13] D. Dai, Y. Shi, and S. He, “Characteristic analysis of nanosilicon rectangular waveguides for planar light-wave circuits of high integration,” *Applied Optics*, vol. 45, pp. 4941–4946, July 2006.
- [14] K. Kakihara, N. Kono, K. Saitoh, T. Fujisawa, and M. Koshiba, “Impact of structural deformations on polarization conversion in high index contrast waveguides,” *Optics Express*, vol. 14, pp. 7046–7056, Aug. 2006.

Chapter 4

Microring Resonator (MRR)-Based Devices

In this Chapter, four published articles demonstrate the design details of four different MRR-based devices for sensing and all-optical switching applications.

4.1 Vertically Coupled Double-Ring

The following manuscript “Temperature-independent vertically coupled double-ring sensor” illustrates details on the simulated athermal performance of a vertically coupled double-ring device. The presented device has application in real time sensing.

Yule Xiong did all the device simulations, data analysis and wrote the manuscript. The device was not fabricated yet due to the limitation of the available fabrication facility. The paper was presented at the refereed international conference Photonics West (in Proc. SPIE Int. Soc. Opt. Eng., vol. 8266, pp. 826603_1-6) Photonics West 2012, in San Francisco, USA, on January 26, 2012.

Temperature-independent vertically coupled double-ring sensor

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4.1.1 Abstract

Optical biosensors on silicon platforms have demonstrated their great potential in label-free detection and analysis tool. The major challenge of microring resonator (MRR) based optical biosensors is their high sensitivity to temperature variations. We have designed a double-ring resonator biosensor using a vertical coupling method. Simulation results show that the double-ring configuration effectively eliminates the temperature and environmental fluctuations by the resonant wavelength shift correction induced from the reference microring. The coupling gap in the vertical coupling method can be tuned by timing the deposition/growth rate of the space layer, without the need of any advanced lithography. The vertical coupling method allows a low fabrication cost.

4.1.2 Introduction

Label-free biosensors, fabricated on silicon-on-insulator (SOI) waveguides [1], based on monitoring the refractive index change induced by molecular interactions, can provide information on sample concentration or density. The evanescent optical field expanded outside the silicon waveguide can sense surface perturbation. A ring-resonator configuration can further amplify the sensing response as the light circulating inside the microring effectively interacts with the same molecule repeatedly [2]. High quality factor (Q-factor) microring resonators have a longer effective interaction length with the surroundings, leading to an increase in sensitivity [3].

One of the major challenges faced by SOI microring resonator (MRR) biosensors is their temperature dependence [4]. One solution to the temperature dependence of SOI waveguides is to engineer the upper cladding polymer [5] since polymers usually have a thermo-optical coefficient opposite in sign to that of silicon. However, such a solution is often sensitive to fabrication variations and is solvent dependent. In addition, for SOI microring resonators to act as biological sensors, the upper cladding is usually reserved for the sensing material, which is in either a gaseous or an aqueous form. An alternative approach used to eliminate the effect of sensor temperature fluctuations uses two microring resonators, coupled laterally in series to a common bus waveguide [4,6].

Conventionally, the lateral coupling mechanism is used to achieve the coupling between the microring and the bus waveguide [3]. However, to fabricate the nanoscale coupling spacing of a laterally coupled SOI MRR biosensor, we need advanced lithography methods, such as e-beam or deep UV lithography, which are associated with high fabrication cost. In comparison to the challenging fabrication of the lateral gap, a vertical coupling gap can be fine tuned by simply timing the deposition/growth rate of the space layer, without the need of any advanced lithography. In addition, the buried bus waveguide will suffer less scattering loss and the coupling strength between the bus and microring waveguides is relatively insensitive to small alignment deviation [7].

Here, we design and analyze a silicon-based athermal double-ring resonator biosensor with a vertically coupled configuration.

4.1.3 Design and Analysis

The schematic of the proposed double-ring resonator structure is illustrated in Figure 4.1 (a). The structure consists of an input bus waveguide and two microring waveguides positioned directly above and under the bus waveguide, respectively. Figure 4.1 (b) shows the side view of the double-ring resonator biosensor. The reference microring and bus waveguide are buried underneath a spacing material (e.g., SiO₂). The vertical coupling separation and the lateral offset between the outer edges of the sensing microring and the bus waveguide are d and l , respectively.

Figure 4.1: Schematic of a vertically coupled double-ring resonator: (a) 3D view (b) side view.

In any optical MRR, the supported optical modes are given by

$$m\lambda_r = 2\pi r n_{eff} \quad (4.1)$$

where m is an integer, λ_r is the resonant wavelength of light, r is the radius of the resonator, and n_{eff} is the effective index. We first designed the waveguide dimension such that only the fundamental mode can be supported by the vertically coupled double-ring resonator. A cross-section dimension of 340 nm × 340 nm was chosen for the silicon bus waveguide because our SOI wafers have a 340 nm core thickness. The small cross-sectioned dimension of the waveguide will support single mode operation and squeeze the guided optical mode outside of the waveguide, causing a fraction of the mode to expand into the spacing material as evanescent field. The evanescent light field is vertically coupled into the two rings above and below the bus waveguide.

For vertical coupling configuration, it is advantageous to treat the fundamental TM mode as the dominant field component that is polarized normal to the surface of the rings. Once the dimension was set, the radii of the rings were determined. The high-index property of the silicon microring allows light to travel in a small radius without excessive bending loss. A small radius will increase bend losses but reduce scattering losses, due to the decreasing of the circumnavigation length. For simulation purposes, the microring radii were set to $6\ \mu\text{m}$ for the reference microring and $8\ \mu\text{m}$ for the sensing microring, respectively.

We performed simulations using a commercial software package, Lumerical Solutions based on the finite-difference time-domain (FDTD) techniques. Figure 4.2 shows the simulated transmission spectra of the silicon-based vertically coupled double-ring resonator structure, with optimized geometrical parameters ($d=325\ \text{nm}$ and $l=-80\ \text{nm}$) [8].

Figure 4.2: Simulated transmission spectra of the silicon-based vertically coupled double-ring resonator structure with radii $6\ \mu\text{m}$ and $8\ \mu\text{m}$ for the reference and sensing rings, respectively. Inset: the configuration of the double-ring resonator (Sensing: Sensing microring waveguide, Ref. Reference microring waveguide).

In Figure 4.2, we assume air cladding with $n_c=1$ and no thermal effects. Due to the differences in the radii of the sensing and reference microring, the free spectral range (FSR) of the reference microring is larger than that of the sensing microring ($\text{FSR}_{ref}=14.13\ \text{nm}$; $\text{FSR}_S=9.8\ \text{nm}$). In the absence of thermal effect, the resonances

from the reference rings remain fixed regardless of the variations of the sensing material on the surface of the sensing microring. The wavelength shifts observed in the sensing resonances will be a direct reflection of the material properties of the sensing material.

4.1.4 Athermal Characteristics

One of the major challenges faced by microring based biosensors is their temperature-dependent resonance shifts, both in wavelength and phase. The temperature dependence is mainly due to material property, high thermo-optical (TO) coefficient, 1.86×10^{-4} RIU/K [4]. In this section, the discussion focuses on our process to obtain an athermal silicon performance over a typical operating temperature range for microprocessors, from 20 °C to 100 °C. Assuming the resonant wavelength shifts are caused by the combined surface sensing effect and temperature changes, the total shifts for the sensing and reference rings can be given by

$$\Delta\lambda_S(\Delta T) = \Delta\lambda_S(\Delta T = 0) + \frac{\lambda_S}{n_g^S} \kappa_S \Delta T \quad (4.2)$$

and

$$\Delta\lambda_{ref}(\Delta T) = \frac{\lambda_{ref}}{n_g^{ref}} \kappa_{ref} \Delta T \quad (4.3)$$

where $\Delta\lambda_S(\Delta T)$ and $\Delta\lambda_{ref}(\Delta T)$ are the measured total wavelength shifts including temperature variation ΔT for the sensing and reference rings respectively; $\Delta\lambda_S(\Delta T = 0)$ is the shift from the sensing biomaterial, λ_S , n_g^S and κ_S are the resonant wavelength, group index and TO coefficient of the sensing microring, respectively, λ_{ref} , n_g^{ref} and κ_{ref} are the resonant wavelength, group index and TO coefficient of the reference microring, respectively, and ΔT is the temperature change.

Combining Eqs. 4.2 and 4.3 to eliminate ΔT , we obtain the desired sensing shift due to the biomaterial as

$$\Delta\lambda_S(\Delta T = 0) = \Delta\lambda_S(\Delta T) - k\Delta\lambda_{ref}(\Delta T) \quad (4.4)$$

where the temperature compensation coefficient k is:

$$k = \frac{n_g^{ref}}{n_g^S} \frac{\lambda_S}{\lambda_{ref}} \frac{\kappa_S}{\kappa_{ref}} \quad (4.5)$$

Figure 4.3: Simulated resonance wavelength shifts with temperature change at $n_c=1$.

From Equation 4.5, we see that k is related to the resonant wavelengths of both the reference and sensing rings. From Equation 4.4, we see that the temperature dependence of our double-ring resonator biosensors can be eliminated by a temperature drift correction term obtained from the reference microring. For the double-ring biosensor, the material refractive indices at room temperature $T=20\text{ }^\circ\text{C}$ are $n_{Si}=3.475$ and $n_{SiO_2}=1.444$ for the waveguide and the substrate silicon dioxide, respectively. For simulation purposes, the spacing material (n_{sp}) is also assumed to be silicon dioxide. The thermo-optical coefficients are $\kappa_{Si} = 1.86 \times 10^{-4}$ RIU/K, $\kappa_{Silica} = 1.0 \times 10^{-5}$ RIU/K and $\kappa_{air}=0$. In the simplest case where sensing cladding material is air (i.e. $n_c=1$ (air)), the resonant wavelength shifts are only caused by the temperature variations where the correction term in Equation 4.4 can be obtained. Figure 4.3 shows

the resonant wavelength shifts as a function of temperature for air cladding without any variation in n_c , the resonant wavelength shifts of both the reference and the sensing microring resonators increase as the temperature increases. Since the resonance of the reference is isolated from the cladding index variation (sensing material), the resonant wavelength shift of the reference microring resonators is solely due to the temperature variation. As shown in Figure 4.3, the resonant wavelengths $\lambda_S=1550.7$ nm of the sensing microring and $\lambda_{ref}=1552.9$ nm of the reference microring at $T=20$ °C shift to $\lambda'_S=1552.23$ nm and $\lambda'_{ref}=1554.37$ nm at $T=40$ °C. Using Equations 4.2, 4.3 and 4.5 with no surface sensing wavelength shift, the temperature compensation coefficient k can be determined to be 1.055, according to Equation 4.4.

Figure 4.4: Simulated resonance wavelength shifts with both temperature and cladding index induced effects.

The information obtained on the temperature compensation coefficient k allows us to derive the temperature-independent wavelength shift caused by cladding variation. Figure 4.4 shows that the cladding index changes from $n_c=1$ to 1.35, while the operating temperature shifts from 20 °C to 40 °C, the resonant wavelength moves from $\lambda_S=1550.7$ nm to $\lambda'_S=1576.89$ nm with $\Delta\lambda_S(\Delta T)=26.19$ nm ($\Delta\lambda_S(\Delta T) = \lambda'_S - \lambda_S$), and $\lambda_{ref}=1552.9$ nm changes to $\lambda'_{ref}=1554.37$ nm with $\Delta\lambda_{ref}(\Delta T) = \lambda'_{ref} - \lambda_{ref} = 1.45$ nm. The $\Delta\lambda_S(\Delta T) = 26.19$ nm includes both the temperature-induced and the

cladding-induced wavelength shifts. To extract the temperature effects such that the results are athermal and only reflect the cladding sensing variations, we apply the temperature compensation coefficient obtained from Equation 4.5, $k=1.055$ and $\Delta\lambda_{ref}(\Delta T)=1.45$ nm from the temperature variation. Then using Equation 4.4, we can calculate the cladding-induced sensing resonant wavelength shift to be $\Delta\lambda_s(\Delta T=0)=24.66$ nm. Our simulation that isolates the cladding-induced effects from temperature predicts a 24.87 nm wavelength shift at $T=20$ °C, offering a 0.8% difference from our extracted $\Delta\lambda_s(\Delta T=0)$. The results demonstrate that the contribution from temperature changes can be subtracted from the total apparent sensing signal using the proposed double-ring structure. Further experiments illustrating the effectiveness of the athermal silicon-based double-ring resonator biosensor are underway, and will be reported.

4.1.5 Summary

We have proposed and studied a silicon-based athermal double-ring resonator biosensor with a vertically coupled configuration. The structure, with two microring resonators of slightly different radii vertically coupled to the bus waveguide, is designed on an SOI wafer platform. The reference MRR and the bus waveguide are buried under the spacing material and are isolated from the sensing medium. The sensing MRR is situated above the spacing material and is exposed to the sensing medium. By determining the resonant wavelength shifts of the reference microring induced by temperature change, the thermal dependent effects from the total response of sensing measurement in the sensing MRR can be extracted and removed to obtain an athermal sensing performance.

4.2 Slotted Microring Resonator

The following paper, “Silicon MMI-Coupled slotted conventional and MZI racetrack microring resonators”, provides the details on the experimental performance of two MRR-based devices, i.e., an MMI-coupled slotted microring resonator and an MZI racetrack microring resonator. The mask layout of the designed devices can be found in Appendix [B](#).

Yule Xiong performed all devices design and measurement, data analysis, and wrote the paper. The devices were fabricated by the OpSIS/IME foundry and the device measurement was completed in at the group of Information and Communication Technologies at the National Research Council (NRC) Canada. The article was published in IEEE Photonics Technology Letters, volume 25, issue 19, on pages 1885-1888 in 2014.

Silicon MMI-Coupled slotted conventional and MZI racetrack microring resonators

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4.2.1 Abstract

We experimentally demonstrate two types of SOI microring devices: (i) a slotted conventional microring resonator (MRR) using a multimode interferometer (MMI) coupler as the coupling element; (ii) an MMI-coupled slotted Mach-Zehnder interferometer (MZI) racetrack microring. We achieved a high bandwidth of 1.1 nm and a quality factor Q of $\sim 1,300$ at the wavelength of 1510 nm for the conventional MRRs with a radius of 20 μm . A high extinction ratio (17-25 dB) is exhibited over a wavelength range from 1490 nm to 1520 nm. At the 1515 nm resonance wavelength, the MMI-coupled MZI racetrack microring demonstrates a quasi-free spectral range (quasi-FSR) of 22.6 nm with a high extinction ratio of 25 dB. The demonstrated devices have many applications such as biochemical and gas sensing and modulation in communication systems.

4.2.2 Introduction

Silicon photonics using the high index contrast silicon-on-insulator (SOI) platform is promising for low-cost and high-density integration of micro-photonic devices. SOI-based microring resonators (MRR) and slot waveguides have attracted intense attention as the building blocks for various photonic applications [9–12]. SOI-based slotted MRRs using slot waveguides have been used for various photonic applications, such as biochemical and gas sensing [13, 14] and electro-optic modulation [15]. Typical slotted MRRs employ directional couplers for the coupling between the bus and the microring waveguides. However, it is difficult to predict the exact coupling length and the coupling gap in the directional coupling mechanism of the slot waveguides. This is because the coupling strength and the waveguide losses are strongly influenced by the actual fabricated dimensions of the slot waveguides [16]. A 2×2 multimode interference (MMI) coupler is one attractive alternative to replace the directional coupler for microring resonators. Compared to directional couplers, MMI couplers have more relaxed fabrication tolerances, and are less sensitive to the wavelength or polarization variations [17].

In this letter, we experimentally demonstrate two types of SOI devices: (i) slotted MRRs using MMI couplers, and (ii) MMI-coupled slotted MZI racetrack microrings (MZIRM). Although similar configurations of MMI-coupled microring resonators and MMI-coupled Mach-Zehnder interferometer have been reported [18–20], the devices we report here are slotted waveguides rather than regular wire waveguides. This is, to the best of our knowledge, the first reported MMI-coupled slotted MRR and MZIRM.

4.2.3 MMI-Coupled Slotted Microring Resonator

The proposed MMI-coupled slotted MRR is shown in Fig. 4.5. The slot microring waveguide is coupled to the slot bus waveguide by an MMI coupler. As illustrated in Fig. 4.5(a), the slot bus waveguide is butt-coupled to the input/output wire waveguide. The 2×2 MMI coupler has a width of $W_{MMI}=3D$, where D is the center-to-center separation between the two access slot waveguides. The top cladding is air. The coupling length L_{MMI} for a 50% splitting ratio of the 2×2 MMI coupler is determined by [21]:

Figure 4.5: (a) Schematic of a MMI-coupled slotted microring resonator (MRR). (b) Microscopic image of the fabricated device.

$$L_{MMI} = \frac{3}{2}L_{\pi} \approx \frac{2n_{eff}W_e^2}{\lambda} \quad (4.6)$$

where L_{π} is the beat length of the first two modes; W_e is the effective width of the MMI coupler; n_{eff} and λ are the effective index and wavelength in vacuum, respectively.

The on-resonance power transmission of the MMI-coupled slotted MRR from the slot bus waveguide is [22]:

$$T_R = |\alpha_{MMI} \frac{\alpha - t}{1 - \alpha t}|^2 \quad (4.7)$$

where t is the couplers through-coupling coefficient, α is the optical amplitude attenuation factor due to the microring loss and the coupler loss; that is $\alpha = \alpha_{MMI} \cdot \alpha_{ring}$. Therefore, in the MMI coupling region, $|t|^2 + |\kappa|^2 = |\alpha_{MMI}|^2$, where κ is the cross-coupling coefficient between bus and microring waveguides. The coupling coefficient

t is insensitive to the wavelength variations and fabrication inaccuracies in the MMI coupler [17]. The corresponding quality factor Q of the MRR can be expressed as:

$$Q \approx \frac{\pi n_g L}{\lambda} \frac{\sqrt{\alpha t}}{1 - \alpha t} \quad (4.8)$$

where λ is the wavelength in vacuum, L is the microring cavity length, n_g is the microring waveguide group index. The free spectral range (FSR) is:

$$FSR \approx \frac{\lambda^2}{n_g L} \quad (4.9)$$

Both Q and FSR are strong functions of the cavity length. Based on Eq. 4.8 and 4.9, an MRR with a longer cavity length gives a larger Q and a smaller FSR.

4.2.4 Fabrication and Measurements of Slotted MRR

The MMI-coupled slotted MRRs were fabricated on a SOI wafer with a silicon core thickness of 220 nm and a buried oxide (BOX) of 2 μm . The slot waveguides are comprised of a 180 nm air gap, sandwiched between two 300 nm-wide silicon wire waveguides, as shown in Fig. 4.6(a). The cladding is air for sensing purposes. The dimension of the MMI coupler is 3 μm (W_{MMI}) $\times$ 9.2 μm (L_{MMI}). The slot waveguides are butt-coupled to the 450-nm-wide input and output waveguide, as illustrated in Fig. 4.5(a). For the fiber-to-waveguide coupling, inversed tapers were integrated at each end of the input/output waveguide, terminating with a nominal width of 200 nm at the facets. Waveguides were fabricated using the OpSIS service, through A*STAR's IME in Singapore. Only MRRs with the radius of 20 μm were fabricated.

Figure 4.6(a) illustrates the fundamental quasi-TE mode profile of the fabricated slot waveguide with a 180 nm gap. A well-confined optical mode is supported in the air slot gap between the two silicon waveguide segments. The simulated optical field distribution in the fabricated MMI coupler with four slot waveguide ports is shown in Fig. 4.6(b). The optical field is attenuated when propagating through the

Figure 4.6: (a) Simulated fundamental TE mode profile (E field primarily parallel to the wafer surface) of the fabricated slot waveguide. (b) Optical field distribution of the fabricated MMI coupler by FDTD simulation.

butt-coupling region, the slot waveguide and the MMI coupler. Figure 4.6(b) also shows the directional coupling effect along the slot waveguides near both ends of the MMI coupler. Simulation results show that the splitting ratio of the fabricated MMI coupler is about 30:70. The simulated MMI coupler loss, α_{MMI} , is ~ -1.02 dB. The measurement setup is as follows: light from a tunable laser was coupled to the input waveguide via a polarization maintaining lensed fiber. The output light was collected and focused onto a photodetector using an objective lens. The measured transmission spectra for a MMI-coupled slotted MRRs with a radius of $20\ \mu\text{m}$ is shown in Fig. 4.7 for the TE polarization. The MMI has a dimension of $3 \times 9.2\ \mu\text{m}^2$. At 1510 nm, the resonance depth is measured to be ~ 25 dB, while the resonance bandwidth λ_{FWHM} is 1.1 nm. The FSR is measured to be 3.95 nm, while the quality factor Q is $\sim 1,300$ near the wavelength of 1510 nm. We have normalized our transmission results by removing the background loss. The background loss here includes the fiber-to-waveguide coupling loss (~ 2.5 dB/facet), the butt-coupling loss of the slot and wire waveguides (~ 1 dB), MMI coupler loss (~ 1 dB) and waveguide propagation loss (~ 1 dB), and system insertion loss (~ 4 dB).

Figure 4.7: (a) Measured transmission spectrum of the MMI-coupled slotted MRR with a radius of 20 m. The wavelength scan step is 1 pm. (b) Magnified transmission spectrum near 1510 nm.

Based on the simulated loss and splitting ratio of the MMI coupler, the calculated Q factor is estimated to be ~ 700 using Eq. 4.8, while the calculated FSR is ~ 4.4 nm. The measured FSR is consistent with the simulated value, while the measured Q factor is higher than the simulation results. One possible source of the discrepancy could be the inaccurate characterization of the splitting ratio of the MMI coupler. The variations in the resonance depth may result from the imperfect imaging length of the MMI coupler [21]. In addition, losses from the butt-coupling between the slot and access waveguide of the MMI are expected to be on the order of 3 dB. The optimization of the device parameters can further enhance the resonator performance.

Figure 4.8: Schematic of the MMI-coupled slotted MZI racetrack microring.

4.2.5 Slotted MZI Racetrack Microrings

We also fabricated MMI-coupled slotted MZIRMs, as shown in Fig. 4.10. This device is similar to the first device presented in Fig. 4.5(a), except there are 2 MMIs with one access arm, bc , connecting to each other. Effectively, this is an MZI racetrack MRR, with a major resonance wavelength at a high extinction ratio in a very large wavelength span (i.e., a large quasi-FSR). The large quasi-FSR is helpful for a wide measurement range in sensing applications [20].

For the MZIRM, the access arm, bc , represents one arm of the MZI, while the part of the microring, bc , is the other arm of the MZI (Fig. 4.10). The length difference between two arms $\Delta L = L_{bc} - L_{bc'}$ impacts the transmission coefficient from port a to port d , t_{ad} . To achieve a high Q factor, the length difference, ΔL , should be chosen to have a maximal transmission coefficient (t_{ad}) such that

$$n_{eff}\Delta L = (m + 1/2)\lambda_r \quad (4.10)$$

where n_{eff} is the effective index of the slot waveguide; m is the interference order; and λ_r is the major resonance wavelength of the MZIRM. In addition, to achieve a high extinction ratio, the transmission coefficient, t_{ad} , should match the loss in the microring to satisfy the “critical coupling” condition. For other resonance wavelengths, the extinction ratio is usually low due to the non-optimal transmission coefficient.

Figure 4.9: (a) Microscopic image of the fabricated MMI-coupled slotted MZI racetrack microring. (b) Measured transmission spectra of the MMI-coupled slotted MZI racetrack microring with a radius of 20 μm . The wavelength scan step is 1 pm.

Therefore, in a broad wavelength range, the MZIRM has only one major resonance wavelength, leading to a large quasi-FSR.

The radius of the MMI-coupled slotted MZIRM is also 20 μm . The length difference between two arms of the MZI is $\Delta L = 13.14 \mu\text{m}$, as shown in Fig. 4.9(a). Again, the slot waveguides are butt-coupled to the input/output wire waveguides. Figure 4.9(b) shows the measured spectrum transmission of the MMI-coupled slotted MZI racetrack MRR. The transmission depth of the major resonance near 1515 nm is ~ 24 dB. The quasi-FSR is 22.60 nm, which is about six times wider than the FSR of the fabricated MRR (FSR = 3.95 nm) in Fig. 4.7(b). Eq. 4.10 suggests that the length difference ΔL should be further reduced in order to obtain a larger quasi-FSR.

4.2.6 Conclusion

We first fabricated a slotted conventional MRR using an MMI coupler between the slot microring and slot bus waveguide. The MMI coupler has a compact footprint of $3 \times 9.2 \mu\text{m}^2$. After a successful demonstration of a ~ 25 dB transmission dip at 1510 nm with a Q factor $\sim 1,300$, we modified the device and fabricated a MMI-coupled slotted MZI racetrack microring. A much wider quasi-FSR of 22.60 nm was achieved

with identical microring radius design. Both slotted devices have a wide range of applications such as biochemical and gas sensing and modulation in communication systems.

Acknowledgement

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4.3 Mach-Zehnder Interferometer Racetrack Microring For Sensing

The following proceeding paper, “Silicon Mach-Zehnder interferometer racetrack microring for sensing”, provides details on the sensing performance of an MMI-coupled slotted and a conventional MZI racetrack microring resonator.

Yule Xiong performed all devices design and measurement, data analysis, and wrote the manuscript. The devices were fabricated by the OpSIS/IME foundry and the device measurement was completed in the group of Information and Communication Technologies at the NRC Canada. The article was presented the refereed international conference Photonics West (in Proc. SPIE Int. Soc. Opt. Eng., vol. 8990, pp. 89901H1-6), Photonics West 2014, in San Francisco, USA, on February 6, 2014.

Silicon Mach-Zehnder interferometer racetrack microring for sensing

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4.3.1 Abstract

SOI-based microring resonators (MRRs) have attracted extensive attentions as ultra-compact sensors. Recently, a new structure design combining a microring and a Mach-Zehnder interferometer (MZI) was proposed as sensors for biomedical applications, and as modulators for communications applications. In this design, the MZI uses two identical couplers, where one arm is formed by connecting the access waveguide of the couplers, while the other arm is part of the microring. Such a device may have only one major resonance with a high extinction ratio in a very broad wavelength span (quasi-free spectral range, quasi-FSR), which offers a very large measurement range for sensing applications. 2×2 multimode interference (MMI) couplers are used to couple the microring and the bus waveguides as MMI couplers have broader wavelength responses. We present the first experimental demonstration of the MMI-coupled MZI racetrack microrings for sensing applications. Two types of MMI-coupled MZI racetrack microrings are discussed: one with wire waveguides, and the other using slot waveguides. For the MZI racetrack microring using wire waveguides, we achieve a quasi-FSR of 34.3 nm near the wavelength of 1520 nm. The corresponding major resonance of the MZI racetrack microring demonstrates a high extinction ratio of

~ 22.4 dB with a full-width-half-maximum (FWHM) of 1.94 nm, and a quality factor Q of ~ 800 . On the other hand, the quasi-FSR of the MZI racetrack microring with slot waveguides is 23.2 nm near the wavelength of 1540 nm; and the extinction ratio of the major resonance is ~ 24.5 dB with $\lambda_{FWHM}=0.82$ nm and $Q=\sim 1,900$. To demonstrate the uses for sensing applications, we measure the resonance shifts corresponding to the concentration change of the ambient aqueous solutions of sucrose. DI water is used as the reference for calibration to avoid any other variations, e.g. temperature change. Experiments show that the sensitivities of the MZI racetrack microring sensors with wire and slot waveguides are 101.7 nm/RIU and 166.7 nm/RIU, respectively.

4.3.2 Introduction

Silicon photonics is promising for low-cost and high-density integration of microphotonic devices. Silicon-based microring resonators (MRRs) have attracted extensive attention as ultra-compact sensors for biomedical and telecommunications applications [2, 9, 10, 13, 23]. In a conventional MRR, directional couplers (DCs) or multimode interference (MMI) couplers are used to couple the microring and the bus waveguides. When using directional couplers, a high quality (Q) factor can be achieved, while MMI couplers are suitable for a low-/moderate- Q factor due to the additional MMI coupler loss [17]. High- Q devices are ideal for sensing applications, while devices with a moderate- Q factor are useful for high speed signal processing and the bandwidth (or the full-width-half-maximum, FWHM) of the operational resonance is wide.

Recently, unique structure designs combining a microring and a Mach-Zehnder interferometer (MZI) have been proposed [18–20, 24–26]. One design involves an MRR side-coupled to an MZI, which exhibits sharp Fano resonances [19, 24], with applications for low-power all-optical switching [18] and sensing applications [25]. Another design incorporates a racetrack MRR into an MZI by connecting the ends of the two bus waveguides of the microring to form one access MZI arm [20, 26]. The MZI racetrack microring has only one major resonance with a high extinction ratio in a very large wavelength span (i.e., quasi-free spectral range, quasi-FSR), which offers a very large measurement range for sensing applications. On the other hand, silicon-based sensor based on high index contrast materials, i.e., silicon-on-insulator (SOI) [27],

measuring refractive index change induced by molecular interaction can provide information on sample concentration or surface density. Highly compact SOI sensors with submicron scale features can be realized by using standard CMOS processing. The optical mode is expanded outside the silicon waveguide can sense surface perturbations with a high response. An MRR configuration can further amplify the sensing response since the light travelling in the microring effectively interacts with the same molecules many times [28]. The key advantages of an MRR include the small device footprint, the possibility of obtaining narrow line widths and high quality factor (Q-factor) performance, and the potential for large-scale monolithic integration. High Q-factor MRRs have longer effective length due to the reduced propagation losses. This raises the effective interaction length with the surroundings, leading to an increase in sensitivity. Owing to these facts, the SOI MRR based sensor have been demonstrated and studied extensively.

The MMI-coupled slotted MZI racetrack microrings has been proposed and demonstrated by our group previously [29]. In this work, we experimentally demonstrate the MMI-coupled MZI racetrack microring design for sensing.

4.3.3 MZI racetrack microring

Figure 4.10 shows the schematic of our MZI racetrack microring. It is composed of a microring, $a'b'c'd'$, and an access waveguide arm, bc , which is coupled to the microring by MMI couplers. The access arm, bc , represents one arm of the MZI, and the section of the microring, $b'c'$, forms the other arm of the MZI.

Using the transfer matrix method (TMM) [26], we obtain the field distribution relationship as

$$\begin{bmatrix} E_d \\ E_{d'} \end{bmatrix} = \begin{bmatrix} k_{cd} & k_{c'd} \\ k_{cd'} & k_{c'd'} \end{bmatrix} \begin{bmatrix} k_{bc} & 0 \\ 0 & k_{b'c'} \end{bmatrix} \begin{bmatrix} k_{ab} & k_{a'b} \\ k_{ab'} & k_{a'b'} \end{bmatrix} \begin{bmatrix} E_a \\ E_{a'} \end{bmatrix} \quad (4.11)$$

where k_{xy} is the coupling coefficient relating to the electric fields (E_x, E_y) at ports x and y . Assuming the two couplers are identical, the coupling coefficients are:

Figure 4.10: Schematic of the MZI racetrack microring with MMI couplers.

$$\begin{bmatrix} k_{ab} & k_{d'b} \\ k_{ab'} & k_{a'b'} \end{bmatrix} = \begin{bmatrix} k_{cd} & k_{c'd} \\ k_{cd'} & k_{c'd'} \end{bmatrix} = \alpha_{ab} \begin{bmatrix} t & \kappa \\ -\kappa^* & t^* \end{bmatrix} \quad (4.12a)$$

$$k_{b'c'} = k_{d'a'} = \alpha_{b'c'} \exp(-j\beta L_{b'c'}) \quad (4.12b)$$

$$k_{bc} = k_{d'a'} = \alpha_{bc} \exp(-j\beta L_{bc}) \quad (4.12c)$$

where t , and κ are the couplers through and cross coupling coefficients, respectively; α_{ab} is the optical amplitude attenuation factors due to the coupling loss of the DC or MMI coupler; α_{bc} and $\alpha_{b'c'}$ are the optical amplitude attenuation factors due to the microring propagation loss; β is the propagation constant of waveguides; L_{bc} and $L_{b'c'}$ are the lengths of the two MZI arms bc and $b'c'$, respectively. The field transmission can then be derived as:

$$\frac{E_d}{E_a} = k_{ab} + \frac{k_{a'd'} k_{d'a'} k_{ad'}}{1 - k_{d'a'} k_{a'd}} \quad (4.13)$$

where

$$k_{ad} = k_{ab}k_{bc}k_{cdab} + k_{ab'}k_{b'c'}k_{c'd'} \quad (4.14a)$$

$$k_{ad'} = k_{ab}k_{bc}k_{cd'} + k_{ab'}k_{b'c'}k_{c'd'} \quad (4.14b)$$

$$k_{a'd} = k_{a'b}k_{bc}k_{cd} + k_{a'b'}k_{b'c'}k_{c'd} \quad (4.14c)$$

Using the coupling coefficients from Eq. 4.12, we obtain

$$k_{ad} = (|t|^2\alpha_{ab}^2\alpha_{bc}\exp(-j\beta\Delta L) - |\kappa|^2\alpha_{ab}^2\alpha_{b'c'})\exp(-j\beta L_{b'c'}) \quad (4.15)$$

where $\Delta L = L_{bc} - L_{b'c'}$ is the length difference between the two arms of the MZI. Eq. 4.15 shows that the length difference ΔL impacts the transmission coefficient from port a to port d , k_{ad} , and therefore the Q factor of the MZI racetrack microring. To achieve a high Q factor, the length difference, ΔL should be chosen such that the transmission coefficient, k_{ad} , reaches its maximum. On the other hand, to achieve a high extinction ratio, the transmission coefficient, k_{ad} , should match the total roundtrip loss which includes both the microring propagation loss and the coupler loss such that the “critical coupling” condition for the microring is satisfied. Therefore, the major resonance wavelength of the MZI racetrack microring, λ_r , is given by the following equation:

$$n_g\Delta L = (p + 1/2)\lambda_r \quad (4.16)$$

where n_g is the group index of the waveguide; p is the interference order. For other resonant wavelengths, the extinction ratio is usually low due to non-critical transmission coefficients. Therefore, in a broad wavelength range, the MZI racetrack microring has only one major resonance wavelength, leading to a large quasi-FSR. The quasi-FSR for the MZI racetrack microring, defined as the wavelength difference between the two adjacent resonant wavelengths with high extinction ratios, can be approximately expressed as:

$$FSR_{quasi} = \frac{\lambda_r^2}{n_g \Delta L} \quad (4.17)$$

Two types of MMI-coupled MZI racetrack microrings are fabricated: One with wire access and microring waveguides [Figs. 4.11(a) and 4.11(b)]; and the other with slotted access and microring waveguides [Figs. 4.11(d) and 4.11(e)]. The cross-section of wire waveguides is 450 nm (Width) $\times$ 220 nm (Height) [Fig. 4.11(a)], while the slot waveguides are comprised of a 180 nm air gap, sandwiched between two 300 nm-wide silicon wire waveguides and the height is 220 nm [Fig. 4.11(d)]. The cladding is air for sensing purposes. The dimension of the MMI coupler is 3 μm (W_{MMI}) $\times$ 9 μm (L_{MMI}). The slot waveguides are butt-coupled to the 450-nm-wide input and output waveguides, as illustrated in Fig. 4.11(d). For the fiber-to-waveguide coupling, inverse tapers were integrated at each end of the input/output waveguide, terminating with a nominal width of 200 nm at the facets. The radius of the wire microring [Fig. 4.11(a)] is 6 μm while the radius of the slot microring [Fig. 4.11(d)] is 20 μm . All the devices were fabricated on a SOI wafer with a silicon core thickness of 220 nm and a buried oxide (BOX) of 2 μm using the OpSIS service, through A*STAR's IME in Singapore. The measurement setup is as follows: light from a tunable laser is coupled to the input waveguide via a polarization maintaining lensed fiber. The output light is collected and focused onto a photodetector using an objective lens. The measured transmission spectra for the MMI-coupled MZI racetrack microring using wire waveguides are shown in Fig. 4.11(c) for the TE polarization. Near the wavelength of 1520 nm, the major resonance extinction ratio (ER) is measured to be ~ 22.4 dB, while the resonance bandwidth λ_{FWHM} is 1.94 nm. The quasi-FSR is measured to be 34.3 nm, while the quality factor Q is ~ 800 near the wavelength of 1520 nm. The measured transmission responses for the MMI-coupled MZI racetrack microrings using slot waveguides are shown in Fig. 4.11(f) for the TE polarization. Near the wavelength of 1540 nm, the major resonance extinction ratio (ER) is measured to be ~ 24.5 dB, while the resonance bandwidth λ_{FWHM} is 0.82 nm. The quasi-FSR is measured to be 23.2 nm, while the quality factor Q is $\sim 1,900$ near the wavelength of 1540 nm.

Figure 4.11: Schematics, optical microscope pictures and measured transmission responses of the designed the MMI-coupled MZI racetrack microrings with (a)-(c) wire waveguides; and (d)-(f) slot waveguides.

4.3.4 Bulk refractive index sensing

The sensing principle of the silicon waveguide-based sensors is that the refractive index of the waveguide may be changed by both the surface covering of the sensing media and bulk index change. The cumulative optical phase delay $\Delta\theta$ in the waveguide is proportional to the waveguide group index perturbation Δn_g caused by the sensing media, and the interaction length L_w between the sensing media and the waveguide [30]. The phase delay can be expressed as:

$$\Delta\theta = \frac{2\pi}{\lambda} \Delta n_g L_w \quad (4.18)$$

where λ is the wavelength in vacuum. For silicon MMI-coupled MZI racetrack microrings based sensing devices, the optical phase delay of waveguides is converted to the major resonance wavelength shift

$$\Delta\lambda_r = \frac{L_r}{m} \Delta n_g \quad (4.19)$$

Figure 4.12: The major resonance wavelength λ_r shifts as the concentration of the sucrose solution varies. (Inset: Measured transmission responses of the MZI racetrack microring covered by the sucrose solution with difference concentrations): (a) MZI racetrack microring using wire waveguides; (b) MZI racetrack microring using slot waveguides.

where L_r is the round trip length and m is the cavity mode order. A change of the refractive index of the cavity's environment shifts the major resonance wavelengths.

Liquids with varying refractive indices (water with different sucrose concentrations) are dropped onto the MMI-coupled MZI racetrack microring in order to characterize the sensor for bulk refractive index sensitivity. No surface chemistry is carried out, so the refractive index is homogenously changed above the MZI racetrack microring. At 20 °C, the refractive index of an aqueous solution of sucrose varies with 0.0015 RIU (Refractive Index Units) per mass % [31]. In our experiment, the concentration varies from 0 to 4% with a step of 2% and the corresponding refractive index ranges from 1.316 to 1.322. All measurements are done three times to verify the reliable and repeatability. Fig. 4.12 shows linear shifts of the major resonance wavelengths with increasing sucrose concentration for the MMI-coupled MZI racetrack microrings using wire and slot waveguides. The corresponding sensitivity of the device with wire waveguides is 101.7 nm/RIU and 166.7 nm/RIU for the device using slot waveguides. A higher sensitivity of the MZI racetrack microrings using slot waveguides is due to a high light-matter interaction in the slot waveguide. However, for the device using slot waveguide, the trapped air may slow down the solution filling into the slot region [32]. For practical sensing applications, this issue can be handled by the integration of the microfluidic sample channel [33].

4.3.5 Conclusion

In summary, we have experimentally demonstrated two types of MMI-coupled MZI racetrack microring sensors, one with wire waveguides and the other with slot waveguides. MZI-coupled racetrack microrings have large quasi-FSR, which makes it accessible for large-range measurements. Using sucrose aqueous solution, it has been illustrated that the major resonance wavelength shifts linearly as the index varies. The sensitivities of the sensors using wire and slot waveguides are 101.7 nm/RIU and 166.7 nm/RIU, respectively. The presented MMI-coupled MZI racetrack microring sensors can be used in various sensing applications, e.g. the concentration measurement of gas or liquid in environmental monitoring.

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4.4 Ring-Assisted Mach-Zehnder interferometer

The following paper, “All-optical switching of a single wavelength in a silicon-based ring-assisted Mach-Zehnder interferometer”, provides the details on the numerical analysis of an all-optical switch based on ring-assisted Mach-Zehnder interferometer.

Yule Xiong performed all devices design and numerical analysis, and wrote the paper. The article was published in Applied Optics, volume 51, issue 32, on pages 7788-7793, in 2012.

All-optical switching of a single wavelength in a silicon-based ring-assisted Mach-Zehnder interferometer

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4.4.1 Abstract

We theoretically investigate, for the first time, an all-optical switch using silicon-based ring-assisted Mach-Zehnder interferometer (RAMZI), where the switch mechanism relies on Raman-induced loss. Compared to the conventional standalone microring resonator (MRR) switches, the RAMZI structure improves the fabrication tolerances by removing the critical coupling requirement for the MRR without compensating the switch performance. Moreover, the RAMZI structure provides an improved switching speed (5 times) by shortening the photon lifetime of the MRR. Finally, the inverse Raman scattering (IRS) of silicon guarantees a single wavelength selectivity for the switch.

4.4.2 Introduction

Silicon photonics is a promising platform for future low cost and high speed integrated optical signal processing due to its compatibility with complementary metal-oxide-semiconductor (CMOS) technology [34]. Silicon-on-insulator (SOI) optical switches

and modulators are essential building blocks for on-chip silicon photonic circuits. Optically induced loss in resonant structure can be used to achieve an all-optical switching by tuning the coupling condition. Switching systems have been proposed by using the two-photon absorption in atomic vapor [35] or the difference frequency generation in III-V materials [36] as the loss mechanism. However, these systems tend to be broadband and require complicated fabrication and/or operating process.

Early in 2012, Raman-induced loss in a silicon microring resonator (MRR) add-drop filter was proposed for all-optical switching of a single wavelength [37] and was subsequently demonstrated experimentally [38]. Optical loss induced by inverse Raman scattering (IRS) at the anti-Stokes wavelength has a bandwidth much narrower than the free spectral range (FSR) of a typical microring cavity, but wider than the resonance linewidth [39]. The narrow bandwidth allows modulation of specific resonance independently while leaving adjacent resonances undisturbed by simply changing the control light wavelength. However, the all-optical MRR switch is restricted to be operated close to the critical coupling point of the MRR in order to achieve a high extinction ratio (ER) because the intensity switching entirely depends on the changes in the coupling conditions of the standalone MRR. As a result of the operation restriction, the achievable fabrication tolerances are extremely demanding. As an alternative to the intensity switching, we propose a phase switching of the MRR by using a ring-assisted Mach-Zehnder interferometer (RAMZI) optical structure. Although the RAMZI configuration has been reported previously [19], this is the first reported use of the IRS induced loss in a silicon-based RAMZI switch. The RAMZI switch works as long as the coupling between the MRR and the MZI arm is over-coupled. Compared to the standalone MRR, a RAMZI switch has less stringent fabrication requirements and offers the potential for achieving a higher switching speed [40].

4.4.3 Design and Theory

The schematic of the proposed RAMZI all-optical switch is illustrated in Fig. 4.13. It consists of an MRR coupled to one arm of an MZI. The MZI has two arms of equal lengths, with two 3 dB couplers (one splitter and one combiner).

Figure 4.13: Schematic of an all-optical switch based on a ring-assisted MZI (RAMZI) with control light and anti-Stokes signal.

Since the waveguide lengths of two arms in the MZI are set to be identical, the output amplitude of the RAMZI switch can be written as

$$E_{out} = \frac{\alpha_{MZI} E_{in}}{2} [\alpha_r e^{i(knL + \phi_r)} + e^{iknL}] \quad (4.20)$$

where E_{in} is the amplitude of the input signal light, α_{MZI} , n , and L are the amplitude attenuation factor, effective index and length of the arms, respectively. The amplitude attenuation factor α_r and phase delay ϕ_r introduced by the side-coupled MRR can be written as follows, respectively [41]

$$\alpha_r = \sqrt{\frac{t_1^2 + t_2^2 \gamma^2 - 2t_1 t_2 \gamma \cos(\theta)}{1 + t_1^2 t_2^2 \gamma^2 - 2t_1 t_2 \gamma \cos(\theta)}} \quad (4.21)$$

$$\phi_r = \tan^{-1} \left[\frac{-(1 - t_1^2) t_2 \gamma \sin(\theta)}{(1 + t_2^2 \gamma^2) t_1 - (1 + t_1^2) t_2 \gamma \cos(\theta)} \right] \quad (4.22)$$

where t_1 , t_2 , γ and θ are the coupling coefficients, the round-trip amplitude attenuation factor and phase delay of the side-coupled MRR, respectively.

If a control light is introduced into the side-coupled MRR, as shown in Fig. 4.13, the IRS effect occurs. The IRS effect in a silicon waveguide is a nonlinear process that the anti-Stokes wavelength is attenuated in the presence of an intense control light

and can be described by using the generalized nonlinear Schrödinger equation [39]:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = i\chi \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}\right) A(z, t) \times \int_{-\infty}^t R(t-t') |A(z, t')|^2 dt' + \left[\frac{i\omega_0 n_{FCR}}{c} - \frac{\alpha_{FCA}}{2}\right] A \quad (4.23)$$

where $A(z, t)$ is the field envelop, β_2 is material dispersion coefficient, χ is the nonlinear coefficient related to the two-photon absorption (TPA) effect, ω_0 is the carrier frequency, $R(t)$ is the third-order nonlinear time response function, n_{FCR} is the index change of the free carrier refraction (FCR) due to the carrier excitation, and α_{FCA} is the free carrier absorption (FCA) coefficient. As shown in Eq. 4.23, the control light also introduces TPA, which generates additional free carriers and the subsequent n_{FCR} and α_{FCA} [42, 43].

Once the IRS occurs in the side-coupled MRR, the round-trip amplitude attenuation factor, γ , decreases, and can be written as:

$$\gamma = e^{-[\alpha_0 + \alpha_{FCA} I_C + \alpha_R(\omega) I_C]l} \quad (4.24)$$

where α_0 and α_{FCA} are the MRR intrinsic attenuation factor and the FCA factor, respectively; $\alpha_R(\omega)$ is the IRS induced attenuation coefficient at the frequency ω , I_C is the power density of the control light inside the side-coupled MRR, and l is the circumference of the MRR. The generated free carriers suffer FCA effects as well as experience changes in the refractive index, n_{FCR} . Such a nonlinear process degrades the IRS effect. To alleviate this undesirable effect, a reversed-biased p-i-n junction is proposed to be used for the side-coupled MRR to shorten the carrier lifetime. In addition, the control light needs to be pulsed [38] and the pulse repetition is required to be shorter than that of the carrier lifetime [44]. Although FCR will blueshift the resonance, the FCR effect can be mitigated by the Kerr index redshift under the control light [37]. In our simulations presented below, we carefully choose the parameters, such that the FCA and FCR effects effectively cancel out in the analysis.

4.4.4 Simulation and Analysis

The cross-section of the waveguide is set to $220 \text{ nm} \times 450 \text{ nm}$ and the MRR radius is $16 \text{ }\mu\text{m}$ such that both the control and anti-Stokes wavelengths are resonant inside the side-coupled MRR. We assume the intrinsic propagation loss of the waveguide is 2 dB/cm [45]. The coupling coefficients are chosen as $t_1=0.97$ and $t_2=0.9998$ to make the MRR over-coupled to one arm of the MZI. Our single-wavelength selective switch has a FWHM (Full width at half maximum) of 0.092 nm and a FSR (Free spectral range) of 8.18 nm , respectively. The finesse ($F=\text{FSR}/\text{FWHM}$) is 89.02 while the Q (quality factor) is $15,567.82$.

For silicon, the Raman linewidth is $\Gamma=105 \text{ GHz}$, and the Raman shift is $\omega=15.6 \text{ THz}$ [19]. The IRS induced attenuation coefficient, α_R , near the anti-Stokes frequency, ω_α , is determined by [39]

$$\alpha_R(\omega) = \frac{g\Gamma^2}{(\omega - \omega_\alpha)^2 + \Gamma^2} \quad (4.25)$$

where g is peak Raman gain. Here we set $g=76 \text{ cm/GW}$ for the control light of 1430 nm , whose corresponding anti-Stokes signal is around 1330 nm .

When the coupling condition of the side-coupled MRR shifts from being over-coupled to critically-coupled, and then to under-coupled, the transmission of the RAMZI switch increases from the minimum to the maximum [46]. By definition, when the MRRs round-trip power loss is weaker than the light coupling between the microring and the coupling waveguides ($\gamma > |t_1|/|t_2|$), the MRR achieves the over-coupled condition; at the critically-coupled condition ($\gamma = |t_1|/|t_2|$), the round-trip power loss is equal to the light coupling; with the under-coupled condition ($\gamma < |t_1|/|t_2|$), the round-trip power loss is stronger than the light coupling. According to Eq. 4.24, the decrease of round-trip amplitude attenuation factor (γ) due to the IRS effect changes the original over-coupled condition of the side-coupled MRR at the anti-Stoke wavelength. Therefore, the switching of a single wavelength can be realized by the RAMZI structure.

The output transmission spectrum of the RAMZI switch is plotted for several control light pulse energies in Fig. 4.14. In the absence of the control light, the

Figure 4.14: (a) Transmission spectrum of the RAMZI switch. (b) Transmission at the anti-Stokes resonance for several control light pulse energies.

side-coupled MRR induces a π phase shift to the resonant wavelength at $\lambda_\alpha = 1330$ nm, which propagates through one arm of the MZI. This π phase shift leads to the minimum transmission at the MZI output. No changes on the spectral shape is observed at $\lambda_\alpha = 1330$ nm, as illustrated in Fig. 4.14(a). In the presence of the control light $\lambda_C = 1430$ nm, the side-coupled MRR introduces additional losses at its anti-Stokes wavelength $\lambda_\alpha = 1330$ nm due to the IRS effect. The MRR provides a minimal phase shift at $\lambda_\alpha = 1330$ nm, allowing the signals in the two MZI arms recombine constructively at the 3dB combiner, yielding the maximum transmission at $\lambda_\alpha = 1330$ nm. The transmission spectrum of the RAMZI is shown in Fig. 4.14(b). The transmission power depends on the control light pulse energy. Figure 4.14(b) shows that with a control pulse of 0.4 pJ and 20 pJ, on-resonance transmissions of -6.81 dB and -0.33 dB can be achievable respectively. Figure 4.14 demonstrates that the transmission at the anti-Stokes resonance can be switched from full extinction to full transmission with high selectivity.

Figure 4.15 shows the corresponding transmission spectrum of the side-coupled MRR. When the control light pulse energy increases from zero to 0.4 pJ, and then to

Figure 4.15: (a) Transmission from Arm 1 of the RAMZI for the side-coupled MRR resonance. (b) Transmission at the anti-Stokes resonance for several control light pulse energies.

20 pJ, the coupling condition of the side-coupled MRR shifts from being over-coupled, to critically-coupled, and then reaching under-coupled, respectively. With a control pulse of 0.4 pJ, the transmission of the side-coupled MRR is -21.28 dB. The control light pulse energy of 0.4 pJ leaves the adjacent resonances undisturbed, while the control pulse of 20 pJ induces around 7 dB variation to the resonances next to the anti-Stokes resonance at $\lambda_a=1330$ nm, as shown in Fig. 4.14. Therefore, appropriate control light pulse energy must be chosen for the trade-off between the transmission of anti-Stokes resonance and the minimal disturbance of the adjacent resonances.

To investigate the switching efficiency of the RAMZI switch, we increase the input control light pulse energy from zero to 20 pJ. The simulated transmission of the switch is shown in Fig. 4.17(a). The switch is most power efficient at the roll-off point (1.2 pJ at ~ -3 dB transmission). Operating slightly above the roll-off point will not only offer a good switching contrast (i.e., switching extinction ratio), but also provide a reduced power consumption.

Figure 4.16: (a) Transmission spectrum of the RAMZI switch. (b) Transmission at the anti-Stokes resonance for the control light pulse energy of 20 pJ (Resonances next to the anti-Stokes wavelength are disturbed). Inset: transmission spectrum around the anti-Stokes wavelength for the control light pulse energy of 0.4 pJ.

The required input control light pulse energy varies with different structure parameters such as the transmission coefficients (t_1 and t_2) and the MRR radius. Since the finesse (F) of the MRR characterizes the MRR cavity and reflects the overall effects of the changes in the structure parameters, we plot in Fig. 4.17(b) the required control light pulse energy at the roll-off point as a function of F . When the finesse of the side-coupled MRR increases, the required input control pulse energy at the roll-off point (3 dB transmission) exponentially decreases.

To investigate the time response of the switch, we introduce a pulse duration of 200 ps for the control light ($\lambda_C = 1430$ nm) to avoid the broadband TPA-induced loss. The control pulse energy is set to 20 pJ in order to achieve full transmission. Figure 4.18 shows the time response of the anti-Stokes signal, $\lambda_\alpha = 1330$ nm, at the output port of the RAMZI. The switch-on time, which is the time required for the anti-Stokes signal to switch from full extinction to full transmission, is predicted to be about 50 ps; while the total response time for a full switching period is approximately 400 ps. This corresponds to data rates of 2.5 GHz on a single channel. The time-domain switching dynamics confirm the switching of a single wavelength at a gigahertz rate.

Figure 4.17: (a) Transmission as a function of the control light pulse energy. Switching is most efficient for transmission values below -3 dB. (b) Required control light pulse energy at the roll-off point (3 dB transmission) for various finesses (F) of the side-coupled MRR.

Figure 4.18: Simulated time response of the anti-Stokes signal with 200 ps control pulse of 20 pJ.

4.4.5 Comparison of RAMZI and MRR Switches

All-optical switch based on the IRS effect was first reported in a standalone MRR configuration [37]. However, fabrication deviations could result in both variations on the MRR losses as well as the coupling coefficients due to variations in the coupling separation between the bus and the microring waveguide. In this paper, our proposed side-coupled MRR in the RAMZI switch does not need to be operated at the exact critical coupling point. The RAMZI device works as long as the MRR is over-coupled. In addition, the fabrication deviations in the lengths of the MZI arm do not significantly degrade the ER of the RAMZI switch. Our simulations show that the variation of the ER is less than 1 dB when the arm length offset ratio $\delta L/\text{arm length (L)}$ is less than 0.0004. Thus the fabrication deviation of the arm length should be less than 86 nm ($L=215\ \mu\text{m}$). This requirement can easily be achieved by employing the e-beam or deep UV lithography [47].

Figures 4.19(a) and 4.19(b) illustrate the simulated ER as a function of the coupling coefficients, t_1 , t_2 , and the microring intrinsic loss, α_0 , for the standalone MRR based switch. Using identical parameters set in [37], we use $16\ \mu\text{m}$ as the MRR radius. The corresponding plots for our proposed RAMZI switch are demonstrated in Figs. 4.19(c) and 4.19(d). We observe that the RAMZI switch achieves a better performance because an acceptable ER can be obtained by a larger range of device parameters (coupling coefficients and loss). High ER values in the standalone MRR switch can only be seen at the critical coupling condition when the MRR intrinsic loss satisfied the relation $\gamma = |t_1|/|t_2|$. Any variations in γ or the coupling coefficients would severely reduce the ER. In contrast, the ER in the RAMZI switch is less sensitive to variations to device parameters. As a result, the proposed switch significantly improves its fabrication tolerances compared to the standalone MRR switch. In addition, the switching speed is limited by the photon lifetime of the MRR, which determines how fast light can be coupled into and out of the MRR. As the MRR is over-coupled to the arm of the MZI in the RAMZI switch, the photon lifetime inside the MRR is shorter than that inside a critically-coupled standalone MRR [40]. Therefore the RAMZI switch has the potential for achieving a higher switching speed. The RAMZI switch has a switching speed five times faster than the standalone MRR switch: 500 MHz reported in [37] for the MRR switch versus 2.5 GHz as seen in Fig. 4.14 for our RAMZI switch. Moreover, smaller MRRs with optimized parameters

Figure 4.19: Simulated ER as a function of the coupling coefficients t_1 , t_2 and the microring intrinsic loss a_0 with 200 ps control pulse of 20 pJ: (a) and (b) are for a standalone MRR switch, and (c) and (d) are for a RAMZI switch, where the blue indicates $ER > 5$ dB, while the green, yellow, brown are for $ER > 10$ dB, > 15 dB, > 20 dB, respectively. In (a) and (c), $a_0 = 2$ dB/cm.

(e.g., t_1 and t_2) would further improve the switching speed due to the reduced photon lifetime, as well as a lower Q of the MRR.

4.4.6 Conclusion

This paper combines the concept of Raman-induced loss for modulation and a silicon-based ring-assisted MZI configuration. The proposed device allows for highly selective single-wavelength switching. The wavelength selective switching is useful for optical signal processing applications. In addition, this device can be fabricated with standard CMOS fabrication processes, with less stringent fabrication tolerances compared to the standalone MRR switches.

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List of References

- [1] A. L. Washburn, L. C. Gunn, and R. C. Bailey, “Label-free quantitation of a cancer biomarker in complex media using silicon photonic microring resonators,” *Analytical chemistry*, vol. 81, pp. 9499–9506, Nov. 2009.
- [2] K. De Vos, I. Bartolozzi, E. Schacht, P. Bienstman, and R. Baets, “Silicon-on-Insulator microring resonator for sensitive and label-free biosensing,” *Optics Express*, vol. 15, pp. 7610–7615, June 2007.
- [3] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, and Y. Sun, “Sensitive optical biosensors for unlabeled targets: a review,” *Analytica chimica acta*, vol. 620, pp. 8–26, July 2008.
- [4] K. B. Gylfason, C. F. Carlborg, A. Ka, F. Dortu, H. Sohlstr, L. Vivien, C. A. Barrios, and W. V. D. Wijngaart, “On-chip temperature compensation in an integrated slot-waveguide ring resonator refractive index sensor array,” *Optics Express*, vol. 18, no. 4, pp. 3226–3237, 2010.
- [5] W. N. Ye, J. Michel, and L. C. Kimerling, “Athermal high-index-contrast waveguide design,” *IEEE Photonics Technology Letters*, vol. 20, pp. 885–887, June 2008.
- [6] D. Xu, E. Post, A. Densmore, P. Waldron, S. Janz, J. Lapointe, A. Delège, P. Cheben, J. H. Schmid, and B. Lamontagne, “Cancellation of the temperature dependence in SOI photonic Wire ring resonator sensors,” in *5th IEEE International Conference on Group IV Photonics*, pp. 398–400, 2008.
- [7] T. Kaneko, Y. Kokubun, and E. Ippen, “Vertically coupled glass microring resonator channel dropping filters,” *IEEE Photonics Technology Letters*, vol. 11, no. 2, pp. 215–217, 1999.
- [8] Y. Xiong and W. N. Ye, “Vertically coupled Si-based athermal double-ring biosensor,” in *Proc. of SPIE 8007* (R. Kashyap, M. Têtu, and R. N. Kleiman, eds.), vol. 8007, p. 80070V, June 2011.
- [9] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. Van Thourhout, and R. Baets, “Silicon microring resonators,” *Laser and Photonics Reviews*, vol. 6, pp. 47–73, Jan. 2012.

- [10] M. Ziebell, D. Marris-Morini, G. Rasigade, P. Crozat, J.-M. Fédéli, P. Grosse, E. Cassan, and L. Vivien, "Ten Gbit/s ring resonator silicon modulator based on interdigitated PN junctions," *Optics Express*, vol. 19, pp. 14690–14695, July 2011.
- [11] V. R. Almeida, Q. Xu, C. A. Barrios, and M. Lipson, "Guiding and confining light in void nanostructure," *Optics Letters*, vol. 29, pp. 1209–1211, June 2004.
- [12] F. Dell'Olio and V. M. Passaro, "Optical sensing by optimized silicon slot waveguides," *Optics Express*, vol. 15, pp. 4977–4993, Apr. 2007.
- [13] T. Claes, J. Molera, K. De Vos, E. Schacht, R. Baets, and P. Bienstman, "Label-free biosensing with a slot-waveguide-based ring resonator in silicon on insulator," *IEEE Photonics Journal*, vol. 1, pp. 197–204, Sept. 2009.
- [14] J. Leuthold, C. Koos, and W. Freude, "Nonlinear silicon photonics," *Nature Photonics*, vol. 4, pp. 535–544, July 2010.
- [15] M. Gould, T. Baehr-Jones, R. Ding, S. Huang, J. Luo, A. K.-Y. Jen, J.-M. Fedeli, M. Fournier, and M. Hochberg, "Silicon-polymer hybrid slot waveguide ring-resonator modulator," *Optics Express*, vol. 19, pp. 3952–3961, Feb. 2011.
- [16] T. Baehr-Jones, M. Hochberg, C. Walker, and A. Scherer, "High-Q optical resonators in silicon-on-insulator-based slot waveguides," *Applied Physics Letters*, vol. 86, no. 8, p. 081101, 2005.
- [17] D.-X. Xu, A. Densmore, P. Waldron, J. Lapointe, E. Post, A. Delâge, S. Janz, P. Cheben, J. H. Schmid, and B. Lamontagne, "High bandwidth SOI photonic wire ring resonators using MMI couplers," *Optics Express*, vol. 15, no. 6, pp. 3149–3155, 2007.
- [18] Y. Xiong and W. N. Ye, "All-optical switching of a single wavelength in a silicon-based ring-assisted Mach-Zehnder interferometer," *Applied Optics*, vol. 51, pp. 7788–7793, Nov. 2012.
- [19] A. M. Gutierrez, A. Brimont, G. Rasigade, M. Ziebell, J. Fédéli, L. Vivien, J. Marti, P. Sanchis, and A. A. M. Zehnder, "Ring-Assisted Mach Zehnder Interferometer Silicon Modulator for Enhanced Performance," *IEEE Journal of Lightwave Technology*, vol. 30, no. 1, pp. 9–14, 2012.
- [20] J. Wang and D. Dai, "Highly sensitive Si nanowire-based optical sensor using a Mach-Zehnder interferometer coupled microring," *Optics Letters*, vol. 35, pp. 4229–4231, Dec. 2010.
- [21] L. Soldano and E. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications," *Journal of Lightwave Technology*, vol. 13, pp. 615–627, Apr. 1995.
- [22] D.-X. Xu, S. Janz, P. Cheben, and A. Abstract, "Design of polarization-insensitive ring resonators in silicon-on-insulator using MMI couplers and cladding stress engineering," *IEEE Photonics Technology Letters*, vol. 18, no. 2, pp. 2005–2007, 2006.

- [23] K. J. Vahala, "Optical microcavities," *Nature*, vol. 424, pp. 839–846, 2003.
- [24] A. Leinse, M. B. J. Diemeer, A. Rousseau, and A. Driessen, "A novel high-speed polymeric EO modulator based on a combination of a microring resonator and an MZI," *IEEE Photonics Technology Letters*, vol. 17, no. 10, pp. 2074–2076, 2005.
- [25] M. Terrel, M. J. F. Digonnet, and S. Fan, "Ring-coupled Mach-Zehnder interferometer optimized for sensing," *Applied Optics*, vol. 48, no. 26, pp. 4874–4879, 2009.
- [26] W. M. J. Green, R. K. Lee, G. A. Derosé, A. Scherer, and A. Yariv, "Hybrid InGaAsP-InP Mach-Zehnder racetrack resonator for thermo-optic switching and coupling control," *Optics Express*, vol. 13, no. 5, pp. 1651–1659, 2005.
- [27] A. Densmore, D. Xu, P. Waldron, S. Janz, P. Cheben, J. Lapointe, A. Delâge, B. Lamontagne, J. H. Schmid, and E. Post, "A silicon-on-insulator photonic wire based evanescent field sensor," *IEEE Photonics Technology Letters*, vol. 18, no. 23, pp. 2520–2522, 2006.
- [28] D.-X. Xu, M. Vachon, A. Densmore, R. Ma, A. Delâge, S. Janz, J. Lapointe, Y. Li, G. Lopinski, D. Zhang, Q. Y. Liu, P. Cheben, and J. H. Schmid, "Label-free biosensor array based on silicon-on-insulator ring resonators addressed using a WDM approach," *Optics Letters*, vol. 35, pp. 2771–2773, Aug. 2010.
- [29] Y. Xiong and W. N. Ye, "Silicon MMI-coupled slotted conventional and MZI racetrack microring resonators," *IEEE Photonics Technology Letters*, vol. 25, no. 19, pp. 1885–1888, 2013.
- [30] D. X. Xu, A. Densmore, A. Delâge, P. Waldron, R. McKinnon, S. Janz, J. Lapointe, G. Lopinski, T. Mischki, E. Post, P. Cheben, and J. H. Schmid, "Folded cavity SOI microring sensors for high sensitivity and real time measurement of biomolecular binding," *Optics Express*, vol. 16, pp. 15137–15148, Sept. 2008.
- [31] W. M. Haynes, "Concentrative properties of aqueous solutions : density , refractive index , freezing point depression , and viscosity," in *Handbook of Chemistry and Physics*, ch. 5, pp. 145–146, CRC Press, 2013.
- [32] K. Yadav, *Perforated Mach-Zehnder interferometer evanescent field sensor in silicon-on-insulator*. Master of applied science, Carleton University, 2006.
- [33] C. F. Carlborg, K. B. Gylfason, A. Kaźmierczak, F. Dortu, M. J. Bañuls Polo, A. Maquieira Catala, G. M. Kresbach, H. Sohlström, T. Moh, L. Vivien, J. Poplewell, G. Ronan, C. a. Barrios, G. Stemme, and W. van der Wijngaart, "A packaged optical slot-waveguide ring resonator sensor array for multiplex label-free assays in labs-on-chips," *Lab on a Chip*, vol. 10, pp. 281–290, Feb. 2010.
- [34] R. Soref, "The past, present, and future of silicon photonics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 6, pp. 1678–1687, 2006.
- [35] B. C. Jacobs, J. D. Franson, and B. County, "All-optical switching using the quantum zeno effect and two-photon absorption," *Physical Review A*, vol. 79, p. 063830, 2009.

- [36] Y.-P. Huang and P. Kumar, "Interaction-free all-optical switching in $\chi(2)$ microdisks for quantum applications," *Optics Letters*, vol. 35, pp. 2376–2378, July 2010.
- [37] Y. H. Wen, O. Kuzucu, T. Hou, M. Lipson, and A. L. Gaeta, "All-optical switching of a single resonance in silicon ring resonators," *Optics Letters*, vol. 36, pp. 1413–1415, Apr. 2011.
- [38] Y. H. Wen, O. Kuzucu, M. Fridman, A. L. Gaeta, L.-W. Luo, and M. Lipson, "All-optical control of an individual resonance in a silicon microresonator," *Physical Review Letters*, vol. 108, p. 223907, June 2012.
- [39] D. Solli, P. Koonath, and B. Jalali, "Inverse Raman scattering in silicon: A free-carrier enhanced effect," *Physical Review A*, vol. 79, p. 053853, May 2009.
- [40] Y. Li, L. Zhang, M. Song, B. Zhang, J.-Y. Yang, R. G. Beausoleil, A. E. Willner, and P. D. Dapkus, "Coupled-ring-resonator-based silicon modulator for enhanced performance," *Optics Express*, vol. 16, pp. 13342–13348, Aug. 2008.
- [41] A. Yariv, "Universal relations for coupling of optical power between microresonators and dielectric waveguides," *Electronics Letters*, vol. 36, no. 4, pp. 1–2, 2000.
- [42] R. Soref and B. Bennett, "Electrooptical effects in silicon," *IEEE Journal of Quantum Electronics*, vol. 23, pp. 123–129, Jan. 1987.
- [43] T. K. Liang and H. K. Tsang, "Role of free carriers from two-photon absorption in Raman amplification in silicon-on-insulator waveguides," *Applied Physics Letters*, vol. 84, no. 15, p. 2745, 2004.
- [44] B. Jalali, D. Dimitropoulos, V. Raghunathan, and S. Fathpour, "Silicon laser," in *Silicon Photonics: The State of the Art* (G. T. Reed, ed.), ch. 4, pp. 166–170, Wiley, 2008.
- [45] S. Xiao, M. H. Khan, H. Shen, and M. Qi, "Compact silicon microring resonators with ultra-low propagation loss in the C band," *Optics Express*, vol. 15, no. 22, pp. 14467–14475, 2007.
- [46] B. E. Little, "Track changing by use of the phase response of microspheres and resonators," *Optics Letters*, vol. 23, no. 12, pp. 894–896, 1998.
- [47] Y. Xia and G. M. Whitesides, "Soft lithography," *Annual Review Material Science*, vol. 28, pp. 153–184, 1998.

Chapter 5

Subwavelength Grating (SWG)-Based Devices

In this chapter, a new waveguide structure, subwavelength grating (SWG), is introduced to implement two devices: one is for providing polarization splitting and rotation; the other is a TE-pass polarizer.

5.1 Polarization splitter and rotator with subwavelength grating

The following paper, “Polarization splitter and rotator with subwavelength grating for enhanced fabrication tolerance,” demonstrates the numerical analysis of the polarization splitter and rotator based on a subwavelength grating waveguide. This paper includes the device design and simulation, discussion and analysis.

Yule Xiong performed the device design, all simulations, and wrote this paper. The paper was conditionally accepted by Optics Letters with minor corrections on November 7, 2014.

Polarization splitter and rotator with subwavelength grating for enhanced fabrication tolerance

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5.1.1 Abstract

We propose a novel method to implement a compact and fabrication tolerant polarization splitter and rotator (PSR) on the silicon-on-insulator platform. The PSR consists of a silicon wire waveguide coupled to a subwavelength grating (SWG) waveguide in an asymmetrical directional coupler. The SWG effect allows an additional degree of design freedom to engineer the equivalent material refractive index. This is advantageously used to effectively compensate for fabrication inaccuracies in PSR. Our simulation results show that the PSR has a low TM-to-TE cross polarization conversion loss of -0.13 dB (a conversion efficiency of 97%) at the wavelength of 1550 nm, and better than -0.4 dB conversion loss over the entire C-band wavelength range. Compared to PSRs made of conventional wire waveguides, the use of SWG index

engineering improves the waveguide width fabrication tolerance substantially, from ± 3 nm to ± 40 nm. A compact device size with a coupling length of $25\ \mu\text{m}$ is achieved.

5.1.2 Introduction

Polarization management is an important research topic in silicon photonics [1]. Polarization splitters and rotators (PSRs) are structures of fundamental importance in polarization diversity systems [2] and polarization multiplexing devices [3]. Various types of passive polarization splitters and rotators have been reported [4–12]. PSRs using asymmetrical directional couplers (DCs) [8] can achieve simultaneously both polarization splitting and rotation functions. However, directional couplers require precise phase matching and therefore inherently sensitive to fabrication dimensional variations. Tapered directional couplers [9] and taper-etched directional couplers [10] were proposed to compensate for the waveguide width fabrication variations, at the cost of a relatively large footprint (on the order of a hundred microns). A more compact PSR with large fabrication tolerance is desirable for silicon-based photonic integrated circuits.

The subwavelength grating is a structure with a pitch substantially smaller than the wavelength of light propagating through the structure, behaving effectively as a homogenous medium [13, 14]. The equivalent material index of the SWG can be modified by changing the duty ratio. The SWG effect provides a new degree of freedom for the design of novel silicon photonic components and many devices with improved performance have been reported. SWGs have been used for efficient fiber-to-chip surface grating couplers [15], edge couplers [13, 16], multimode interference (MMI) couplers for integrated coherent receivers [17], and low loss waveguide crossings [18], to name a few. Recently, it has been shown that the SWG effect can also be used to engineer the dispersive properties of both MMIs [19] and DCs [20]. All these results are comprehensively reviewed in [21].

Here we propose a general strategy to improve the fabrication tolerance of PSRs based on directional couplers. The key to our approach is to allow the two waveguides in the DC to have different material indices. By doing so, the mode effective indices of both waveguides can be made to change equally when the waveguide width

fluctuates, therefore maintaining the phase-matching condition. This can be achieved by using a material with a different refractive index to form the second waveguide, or practically by using subwavelength grating (SWG) structures. We show for the first time that SWG waveguides can be utilized to engineer the *dimension dependence* of the waveguide mode effective index. We use the unique property of SWGs to implement a polarization splitter and rotator with a substantially enhanced tolerance to waveguide size variations resulting from fabrication.

5.1.3 Structure Design and Operation Principle

The proposed PSR is schematically illustrated in Fig. 5.1. It comprises a silicon wire waveguide (A) of width W_A , evanescently coupled to a waveguide (B) with a refractive index n_B , a width W_B , and a gap D between the two waveguides. The height of both waveguides is H and the coupling length is L . Here we set H to 220 nm since this is the value commonly used by photonic foundries [22]. An s-bend with a radius of R_S is used near the output ports to decouple the waveguides. The superstrate medium is air in order to achieve an efficient cross-polarization coupling by breaking the vertical symmetry. Specifically, waveguide B is considered as a SWG waveguide comprised of alternating media with high (silicon) and low (air) refractive indices, with a subwavelength pitch Λ along the direction of propagation (z). Segment lengths of the high and low-refractive index media along the propagation direction are a and $\Lambda - a$, respectively, as shown in Fig. 5.1(a). An SWG-wire transition taper [18] is used to couple light between the SWG waveguide and the silicon wire. Due to the properties of SWGs, waveguide B can be considered as an equivalent wire waveguide with an engineered material refractive index n_B [Fig. 5.1(c)], which can be controlled by selecting a specific duty ratio $\eta = a/\Lambda$. Within a considerable range of waveguide widths ($W_B \pm 50$ nm), n_B can be well approximated as a constant.

The operation principle of the PSR is similar to those based on conventional photonic wire directional couplers: the widths of the waveguides are chosen such that the effective index of the quasi-TM mode (referred simply as TM mode hereafter) in waveguide A is similar to that of the quasi-TE mode in waveguide B (i.e., $n_A^{TM} \sim n_B^{TE}$), as shown in Fig. 5.2(a). At the same time, $n_A^{TE} \gg n_B^{TE}$. Under these conditions, the TE mode injected in the input port A_1 propagates to the through port A_2 with a

minimal cross-coupling to the waveguide B; while the TM mode injected into port A_1 couples to the fundamental TE Bloch mode of the waveguide B. The cross-coupling between the two polarizations is facilitated by two orthogonal hybrid modes supported in the coupling region, in which the horizontal and vertical asymmetries are created by the asymmetrical DC geometry and the difference between the upper and bottom cladding indices [8].

Figure 5.1: Schematics of the polarization splitter and rotator based on an asymmetrical directional coupler with a subwavelength grating (SWG) waveguide. (a) Top view, (b) 3D view, and (c) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index n_B .

As it can be observed in Fig. 5.2(a), the effective index dependence on waveguide width for the TE and TM modes (with slopes of S_{wire}^{TE} and S_{wire}^{TM}) are significantly different. Consequently, the phase matching condition for TM-TE polarization conversion can be easily lost due to fabrication variations of the waveguide widths [9]. This is the main reason that DC-based photonic wire PSRs are highly sensitive to waveguide dimensions. Ideally, the phase-matching condition could be preserved if the effective indices for waveguides A and B have the same waveguide width dependence. This is, however, impossible to achieve with conventional silicon photonic wire

waveguides. The solution we propose in this Letter is to utilize an SWG waveguide as the second waveguide (B). By adjusting the SWG equivalent material refractive index, not only the mode effective index but also the slope S_{SWG}^{TE} can be modified, as illustrated in Fig. 5.2(b). When setting the width ($W_A=450$ nm) for waveguide A, we can satisfy the phase matching condition for a range of widths W_B of waveguide B by manipulating the SWG equivalent material refractive index n_B . In addition, when n_B is reduced from 3.476 (i.e., a wire waveguide) to 2.3, the slope S_{SWG}^{TE} for the waveguide B at the phase-matching position decreases correspondingly. In particular, the slope S_{SWG}^{TE} in waveguide B with $n_B=2.4$ is similar to S_{wire}^{TM} in waveguide A. In other words, the phase-matching condition can still be maintained if the widths of both waveguides vary similarly, thereby improving the fabrication tolerance.

Figure 5.2: Effective indices of the fundamental TE and/or TM modes of (a) the wire waveguide A and (b) the SWG waveguide B with different equivalent refractive indices $n_B=3.476$, 2.525, 2.4, and 2.3, as a function of the waveguide widths W_A and W_B . Red curves represent the phase matching condition where the width W_A is set to 450 nm.

When the width of an SWG waveguide varies, a change in the duty ratio is generally expected. Based on our experience, the correlation between the width and duty ratio fluctuations for a particular fabrication process is not known a priori. Here we have chosen to primarily focus on the waveguide width variation, to illustrate the working principle. A more sophisticated design strategy may be adopted to include the experimentally determined relations between the waveguide width and the SWG duty ratio. However, it is an advantage of our approach that it is possible to find a combination of W_A , W_B and η , as an extra design freedom, to satisfy the

phase-matching condition.

We evaluate the general characteristics of the PSR by using the fully-vectorial eigenmode expansion (EME) method [23]. The SWG waveguide B is considered as an equivalent wire waveguide with an engineered material refractive index n_B , which is a convenient approximation to limit the computing time. Then 3D-FDTD simulations of the PSR with the actual periodic SWG configuration are carried out to determine the performance of the PSR. We assume a free-space central wavelength of $\lambda_0=1550$ nm. The refractive indices of silicon and the bottom oxide are $n_{Si}=3.476$ and $n_{SiO_2}=1.444$, respectively, the bend radius of the s-bend is $R_S=50$ μm ; the width of the waveguide A is $W_A = 450$ nm; and the pitch of the SWG waveguide B is $\Lambda=300$ nm. These feature sizes are compatible with standard processing in silicon photonics foundries [24]. The coupling gap D is set to be 100 nm to achieve a short coupling length, i.e., 25 μm for the engineered refractive index $n_B=2.4$ and $W_B=685$ nm. A larger gap may be used for ease of fabrication using deep ultraviolet (DUV) lithography, but it will result in a slight longer rotator.

The required value of the duty ratio η for an SWG waveguide with an engineered refractive index n_B can be estimated using the effective medium approximation [25]. A more accurate estimate can be obtained by the following procedure: i) the PSR parameters are optimized by using the EME method for the equivalent refractive index n_B ; ii) a series of 3D-FDTD simulations with varying duty ratio are performed until the same conversion efficiency is obtained as in i).

The polarization conversion is confirmed by a 3D-FDTD simulation in Fig. 5.3, with an actual periodic SWG waveguide used as the waveguide B. The fundamental TE mode launched in the input port A_1 propagates to the through port A_2 with negligible cross-coupling [Fig. 5.3(a)]. The fundamental TM mode from the input port A_1 is gradually coupled to the fundamental TE Bloch mode of the SWG waveguide B and the corresponding cross port B_2 [Fig. 5.3(b)].

Figure 5.3: Light propagation along the polarization splitter and rotator (top view) for (a) TE mode and (b) TM mode injected at the input (the left port). Calculated by the 3D-FDTD method with the grid sizes $\Delta x=15$ nm, $\Delta y=15$ nm, and $\Delta z=20$ nm.

Figure 5.4 shows the transmission characteristics of the PSR using the nominal design with the engineered refractive index $n_B=2.4$ (SWG with duty ratio $\eta=0.5$) for waveguide B. For the TE mode input, the TE-TE insertion loss (IL) at the through port A_2 and the crosstalk (XT) at the cross port B_2 are defined as $IL = P(\text{out})_{TE}^A / P(\text{in})_{TE}^A$ and $XT_{TE} = P(\text{out})_{TE}^B / P(\text{out})_{TE}^A$, respectively. For TM input, the polarization conversion loss (PCL) at the cross port B_2 and the crosstalk at the through port A_2 are defined as $PCL = P(\text{out})_{TE}^B / P(\text{in})_{TM}^A$ and $XT_{TM} = P(\text{out})_{TM}^A / P(\text{out})_{TE}^B$, respectively. As it is shown in Fig. 5.4(a), the TE mode insertion loss is below -0.06 dB within the wavelength range from 1500 nm to 1600 nm, while the TM-TE polarization conversion loss is less than -0.4 dB across the entire C-band (1530 nm to 1565 nm), with the minimum PCL of -0.13 dB at the central wavelength of 1550 nm. As it is shown in Fig. 5.4(b), the crosstalk values XT_{TE} and XT_{TM} are around -30 dB and -10 dB, respectively, in the wavelength range from 1500 nm to 1600 nm. The crosstalk of the TM input, XT_{TM} , is relatively high but

typical of such devices [12]. This is mainly due to the residual unconverted TM mode passing through the waveguide A, and can be substantially improved by adding a polarization filter before the output [3].

Figure 5.4: Wavelength dependence of the polarization splitter and rotator, calculated by 3D-FDTD simulations. (a) TE mode insertion loss and TM-TE polarization conversion loss; (b) Polarization crosstalk XT_{TE} and XT_{TM} . Waveguide parameters: $W_A = 450$ nm, $H = 220$ nm, $W_B = 685$ nm, $\eta=0.5$, $D = 100$ nm, and $L = 25$ μm .

5.1.4 Fabrication Tolerances

As we have shown in Fig. 5.2, for a width of $W_A=450$ nm (waveguide A), the phase-matching condition is fulfilled for the widths of the waveguide B of 298 nm, 575 nm, 685 nm and 820 nm for $n_B=3.476$, 2.525, 2.4 and 2.3, respectively ($\eta=1$, 0.6, 0.5, and 0.4). The calculated TM-TE polarization conversion losses are listed in Table 5.1.

Table 5.1: Performance of the PSR at phase-matching conditions, for waveguide width $W_A=450$ nm and gap $D=100$ nm

n_B	η	W_B (nm)	L_{DC} (μm)	PCL (dB)
3.476	1	298	13	-0.54
2.525	0.6	575	21	-0.4
2.4	0.5	685	25	-0.13
2.3	0.4	820	29	-0.18

Figure 5.5 shows the TM-TE polarization conversion loss as a function of the wavelength width variation (δW), for both the wire waveguide A and the SWG waveguide B, while the confirmation by 3D-FDTD simulations for $\eta=0.5$ is illustrated in Fig. 5.5(b). The corresponding gap variation is also included by maintaining a constant center-to-center waveguide distance. Other parameters are at their nominal design values, as listed in Table 5.1. To maintain a low polarization conversion loss with $\text{PCL} > -1$ dB at the central wavelength of 1550 nm, it is required $\delta W \leq \pm 3$ nm, ± 17 nm, ± 40 nm and ± 27 nm for $\eta=1, 0.6, 0.5$ and 0.4 respectively. The maximum fabrication tolerance of waveguide width is achieved at $\eta=0.5$ ($n_B=2.4$), where the highest TM-TE polarization conversion efficiency is obtained. Compared with previously reported device with similar minimum feature sizes (100 nm) [8,9], the proposed design has a 10-fold improvement in the fabrication tolerance of waveguide widths, while maintaining similar TM-TE polarization conversion efficiency. Furthermore, the peak wavelength of the PSR is also much less sensitive to waveguide width variations, shifting with a rate of ≤ 2 nm/nm with respect to δW , a substantial improvement over previous designs [8]. Additionally, as it is shown in Table 5.1, the coupling length L is less than 30 μm . Therefore, the fabrication tolerance of waveguide widths can be markedly enhanced by manipulating the engineered material refractive index n_B of the SWG waveguide with adjusting the SWG duty ratio η . This is achieved without incurring any penalty on device footprint, making the SWG structure a promising candidate for practical and compact polarization rotators and splitters.

With regard to the waveguide thickness variations, we found that $\delta H \leq \pm 4$ nm is required in order to maintain a PCL better than -1 dB. The proposed PSR is still

relatively sensitive to the thickness variations, which is similar to previously reported devices. For improvements in this aspect, other strategies need to be incorporated, such as using a larger silicon thickness [26] or varying the width of waveguide B in the coupling section [10].

Figure 5.5: Dependence of the TM-TE polarization conversion loss PCL on the width variation δW of both the wire waveguide A and the SWG waveguide B, (a) for $n_B = 3.476, 2.525, 2.4, 2.3$ (duty ratios $\eta = 1, 0.6, 0.5$ and 0.4), as calculated by an EME method; (b) confirmation by the 3D-FDTD method for $\eta = 0.5$

5.1.5 Conclusion

In summary, we have proposed and investigated a novel method to achieve a compact and fabrication-tolerant polarization splitter and rotator (PSR) using a subwavelength grating (SWG) waveguide. The PSR comprises a silicon wire waveguide coupled to a SWG waveguide. The fabrication tolerance is improved by engineering the equivalent refractive index of the SWG waveguide. Our calculations confirm a remarkably high fabrication tolerance to waveguide width variations of ± 40 nm for PCL better than -1 dB at the central wavelength of 1550 nm, a PSR peak wavelength shift of ≤ 2 nm/nm, while maintaining a short coupling length of 25 μm . Compared to the PSR devices based on conventional wire waveguides, the fabrication tolerance of the waveguide widths is enhanced in our design by more than a factor of 10. The proposed method opens a promising solution for improving fabrication tolerances of silicon devices based on directional couplers.

5.2 Polarizer with subwavelength grating

The following paper, “Compact and broadband silicon TE-pass polarizer with sub-wavelength grating,” experimentally demonstrates a low loss and compact TE-pass polarizer based on a subwavelength grating waveguide. This paper includes the device design and simulation, measurement and analysis.

Yule Xiong performed the device design, all simulations, device measurement, and wrote this paper. The paper is submitted to Optics Express for publication in December 2014.

Compact and broadband silicon TE-pass polarizer with subwavelength grating

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5.2.1 Abstract

We propose and experimentally demonstrate a novel way to implement a low loss, broadband and compact transverse electric (TE)-pass polarizer on the silicon-on-insulator platform. The uniqueness of the polarizer utilizes a silicon subwavelength grating (SWG) structure. Due to SWG’s capability to engineer the effective index of the waveguide, the SWG effect offers an additional degree of freedom for designing waveguide-based devices. In this work, we use the SWG to implement a waveguide supporting only its TE mode while the transverse magnetic (TM) mode is under the cut-off condition, i.e., TM mode will leak away from the waveguide with a low reflection. The simulated bandwidth to achieve a polarization extinction ratio (ER) of 20 dB is more than 200 nm; while the measured bandwidth is from 1470 nm to 1550 nm, limited by the tunable laser and the fiber-to-chip couplers. The measured polarization ER is ~ 23 dB and the insertion loss is -0.3 dB around the wavelength of 1550 nm. Although the length of the fabricated SWG waveguide is $50\ \mu\text{m}$, the

simulations show that the length of the SWG waveguide can be as short as 10 μm while maintaining polarization ER of 20 dB.

5.2.2 Introduction

Polarization management is an important research topic in silicon photonics [1]. High refractive index contrast makes silicon waveguides highly polarization dependent. To solve this issue, various types of passive polarization management components have been reported recently, including polarization splitters, rotators [4, 6, 7, 10, 11, 27, 28] and polarizers [29–34]. Among them, polarizers that provide filtering of the undesired polarization state are satisfactory for many practical situations. Silicon hybrid plasmonic waveguide based polarizers [29, 30] have attracted significant attention due to their ultracompact footprint and broadband operation. However, such devices generally have a large excess loss and the metal-involved fabrication process restricts their application. Another proposed polarizer design was based on photonic-crystal (PhC) structures, which are inherently lossy and comparatively sensitive to fabrication variations [31]. The third design of a polarizer used a shallow etched silicon waveguide, which is simple to fabricate [32], but the TE-pass polarizer length is too long (1000 μm). In [34], a simple TM-pass polarizer was designed based on specific width (between 250 nm and 180 nm) and height (300 nm) of a wire waveguide. Only the TM fundamental mode can be supported in this specific geometry. By taking advantage of the cut-off condition of the TE mode, a TM-pass polarizer was realized. By selecting a specific width and height, the silicon nanophotonic waveguide only supports TM mode, while the TE mode leaks away to the substrate. Since the material refractive index of silicon is fixed, the parameters of the polarizer is inflexible, which limits its application. Recently, a TM-pass polarizer was demonstrated using a subwaveguide grating (SWG) waveguide [33]. Instead of eliminating the TE polarized light, the SWG waveguide works as a Bragg reflector to reflect back the incident TE-polarized light, which can be undesirable for many practical applications.

Here we propose a general strategy to improve the parameter selection range of polarizers based on silicon nanophotonic waveguides. The key to our approach is to introduce different material index to different sections of the waveguide structure.

By doing so, the mode cut-off condition can be adjusted for various device parameters. This can be achieved either by utilizing different materials to form a composite waveguide, or more practically by using subwavelength grating (SWG) structures.

The SWG is a structure with a pitch substantially smaller than the wavelength of light propagating through the structure, behaving effectively as a homogenous medium [13, 14], while the pitch of the SWG used in [33] is too large for the TE mode to suppress the Bragg diffraction. The equivalent material index of the SWG can be modified by changing the duty ratio. The SWG effect provides a new degree of freedom for the design of novel silicon photonic components. Several devices with improved performance have been reported using SWGs [35]: efficient fiber-to-chip surface grating couplers [15], edge couplers [13, 16], multimode interference (MMI) couplers for integrated coherent receivers [17], and low loss waveguide crossings [18]. Recently, it has been shown that the SWG effect can also be used to engineer the dispersive properties of both MMIs [19] and DCs [20]. In this work, we use the index engineering of the SWG to adjust the TM mode cut-off condition in the waveguide, thus obtaining a low loss and broadband TE-pass polarizer with flexible device parameter selections.

5.2.3 TE-pass Polarizer Design

The proposed TE-pass polarizer is schematically illustrated in Fig. 5.6(a), which is a SWG waveguide with a refractive index n_{SWG} , a width W , a height H (set to be 220 nm), and a length L . The top cladding is air. The SWG waveguide comprises of alternating media with high (silicon) and low (air) refractive indices, with a pitch Λ along the direction of propagation. Segment lengths of the high and low refractive index media along the propagation direction are a and $(\Lambda - a)$, respectively. An SWG-wire transition taper with a length L_t [18] is used to couple light between the SWG and the input/output wire waveguide. Due to the subwavelength nature, the SWG waveguide is equivalent to a homogeneous wire waveguide with an engineered material refractive index of n_{SWG} [Fig. 5.6(b)], which can be controlled by selecting a specific duty ratio $\eta = a/\Lambda$ [25]. With this unique property, SWGs can be used in applications where conventional wire waveguides can never achieve.

The operating principle of the TE-pass polarizer is as follows: the high polarization dependence of the SWG waveguide leads to the different cut-off conditions between the TE and TM Bloch modes. By manipulating the engineered material index n_{SWG} , the silicon SWG waveguide supports only the TE Bloch mode with a low propagation loss. For a TM input, the SWG waveguide is under the mode cut-off condition, where the incident TM mode radiates away to the SiO_2 substrate along propagation. The effective indices of the TE and TM modes depends on the engineered material index n_{SWG} of the SWG waveguide, which can be seen in Fig. 5.6(c). It is clear that the mode cut-off condition could be satisfied within a specific range of the engineered material index n_{SWG} . In this example, TE-pass region happens when $2 < n_{SWG} < 2.5$.

Figure 5.6: Schematics of the TE-pass polarizer based on a subwavelength grating (SWG) waveguide with an air top cladding. (a) Top view, (b) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index n_{SWG} ; and (c) effective indices of the TE and TM modes of the SWG waveguide as a function of the engineered refractive index n_{SWG} when $W=1100$ nm, $H=220$ nm: (i) cut-off region with no mode supported; (ii) TE only (on TM); (iii) TE and TM modes region.

We first evaluate the general characteristics of the proposed TE-pass polarizer by using the three-dimensional finite-difference time-domain (3D-FDTD) method. We assume a free-space wavelength of $\lambda_0 = 1550$ nm, the refractive index of silicon $n_{Si} = 3.476$, and the SiO_2 substrate with a refractive index $n_{SiO_2} = 1.444$. The width of the silicon SWG waveguide is set to $W = 1100$ nm, and the pitch of the SWG waveguide is $\Lambda = 300$ nm, which are typical feature sizes used in silicon photonics foundries with public access. The advantage of the proposed polarizer can be observed in Fig.

5.6(c), where the effective indices of the TE and TM modes of the SWG waveguide are a function of the engineered refractive index n_{SWG} . With specific choices of duty ratio η , n_{SWG} can range from 1 (i.e., air) to 3.476 (i.e., silicon). When the engineered refractive index n_{SWG} is less than 2, neither TE nor TM mode can be supported in the SWG waveguide (i.e., cut-off region). However, when n_{SWG} is between 2 and 2.5, only the fundamental TE mode is supported in the waveguide. When n_{SWG} is above 2.5, both TE and TM modes co-propagate in the SWG waveguide. In other words, the TE-pass polarizer can be achieved by engineering the material refractive index n_{SWG} using a specific duty ratio η . The required value of the duty ratio η for an SWG waveguide with an engineered refractive index n_{SWG} can be estimated using the effective medium approximation [25]. To realize the TE-pass polarizer, simulations show that n_{SWG} of 2.4 corresponds to a duty ratio of $\eta=0.5$.

Figure 5.7: Light intensity (input from the left port) propagates along the proposed SWG TE-pass polarizer, as simulated by a 3D-FDTD method. With a TE input, the TE mode field distribution along the x-z plane (a), and along the y-z plane (b). With a TM input, the TM mode field distribution along the x-z plane (c), and along the y-z plane (d). $W=1100$ nm, $L=50$ μm , $L_t=5$ μm , $\Lambda=300$ nm, $\eta=0.5$, $\lambda_0=1550$ nm

The light propagation for the TE and TM modes in the designed polarizer is simulated in Fig. 5.7 by a 3D-FDTD method. Figures 5.7(a) and 5.7(b) show the light propagation along the x-z and y-z planes for the TE mode at the center of the SWG waveguide. The TE mode passes through the SWG waveguide with negligible

loss. Figures 5.7(c) and 5.7(d) illustrate the light propagation for the TM mode; and it clearly shows that the TM light is attenuated by nearly 99.9% and radiates away from the SWG waveguide. For the TE or TM mode input, the transmission $T(\lambda)$ and reflection $R(\lambda)$ are defined as $T(\lambda) = P(\lambda)_{out}/P(\lambda)_{in}$ and $R(\lambda) = P(\lambda)_{back}/P(\lambda)_{in}$, respectively. The calculated transmission for the TE mode $T_{TE}(\lambda)$ has a low insertion loss (-0.4 dB) while the transmission response for the TM mode $T_{TM}(\lambda)$ is very low (-35 dB) in a broad wavelength range from 1450 nm to 1650 nm, as illustrated in Fig. 5.8. The simulated reflections $R(\lambda)$ for the TE and TM modes are <-16 dB and <-20 dB, respectively, at the central wavelength of $\lambda_0 = 1550$ nm. Both the transmission loss and the reflection are caused by the SWG-wire transition section due to the effective index transition from the wire waveguide to the SWG waveguide.

Figure 5.8: Simulated wavelength dependence of transmission [$T_{TE}(\lambda)$ and $T_{TM}(\lambda)$] and reflection [$R_{TE}(\lambda)$ and $R_{TM}(\lambda)$] for the proposed TE-pass polarizer. $W=1100$ nm, $H=220$ nm, $L=50\mu\text{m}$, $\eta=0.5$.

Figure 5.9 shows the simulated transmissions for the TE and TM modes for various SWG waveguide lengths L with different widths of the SWG waveguide at the central wavelength of $\lambda_0 = 1550$ nm. The insertion loss of the TE and TM Bloch modes decreases as the width of the SWG increases. The reason is that the light is easy to leak away the waveguide core with a narrow waveguide width. Figure 5.9 also shows that the SWG length L has very little effect on the TE, while TM mode attenuates exponentially along L . The TE propagates along the SWG waveguide with low propagation loss while the TM mode leaks away the SWG waveguide core to the substrate along the propagation direction. For $W=1100$ nm, the SWG waveguide

Figure 5.9: Calculated transmission of the TE-pass polarizer as a function of the SWG waveguide length L for different SWG waveguide widths. $H=220$ nm, $\eta=0.5$.

length L can be as short as 10 μm to achieve a polarization ER of 20 dB.

5.2.4 Fabrication and Experimental Results

The designed SWG TE-pass polarizer was fabricated on a SOI substrate with a 220 nm thick silicon and a 2 μm thick buried oxide (BOX) layers. Electron beam lithography was used to pattern the SWG structure under an etch mask of a high contrast hydrogen silsesquioxane photoresist. Inductively coupled plasma reactive ion etching (ICP-RIE) was used to transfer the waveguide layout onto the silicon layer. Schematic of the mask layout and pictures of the fabricated TE-pass polarizer are illustrated in Fig. 5.10. The bending waveguides offer an effective vertical offset between the input and output, providing more accurate measurements of the output power.

To measure the transmission of the TE-pass polarizer, a tunable laser was coupled into the chip via a lensed fiber with a Gaussian beam waist of ~ 3 μm , through an in-line polarization controller. Figure 5.11 shows the measured transmissions for both TE and TM inputs. Here, the coupling loss of the two inverse-tapers is included. The measured transmissions of a reference waveguide without SWGs are illustrated for comparison. It can be observed that there exists a roll-off from 1540 nm to 1580 nm in Fig. 5.11(a). We believe that the wavelength dependence is caused by the bending waveguides. As shown in Fig. 5.11(a), the insertion loss for the TE mode is around -0.3 dB while the polarization ER is ~ 23 dB around the wavelength of 1550

nm. The bandwidth to achieve a polarization ER of 20 dB is about 80 nm (from 1470 nm to 1550 nm), which is limited by the available bandwidth of our tunable laser, the inverse-tapers and the bending waveguides for the input-output offset. The spectrum of the tunable laser is from 1475 nm to 1580 nm, while the inverse-tapers introduced a large coupling loss and the bending waveguides induced a high bending loss near the wavelength range from 1540 nm to 1580 nm. All these factors limit the measured bandwidth of the polarizer with a high polarization ER. As it is shown in Fig. 5.11(b), the reflections of TE and TM modes from the polarizer are around -30 dB, which are mainly due to facet reflection. Since the reflection response of the reference waveguide is similar to that in Fig. 5.11(b), we conclude that the reflections for both TE and TM modes are low.

Figure 5.10: (a) Schematic of the mask layout; microscopic pictures of (b) the fabricated polarizer; (c) the enlarged view.

5.2.5 Conclusion

We have proposed and experimentally demonstrated a low loss TE-pass polarizer based on a subwavelength grating (SWG) waveguide. The SWG waveguide can work under the mode cut-off condition by engineering the SWG effective index using a specific duty ratio of the SWG waveguide. Both simulations and experiments show that only the TE mode can be supported in the SWG waveguide while the TM

mode leaks away to the substrate. In addition, very low reflection of the input light is demonstrated. The experimental results illustrate a polarization extinction ratio (ER) of ~ 23 dB and a TE insertion loss of -0.3 dB at the central wavelength of 1550 nm, while the measured bandwidth is about 80 nm (from 1470 nm to 1550 nm) for the polarization ER of 20 dB. However, our 3D-FDTD calculations show that the length of the SWG TE-pass polarizer can be as short as $10\ \mu\text{m}$ to achieve a polarization ER of 20 dB, with a simulated bandwidth of more than 200 nm. The discrepancy in the bandwidth performance is believed to be caused by the limitation of the tunable laser, the inverse-tapers and the bending waveguides for the input-output offset.

Figure 5.11: Measured results of the fabricated polarizer and the reference waveguide: (a) transmission of TE and TM in the SWG-polarizer compared to the straight wire reference waveguide; (b) reflection of TE and TM in the SWG-polarizer.

List of References

- [1] D. Dai, L. Liu, S. Gao, D.-X. Xu, and S. He, “Polarization management for silicon photonic integrated circuits,” *Laser and Photonics Reviews*, vol. 7, pp. 303–328, May 2013.
- [2] T. Barwicz, M. R. Watts, M. A. Popović, P. T. Rakich, L. Socci, F. X. Kärtner, E. P. Ippen, and H. I. Smith, “Polarization-transparent microphotonic devices in the strong confinement limit,” *Nature Photonics*, vol. 1, pp. 57–60, Jan. 2007.
- [3] P. Dong, C. Xie, L. Chen, L. L. Buhl, and Y.-K. Chen, “112-Gb/s monolithic PDM-QPSK modulator in silicon,” *Optics Express*, vol. 20, pp. B624–B629, Dec. 2012.
- [4] H. Zhang, S. Das, Y. Huang, C. Li, S. Chen, H. Zhou, M. Yu, P. Guo-Qiang Lo, and J. T. L. Thong, “Efficient and broadband polarization rotator using horizontal slot waveguide for silicon photonics,” *Applied Physics Letters*, vol. 101, no. 2, p. 021105, 2012.
- [5] D. Vermeulen, S. Member, S. Selvaraja, P. Verheyen, P. Absil, W. Bogaerts, D. V. Thourhout, and G. Roelkens, “Silicon-on-insulator polarization rotator based on a symmetry breaking silicon overlay,” *IEEE Photonics Technology Letters*, vol. 24, no. 6, pp. 482–484, 2012.
- [6] Y. Xiong, D.-X. Xu, J. H. Schmid, P. Cheben, S. Janz, and W. N. Ye, “Robust Silicon Waveguide Polarization Rotator With an Amorphous Silicon Overlayer,” *IEEE Photonics Journal*, vol. 6, p. 2200308, Apr. 2014.
- [7] A. V. Velasco, M. L. Calvo, P. Cheben, A. Ortega-Moñux, J. H. Schmid, C. A. Ramos, I. n. M. Fernandez, J. Lapointe, M. Vachon, S. Janz, and D.-X. Xu, “Ultracompact polarization converter with a dual subwavelength trench built in a silicon-on-insulator waveguide,” *Optics Letters*, vol. 37, pp. 365–367, Feb. 2012.
- [8] L. Liu, Y. Ding, K. Yvind, and J. M. Hvam, “Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits,” *Optics Express*, vol. 19, pp. 12646–12651, June 2011.
- [9] Y. Ding, L. Liu, C. Peucheret, and H. Ou, “Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler,” *Optics Express*, vol. 20, pp. 20021–20027, Aug. 2012.

- [10] Y. Xiong, D.-X. Xu, J. H. Schmid, P. Cheben, S. Janz, and W. N. Ye, "Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler," *Optics Express*, vol. 22, no. 14, pp. 17458–17465, 2014.
- [11] H. Guan, A. Novack, M. Streshinsky, R. Shi, Q. Fang, A. E.-J. Lim, G.-Q. Lo, T. Baehr-Jones, and M. Hochberg, "CMOS-compatible highly efficient polarization splitter and rotator based on a double-etched directional coupler," *Optics Express*, vol. 22, pp. 2489–2496, Jan. 2014.
- [12] J. Wang, B. Niu, Z. Sheng, A. Wu, X. Wang, S. Zou, M. Qi, and F. Gan, "Design of a SiO₂ top-cladding and compact polarization splitter-rotator based on a rib directional coupler," *Optics Express*, vol. 22, no. 4, pp. 4137–4143, 2014.
- [13] P. Cheben, D.-X. Xu, S. Janz, and A. Densmore, "Subwavelength waveguide grating for mode conversion and light coupling in integrated optics," *Optics Express*, vol. 14, pp. 4695–4702, May 2006.
- [14] P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Delge, S. Janz, G. C. Aers, D.-x. Xu, A. Densmore, and T. J. Hall, "Subwavelength grating periodic structures in silicon-on-insulator : a new type of microphotonic waveguide," *Optics Express*, vol. 18, no. 19, pp. 20251–20262, 2010.
- [15] R. Halir, P. Cheben, J. H. Schmid, R. Ma, D. Bedard, S. Janz, D.-X. Xu, A. Densmore, J. Lapointe, and I. Molina-Fernndez, "Continuously apodized fiber-to-chip surface grating coupler with refractive index engineered subwavelength structure," *Optics Letters*, vol. 35, pp. 3243–3245, Oct. 2010.
- [16] P. Cheben, P. J. Bock, J. H. Schmid, J. Lapointe, S. Janz, D.-X. Xu, A. Densmore, A. Delge, B. Lamontagne, and T. J. Hall, "Refractive index engineering with subwavelength gratings for efficient microphotonic couplers and planar waveguide multiplexers," *Optics Letters*, vol. 35, pp. 2526–2528, Aug. 2010.
- [17] A. Ortega-Monux, L. Zavargo-Peche, A. Maese-Novo, I. Molina-Fernndez, R. Halir, J. G. Wangmert-Prez, P. Cheben, and J. H. Schmid, "High-performance multimode interference coupler in silicon waveguides with subwavelength structures," *IEEE Photonics Technology Letters*, vol. 23, pp. 1406–1408, Oct. 2011.
- [18] P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Delge, D.-X. Xu, S. Janz, A. Densmore, and T. J. Hall, "Subwavelength grating crossings for silicon wire waveguides," *Optics Express*, vol. 18, no. 15, pp. 16146–16155, 2010.
- [19] A. Maese-Novo, R. Halir, S. Romero-Garca, D. Prez-Galacho, L. Zavargo-Peche, A. Ortega-Monux, I. Molina-Fernndez, J. G. Wangmert-Prez, and P. Cheben, "Wavelength independent multimode interference coupler," *Optics Express*, vol. 21, pp. 7033–7040, Mar. 2013.
- [20] R. Halir, A. Maese-Novo, A. Ortega-Monux, I. Molina-Fernndez, J. G. Wangmert-Prez, P. Cheben, D.-X. Xu, J. H. Schmid, and S. Janz, "Colorless directional coupler with dispersion engineered sub-wavelength structure," *Optics Express*, vol. 20, pp. 13470–13477, June 2012.

- [21] R. Halir, A. Ortega-mo, J. H. Schmid, C. Alonso-ramos, J. Lapointe, D.-x. Xu, and J. G. Wang, "Recent advances in silicon waveguide devices using sub-wavelength gratings," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 4, p. 8201313, 2013.
- [22] A. E.-j. Lim, J. Song, Q. Fang, C. Li, X. Tu, N. Duan, K. K. Chen, R. P.-c. Tern, T.-y. Liow, and A. F. S. Model, "Review of silicon photonics foundry efforts," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 4, p. 8300112, 2014.
- [23] D. F. G. Gallagher and T. P. Felici, "Eigenmode Expansion Methods for Photonics - Pros and Cons," in *Proc. SPIE 4987* (Y. S. Sidorin and A. Tervonen, eds.), pp. 69–82, 2003.
- [24] M. Settle, M. Salib, A. Michaeli, and T. F. Krauss, "Low loss silicon on insulator photonic crystal waveguides made by 193nm optical lithography," *Optics Express*, vol. 14, no. 6, pp. 2440–2445, 2006.
- [25] J. H. Schmid, P. Cheben, P. J. Bock, R. Halir, J. Lapointe, S. Janz, A. Delage, A. Densmore, J.-M. Fedeli, T. J. Hall, B. Lamontagne, R. Ma, I. Molina-Fernandez, and D.-X. Xu, "Refractive index engineering with subwavelength gratings in silicon microphotonic waveguides," *IEEE Photonics Journal*, vol. 3, pp. 597–607, June 2011.
- [26] D.-x. Xu, J. H. Schmid, G. T. Reed, G. Z. Mashanovich, D. J. Thomson, M. Nedeljkovic, X. Chen, D. V. Thourhout, S. Keyvaninia, and S. K. Selvaraja, "Silicon photonic integration platform Have we found the sweet spot ?," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 4, p. 8100217, 2014.
- [27] L. Chen, C. R. Doerr, and Y.-K. Chen, "Compact polarization rotator on silicon for polarization-diversified circuits," *Optics Letters*, vol. 36, pp. 469–471, Feb. 2011.
- [28] L. Liu, Y. Ding, K. Yvind, and J. M. Hvam, "Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits," *Optics Express*, vol. 19, pp. 12646–12651, June 2011.
- [29] M. Z. Alam, J. S. Aitchison, and M. Mojahedi, "Compact and silicon-on-insulator-compatible hybrid plasmonic TE-pass polarizer," *Optics Letters*, vol. 37, pp. 55–57, Jan. 2012.
- [30] Y. Huang, S. Zhu, H. Zhang, T.-Y. Liow, and G.-Q. Lo, "CMOS compatible horizontal nanoplasmonic slot waveguides TE-pass polarizer on silicon-on-insulator platform," *Optics Express*, vol. 21, pp. 127901279–6, May 2013.
- [31] Y. Cui, Q. Wu, E. Schonbrun, M. Tinker, J. Lee, and S. Member, "Silicon-based 2-D slab photonic crystal TM polarizer at telecommunication wavelength," *IEEE Photonics Technology Letters*, vol. 20, no. 8, pp. 641–643, 2008.

- [32] D. Dai, Z. Wang, N. Julian, and J. E. Bowers, “Compact broadband polarizer based on shallowly-etched silicon-on-insulator ridge optical waveguides,” *Optics Express*, vol. 18, no. 26, pp. 27404–27415, 2010.
- [33] X. Guan, P. Chen, S. Chen, P. Xu, Y. Shi, and D. Dai, “Low-loss ultracompact transverse-magnetic-pass polarizer with a silicon subwavelength grating waveguide,” *Optics Letters*, vol. 39, pp. 4514–4517, Aug. 2014.
- [34] Q. Wang, “Ultracompact TM-Pass Silicon Nanophotonic Waveguide Polarizer and Design,” *IEEE Photonics Journal*, vol. 2, pp. 49–56, Feb. 2010.
- [35] R. Halir, P. J. Bock, P. Cheben, A. Ortega-Moñux, C. Alonso-Ramos, J. H. Schmid, J. Lapointe, D.-X. Xu, J. G. Wangüemert-Pérez, I. n. Molina-Fernández, and S. Janz, “Waveguide sub-wavelength structures: a review of principles and applications,” *Laser and Photonics Reviews*, pp. 1–25, Sept. 2014.

Chapter 6

Taper-Based Devices

In this Chapter, two journal papers and one conference proceeding show three different taper based devices for polarization splitting, rotating and two-mode (de)multiplexing.

6.1 Polarization Rotator with an Amorphous Silicon Overlayer

The following article, “Robust silicon waveguide polarization rotator with an amorphous silicon overlayer,” provides details on the characteristics of the polarization rotator with a tapered amorphous silicon overlayer. This article includes the device design and simulation, discussion and analysis. The AutoCAD mask layout used to fabricate the polarization rotator is shown in Appendix [B](#).

Yule Xiong performed the device design, all simulations, and wrote this article. The article was published in IEEE Photonics Journal, volume 6, issue 2, on pages 2200308.1-8 in 2014.

Robust silicon waveguide polarization rotator with an amorphous silicon overlayer

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6.1.1 Abstract

We propose a robust polarization rotator based on the mode-evolution mechanism. The polarization rotation in a silicon wire waveguide is achieved by forming an amorphous silicon (a-Si) overlayer and SiO₂ spacer on top of the waveguide. A strip pattern of a constant width is designed to be etched through the overlayer at a specific angle with respect to the Si waveguide. The asymmetry in the a-Si overlayer affects the waveguide mode by rotating the modal axis. This polarization rotator design is amenable to comparatively simple fabrication compatible with the standard silicon photonic processing for integration. The length of the rotation section is 17 μm and broadband operation is achieved with a rotation efficiency higher than 90% for a wavelength range exceeding 135 nm. A maximum polarization rotation efficiency of 99.5% is predicted by calculation.

6.1.2 Introduction

Polarization management is an important research topic in the development of silicon photonic integrated circuits because of the high polarization sensitivity of silicon-wire waveguides [1]. To circumvent the intrinsic limitations imposed by waveguide polarization sensitivity, a polarization diversity approach is typically used in Si-wire photonic circuits [2]. In this approach, the input light of arbitrary polarization is first split into two orthogonal polarization states (quasi-TE and quasi-TM) by a polarization beam splitter, followed by rotating one of the polarization states by 90° using a polarization rotator. After independently processing these two signals of the identical polarization state, one of them is rotated back 90° using a second polarization rotator, and the two orthogonal components are recombined with a polarization beam splitter. Two main polarization rotation mechanisms used in integrated optics are mode coupling [3,4] and mode evolution [5–10]. Mode-coupling structures require phase matching and precisely tuned coupling. As such, mode-coupling structures (e.g. directional couplers) are inherently wavelength dependent and sensitive to fabrication variations [3,4]. Mode-evolution structures, on the other hand, generally operates in a broad wavelength range and are more tolerant to dimensional changes [5–7]. Previously reported devices typically require precise lithographic alignments and high fabrication accuracy of small features. For example, in the mode evolution polarization splitter/rotator reported in [2], e-beam lithography was used to achieve the precise dimensional control of the asymmetric bi-level tapers with a minimum feature size of 70 nm. More recently, several groups have proposed and demonstrated mode evolution polarization rotators using asymmetric amorphous silicon (a-Si) overlayers [7,8]. However, all these designs required geometrical modification for the access waveguide and precise placement of the a-Si overlayer relative to the access waveguide, which may reduce the manufacturing yield thus increasing the cost per individual device.

Here, we propose a novel polarization rotator design by simply loading a silicon wire waveguide with a diagonally positioned a-Si overlayer based on the mode evolution principle, as illustrated in Fig. 6.1. An a-Si layer is first deposited on a SOI wafer, separated by a thin etch-stop oxide layer. The single crystalline silicon (c-Si) wire waveguide is formed with the a-Si top layer. The a-Si layer is patterned with a strip of a constant width, tilted by an angle θ relative to the silicon access waveguide. The cross-section of the rotator is asymmetric with a varying a-Si width. This

asymmetry induces polarization rotation. The cross-sectional structure of our design is similar to that reported in [6, 8]. Unlike in those designs, however, in our device the widths of the c-Si access waveguide and the a-Si overlayer both remain constant from a lithography point of view. Therefore high-precision lithographic alignment is not required. The varying cross-section geometry is introduced simply by placing the a-Si strip on top of the c-Si access waveguide at an angle. No loss penalty or changes in the rotation efficiency are observed in the fabrication tolerance range, as it is demonstrated in Section 3. Furthermore, unlike in mode coupling polarization rotators where air is typically used as superstrate to achieve vertical asymmetry, our design assumes SiO_2 upper cladding, allowing the polarization rotator to be readily integrated within a planar waveguide circuit.

6.1.3 Structure Design and Operation Principle

The proposed polarization rotator illustrated in Fig. 6.1 has a silicon access waveguide of width W and height H , separated from an a-Si overlayer by a thin SiO_2 pad layer of thickness H_{pad} . The a-Si layer is formed as a strip of thickness H_R and width W_R , positioned at a tilt angle θ with respect to the c-silicon waveguide. The length L_R of the polarization rotator is determined by θ and W_R . Although the polarization rotator described here can also function well with an air upper cladding, here we assume an SiO_2 upper cladding to facilitate integration with other components.

Figure 6.1: (a) Schematic of the polarization rotator with a-Si overlayer. (b) Waveguide cross-section with asymmetric a-Si loading and SiO_2 upper cladding.

The performance of the polarization rotator is evaluated using the eigenmode expansion (EME) method and the three-dimensional finite-difference time-domain (3D-FDTD) simulations. We assume a quasi-TE input mode (E_x component dominant), but since the polarization rotator is reciprocal, equivalent results are obtained for a quasi-TM polarized input mode. In our simulations we assume the wavelength of 1550 nm, and the refractive indices of c-Si and a-Si of $n_{c-Si}=3.476$ and $n_{a-Si}=3.55$. The upper and lower SiO₂ cladding index is assumed $n_{SiO_2}=1.444$. The polarization rotator performance is examined for two heights of access wire waveguide: (i) $H=260$ nm, which is similar to that reported for several mode evolution rotators [8,9] and which has been extensively used in evanescent filed biosensors operating in TM polarization [11,12]; and (ii) $H=220$ nm, which is typically used in silicon photonics foundries with public access. Figures 6.2(a) and 6.2(b) shows the evolution of the electric field components E_x and E_y of the waveguide mode. Along the rotation section, the quasi-TE mode in the access waveguide is gradually coupled into the c-Si/a-Si composite waveguide where the mode becomes substantially hybridized as the a-Si width increases. The major component E_x of the input mode gradually transforms into the orthogonal E_y component and quasi-TE polarization is rotated to quasi-TM polarization at the rotator output, as shown in Fig. 6.2(c). Similarly, polarization rotation can be obtained from a quasi-TM input mode to quasi-TE output mode for the same device parameters, because of the reciprocity condition. A thin SiO₂ pad layer is introduced in between the c-Si access waveguide and the a-Si overlayer to provide etch-stop for the a-Si layer. We choose a thin pad oxide layer of only 10 nm to frustrate slot waveguide effect [13]. This substantially improves the optical performance of the rotator, as it is further discussed in Section 6.1.4.

The polarization rotator performance is evaluated in terms of polarization rotation efficiency (PRE), which is the ratio of the power transferred between the two orthogonally polarized waveguide modes for a given input polarization state. For example, for the TE input, PRE is defined as the ratio of the output TM mode power to the input TE mode power: $PRE=P_{TM}^{out}/P_{TE}^{in}$. Other important device parameters include the insertion loss (IL), extinction ratio (ER), tolerance to dimensional variations and the operational wavelength range (bandwidth). In our design, we attempt to increase the access waveguide width W to reduce scattering loss due to sidewall roughness, and to minimize the rotator length L_R while maximizing the polarization rotation

Figure 6.2: Electric field components (a) E_x and (b) E_y evolution along the polarization rotator (top view), as calculated by a 3D-FDTD method. (c) Transverse electric field distributions at the corresponding positions along the polarization rotator.

efficiency.

For a given access waveguide width W and a-Si height H_R , the PRE depends on the a-Si strip width W_R and tilt angle θ with respect to the access waveguide. Within a range of tilt angle θ , there exist a set of (θ, W_R) combinations that provide a high PRE, as shown in Fig. 6.3(a). For example, to meet $\text{PRE} > 99\%$, the tilt angle θ ranges are from 1.5° to 2.4° for $H_R=H=220$ nm and $W=390$ nm, and from 1.1° to 1.7° for $H_R=H=260$ nm and $W=430$ nm. Although both θ and W_R determine the polarization rotator length, using a large θ is more effective in obtaining a small L_R . The design with the largest θ and $\text{PRE} > 99\%$ is chosen as the optimization goal. We also note that the rotation behavior is periodic with W_R , but this leads to a longer rotator section and the tolerance to the width inaccuracy of the access waveguide is correspondingly reduced. Fig. 6.3(b) illustrates the total rotator length and the strip width W_R as a function of tilt angle θ for a scanning result similar to that presented in Fig. 6.3(a). To obtain a short rotator length (L_R), the largest angle, for which PRE is still more than 99%, is used. Therefore, the tilt angle θ is set to 2.4° for

$H_R=H=220$ nm, and 1.7° for $H_R=H=260$ nm, as shown by the data points in Fig. 6.3(b).

Figure 6.3: (a) Polarization Rotation Efficiency (PRE) as a function of the a-Si strip width W_R for access waveguide width $W=430$ nm; $H=H_R=260$ nm. (b) Length of the rotation section L_R and the corresponding W_R as a function of tilt angle θ for two different heights H (220 nm and 260 nm) of the access waveguide; two heights (220nm and 260nm) of the access wire waveguide.

As shown in Fig. 6.4(a), for a given a-Si thickness H_R , a range of W values can be used to obtain a high PRE (for optimized θ and W_R shown in Fig. 6.3(a)). When the waveguide is too wide and the aspect ratio of the composite c-Si/a-Si waveguide is lower than 1.2, the rotation ceases to be efficient. The maximum width of the silicon core required to achieve $\text{PRE} > 99\%$ is shown in Fig. 6.4(b) as a function of a-Si overlayer height H_R , for 220 nm and 260 nm thick SOI. Given the same H_R , a smaller W is required for $H=220$ nm, a trend which was also observed in a previous study [7]. However, a larger W can accommodate a larger H_R . In addition, a large W is preferred for reducing scattering loss, and for better dimensional tolerances, which will be discussed in detail in Section 6.1.4. From the fabrication point of view, a low aspect ratio in cross-section is desirable. Therefore, there is a trade-off between the maximum c-Si core width and the height of the a-Si overlayer. In the following, we choose the two layers to have the same thickness ($H=H_R$) as a trade-off. The corresponding maximum widths of the silicon cores are $W=390$ nm for $H=220$ nm and $W=430$ nm for $H=260$ nm. The optimized designs have the following parameters (Table 6.1):

Figure 6.4: (a) Polarization rotation efficiency as a function of the access waveguide width W for different thickness H_R of a-Si overlayer. (b) Possible combinations of the width of the access waveguide W and the height of the a-Si layer H_R for a PRE of >99%. Grey area: $H=220$ nm; hatched area: $H=260$ nm.

6.1.4 Fabrication Tolerances

The designed asymmetric structures can be readily fabricated using the standard silicon photonics processing, and it is compatible with the processes for the high-efficiency surface grating couplers with an a-Si overlayer [14]. To investigate the robustness of our polarization rotator design, we calculate the polarization rotation efficiency as a function of several fabrication variations, shown in Fig. 6.5. For each scan of a given parameter, all other parameters remain constant at their nominal values. We determine the fabrication tolerances with a condition of $\text{PRE} > 90\%$, with the results summarized in Table 6.2. In the following, the calculated fabrication tolerances refer to the condition of $\text{PRE} > 90\%$.

It is observed from Fig. 6.5 and Table 6.2 that the PRE is most sensitive to the width of the silicon core (W), which is expected since W contributes significantly to the propagation constants of the first two modes. As it is shown in Fig. 6.6,

Table 6.1: Optimized parameters of the rotator structures for $H=220$ nm and $H=260$ nm by assuming a TE input

W (nm)	H (nm)	W_R (nm)	H_R (nm)	θ ($^\circ$)	L_R (μm)	PRE
390	220	343	220	2.4	17	99.0%
430	260	386	260	1.7	27	99.5%

waveguides with smaller width W are more sensitive to the width variation, e.g. ΔW is only ± 6 nm for $W=400$ nm to meet the condition $\text{PRE} > 90\%$. For this reason, larger waveguide widths are preferred. By using a waveguide of $W=430$ nm, the width tolerance is improved to ± 12 nm. For most lithography tools, angular alignment is highly accurate and an angle control of $< 0.3^\circ$ is readily achievable. In practical consideration, the tip termination of the a-Si layer (D_t) has a finite width size. Figure 6.5(f) shows calculated PRE efficiency as a function of D_t . Our starting simulation value for D_t is 10 nm, which is a reasonably achievable tip size using e-beam patterning. When $D_t < 60$ nm for $H=220$ nm, and $D_t < 75$ nm for $H=260$ nm, the PREs are $>90\%$. Finally, we found that a variation in the refractive index of the a-Si overlayer of $\pm 8\%$, results in a PRE penalty of only 1%. These tolerances are all within the process specifications offered by photonic foundries, demonstrating the robustness of our polarization rotator design.

Table 6.2: Calculated tolerances of the polarization rotator structures for $\text{PRE} > 90\%$ a TE input

H_{Si} (nm)	W (nm)	H (nm)	W_R (nm)	H_R (nm)	θ ($^\circ$)	D_t (nm)
220	390 ± 13	220 ± 21	343 ± 50	220 ± 13	2.4 ± 0.5	< 60
260	430 ± 11	260 ± 22	386 ± 50	260 ± 13	1.7 ± 0.3	< 75

Besides the above geometrical parameters, the thickness of the pad oxide layer between the waveguide core and the a-Si overlayer plays an important role in the rotator efficiency. Horizontal slot waveguide is formed in the pad oxide layer [as shown in Fig. 6.2(c)], such that the quasi-TM mode is strongly confined in the slot region, resulting in its propagation constant to be highly sensitive to the slot thickness and refractive index. In the simulations presented above, the pad layer material underneath the a-Si overlayer is SiO_2 of thickness $H_{pad}=10$ nm. The corresponding fabrication tolerance is $\Delta H_{pad}=2$ nm for $\text{PRE} > 90\%$. We find that the fabrication tolerance can be improved by using a pad material with a higher refractive index (e.g., Si_3N_4 with $n_{\text{Si}_3\text{N}_4}=1.989$). If Si_3N_4 is used as a pad spacer, $\Delta H_{\text{Si}_3\text{N}_4}=4$ nm for $H_{\text{Si}_3\text{N}_4}=10$ nm. Therefore, the fabrication tolerance of the Si_3N_4 pad spacer is about twice that of the SiO_2 pad spacer.

Figure 6.5: Dependence of the polarization rotation efficiency (PRE) on structure geometrical tolerances calculated with fully vectorial EME simulations for: (a) Width of the access waveguide, ΔW ; (b) height of the access waveguide, ΔH ; (c) width of the a-Si patch, ΔW_R ; (d) height of the a-Si patch, ΔH_R ; (e) angle between the a-Si layer and the access waveguide, $\Delta \theta$; and (f) tip width of the a-Si layer, D_t . The optimal parameters are listed in Table 6.1; For H=220 nm: $H_R=220$ nm, $W=430$ nm, $W_R=386$ nm, and $\theta=2.4^\circ$; For H=260 nm: $H_R=260$ nm, $W=430$ nm, $W_R=386$ nm, and $\theta=1.7^\circ$.

Figure 6.6: Waveguide width tolerances for different widths of the access waveguide, calculated by fully vectorial EME simulations. Dash curve: $W=400$ nm, $H=H_R=260$ nm, $W_R=860$ nm, $\theta=3^\circ$; Solid curve: $W=430$ nm, $H=H_R=260$ nm, $W_R=386$ nm, $\theta=1.7^\circ$.

Figure 6.7: Wavelength dependence of polarization rotation for TE polarized input calculated by 3D-FDTD and fully vectorial EME simulations. (a) $H=H_R=220$ nm, $W=390$ nm, $W_R=343$ nm and $\theta=2.4^\circ$; (b) $H=H_R=260$ nm, $W=430$ nm, $W_R=386$ nm and $\theta=1.7^\circ$.

Finally, we examine the operating wavelength range of our polarization rotator. The extinction ratio (ER) and the insertion loss (IL) are defined as $ER=10\log_{10}(P_{TM}^{out}/P_{TE}^{out})$ and $IL=10\log_{10}(P_{TM}^{out}/P_{TE}^{in})$, respectively. Figure 6.7(a) shows the wavelength dependent relative power transmission of the rotator for $H=220$ nm assuming TE polarized input signal. It is observed that ER is >10 dB for the wavelength range of 1490 nm to 1625 nm (bandwidth >135 nm), while the calculated

ER exceeds 17 dB across the entire C-band (1530 nm to 1565 nm). The calculated insertion loss is below -0.16 dB. The wavelength dependent relative power transmission of the rotator with the 260 nm silicon core for TE input is shown in Fig. 6.7(b). ER>10 dB is obtained for the wavelength range of 1500 nm to 1610 nm. This broad bandwidth (>110 nm) is a distinct advantage of a mode-evolution type polarization rotator. The calculated insertion loss is less than -0.3 dB.

6.1.5 Conclusion

We have proposed and demonstrated by simulations a robust polarization rotator design based on the mode-evolution mechanism. The rotator comprises a silicon wire waveguide with an amorphous silicon overlayer and a thin SiO₂ pad layer and it can be fabricated by standard silicon photonics processing without the need for precise lithographic alignments. Our calculations show that a polarization rotation efficiency of >99% can be readily achieved at the same time as a broadband operation with 90% rotation efficiency within C-band wavelength range. Considering the anticipated device dimensional variations within typical specifications of silicon photonic foundries, the calculated rotation efficiency exceeds 90%.

6.2 Polarization Splitter and Rotator with Taper-etched Directional Coupler

The following paper, “Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler,” demonstrates the numerical analysis of the polarization splitter and rotator based on a taper-etched directional coupler. This paper includes the device design and simulation, discussion and analysis. The mask layout of the polarization rotator is shown in Appendix [B](#).

Yule Xiong performed the device design, all simulations, and wrote this paper. The paper was published in Optics Express, volume 22, issue 14, on pages 17458-17465 in 2014.

Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler

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6.2.1 Abstract

We propose a fabrication tolerant polarization splitter and rotator (PSR) on the silicon-on-insulator platform based on the mode-coupling mechanism. The PSR consists of a silicon wire waveguide coupled to a taper-etched waveguide. Compared to previously reported PSRs based on directional couplers which are sensitive to fabrication variations, the partially etched taper structure can compensate for fabrication inaccuracies. In addition, the taper-etched geometry breaks both the horizontal and vertical symmetries of the waveguide, introducing an additional degree of design freedom to accommodate different upper cladding layers. The proposed PSR can be readily integrated in a planar waveguide circuit using e.g. SiO₂ cladding, making it compatible with typical metal back-end-of-line processes. Our simulation results show that the PSR has a low TM-to-TE polarization conversion loss of -0.09 dB in the C-band (or a conversion efficiency of 98%). A low TE-to-TE through insertion

loss (-0.07 dB) and a very low polarization crosstalk (-30 dB) over a wide wavelength range exceeding 160 nm with a large fabrication tolerance (>50 nm) are numerically demonstrated.

6.2.2 Introduction

Polarization management is an important topic of research in silicon photonic circuits [1]. Polarization splitters and rotators are structures of fundamental importance in polarization diversity systems [2] and polarization division multiplexed devices [15]. Various types of passive polarization splitters and rotators have been reported [4, 6–9, 16–19]. Mode-evolution polarization rotators [6–9, 16] have attracted significant attention because of their broad operation wavelength range and robust fabrication tolerance, typically with amorphous silicon or silicon nitride overlayers used to modify the waveguide cross-section in order to break the waveguide vertical symmetry [6–8, 16]. However, such devices generally require a rather complex fabrication process. Another class of polarization rotators are mode-coupling structures, which are inherently wavelength dependent and comparatively sensitive to fabrication variations. Polarization splitter and rotators (PSRs) using asymmetrical directional couplers (DCs) optimized for a single etch process have been reported [4, 17]. However, the air cladding is used to realize vertical asymmetry, which is incompatible with most metal back-end-of-line (BOEL) processes, and these devices are also sensitive to fabrication variation. Recently, double-etch asymmetrical wire and rib DC-based PSRs using silica cladding have been demonstrated [18, 19]. The main practical issue of limited fabrication tolerance (typically <10 nm for a loss penalty of -1 dB) still remains. Here we propose a fabrication tolerant and broadband PSR based on mode-coupling mechanism. The PSR comprises a taper-etched DC, specifically a silicon wire waveguide evanescently coupled to a taper-etched waveguide with a silica upper cladding. The proposed PSR utilizes a partial etch process, which is available in most silicon photonics foundries.

6.2.3 Structure Design and Operation Principle

The proposed PSR is schematically illustrated in Fig. 6.8(a). It comprises a silicon wire waveguide (waveguide A) of width W and height H , coupled to a taper-etched waveguide (waveguide B) with a width W_t , a ridge width W_e , a post-etch slab height H_e , a taper angle θ , and a gap between the waveguides D_{gap} . The coupling length L_{DC} is the taper end-to-end distance in the waveguide B, where $L_{DC} = W_t / \tan(\theta)$. Two S-bends with a bending radius of R_S are used near the input and the output ports to decouple the waveguides in these two regions.

Figure 6.8: (a) Schematic of the polarization splitter and rotator based on the taper-etched directional coupler. For clarity, the SiO₂ upper cladding is not shown. (b) Effective index of the TE-like mode of the taper-etched waveguide B as a function of the ridge width W_e for a post-etch height $H_e = 110$ nm, $W_t = 350$ nm, and $H = 220$ nm. Effective indices of the TM-like mode of the access waveguide A ($H = 220$ nm) are shown for different widths W of the access waveguide A (black lines). Red circles indicate the phase matching condition.

The operation principle of the PSR is as follows: The dimensions of the waveguide B are chosen based on two conditions: 1) a significant effective index mismatch of the TE-like mode (with dominant E_x component) for the waveguides A and B, i.e., $n_{eff}^B(TE) < n_{eff}^A(TE)$, to ensure that the TE-like mode injected in the input port A₁ propagates to the through port A₂ with a minimal cross-coupling to the waveguide

B; 2) a phase matching condition $n_{eff}^B(\text{TE}) \sim n_{eff}^A(\text{TM})$, so that the TM-like mode (with dominant E_y component) injected into port A_1 couples to the TE-like mode of the waveguide B. The coupling process from the TM-like mode in the waveguide A to the TE-like mode in the waveguide B is facilitated by hybrid modes supported in the waveguide B, in which both the horizontal and vertical asymmetries are created by the tapered-etch. Under these conditions, a high polarization conversion efficiency $\text{CE}_{TM-TE} = 10\log_{10}(\text{P}(\text{out})_{TE}^B / \text{P}(\text{in})_{TM}^A)$ can be achieved.

In our simulations we assume a free-space wavelength of 1550 nm, the refractive index of silicon $n_{Si} = 3.476$, the bending radius of S-bend $R_S = 50 \mu\text{m}$, and the upper and lower SiO_2 cladding with a refractive index $n_{\text{SiO}_2} = 1.444$. The silicon layer thickness is $H=220$ nm, the width of the waveguide A is $W=450$ nm, and the gap in the coupling section is $D_{gap} = 200$ nm, which are typical feature sizes used in silicon photonics foundries with public access. The robustness advantage of the proposed PSR can be observed in Fig. 6.8(b), which shows the TE-like mode effective index in the waveguide B as a function of its ridge width W_e for a post-etch slab height $H_e=110$ nm. The TM-like mode effective indices of the waveguide A, $n_{eff}^A(\text{TM})$, are shown for three different waveguide widths. The TE-TM polarization coupling is achieved for the phase matching condition $n_{eff}^B(\text{TE})=n_{eff}^A(\text{TM})$. This condition can be fulfilled for a specific combinations of parameters H_e , W_e and W_t of the coupling section. As the width of the waveguide A varies, the phase matching is still achieved just for a different W_e , i.e., at a different position along the taper. Similar behavior is also found for varying the post-etch slab height H_e . As a result, the TM-TE phase matching condition is remarkably insensitive to variations in waveguide dimensions.

The polarization conversion is further illustrated in Fig. 6.9, which includes the top views [Figs. 6.9(a) and 6.9(b)] and the cross-sectional views [Fig. 6.9(c)] of the mode evolution along the PSR structure, as calculated by the 3D-FDTD method. The TE-like mode launched in the input port A_1 propagates to the through port A_2 without cross-coupling [Fig. 6.9(a)]. On the other hand, the TM-like mode from the input port A_1 is gradually coupled to the waveguide B, being transformed into the TE-like mode propagating to the cross port B_2 [Fig. 6.9(b)]. Figure 6.9(c) shows the cross-sectional views of the mode evolution for the TM-like mode input. In the middle of the taper section, the E_x and E_y components are equalized, yielding an efficient mode hybridization. In the following we optimize the device design by varying several

parameters of the structure. We use the full-vectorial eigenmode expansion (EME) method and some results are cross-checked by the 3D-FDTD simulations.

Figure 6.9: Light intensity (Light input from the left port) of (a) TE-like mode input and (b) TM-like mode input evolution along the polarization splitter and rotator (top views), as calculated by a 3D-FDTD method. (c) Transverse electric field distributions at the corresponding positions along the polarization splitter and rotator when launching TM-like mode as input.

The PSR performance is examined for three post-etch slab heights: (i) $H_e=70$ nm (deep etch with an etch depth of $D=150$ nm); (ii) $H_e=110$ nm (moderate etch depth, $D=110$ nm); and (iii) $H_e=150$ nm (shallow etch depth, $D=70$ nm). The selection of these parameters is guided by the availability in foundry offerings. Figure 6.10(a) shows the effective indices of the TE-like mode in the waveguide B for these etch depths, as a function of the width ratio W_e/W_t . A deep etch introduces a large $n_{eff}^B(\text{TE})$ change in the coupling region and a longer coupling length L_{DC} is required

[Fig. 6.10(b)]. The width W_t of the waveguide B should be sufficiently smaller than the width W of the waveguide A to avoid the TE-to-TE mode coupling between the two waveguides. Here, the phase matching condition is designed to be fulfilled in the middle of the taper section, i.e. $n_{eff}^B(TE) = n_{eff}^A(TM)$ when $W_e = W_t/2$. By setting the width of the waveguide A to $W = 450$ nm, we obtain $W_t = 410$ nm, 350 nm and 310 nm for $H_e = 70$ nm, 110 nm, and 150 nm, respectively. These parameters are summarized in Table 6.3. Using the selected values of parameters H_e and W_t , the polarization conversion efficiency CE_{TM-TE} is calculated as a function of the coupling length L_{DC} using the EME method. The results are shown in Fig. 6.10(b). For each etch depth, the polarization conversion efficiency eventually saturates and reaches its maximum value provided the coupler is long enough. For the shallow etch ($H_e = 150$ nm), a comparatively short L_{DC} is required. The L_{DC} values required for reaching the maximum polarization conversion efficiency CE_{TM-TE} are listed in Table 6.3.

Figure 6.10: (a) Effective index of the TE-like mode of the taper-etched waveguide B as a function of a width ratio W_e/W_t , for three different post-etch slab heights ($H_e = 70$ nm, 110 nm and 150 nm). The corresponding width W_t is 410 nm, 350 nm and 310 nm, for the phase matching near the position $W_e/W_t = 0.5$. Effective index of the TM-like mode of the access waveguide A ($H = 220$ nm) are shown for a waveguide width range $W = 450 \pm 50$ nm (shadow region). (b) Polarization conversion efficiency CE_{TM-TE} as a function of coupling length L_{DC} for post-etch slab heights $H_e = 70$ nm, 110 nm, and 150 nm.

It is observed that the minimum polarization conversion loss (i.e., maximum CE_{TM-TE}) is achieved for a post-etch slab height of $H_e = 110$ nm. At this height ($H_e = 0.5H$), the mode is efficiently hybridized (50% E_x and 50% E_y) near the phase-matching position, yielding a high polarization conversion efficiency. Some of our

Table 6.3: Optimized parameters of the polarization splitter and rotator calculated using the EME method

W (nm)	H (nm)	H _e (nm)	W _t (nm)	D _{gap} (nm)	L _{DC} (μm)	CE _{TM-TE} (dB)
450	220	70	410	200	>390	-0.38
450	220	110	350	200	>120	-0.26
450	220	150	310	200	>80	-0.32

results have been also verified using the 3D-FDTD method. For example, using the parameters in Table 6.3 for H_e=110 nm, the calculated polarization conversion efficiency CE_{TM-TE} is $\sim$ -0.09 dB across the entire C-band (from 1530 nm to 1565 nm), which is slightly better than the result obtained using the EME method.

6.2.4 Fabrication Tolerances

The designed taper-etched DC structures can be readily fabricated using the standard silicon photonics processing, including the two-step etch process often used for making high-efficiency surface grating couplers [20]. To investigate the fabrication tolerance of our PSR design, we study the polarization conversion efficiency CE_{TM-TE} as a function of several device parameters, as shown in Fig. 6.11 and Table 6.4. Simulations show that the longer the coupling length L_{DC}, the more fabrication tolerant the PSR is, but with a penalty in device footprint. The reason is that a long coupling length L_{DC} provides a sufficiently long phase-matching region to ensure the full power transfer from the TM-like mode to the TE-like mode. Here, we set L_{DC}= 400 μm, 200 μm and 150 μm for H_e=70 nm, 110 nm and 150 nm, respectively, larger than the values indicated in Table 1. Longer L_{DC} will slightly increase the insertion loss of the PSR while shorter L_{DC} decreases the fabrication tolerances. Figure 6.11(a) illustrates the dependence of polarization conversion efficiency CE_{TM-TE} on the variation of the post-etch slab height (ΔH_e). All other parameters are assumed constant at their nominal design values listed in Table 1. It is observed that CE_{TM-TE} is rather tolerant to over-etching (ΔH_e < 0) in the taper section. On the other hand,

CE_{TM-TE} drops dramatically for substantial under-etching errors as the $n_{eff}^A(TM)$ exceeds the maximum effective index range for which the phase matching condition holds.

Figure 6.11: Dependence of the polarization conversion efficiency CE_{TM-TE} on structure geometrical tolerances. Calculated using the full-vectorial EME simulations for (a) post-etch slab height, ΔH_e , and (b) tip width D_t . The optimized parameters are listed in Table 6.3.

The fabrication tolerance of the PSR is also evaluated for other device parameters, with a condition of $CE_{TM-TE} > -0.5$ dB. For each scan of a given parameter, all other parameters are assumed constant at their nominal design values listed in Table 6.3. In practical implementation, the tip termination of the taper-etched waveguide has a finite width. Figure 6.11(b) shows the calculated polarization conversion efficiency CE_{TM-TE} as a function of tip width D_t . When $D_t \sim 80$ nm, CE_{TM-TE} is > -0.5 dB while the loss penalty is 0.2 dB. As shown in Table 6.4 and Fig. 6.11, the designed device is very fabrication tolerant to W , D_{gap} and D_t . Meanwhile, the fabrication tolerance of the proposed design is similar for different etching depths, i.e., $H_e = 70$ nm, 110 nm and 150 nm. In Table 6.4, it is also shown that the overall tolerances are better than 50 nm for a penalty of -0.5 dB in CE_{TM-TE} . These tolerances are within the process specifications offered by photonic foundries, demonstrating the fabrication resilience of our PSR design.

Figure 6.12: Wavelength dependence of the polarization splitter and rotator as calculated by the full-vectorial EME simulations. (a) TE-like mode insertion loss and TM-to-TE polarization conversion loss; (b) Crosstalk XT_{TE} and XT_{TM} . $W=450$ nm, $H=220$ nm, $W_t=350$ nm, $H_e=110$ nm, $D_{gap}=200$ nm, and $L_{DC}=200$ μm .

Finally, we examine the operational wavelength range of our PSR. For a TE-like mode input, the TE-to-TE insertion loss (IL) at the through port A_2 and the crosstalk (XT) at the cross port B_2 are defined as $IL = 10\log_{10}(P(\text{out})_{TE}^A / P(\text{in})_{TE}^A)$ and $XT_{TE} = 10\log_{10}(P(\text{out})_{TE}^B / P(\text{out})_{TE}^A)$ respectively. For the TM-like mode input, the polarization conversion loss (PCL) at the cross port B_2 and the XT at the through port A_2 are defined as $PCL = 10\log_{10}(P(\text{out})_{TE}^B / P(\text{in})_{TM}^A)$ and $XT_{TM} = 10\log_{10}(P(\text{out})_{TE}^A / P(\text{out})_{TE}^B)$, respectively. Figure 6.12 shows the wavelength dependence of the loss and crosstalk of the PSR for $H_e=110$ nm. The TE-like mode insertion loss is below -0.07 dB within the wavelength range of 1450 nm to 1650 nm (bandwidth > 200 nm), while the TM-to-TE conversion loss is less than -0.5 dB across the entire S, C and L-bands (1460 nm to 1625 nm), and below -0.3 dB over the

Table 6.4: Calculated tolerance of the polarization splitter and rotator for $CE_{TM-TE} > -0.5$ dB and a TM-like input mode

W (nm)	H (nm)	H_e (nm)	W_t (nm)	D_{gap} (nm)	D_t (nm)
450 ± 70	220 ± 30	$70 + 40 / - 15$	410 ± 25	200 ± 60	< 100
450 ± 55	220 ± 30	110 ± 25	350 ± 30	200 ± 100	< 95
450 ± 50	220 ± 28	$150 + 18 / - 40$	310 ± 25	200 ± 90	< 80

Table 6.5: Performance of the polarization splitter and rotator for the S, C and L bands (the wavelength range from 1460 nm to 1625 nm)

H_e (nm)	W_t (nm)	IL (dB)	XT_{TE} (dB)	PCL (dB)	XT_{TM} (dB)
70	410	> -0.15	< -25	> -0.5	< -15
110	350	> -0.07	< -30	> -0.5	< -30
150	310	> -0.05	< -30	> -0.5	< -30

C-band (1530 nm to 1565 nm). As shown in Fig. 6.12(b), the crosstalk XT_{TE} and XT_{TM} are below -30 dB in the investigated S, C and L bands. This broad bandwidth is a distinct advantage of our PSR based on the taper-etched directional coupler. In Table 6.5 we summarize the wavelength dependence of the PSR parameters for the three different post-etch slab heights H_e . For the deep-etch ($H_e=70$ nm), the TE-to-TE insertion loss is about -0.15 dB and the crosstalk XT_{TM} is below -20 dB. This is because the width $W_t=410$ nm of the waveguide B is closer to $W=450$ nm, resulting in TE-to-TE mode coupling between the two waveguides. In addition, simulations show that fabrication tolerances remain similar over the entire C band. Since $n_{eff}^B(TE)$ of the waveguide B and $n_{eff}^A(TM)$ of the waveguide A varies with the wavelength in a similar trend, the phase-matching condition $n_{eff}^B(TE)=n_{eff}^A(TM)$ is expected to be achieved at the same position for different wavelengths.

6.2.5 Comparison with Literature Results

Table 6.6 summarizes several results of the DC-based PSRs from the current literature and compares them with our design. The PSRs using a one-step etch in [4, 17] required an air cladding to break the vertical asymmetry in order to achieve a high polarization conversion efficiency. The two-step etching processes in [18, 19] induced both the horizontal and vertical asymmetry without the need of an air cladding. However, the parallel DC structures in [17–19] required precisely tuned phase matching. As a result, these DCs are all inherently wavelength dependent and sensitive to fabrication variations. The tapered DC in [4] was used to compensate the fabrication variations

at the cost of a relatively large footprint. However, the improvement of the fabrication tolerance was still limited. The taper-etched DC structure in this work enhances the fabrication tolerance significantly while using a similar footprint as in [4]. Furthermore, the structure reported here has a broadband operation bandwidth without the need for precise lithographic alignments.

Table 6.6: Comparison of directional coupler based polarization splitter and rotator

Reference	Height (nm)	Gap (nm)	Length (μm)	Cladding	Tolerance (nm)	Bandwidth (nm)
[17]	250	100	36.8	air	<10	35 (C band)
[4]	250	100	>100	air	14	35 (C band)
[4]	250	150	>200	air	14	35 (C band)
[18]	220	150	27	SiO ₂	<10	30
[19]	250	150	24	SiO ₂	<10	100
Our work	220	200	>80	SiO ₂	50*	160

*Note the fabrication tolerances for Refs. [4, 17–19] refer to a criterion of $CE_{TM-TE} > -1$ dB, while for the current work the criterion is for $CE_{TM-TE} > -0.5$ dB

6.2.6 Conclusion

We have proposed and investigated a fabrication-tolerant polarization splitter and rotator (PSR) design based on the cross-polarization coupling mechanism. The PSR comprises a silicon wire waveguide coupled to a taper-etched waveguide and it can be fabricated by standard silicon photonics processing without the need for precise lithographic alignments. We used the full-vectorial EME and the 3D-FDTD methods for the numerical evaluation of the device performance. Our calculations show that a high TM-to-TE polarization conversion efficiency can be readily achieved over a broad wavelength range, i.e. -0.5 dB polarization conversion loss within the S, C and L band wavelength range of exceeding 160 nm. The conversion loss in the C-band is below -0.09 dB. A TE-to-TE through insertion loss is better than -0.07 dB for the

same wavelength range, with a low polarization crosstalk of -30 dB. Among the PSR structures designed for an SOI platform, our design is among the most fabrication tolerant and broadband reported to date.

6.3 Two-Mode Multiplexer with Taper-etched Directional Coupler

The following manuscript, “Broadband two-mode multiplexer with taper-etched directional coupler on SOI platform”, illustrates details on the simulated performance of a two-mode multiplexer with taper-etched directional coupler. The mask layout used to fabricate the two-mode multiplexer and demultiplexer is shown in Appendix [B](#).

Yule Xiong did all the device simulations, data analysis and wrote the manuscript. The proceeding was presented at Group IV Photonics (GFP), IEEE 11th International Conference on, August 27 in 2014.

Broadband two-mode multiplexer with taper-etched directional coupler on SOI platform

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6.3.1 Abstract

We propose an original two-mode (TE_0/TE_1) division multiplexer using a taper-etched directional coupler. The multiplexer has a low insertion loss of -0.1 dB within C-band with a minimum loss of -0.05 dB, a modal crosstalk below -40 dB and a robust fabrication tolerance (>100 nm).

6.3.2 Introduction

Silicon-based optical interconnects can offer high data transmission bandwidths by using wavelength-division multiplexing (WDM) technology [21]. For WDM systems, especially dense WDM systems, many laser sources with different wavelengths are required. Mode-division multiplexing (MDM) offers an alternative route to increase

the capacity of SOI optical links by supplying multiple guided modes through a single wavelength carrier [22]. Several designs for mode multiplexers have been proposed, including multimode interferometers [23], asymmetrical Y-junctions [24] and directional couplers (DCs) [25], and ring resonators [26]. However, the performance of these devices is limited by their comparatively low tolerances to fabrication variations. Recently, a tapered DC-based mode multiplexer with enhanced fabrication tolerance has been reported [27]. To further improve the performance and fabrication tolerances, we introduce a taper-etched directional coupler as a broadband two-mode (de)multiplexer, where a silicon taper-etched wire is coupled to a silicon wire multimode waveguide. The proposed device uses a shallow etch process, which is typically available in silicon photonics foundries.

6.3.3 Structure Design and Operation Principle

A schematic of the proposed two-mode (TE_0 - TE_1) multiplexer design is shown in Fig. 6.13. It has a taper-etched waveguide with a width of W_t and a post-etch slab height of H_e . A silicon multimode wire waveguide of width W and height H is placed adjacently to form a directional coupler. The coupling gap between the two waveguides is D_{gap} and the coupling length is L_{DC} . The TE_0 - TE_1 coupling can be achieved under the phase matching condition where the effective index of the TE_0 mode of the taper-etched equals that of the TE_1 mode in the multimode wire waveguide, as shown in Fig. 2(a). In other words, when the TE_0 mode is injected into the taper-etched waveguide, a high coupling efficiency $T_{TE_0-TE_1} = P(\text{out})_{TE_1}^{wire} / P(\text{in})_{TE_0}^{taper}$ can be reached in the multimode output waveguide where the TE_1 mode is excited. Furthermore, because of the large effective index difference between the TE_0 modes in the two waveguides, modal crosstalk between the two TE_0 modes is very low, with a near zero coupling efficiency, $T_{TE_0-TE_0} = P(\text{out})_{TE_0}^{wire} / P(\text{in})_{TE_0}^{taper} = 0$. Furthermore, the TE_0 - TE_1 phase matching condition is remarkably insensitive to fabrication variations such as deviations from nominal waveguide width. The phase matching condition can be fulfilled for a range of waveguide width errors (albeit at a shifted position along the coupler) because of the taper-etched waveguide geometry. Therefore, the TE_0 - TE_1 mode coupling efficiency is maintained and the fabrication tolerance of the coupling length is relaxed.

Figure 6.13: (a) Schematic of the TE₀/TE₁ mode multiplexer with a taper-etched directional coupler; (b) Calculated electric field for the TE₀-TE₁ coupling, obtained by the eigenmode expansion method (EME).

The performance of the mode multiplexer is evaluated using the eigenmode expansion (EME) method. In the simulations, we assume a central wavelength of 1550 nm, the refractive index of silicon $n_{Si}=3.476$, and the upper and bottom SiO₂ cladding layers with the refractive index $n_{SiO_2}=1.444$. The multiplexer performance is examined for a height of $H=220$ nm for both the wire multimode and taper-etched waveguides. The post-etch slab height of the taper-etched waveguides is set to $H_e=150$ nm, which is commonly used in silicon photonics foundries with public access. Figure 6.14(a) shows the effective index of the TE₀ mode in the taper-etched waveguide as a function of a ridge width W_e (see Fig. 6.14(a) inset) for $H_e=150$ nm (with an etch depth of 70 nm). The phase matching condition can be fulfilled provided the effective index of the TE₁ mode in the multimode wire waveguide is within the effective index range of the TE₀ mode in the taper-etched waveguide, i.e. from 2.08 to 2.43. Figure 6.14(b) shows the coupling efficiency $T_{TE_0-TE_1}$ and modal crosstalk calculated as a function of wavelength for a structure with the following parameters: the width of the multimode wire waveguide $W=840$ nm; the width of the taper-etched waveguide $W_t=490$ nm with a height of $H_e=150$ nm; and the gap and the coupling length of $D_{gap}=200$ nm and $L_{DC}=330$ μ m, respectively. It is observed that a high coupling efficiency $T_{TE_0-TE_1}$ and a modal crosstalk $T_{TE_0-TE_0}$ lower than -40 dB is achieved for

a wavelength range of 200 nm. The minimum coupling loss (the maximum coupling efficiency $T_{TE_0-TE_1}$) is -0.05 dB. Our simulations show that for the wavelength range of 1490 nm-1650 nm the coupling loss is below -0.3 dB while within the C-band (1530 nm-1565 nm) the loss is less than -0.1 dB. In addition, the total power conversion from the TE modes to all TM modes is calculated to be lower than -50 dB.

Figure 6.14: (a) Effective TE₀ mode index in the taper-etched waveguide as a function of the ridge width W_e for a post-etch height $H_e=150$ nm. Effective indices of the TE₁ mode of the wire waveguide ($H=220$ nm) are shown for different waveguide widths W (red lines); (b) Calculated TE₀-TE₁ coupling efficiency and mode crosstalk $T_{TE_0-TE_0}$ as a function of wavelength for $W=840$ nm, $H=220$ nm, $W_t=490$ nm, $H_e=150$ nm, $D_{gap}=200$ nm and $L_{DC}=330$ μm .

6.3.4 Fabrication Tolerances

The proposed mode multiplexer can be fabricated using conventional silicon photonics processing, with a two-step etch process often used for making surface grating couplers. To investigate the fabrication tolerance of our mode multiplexer device, we studied the coupling efficiency $T_{TE_0-TE_1}$ as a function of several device parameters, as shown in Fig. 6.15. For each scan of a given parameter, all other parameters remain constant at their nominal design values. For a coupling loss of -0.3 dB or less, the calculated fabrication tolerances are as follows: the width and height of the silicon multimode wire waveguide $W=840\pm 50$ nm and $H=220\pm 50$ nm, respectively; the width of the taper-etched waveguide $W_t=490\pm 70$ nm; the etched waveguide height $H_e=40$ to 165 nm; and the gap width $D_{gap}=200\pm 50$ nm. Even if the taper etched section has a large termination width, provided the tip width of the taper-etched

waveguide is $D_t < 140$ nm (see Fig. 6.15(f), inset), the coupling loss is still < -0.3 dB. As shown in Fig. 6.15(d), the performance of the device is significantly more tolerant to over-etching than it is to under-etching ($H_e = 40$ to 165 nm with a 150 nm nominal post-etch slab height of the taper-etched waveguide). The calculated tolerances are within the process specifications offered in various CMOS photonic foundries and demonstrate the robust performance of our TE_0 - TE_1 mode multiplexer design.

Figure 6.15: Dependence of the TE_0 - TE_1 mode coupling efficiency on the following parameters: (a) error in width ΔW and (b) height ΔH of the multimode wire waveguide, (c) error in width of the taper-etched waveguide ΔW_t , (d) slab height error ΔH_e , (e) coupling gap error ΔD_{gap} , and (f) tip width error ΔD_t of the etched taper. Other parameters are specified in Fig. 6.14(b).

6.3.5 Conclusion

We have proposed and demonstrated a new type of mode multiplexer design optimized for the 220 nm SOI. Using the taper-etched directional coupler, a mode coupling efficiency of >-0.1 dB can be readily achieved across the entire C-band with minimal modal crosstalk of -40 dB. The proposed device shows fabrication tolerances for the dimensional variations are on the order of 100 nm, which can be readily realized in existing silicon photonic foundries.

List of References

- [1] D. Dai, L. Liu, S. Gao, D.-X. Xu, and S. He, “Polarization management for silicon photonic integrated circuits,” *Laser and Photonics Reviews*, vol. 7, pp. 303–328, May 2013.
- [2] T. Barwicz, M. R. Watts, M. A. Popović, P. T. Rakich, L. Socci, F. X. Kärtner, E. P. Ippen, and H. I. Smith, “Polarization-transparent microphotonic devices in the strong confinement limit,” *Nature Photonics*, vol. 1, pp. 57–60, Jan. 2007.
- [3] L. Liu, Y. Ding, K. Yvind, and J. r. M. Hvam, “Efficient and compact TE-TM polarization converter built on silicon-on-insulator platform with a simple fabrication process,” *Optics Letters*, vol. 36, pp. 1059–1061, Apr. 2011.
- [4] Y. Ding, L. Liu, C. Peucheret, and H. Ou, “Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler,” *Optics Express*, vol. 20, pp. 20021–20027, Aug. 2012.
- [5] H. Fukuda, K. Yamada, T. Tsuchizawa, T. Watanabe, H. Shinojima, and S.-i. Itabashi, “Polarization rotator based on silicon wire waveguides,” *Optics Express*, vol. 16, pp. 2628–2635, Feb. 2008.
- [6] L. Chen, C. R. Doerr, and Y.-K. Chen, “Compact polarization rotator on silicon for polarization-diversified circuits,” *Optics Letters*, vol. 36, pp. 469–471, Feb. 2011.
- [7] D. Vermeulen, S. Member, S. Selvaraja, P. Verheyen, P. Absil, W. Bogaerts, D. V. Thourhout, and G. Roelkens, “Silicon-on-insulator polarization rotator based on a symmetry breaking silicon overlay,” *IEEE Photonics Technology Letters*, vol. 24, no. 6, pp. 482–484, 2012.
- [8] H. Zhang, S. Das, Y. Huang, C. Li, S. Chen, H. Zhou, M. Yu, P. Guo-Qiang Lo, and J. T. L. Thong, “Efficient and broadband polarization rotator using horizontal slot waveguide for silicon photonics,” *Applied Physics Letters*, vol. 101, no. 2, p. 021105, 2012.
- [9] A. V. Velasco, M. L. Calvo, P. Cheben, A. Ortega-Moñux, J. H. Schmid, C. A. Ramos, I. n. M. Fernandez, J. Lapointe, M. Vachon, S. Janz, and D.-X. Xu, “Ultracompact polarization converter with a dual subwavelength trench built in a silicon-on-insulator waveguide,” *Optics Letters*, vol. 37, pp. 365–367, Feb. 2012.

- [10] Z. Wang and D. Dai, "Ultrasmall Si-nanowire-based polarization rotator," *Journal of the Optical Society of America B*, vol. 25, pp. 747–753, Apr. 2008.
- [11] A. Densmore, D. Xu, P. Waldron, S. Janz, P. Cheben, J. Lapointe, A. Delge, B. Lamontagne, J. H. Schmid, and E. Post, "A silicon-on-insulator photonic wire based evanescent field sensor," *IEEE Photonics Technology Letters*, vol. 18, no. 23, pp. 2520–2522, 2006.
- [12] D. X. Xu, A. Densmore, A. Delge, P. Waldron, R. McKinnon, S. Janz, J. Lapointe, G. Lopinski, T. Mischki, E. Post, P. Cheben, and J. H. Schmid, "Folded cavity SOI microring sensors for high sensitivity and real time measurement of biomolecular binding," *Optics Express*, vol. 16, pp. 15137–15148, Sept. 2008.
- [13] R. Sun, P. Dong, N.-N. Feng, C.-Y. Hong, J. Michel, M. Lipson, and L. Kimerling, "Horizontal single and multiple slot waveguides: optical transmission at $\lambda = 1550$ nm," *Optics Express*, vol. 15, pp. 17967–17972, Dec. 2007.
- [14] G. Roelkens, D. Van Thourhout, and R. Baets, "High efficiency Silicon-on-Insulator grating coupler based on a poly-Silicon overlay," *Optics Express*, vol. 14, pp. 11622–11630, Nov. 2006.
- [15] P. Dong, C. Xie, L. Chen, L. L. Buhl, and Y.-K. Chen, "112-Gb/s monolithic PDM-QPSK modulator in silicon," *Optics Express*, vol. 20, pp. B624–B629, Dec. 2012.
- [16] Y. Xiong, D.-X. Xu, J. H. Schmid, P. Cheben, S. Janz, and W. N. Ye, "Robust Silicon Waveguide Polarization Rotator With an Amorphous Silicon Overlayer," *IEEE Photonics Journal*, vol. 6, p. 2200308, Apr. 2014.
- [17] L. Liu, Y. Ding, K. Yvind, and J. M. Hvam, "Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits," *Optics Express*, vol. 19, pp. 12646–12651, June 2011.
- [18] H. Guan, A. Novack, M. Streshinsky, R. Shi, Q. Fang, A. E.-J. Lim, G.-Q. Lo, T. Baehr-Jones, and M. Hochberg, "CMOS-compatible highly efficient polarization splitter and rotator based on a double-etched directional coupler," *Optics Express*, vol. 22, pp. 2489–2496, Jan. 2014.
- [19] J. Wang, B. Niu, Z. Sheng, A. Wu, X. Wang, S. Zou, M. Qi, and F. Gan, "Design of a SiO₂ top-cladding and compact polarization splitter-rotator based on a rib directional coupler," *Optics Express*, vol. 22, no. 4, pp. 4137–4143, 2014.
- [20] D. Taillaert, F. Van Laere, M. Ayre, W. Bogaerts, D. Van Thourhout, P. Bienstman, and R. Baets, "Grating couplers for coupling between optical fibers and nanophotonic waveguides," *Japanese Journal of Applied Physics*, vol. 45, pp. 6071–6077, Aug. 2006.
- [21] R. Kirchain and L. Kimerling, "A roadmap for nanophotonics," *Nature Photonics*, vol. 1, pp. 303–305, 2007.
- [22] D. Dai, J. Wang, and Y. Shi, "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," *Optics Letters*, vol. 38, pp. 1422–1424, May 2013.

- [23] T. Uematsu, Y. Ishizaka, Y. Kawaguchi, K. Saitoh, and M. Koshiba, "Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission," *Journal of Lightwave Technology*, vol. 30, pp. 2421–2426, Aug. 2012.
- [24] N. Riesen and J. D. Love, "Design of mode-sorting asymmetric Y-junctions," *Applied Optics*, vol. 51, pp. 2778–2783, May 2012.
- [25] L.-W. Luo, N. Ophir, C. P. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergmen, and M. Lipson, "WDM-compatible mode-division multiplexing on a silicon chip," *Nature Communications*, vol. 5, p. 3069, Jan. 2014.
- [26] B. A. Dorin and W. N. Ye, "Two-mode division multiplexing in a silicon-on-insulator ring resonator," *Optics Express*, vol. 22, no. 4, pp. 4547–4558, 2014.
- [27] Y. Ding, J. Xu, F. D. Ros, B. Huang, H. Ou, and C. Peucheret, "On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer," *Optics Express*, vol. 21, no. 8, pp. 10376–10382, 2013.

Chapter 7

Conclusions

This thesis first presented the investigation of a fabrication alternative method, the LOCal Oxidation of Silicon (LOCOS), for making submicron size waveguides. The impact of the LOCOS technique on silicon wire waveguides is an alternative for mass producing submicron-sized waveguides. For feasibility evaluation, both straight and bending waveguides were fabricated by the LOCOS technique using only the basic optical lithography method. The pad oxide layer used in the LOCOS technique can significantly affect the cross-sectional profile of the fabricated waveguide. The minimum propagation loss of 8.78 dB/cm and the bending loss of 0.0089 dB/90° for a 5 μm bending radius were demonstrated experimentally.

After the discussion of the LOCOS technique, the thesis shifted its focus from fabrication to device design. The fabrication tolerance is the key design consideration. Three types of silicon devices with improved fabrication tolerance were designed: i) microring resonator (MRR)-based devices, ii) subwavelength grating (SWG)-based devices, and iii) taper-based devices.

MRRs play an important role in silicon photonics due to their versatile applications ranging from sensing to switching, to modulation, and to lasing. The thesis work started with a vertically coupled double-ring sensor design for achieving temperature-insensitive sensing. The reference microring is buried under the spacing material and is isolated from the sensing medium. By determining the resonant wavelength shifts of the reference microring due to temperature change, the temperature and environment fluctuations in the sensing measurements can be extracted and removed to

obtain athermal sensing performance. The vertical stack is designed for the ease of fabrication as the coupling gap can be simply controlled by the deposition. Next, slotted MRRs coupled by multimode interference (MMI) couplers and Mach-Zehnder interferometers (MZIs) were designed and demonstrated experimentally. The MMI coupler is introduced to improve the fabrication tolerance of the coupling region. These devices can be used to improve the sensitivity in sensing applications. Experiments confirmed that the MMI coupler is able to couple the slot bus waveguide to the slot ring waveguide without excess loss. The MZI-coupled slot ring resonator has a wide quasi-FSR. In addition, a ring-assisted Mach-Zehnder interferometer (RAMZI) was numerically demonstrated to achieve nonlinear Raman switching. The RAMZI structure is designed to enhance the fabrication tolerance of the coupling region for the side-coupled MRR.

The second class of silicon photonic devices designed is based on subwavelength grating (SWG) waveguides. The thesis work demonstrated that the SWGs can enhance the fabrication tolerance of polarization splitting and rotation by engineering the equivalent material refractive index of the SWG waveguide. The SWG waveguide significantly improves the waveguide width fabrication tolerance from ± 3 nm to ± 40 nm while maintaining a compact size with a coupling length as short as 25 μm . Furthermore, a TE-pass polarizer using a SWG waveguide was experimentally demonstrated by adjusting the duty ratio of the SWG waveguide, where the mode cut-off condition is carefully engineered to filter out the TM mode.

The third class of silicon photonic devices discussed in the thesis is tapered structures. They were used to realize fabrication-tolerant and broadband devices for polarization and mode management. As tapered structures can convert modes adiabatically, these devices are inherently with low insertion loss. Polarization splitter and rotator using a taper-etched directional coupler has a large fabrication tolerance and a broad bandwidth while maintaining a high polarization conversion efficiency. In addition, the taper-etched geometry breaks both the horizontal and vertical symmetries of the waveguide, introducing an additional degree of freedom to accommodate for the different upper cladding materials. The versatile taper-etched design inspired the adoption of the structure for a fabrication tolerant and broadband two-mode multiplexer for mode division multiplexing.

Numerical methods including the finite-element method (FEM), the finite-difference method (FDM), the eigenmode expansion (EME) and the finite-difference time-domain (FDTD) methods were used to optimize parameters of the designed devices in this thesis. The FEM and FDM were used to calculate the effective indices and field profiles of modes in the waveguides while the propagation performance were simulated by the EME and FDTD methods.

Due to limitation of the fabrication availability and capability, only a selective set of devices were fabricated and experimentally characterized. The fabrication includes

- the LOCOS waveguides (done at Carleton University MicroFabrication Facility)
- the MRRs (fabricated by the OpSIS/IME foundry)
- the SWG (fabricated by the Fabrication Facility at the NRC Canada)
- the tapered devices (fabricated by the IMEC foundry)

In summary, the main theme of the thesis is on the topic of silicon photonics, where fabrication techniques and a selective set of devices were designed with successful experimental demonstrations. The thesis work has resulted in 7 refereed publications in reputable journals and 7 international refereed conference papers. The major recognition of the research work includes the SPIE Optics and Photonics Education Scholarship (international), the three-time award winner of the Ed Ireland Award for Engineering (institutional), and the David and Rachel Epstein Foundation Scholarship (institutional).

Chapter 8

Future Work

Several directions for future work based on this thesis can be recommended, which can be categorized into three topics.

1. Further development of ring-based devices

The vertically coupled double-ring structures and ring-assisted Mach-Zehnder interferometer structure were only numerically analyzed in this thesis. Due to the current fabrication capability, these devices were not demonstrated experimentally. Fabrication of these two devices is recommended in the future.

One possible technique to fabrication the vertically coupled double-ring structure is 3-D sculpting to stack bus and ring waveguides in multiple layers [1]. Another feasible method uses polycrystalline silicon, which is available in the IMEC fabrication foundry [2]. For the experimental demonstration of sensing applications, microfluidic channels are necessary to be implemented for introducing liquid flow [3].

The ring-assisted Mach-Zehnder interferometer structure can be readily fabricated by the e-beam lithography processing [4]. However, in order to realize an all-optical effect via the inverse Raman scattering, advanced experimental setup including a tunable continuous wave laser and an optical parametric amplifier should be constructed.

2. Application of taper-based devices in diversity/division systems

Combining a polarization rotator with a mode division (de)multiplexer can achieve

a hybrid (de)multiplexer, enabling simultaneous mode- and polarization-division-multiplexing. In addition, combining the existing silicon photonic modulator, the polarization splitter and rotator discussed in Chapter 6 can be applied to realize a high-speed dual-polarization quadrature phase-shift keying (QPSK) modulator [5], which is a crucial element for high-speed coherent optical communication systems [6].

3. Fabrication of the subwavelength grating based polarization splitter and rotator

The polarization splitter and rotator using subwavelength grating (SWG) waveguides presented in Chapter 5 can be fabricated by e-beam lithography, as the SWG structures have stringent fabrication requirements (i.e., smooth surface roughness and low scattering loss). To take into account for the fabrication inaccuracies on both the width and duty cycle variations of the SWG waveguide, advanced search algorithms such as the genetic algorithm and the particle swarm algorithm should be used to optimize the target geometrical parameters of the polarization splitter and rotator based on SWG waveguides.

List of References

- [1] P. Koonath and B. Jalali, “Multilayer 3-D photonics in silicon,” *Optics Express*, vol. 15, pp. 12686–12691, Oct. 2007.
- [2] G. Roelkens, D. Van Thourhout, and R. Baets, “High efficiency Silicon-on-Insulator grating coupler based on a poly-Silicon overlay,” *Optics Express*, vol. 14, pp. 11622–11630, Nov. 2006.
- [3] J. O. Tegenfeldt, C. Prinz, H. Cao, R. L. Huang, R. H. Austin, S. Y. Chou, E. C. Cox, and J. C. Sturm, “Micro- and nanofluidics for DNA analysis,” *Analytical and Bioanalytical Chemistry*, vol. 378, pp. 1678–1692, Apr. 2004.
- [4] Y. H. Wen, O. Kuzucu, M. Fridman, A. L. Gaeta, L.-W. Luo, and M. Lipson, “All-optical control of an individual resonance in a silicon microresonator,” *Physical Review Letters*, vol. 108, p. 223907, June 2012.
- [5] P. Dong, C. Xie, L. Chen, L. L. Buhl, and Y.-K. Chen, “112-Gb/s monolithic PDM-QPSK modulator in silicon,” *Optics Express*, vol. 20, pp. B624–B629, Dec. 2012.
- [6] T. Pfau, S. Hoffmann, O. Adamczyk, R. Peveling, V. Herath, M. Porrmann, and R. Noé, “Coherent optical communication : Towards realtime systems at 40 Gbit / s and beyond,” *Optics Express*, vol. 16, no. 2, pp. 866–872, 2008.

Appendix A

Derivation of Transmission on Microring Resonators

Based on the analytical expression about the transmission of the microring resonator was proposed by Yariv. The interaction between the bus and ring waveguides in Fig. [A.1](#) can be described by the matrix relation:

$$\begin{bmatrix} E_2 \\ E_4 \end{bmatrix} = \alpha_C \begin{bmatrix} t & -\kappa^* \\ \kappa & t^* \end{bmatrix} \begin{bmatrix} E_1 \\ E_3 \end{bmatrix} \quad (\text{A.1})$$

where α_C is the coupler loss, t and κ are the self- and cross-coupling coefficients, respectively. t^2 and κ^2 are the power splitting ratios of the coupler, and $t^2 + \kappa^2 = \alpha_C^2$, which means that the total transmitted power through the coupling region is α_C^2 .

The round trip in the ring is given by

$$E_3 = \alpha_R \cdot e^{j\phi} E_4 \quad (\text{A.2})$$

where α_R is the round trip propagation loss of the ring, and $\phi = \omega L/c$, L being the circumference of the ring ($L = 2\pi r$), r being the radius of the ring, c the phase velocity of the ring mode ($c = c_0/n_{eff}$), and the angular frequency $\omega = kc_0$, c_0 refers to the vacuum speed of light. The vacuum wavenumber k is related to the waveguide λ through: $k = 2\pi/\lambda$. The effective index n_{eff} can be introduced easily into the ring

coupling relations by

Figure A.1: Schematic of an all-pass ring resonator.

$$\beta = k \cdot n_{eff} = \frac{2\pi \cdot n_{eff}}{\lambda} \quad (\text{A.3})$$

where β is the propagation constant. Therefore

$$\phi = \frac{\omega L}{c} = \frac{kc_0 L}{c} = k \cdot n_{eff} \cdot 2\pi r = \frac{2\pi \cdot n_{eff} \cdot 2\pi r}{\lambda} = 4\pi^2 n_{eff} \frac{r}{\lambda} \quad (\text{A.4})$$

From Eq. A.6 and A.2, we obtain

$$\frac{E_2}{E_1} = \alpha_C e^{i(\pi+\phi)} \frac{\alpha - t e^{-i\phi}}{1 - \alpha t e^{i\phi}} \quad (\text{A.5})$$

Therefore, the transmission T in the output port of the bus waveguide is

$$T = \frac{P_{out}}{P_{in}} = \alpha_C^2 \frac{\alpha^2 - 2t\alpha\cos(\phi) + t^2}{1 - 2t\alpha\cos(\phi) + (t\alpha)^2} \quad (\text{A.6})$$

Appendix B

Mask Layout Design

Here images of the mask layouts for the LOCOS waveguides, ring-based devices and taper-based devices are demonstrated. In Fig. B.1, the paper-clip pattern is used to evaluate the propagation loss of the LOCOS waveguide while the serpentine pattern is used to assess the bending loss. In Fig. B.2, MMI-coupled slotted microring resonators and MZI racetrack microring resonators are designed. Furthermore, the DC-coupled structures are designed as reference. In Fig. ??, a $300\text{ }\mu\text{m}$ vertical offset is introduced to avoid the disturbance of the input light on testing the polarization rotators. In Fig. B.3, the TM mode through the input port will be coupled into the TE mode in the cross port while the TE mode injected into the input port will propagate and exit out the through port. Both the TM and TE fiber-to-waveguide grating couplers are used to test the TM-to-TE polarization conversion loss and TE-to-TE insertion loss. The two-mode multiplexer and demultiplexer shown in Fig. B.4 has TE₀ and TE₁ input and output ports. In the multiplexer part, the TE₀ injected into the TE₁ input will be converted into the TE₁ mode. In the demultiplexer part, the TE₁ mode will be coupled to the TE₀ in the TE₁ output port.

Figure B.1: Mask layout of the LOCOS waveguide. Both the paper-clip pattern for the propagation loss and the serpentine pattern for the bending loss are included. The target waveguide lengths range from 0.48 cm to 1.92 cm, while the bending radius are $5\ \mu\text{m}$ to $50\ \mu\text{m}$

Figure B.2: Mask layout of microring resonators and MZI racetrack microring resonators. 42 microring resonators with a radius ranging from $5\ \mu\text{m}$ to $20\ \mu\text{m}$. Both MMIs and DCs are used for light coupling.

Figure B.3: Mask layout of the polarization splitter and rotator (PSR) with the taper-etched directional coupler. The target gap is $200\ \text{nm}$ while the PSR length is $80\ \mu\text{m}$.

Figure B.4: Mask layout of the two-mode (de)multiplexer with the taper-etched directional coupler. The length of the (de)multiplexer is 313 μm , and the gap is 200 nm.