Silicon Photonic Switches for Optical Communication Applications

by

Zeqin Lu

B. Eng., Shenzhen University, China, 2011
M. A. Sc, Huazhong University of Science and Technology, China, 2013

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY in

The Faculty of Graduate and Postdoctoral Studies (Electrical and Computer Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)
September 2017
© Zeqin Lu 2017
Abstract

Optical switches are used for network reconfiguration in optical communication systems. Silicon photonics is a low-cost and mature technology to develop high-performance optical switches. This thesis is a theoretical and experimental study on silicon photonic switches, featuring broadband, low-power, high-speed, and low-crosstalk performance.

Broadband 3-dB couplers are fundamental building blocks for broadband switches based on Mach-Zehnder interferometer (MZI) structures. A broadband 3-dB coupler, which has a 100 nm operation bandwidth with coupling imbalance being much less than its competitors, i.e., adiabatic couplers and multimode interference couplers, has been theoretically designed and experimentally demonstrated.

Switches using thermo-optic phase tuning typically have high power consumption. In this thesis, two methods to improve the tuning efficiency of thermo-optic phase shifters have been investigated and employed: 1) using thermal isolation structures and 2) using folded waveguides structures. Accordingly, thermo-optic switches with state-of-the-art, ultra-low power consumptions of down to 50 µW/π have been demonstrated.

MZI switches using carrier injection phase tuning have high-speed performance but with a large switching crosstalk, due to the imbalanced tuning loss in the MZI structure. A novel carrier injection switch based on a balanced nested Mach-Zehnder interferometer (BNMZI) structure has been theoretically proposed. The BNMZI switch has balanced tuning schemes and therefore can be both high-speed and crosstalk-free. Besides, the switch has three switching states: cross, bar, and blocking.

Polarization control is necessary for single-mode switches. A high performance polarization beamsplitter (PBS), which has a 120 nm operation
Abstract

bandwidth with modal isolations of more than 20 dB, has been designed and demonstrated, and it can be used for polarization control for single-mode switches.

Characterizing fabrication variability and performing yield prediction for photonic integrated circuits (PICs) are both challenging for photonics designers. We have developed an accurate and cost-efficient characterization method for fabrication variations, which extracts waveguide dimension variations from the spectral response of a single racetrack resonator. In addition, we have proposed a novel yield prediction method for PICs, which, for the first time in silicon photonics, is able to model the impacts of layout-dependent correlated manufacturing variations and take them into account in circuit simulations.
Lay Summary

Data switches are critical components in optical communication networks. They are deployed to establish reconfigurable point-to-point optical links according to the dynamic traffic request in networks. This thesis is devoted to develop high-performance optical data switches using a low-cost, well-developed silicon photonics technology.

In terms of technical contributions, this research has developed building blocks for high-performance integrated optical switches, including a broadband coupler, low-power phase shifters and a broadband polarization beamsplitter, and has proposed a technical solution for switching crosstalk suppression. In terms of design methodology contributions, this research has developed methods to analyze silicon photonics manufacturing variations and yield.
Preface

The content of this thesis is mostly based on the publications listed below, which resulted from collaborations with other researchers. Note that only publications directly arising from the work presented in this thesis are listed here. A complete list of publications is given in Appendix A. It should also be noted that many devices demonstrated in this thesis have been re-designed or updated in order to improve their performance. Hence, many of the experimental results presented in this thesis are original and do not reference the similar results that were previously published.


   I conceived the idea, conducted the device design, performed the measurements and data analysis, and drafted the manuscript. H. Yun and F. Zhang assisted the measurements. L. Chrostowski and N. Jaeger supervised the project. All authors commented on the manuscript.

   Location: Chapter 2.


   I conceived the idea of combining thermal isolation, folded waveguides, and Michelson interferometer structure to improve tuning efficiency. K. Murray contributed the idea of using dissimilar waveguides
Preface

for crosstalk suppression. I conducted the device design, performed
the measurements and data analysis, and drafted the manuscript. K.
Murray assisted the measurements and microscope images. H. Jay-
atilleka helped edit the final draft of the manuscript. L. Chrostowski
supervised the project.

Location: Chapter 3.

similar waveguide routing for highly efficient thermo-optic switches on

K. Murray designed the switch, performed measurements on a first
batch wafer, and drafted the manuscript based on the results. I pro-
vided feedback on the switch designs and assisted the measurements
on the first batch wafer. I performed measurements on a second batch
wafer and obtained the measurement data presented in Fig. 3.9 of this
dissertation. L. Chrostowski supervised the project. H. Jayatilleka
helped edit the final draft of the manuscript.

Location: Chapter 3.

performance silicon photonic tri-state switch based on balanced nested

I conceived the idea, modeled the device, performed data analysis, and
drafted the manuscript. H. Mehrvar assisted the modelling of the 8×8
switch matrix. L. Chrostowski supervised the project. All authors
provided feedback on the manuscript.

Location: Chapter 4.

5. Z. Lu, Y. Wang, F. Zhang, N. A. F. Jaeger, and L. Chrostowski,
“Wideband silicon photonic polarization beamsplitter based on point-
symmetric cascaded broadband couplers,” Optics Express, vol. 23,
Preface

I conceived the idea, designed the devices, performed data analysis, and drafted the manuscript. Y. Wang assisted my layout design and provided broadband optical I/O solutions. F. Zhang conducted the measurements. L. Chrostowski supervised the project. All authors helped edit the paper draft.

Location: Chapter 5.


In the manufacturing characterization project presented in Ch. 6, L. Chrostowski proposed the method of extracting waveguide dimension variations (i.e., ∆w and ∆h) of a Micro-ring resonator (MRR) based on its resonance wavelength variation and group index variation (i.e., ∆λ and ∆ng), and supervised the project. I implemented the extraction model, studied the extraction accuracy, designed the layout for characterization, and performed measurements and data analysis. J. Jhoja assisted the measurements.

In the yield prediction project presented in Ch. 7, I proposed the simulation approach, developed the virtual wafer model and some of the component compact models, and performed numerical simulations and data analysis. J. Jhoja implemented the GUI interface of the Monte Carlo simulation. X. Wang contributed to the directional coupler compact model for the Monte Carlo simulation. L. Chrostowski suggested the virtual wafer approach, programmed the Klayout-INTERCONNECT co-simulation platform, and supervised the project.

I drafted the manuscript. All authors helped edit the paper draft.

Location: Chapter 6 & 7.
# Table of Contents

Abstract ................................................. ii

Lay Summary .............................................. iv

Preface .................................................... v

Table of Contents ........................................ viii

List of Tables ............................................ xii

List of Figures ............................................ xiii

List of Abbreviation ...................................... xxii

Acknowledgements ....................................... xxiv

1 Introduction .......................................... 1

1.1 Background and Motivations .......................... 1

1.2 Silicon Photonic Switches ......................... 6

1.2.1 Switching Elements .............................. 6

1.2.2 Phase Tuning Schemes ............................ 8

1.2.3 Performance Metrics ............................. 11

1.2.4 Remaining Issues ................................. 14

1.3 About This Thesis ..................................... 15

1.3.1 Objectives and Contributions ................... 15

1.3.2 Thesis Organization ............................... 16
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Broadband 3-dB Couplers for Broadband Switching</td>
<td>18</td>
</tr>
<tr>
<td>2.1</td>
<td>Broadband 3-dB coupler Designs</td>
<td>19</td>
</tr>
<tr>
<td>2.1.1</td>
<td>Schematic</td>
<td>19</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Design Principle</td>
<td>21</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Corner Analysis</td>
<td>25</td>
</tr>
<tr>
<td>2.1.4</td>
<td>Characterization Results</td>
<td>25</td>
</tr>
<tr>
<td>2.2</td>
<td>Broadband Mach-Zehnder Interferometer Switch</td>
<td>27</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Design</td>
<td>27</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Characterization Results</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Ultra-Low Power Thermo-Optic Switches</td>
<td>31</td>
</tr>
<tr>
<td>3.1</td>
<td>Design of Ultra-Low Power Thermo-Optic Phase Shifter</td>
<td>32</td>
</tr>
<tr>
<td>3.2</td>
<td>Ultra-Low Power Thermo-Optic On/Off Switches</td>
<td>34</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Design</td>
<td>34</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Characterization Results</td>
<td>36</td>
</tr>
<tr>
<td>3.3</td>
<td>Ultra-Low Power Thermo-Optic Cross/Bar Switches</td>
<td>40</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Design</td>
<td>40</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Characterization Results</td>
<td>40</td>
</tr>
<tr>
<td>3.4</td>
<td>Breakdown Test</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>Crosstalk-free Carrier Injection Tri-State Switches</td>
<td>44</td>
</tr>
<tr>
<td>4.1</td>
<td>Switch Design</td>
<td>45</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Schematic</td>
<td>45</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Operation Principles</td>
<td>46</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Carrier Injection Phase Shifter Design</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>Performance</td>
<td>54</td>
</tr>
<tr>
<td>4.3</td>
<td>Crosstalk Suppression Functionality</td>
<td>57</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Crosstalk Suppression for Partially-Loaded Switches</td>
<td>58</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Crosstalk Suppression for Fully-Loaded Switches</td>
<td>59</td>
</tr>
<tr>
<td>5</td>
<td>Polarization Control for Switches</td>
<td>62</td>
</tr>
<tr>
<td>5.1</td>
<td>Broadband Polarization Beamsplitter</td>
<td>64</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Principles</td>
<td>65</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Device Design</td>
<td>68</td>
</tr>
</tbody>
</table>
## Table of Contents

5.1.3 Characterization Results ........................................ 72
5.2 Polarization Control for Switches using Polarization Beam-
splitters ................................................................. 75

6 Wafer-Scale Manufacturing Variation Characterization .... 77
6.1 Characterization Methodology ......................................... 78
  6.1.1 Principle ......................................................... 78
  6.1.2 Characterization Errors .......................................... 83
6.2 Characterization Results ............................................... 84
  6.2.1 Within-Die Variations ........................................... 85
  6.2.2 Within-wafer Variations ......................................... 89
  6.2.3 Literature Results ............................................... 89
6.3 Summary ............................................................... 91

7 Layout-Dependent Yield Prediction for Photonics Integrated
  Circuits ................................................................. 92
7.1 Methodology .......................................................... 93
  7.1.1 Approach ......................................................... 93
  7.1.2 Simulation Flow Chart ........................................... 94
7.2 Models ................................................................. 97
  7.2.1 Virtual Wafer Model ............................................ 97
  7.2.2 Parameterized Component Models ............................... 100
7.3 Yield Prediction for Mach-Zehnder Interferometer Switches 104
  7.3.1 Switch Layout .................................................... 104
  7.3.2 Input Parameters for Manufacturing Variability ............ 105
  7.3.3 Yield Prediction Results ......................................... 106
7.4 Summary ............................................................... 110

8 Conclusion and Future Work ........................................... 111
  8.1 Conclusion .......................................................... 111
  8.2 Future Work ........................................................ 115

Bibliography ............................................................... 118
# Table of Contents

Appendices ................................................................. 132

A Publications ............................................................. 132
   A.1 Patents ............................................................... 132
   A.2 Journal Publications .............................................. 132
   A.3 Conference Proceedings ......................................... 134

B Derivation of the Transfer Functions of a MZI Switch ........ 137

C Derivation of Coupling Ratios Extractions for $2 \times 2$ Couplers 140
List of Tables

3.1 List for the fabricated on/off switches ............................ 36
3.2 Performance comparison for the fabricated on/off switches . 39

4.1 Phase tuning for the switching states of BNMZI switch. . . . 50
4.2 Performance of an example BNMZI switch with $\kappa^2 = 0.48$
and $A_\pi = 0.8613$. .................................................. 58

6.1 Statistical results for the characterized variations for all of
the wafer dies. ............................................................. 88
6.2 Statistical results for the characterized variations across the
200-mm-wafer. ............................................................ 89
6.3 Literature results for wafer-to-wafer fabrication variations . . 90
6.4 Literature results for within-wafer fabrication variations . . . 90

7.1 Input parameters for the virtual wafer model ...................... 106
7.2 Statistical results for the phase errors at 1550 nm for switch
designs with $d=25$ $\mu$m, $d=50$ $\mu$m, and $d=100$ $\mu$m. .... 110

8.1 Comparisons of high-performance 3-dB couplers demonstrated
on the 220 nm SOI platform. ........................................... 113
8.2 Summary of SOI based thermo-optic switches that were experi-
mentally demonstrated in recent years. ............................ 114
8.3 Summary of representative, high-performance PBSs demon-
strated on SOI platforms. ............................................. 114
## List of Figures

1.1 (a) Long-haul telecommunication architecture; (b) short-reach data center communication architecture. .......................... 1

1.2 (a) Diagram for an electrical switch; O/E: optical to electrical conversion; E/O: electrical to optical conversion; (b) diagram for an optical switch. ................................................. 3

1.3 Cross section schematic of a typical Silicon-on-Insulator (SOI) wafer. ................................................................. 5

1.4 A 2×2 Mach-Zehnder interferometer switch. (a) Schematic of the switch; (b) switching states; (c) and (d) are simulated spectral responses at the cross and bar state, respectively, for a particular MZI switch design. .............................. 6

1.5 An example micro-ring resonator (MRR) switch. (a) Schematic of the switch; (b) spectral responses; (c) switching paths. . . 8

1.6 Cross section schematics of SOI phase shifters. (a) Carrier depletion phase shifter; (b) carrier injection phase shifter; (c) thermo-optic phase shifter using a metal heater; (d) thermo-optic phase shifter using a resistive heater integrated in a rib waveguide. ......................................................... 9

1.7 Cross state extinction ratio (ER) of an Mach-Zehnder interferometer (MZI) switch versus the coupling ratios ($\kappa^2$ and $t^2$) of its 2×2 couplers. Inset illustrates the $\kappa^2$ and $t^2$ parameters for the 2×2 coupler. .......................... 12

1.8 Diagram that shows the 126 channels within a 100 nm bandwidth that are used in DWDM applications for a channel spacing of 100 GHz. ......................................................... 12
List of Figures

2.1 (a) Schematic for a photonic directional coupler; (b) performance of a directional coupler design. The coupling length is 17.5 µm. The coupler waveguides are 500 nm wide by 220 nm height, and are separated by a 200 nm gap. ................. 19

2.2 (a) Schematic of the proposed broadband 3-dB coupler; (b) cross section schematic of the directional coupler (DC) segment; (c) cross section schematic of the phase shifter segment. 20

2.3 (a) Supermode profiles in directional couplers; (b) Supermode profiles in phase shifter. wg a and wg b refer to waveguide a and waveguide b, respectively. .................. 22

2.4 Transfer matrix method (TMM) simulation results for an optimized device with $L_1 = 33$ µm, $L_2 = 0.55$ µm, and $L_3 = 15$ µm. (a) Phase difference of the symmetric and anti-symmetric modes; (b) coupling ratios versus operation wavelength. .................. 23

2.5 (a) Broadband 3-dB coupler design with s-bent waveguides as input and output ports; (b) FDTD simulation configuration; (c) FDTD simulation results. .................. 24

2.6 Corner analysis for the broadband 3-dB coupler design. (a) Process corners; (b) corner analysis results for the coupling imbalance, $|κ^2 - t^2|$. .................. 25

2.7 Block diagram illustrating the indirect measurement. .... 26

2.8 (a) Measured spectrum for the MZI circuit; (b) extracted coupling ratios of the fabricated broadband 3-dB couplers. .... 27

2.9 A 2×2 broadband MZI switch design. (a) Switch schematic; (b) INTERCONNECT simulation; (c) simulated cross state performance; (d) simulated bar state performance. .... 29

2.10 A fabricated 2×2 broadband MZI switch. (a) Optical image for the switch; (b) measured cross state performance; (c) measured bar state performance. Data in (b) and (c) were calibrated using a pair of GCs connecting by a short waveguide. 30
List of Figures

3.1 Schematics for the proposed ultra-low power phase shifter. (a) Cross section; (b) top view. ............................... 32

3.2 Heat transport modelling results for thermo-optic phase shifters with tuning power of 1mW/m. (a) A proposed design with thermal isolation structure; (b) a regular design without thermal isolation structure. ....................................................... 33

3.3 Maximum coupling at 1550 nm between two waveguides with dissimilar widths. Waveguide thicknesses are both 220 nm. 34

3.4 An ultra-low power Michelson interferometer on/off switch. (a) Schematic of the switch; (b) block diagrams for switching states. ................................................................. 35

3.5 Optical images for the fabricated ultra-low power thermo-optic on/off switches. (a) A switch without thermal isolation structure; (b) a switch with thermal isolation structure. 37

3.6 Block diagram illustrating the measurement setups. (a) Spectrum characterization; (b) switching speed characterization. 37

3.7 Measurement results for Device 6. (a) on/off states transmission spectra; (b) transmission at 1550 nm versus tuning power; (c) time-domain response at 1550 nm. ............................... 39

3.8 Schematic of an ultra-low power MZI cross/bar switch. 40

3.9 Measurement results for a fabricated ultra-low power MZI cross/bar switch. (a) Output transmissions at 1550 nm versus tuning power; (b) output spectra at the bar state; (c) output spectra at the cross state. ...................................................... 41

3.10 Breakdown test results for a demonstrated ultra-low power thermo-optic switch. ........................................ 42

4.1 (a) Schematic for a Mach-Zehnder interferometer (MZI) switch; (b) Schematic for the proposed balanced nested Mach-Zehnder interferometer (BNMZI) switch. ........................................ 45

4.2 Cross state output transmissions as a function of $\kappa^2$ and $A_\pi$. (a) Output 1. (b) Output 2. ................................. 48
List of Figures

4.3  Bar state output transmissions as a function of $\kappa^2$ and $A_\pi$.  
(a) Output 1. (b) Output 2.                49

4.4  Blocking state output transmissions as a function of $\kappa^2$. (a) 
Output 1. (b) Output 2.                50

4.5  Schematic of a carrier injection phase shifter design on a 
silicon-on-insulator (SOI) platform.                51

4.6  Performance of the carrier injection phase shifter with a $\pi$ 
phase shift. (a) Change of waveguide absorption, $\Delta \alpha$, versus 
phase shifter length, $L$; (b) optical field transmission factor, 
$A_\pi$, versus phase shifter length, $L$. Waveguide propagation 
loss is not included in the $A_\pi$ calculation.          52

4.7  Electrical responses of the carrier injection phase shifter for 
a $\pi$ phase shift. (a) Injected current, $I$, versus phase shifter 
length, $L$; (b) power consumption versus phase shifter length, 
$L$.                                        54

4.8  Circuit simulation schematics. (a) BNMZI switch; (b) MZI 
switch.                                         55

4.9  Performance comparison for the BNMZI switch and the MZI 
switch, when the $2 \times 2$ couplers in the switches have identical 
$\kappa^2$. (a) Cross state performance; (b) bar state performance.  56

4.10 (a) and (b) are Monte Carlo (MC) simulation results for the 
BNMZI switch operating at the cross state and the bar state, 
respectively. (c) and (d) are MC simulation results for the 
MZI switch operating at the cross state and the bar state, 
respectively. In the MC simulations, each $2 \times 2$ coupler has a 
random $\kappa^2$ in between 0.48 and 0.52.            57

4.11 Illustration for first-order crosstalk suppression.                59

4.12 (a) Schematic of an example $8 \times 8$ dilated Benes switch fabric 
with established connections: I1-O5, I4-O4, I6-O1, and I7-O7. 
(b) Output transmissions of the $8 \times 8$ switch without blocking 
the idle switches (idle switches are randomly at the cross or 
bar states). (c) Output transmissions of the $8 \times 8$ switch with 
blocking the idle switches.                60
4.13 (a) Schematic of an example 8×8 dilated Banyan switch fabric with established connections: I1-O3, I2-O7, I3-O5, I4-O1, I5-O6, I6-O2, I7-O4, and I8-O8. (b) Output transmissions of the 8×8 switch without blocking the idle switches (idle switches are randomly at the cross or bar states). (c) Output transmissions of the 8×8 switch with blocking the idle switches. 61

5.1 (a) Edge coupling solution in silicon photonic integrated circuits; (b) fibre Gaussian beam with a waist radius of 2.5 µm; (c) TE$_0$ mode profile in a 180 nm × 220 nm edge coupler waveguide; (d) TM$_0$ mode profile in a 180 nm × 220 nm edge coupler waveguide. (e) Power transmission for the coupled TE$_0$ and TM$_0$ modes versus polarization angle, $\theta$, of the fibre Gaussian beam. .......................... 63

5.2 A proposed polarization control solution for high performance silicon photonic switches, which uses polarization beam splitters as input mode filters. .......................... 64

5.3 (a) Schematic of a point-symmetric network; (b) responses of a 3-dB, 2×2 coupler and its point-symmetric network. The shadow regions mark out the variations of their respective cross-coupling powers. .......................... 66

5.4 (a) Schematic of our broadband PBS; (b) schematic of the first broadband 3-dB coupler in the PBS. .......................... 68

5.5 FDTD simulation results of the broadband 3-dB coupler operating at the (a) TE$_0$ mode and (b) TM$_0$ mode. .......................... 69

5.6 FDTD simulation results for the PBS. (a) Spectral responses for the TE$_0$ mode; (b) spectral responses for the TM$_0$ mode; (c) modal isolation at the through port; (d) modal isolation at the cross port. .......................... 70

5.7 Normalized field intensities of 1550 nm wavelength in the PBS waveguide cores along propagation length. (a) TE$_0$ mode; (b) TM$_0$ mode. .......................... 72
List of Figures

5.8 Scanning electron microscope (SEM) images for one of the fabricated broadband polarization beamsplitters. 72
5.9 Sketch of measurement setup. The yellow and pink triangles are the on-chip grating couplers for the TE\textsubscript{0} mode and TM\textsubscript{0} mode, respectively. 73
5.10 Measurement results for the fabricated PBS. (a) Spectral responses for the TE\textsubscript{0} mode; (b) spectral responses for the TM\textsubscript{0} mode; (c) modal isolation at the through port; (d) modal isolation at the cross port. 74
5.11 (a) A broadband MZI switch without polarization control; (b) simulated cross state performance of the switch; (c) simulated bar state performance of the switch. 75
5.12 (a) A broadband switch having polarization control; (b) simulated cross state performance of the switch; (c) simulated bar state performance of the switch. 76
6.1 (a) Schematic layout of the racetrack resonator test device; (b) transmission spectrum for such a device without fabrication variations. FSR is free-spectral-range. 79
6.2 Simulation results for racetrack resonators with a nominal waveguide height, $h$, of 220 nm and various waveguide widths, $w$. (a) Transmission spectra; (b) group indices at resonances; (c) resonance wavelength versus waveguide width for a selected resonance mode; (d) group index versus waveguide width for a selected resonance mode. 80
6.3 Simulation results for racetrack resonators with a nominal waveguide width, $w$, of 500 nm and various waveguide heights, $h$. (a) Transmission spectra; (b) group indices at resonances; (c) resonance wavelength versus waveguide height for a selected resonance mode; (d) group index versus waveguide height for a selected resonance mode. 82
List of Figures

6.4 Error test results in a $\Delta w$ deviation range of $\pm 20$ nm and a $\Delta h$ deviation range of $\pm 10$ nm, for the proposed variation characterization method. (a) Width extraction error, $Error_{\Delta w}$; (b) height extraction error, $Error_{\Delta h}$.

6.5 (a) Schematic layout for the racetrack resonator test device; (b) distribution of racetrack resonators on each wafer die; (c) wafer map for the fabricated multi-project-wafer.

6.6 Characterization results for die #20. (a) Measured spectra for the 61 identical test devices; (b) extracted $n_g$ for the 61 devices; (c) distribution map for extracted $\Delta w$; (d) distribution map for extracted $\Delta h$.

6.7 Characterization results for all of the fabricated wafer dies. (a) Waveguide width variations, $\Delta w$; (b) waveguide height variations, $\Delta h$.

6.8 Histograms for the characterized variations across the 200-mm-wafer. (a) Width variations, $\Delta w$; (b) height variations, $\Delta h$.

7.1 Proposed simulation approach for photonics yield prediction. Primary simulation steps include: (1) layout-to-schematic transformation, (2) virtual wafer simulation and mapping, (3) components’ performance update, and (4) circuit simulation.

7.2 (a) Detailed simulation flow chart for the proposed approach; (b) and (c) illustrate the simulated virtual wafers for waveguide width and height variations, respectively.

7.3 An example circuit consisting of two grating couplers connected by a waveguide. (a) Physical layout; (b) simulation schematic in the circuit simulator.

7.4 Illustration for the die selection and variation mapping in the within-wafer analysis.

7.5 Illustration for the manufacturing variation simulations of wafer-to-wafer analysis.
List of Figures

7.6 (a) A 100 mm × 100 mm random distribution map $z(x, y)$ generated with $\sigma=2$; (b) a Gaussian filter map $g(x, y)$ generated with $l = 4$ mm; (c) the correlated variation wafer map $m(x, y)$. .............................................. 99

7.7 (a) A 100 mm × 100 mm correlated variation wafer map $m(x, y)$, which is simulated using a coarse simulation mesh; (b) and (c) are the variation maps of a 10 mm × 10 mm die located at the top right corner of the wafer, before and after interpolation, respectively. ................................. 99

7.8 Diagram for $\Delta w$ and $\Delta h$ averaging in the waveguide compact model. .............................................. 102

7.9 S-parameter component model. (a) Process corners for two process parameters: waveguide width variation, $\Delta w$, and height variation, $\Delta h$; (b) and (c) are $S_{31}$ amplitude and phase of a 2×2 directional coupler, respectively. ......................... 103

7.10 Layout decomposition for an Mach-Zehnder interferometer device. .............................................. 104

7.11 A thermo-optic MZI switch. (a) Physical layout; (b) circuit simulation schematic in Lumerical INTERCONNECT. .... 105

7.12 Ideal performance for the 2×2 Mach-Zehnder interferometer switch. (a) Cross state; (b) bar state. ......................... 107

7.13 Within-wafer yield prediction results for the 2×2 Mach-Zehnder interferometer switch. (a) Spectral variations at the cross state; (b) spectral variations at the bar state; (c) histograms for the cross state bandwidth; (d) histograms for the bar state bandwidth; (e) histograms for the cross state insertion loss; (e) histograms for the bar state insertion loss. .............. 108

7.14 Histograms for phase errors at 1550 nm, for switch designs with $d=25$ µm, $d=50$ µm, and $d=100$ µm. .............. 109
8.1 A proposed temperature stabilization solution for MZI switches; (a) Schematic for a MZI switch with feedback control; (b) schematic for series connected temperature sensing diodes (TSD). ................................. 117

B.1 Schematic for a typical Mach-Zehnder interferometer (MZI) circuit. ................................. 137
# List of Abbreviation

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNMZI</td>
<td>Balanced Nested Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide-Semiconductor</td>
</tr>
<tr>
<td>DC</td>
<td>Directional Coupler</td>
</tr>
<tr>
<td>DUV</td>
<td>Deep Ultra-Violet</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectrum Range</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain</td>
</tr>
<tr>
<td>GC</td>
<td>Grating coupler</td>
</tr>
<tr>
<td>InP</td>
<td>Indium Phosphide</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>MI</td>
<td>Michelson Interferometer</td>
</tr>
<tr>
<td>MPW</td>
<td>Multi-Project Wafer</td>
</tr>
<tr>
<td>MRR</td>
<td>Micro-Ring Resonator</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarization Beam-Splitter</td>
</tr>
<tr>
<td>PM</td>
<td>Polarization-Maintaining</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonics Integrated Circuit</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Silicon Oxide</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon-on-Insulator</td>
</tr>
</tbody>
</table>
### List of Abbreviation

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWG</td>
<td>Sub-Wavelength Grating</td>
</tr>
<tr>
<td>TMM</td>
<td>Transfer Matrix Method</td>
</tr>
<tr>
<td>TiN</td>
<td>Titanium Nitride</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
</tbody>
</table>
I would like to express my heartfelt thanks to my supervisor Prof. Lukas Chrostowski, for the inspiration, great support and guidance that he has provided throughout my PhD, which has been a very wonderful journey in my life. I appreciate his way of supervision, which encouraged me to start my research project independently. This challenging experience will truly benefit my future career.

I especially appreciate Prof. Nicolas Jaeger for his generous help on my research projects and guidance on my scientific writing, which significantly boost my PhD research. I give thanks to the rest of my thesis committee members for their invaluable comments and support during my PhD program.

I thank my group members, Han Yun, Yun Wang, Fan Zhang, Minglei Ma, and Hasitha Jayatilleka, for their help and many valuable discussions. Discussions in the lab were very beneficial to my research and have been an interesting part of my journey.
Chapter 1

Introduction

1.1 Background and Motivations

![Diagram of telecommunication and data center communication architectures](image)

**Figure 1.1:** (a) Long-haul telecommunication architecture; (b) short-reach data center communication architecture.

Optical fibre links, which have high bandwidth and large capacity for data transmission, are widely deployed in both long-haul telecommunications and short-reach data center communications, as illustrated in Fig. 1.1. In communication networks, data switches are critical network nodes which establish point-to-point communication channels. In long-haul communication networks, optical switching based on wavelength selective switch (WSS) and free-space micro-electro-mechanical system (MEMS) switch technologies has been deployed for network provisioning and patch panel applications, where switching time of milliseconds to seconds is typical. In short-reach data center networks, where most of the global data traffic take place, network
1.1. Background and Motivations

reconfiguration according to dynamic workloads is frequently requested. At present, the reconfiguration in data center networks are dominated by high-speed electrical switches. Optical switching is currently being promoted for such an application, although there is a lack of published examples of real deployments.

Figure 1.2(a) illustrates a reconfigurable optical network through an electrical switch, where input optical signals are converted to electrical signals for switching and converted back to optical signals after switching. The optical/electrical/optical (O/E/O) conversions of an electrical switch make it convenient for signal reamplification, reshaping, and retiming in electrical domain, which can be beneficial for some networks in need of such services. High-speed switching is an advantages for many data center electrical switches; however, they also have many disadvantages:

- The O/E/O conversions require optical transceivers (i.e., receiver for the optical/electrical conversion and transmitter for the electrical/optical conversion), which bring extra power penalty to the switch system. Commercial electrical switches typically have high power consumption, e.g., a 36-port, 100 Gbps per port data center switch, Arista DCS-7500R-36CQ-LC [1], consumes 25W per port, which is 250pJ/bit.

- Cost penalty of optical transceivers is another issue. By 2017, the average cost for optical transceivers is around $3/Gbps. A simple estimation can be made that the cost of transceivers in the aforementioned Arista DCS-7500R-36CQ-LC switch is around $36,000, which is almost 50% of the total price for switch ($73,307/switch released by May 2017 [2]).

- Scalability issues. As electrical switching is incompatible with optical wavelength-division multiplexing (WDM) technology, multiplexers (MUX) and demultiplexers (DMUX) are required for the O/E/O conversions, as illustrated in Fig. 1.2(a) (In some embodiments, MUX and DMUX are incorporated in the O/E/O transceivers). Such a configuration makes it unable to scale up with optical links. For example,
1.1. Background and Motivations

when upgrading each optical link with more WDM channels and/or higher bit-rate per channel, the O/E/O conversion interfaces and the switch core need to be rebuilt accordingly.

Figure 1.2(b) illustrates the diagram of an optical switch, where signal switching happens by changing the light paths without processing the signal data. Optical switching has many advantages as compared with electrical switching:

- Lower cost. Optical switching does not have O/E/O conversions and does not require any optical transceiver. Therefore, it can be signifi-
1.1. Background and Motivations

- Optical switching is significantly cheaper. For example, a $32 \times 32$ optical MEMS switch commercialized by DiCon Fiberoptics [3] has a total power consumption of only 2.4W. Conservatively assuming a bit-rate of 100Gbps per port, the switch has a power consumption of 0.75pJ/bit, being two orders of magnitude lower than that of the aforementioned electrical switch. As the bit-rate in the optical link goes higher, the switch can have even lower energy per bit.

- Optical switching is transparent to signal format and protocol (within limitations of optical bandwidth, loss budget and other effects) as it does not process the signal data, and hence it has simpler system hardware.

Although having many strengths, at present the speeds of optical switches (nanoseconds to milliseconds depending on technologies) are still slower than the speeds of electrical switches (sub-nanoseconds). Besides, signal reamplification, reshaping, and retiming are difficult in optical switches since all signals are in the optical domain (short distance optical links with small signal degradation may not require such services). In practical solutions, it is likely that electrical and optical switches will coexist and cooperate to deliver their own strengths. According to [4], optical switches can be designated to handle slowly changing portion of communication (e.g., data flows and long packets); electrical switches are suitable for the bursty portion of communication (e.g., short packets).

In the past two decades, various optical switches have been developed based on Indium Phosphide (InP) technologies [5] and MEMS technologies [1, 6]. As compared with InP and MEMS platforms, silicon photonics is a more promising technology to develop integrated optical switches, as its manufacturing shares the same fabrication facilities of advanced microelectronics, i.e., the complementary metal-oxide-semiconductor (CMOS) technologies, and as a result, silicon photonics can be low-cost and potentially
1.1. Background and Motivations

able to integrate with CMOS electronics. With such advantages, silicon photonics is gaining tremendous momentum in both academia and industry. Over the past two decades, various silicon photonic devices have been demonstrated, and these include passive components (such as waveguides, power splitters, and I/O interfaces) [7–9] and active components (such as modulators, photodetectors, and tunable filters) [10–12]. One major application for these photonic devices is high-speed data transceiver. Another important application for those devices, which is driving more and more attention from both academia and industry, is high-performance data switches.

Figure 1.3: Cross section schematic of a typical Silicon-on-Insulator (SOI) wafer.

Silicon photonics manufacturing use Silicon-on-Insulator (SOI) wafers. Figure 1.3 shows the cross-section schematic of a typical SOI wafer, the layer stack of which includes an approximately 725 µm thick silicon substrate, a 2 to 3 µm thick buried oxide (BOX) layer as the insulator and cladding for waveguides, a 220 nm thick silicon layer to define planar lightwave circuits (PLCs), and a 2 to 3 µm thick cladding oxide layer for perfection. Such an SOI layer stack, well-known as 220 nm SOI platform, has been widely adopted by many photonics foundries, such as IME [13], imec [14], CEA-Leti [15] and IHP [16]. This dissertation develops high-performance photonic switches based on the 220 nm SOI platform.
1.2 Silicon Photonic Switches

1.2.1 Switching Elements

Silicon photonic switches operate using interferometers. Most common forms of interferometers are Mach-Zehnder interferometers (MZIs) and micro-ring resonators (MRRs). The actuator for an interferometer based switch is an optical phase shifter. Light paths of the switch can be changed by changing the optical phase in the interferometer.

1.2.1.1 Mach-Zehnder Interferometer

![Mach-Zehnder Interferometer Diagram](image)

Figure 1.4: A 2×2 Mach-Zehnder interferometer switch. (a) Schematic of the switch; (b) switching states; (c) and (d) are simulated spectral responses at the cross and bar state, respectively, for a particular MZI switch design.

Figure 1.4(a) shows a 2×2 (i.e., 2 inputs and 2 outputs) MZI switch design,
1.2. Silicon Photonic Switches

which consists of two $2 \times 2$ couplers and two balanced waveguide arms. One of the waveguide arms has an optical phase shifter for phase tuning. When light enters a switch input, it is equally split by the first $2 \times 2$ coupler. Then, the two resulting beams propagate through the waveguide arms, and they are finally recombined by the second $2 \times 2$ coupler. Depending on phase tuning, $\varphi$, the input light can be switched to either of the switch outputs. The MZI switch can operate at a bar state when $\varphi = \pi$; it can operate at a cross state when $\varphi = 0$, as illustrated in Fig. 1.4(b). The derivation of the transfer functions of a MZI switch is given in Appendix B.

As an illustrative example, Figs. 1.4(c) and 1.4(d) respectively show the simulated performance at the cross state and the bar state of a particular MZI switch, which use $2 \times 2$ directional couplers [17] in the switch design. In the simulations, the input source was set to the switch input 1 shown in Fig. 1.4(a). The phase tuning at the bar state is wavelength-dependent, based on Eq. B.13. Simulation results show that the MZI switch can operate in the wavelength span from 1538 nm to 1567 nm with switching crosstalk (i.e., transmission at the unintended output) of less than -20 dB at both switching states, which can be compatible for wavelength-division multiplexing (WDM) applications.

1.2.1.2 Micro-Ring Resonators

An add-drop MRR can be designed for signal switching. Such a device, as shown in Fig. 1.5(a), consists of a micro-ring resonator, two waveguides coupled to the resonator, and an optical phase shifter on the resonator. Figure 1.5(b) shows spectral responses for an example MRR switch, and Fig. 1.5(c) illustrates its corresponding switching paths. Fundamentally, an MRR switch has wavelength-dependent performance. Light enters the input port of an MRR switch can be selectively switched to either the drop port or the through port, depending on its wavelength alignment with the resonance wavelength of the MRR. If the signal wavelength is aligned with the resonance wavelength, light will be switched to the drop port; otherwise, light will propagate to through port, as shown in Fig. 1.5(c). The resonance
1.2. Silicon Photonic Switches

![Diagram of a micro-ring resonator (MRR) switch](image)

**Figure 1.5:** An example micro-ring resonator (MRR) switch. (a) Schematic of the switch; (b) spectral responses; (c) switching paths.

The wavelength of an MRR is sensitive to the width and thickness variations of the waveguide as well as on-chip temperature variations, and as a result, an MRR requires dynamic control and stabilization [12]. The MRR switch is not the most popular candidate in SOI switch designs due to its wavelength-selective performance and the complexities in control and stabilization.

### 1.2.2 Phase Tuning Schemes

In SOI waveguides, optical phase tuning can be achieved using either the plasma dispersion effect or the thermo-optic effect.

#### 1.2.2.1 Plasma Dispersion Effect

The plasma dispersion effect [18] describes the change of refractive index of a material due to a change of carrier concentration. According to Soerf
1.2. Silicon Photonic Switches

Figure 1.6: Cross section schematics of SOI phase shifters. (a) Carrier depletion phase shifter; (b) carrier injection phase shifter; (c) thermo-optic phase shifter using a metal heater; (d) thermo-optic phase shifter using a resistive heater integrated in a rib waveguide.

equations [19], the change of refractive index for Si is described by:

\[
\Delta n(at 1550 \text{ nm}) = -5.4 \times 10^{-22} \Delta N^{1.011} - 1.53 \times 10^{-18} \Delta P^{0.838} \tag{1.1}
\]

where \(\Delta N\) and \(\Delta P\) are the changes of carrier concentrations for electrons and holes. The change of carrier concentration also changes the absorption of Si due to free-carrier absorption, which is given by:

\[
\Delta \alpha(at 1550 \text{nm}) = 8.88 \times 10^{-21} \Delta N^{1.167} + 5.84 \times 10^{-20} \Delta P^{1.109} \text{ [cm}^{-1}] \tag{1.2}
\]

In SOI waveguides, the change of carrier concentration can be achieved using either carrier depletion through a PN junction or carrier injection through a PIN junction, the cross section schematics of which are shown in Figs. 1.6(a) and 1.6(b), respectively. Carrier depletion phase shifters have tuning speeds of greater than tens of GHz, and are typically deployed in high-speed modulator designs [20]; however, they are typically a few millimetres long due to the carrier depletion being a weak effect. Carrier injection is a comparatively stronger effect than carrier depletion, and carrier injection phase shifters can be as compact as hundreds of micrometers long [21–23]. However, as the change of carrier concentration varies the absorption of silicon waveguides, MZI switches with phase shifters based on plasma dispersion effect typically have high insertion loss and large switching crosstalk.
1.2. Silicon Photonic Switches

1.2.2.2 Thermo-optic Effect

The thermo-optic effect, as the name implies, is the change in the refractive index of a material due to a change in temperature. Si has a relatively high thermo-optic coefficient, which is $\frac{dn}{dT} = 1.86 \times 10^{-4}/K$ at room temperature, making thermo-optic phase tuning very efficient. Optical phase tuning, $\Delta \varphi$, for a thermo-optic phase shifter can be expressed by:

$$\Delta \varphi \propto \frac{2\pi}{\lambda} \frac{dn}{dT} \Delta TL$$

(1.3)

where $\lambda$ is wavelength; $\Delta T$ is waveguide temperature change introduced by the phase shifter with a certain amount of tuning power; $L$ is the heating length of waveguide. In principle, switches based on this effect have no excess loss and can be highly compact. These advantages make thermo-optic switches promising in applications that require a large number of phase shifter elements.

On SOI platforms, there are two common methods [17] to implement a thermo-optic phase shifter. One method is to heat a waveguide by placing a metal heater above it, which is shown in Fig. 1.6(c). The tuning efficiency of such a phase shifter design is limited by the low thermal conductivity of the SiO$_2$ cladding material and the buffer distance between the heater and the waveguide. Typically, silicon photonics foundries, such as imec and IME, have standard buffer distances, and as a result, thermo-optic phase shifters based on such designs have similar power consumption of more than tens of milliwatts [24–26].

The other method for thermo-optic phase shifter design is to integrate a heater in a rib waveguide, as depicted in Fig. 1.6(d). This method enables a faster and more efficient heating due to the high thermal conductivity of Si. The integrated heater is formed using an N++/N/N+/N++ structure, where the two heavily doped N++ regions are used to make electrical contacts to the silicon waveguide while the lightly doped N region is a highly resistive region for heating. Typically, the clearance distance between the edge of waveguide to the edge of N++ region is more than 1 $\mu$m in order to reduce optical absorption loss induced by free-carrier absorption. However, opti-
1.2. Silicon Photonic Switches

cal absorption loss caused in the lightly doped waveguide core can not be eliminated.

1.2.3 Performance Metrics

Performance metrics for silicon photonic switches include crosstalk, extinction ratio, bandwidth, power consumption, switching speed, insertion loss, and footprint.

Crosstalk and Extinction Ratio

Crosstalk in a switch is a measure of the amount of signal leaking into an unintended switch output port. This is often measured using extinction ratio (ER). The ER of a $2 \times 2$ switch at a switching state is defined as the difference, on a logarithmic scale, for the power of the same input signal presenting at the two switch outputs:

$$ER = 10 \log_{10}\left(\frac{P_{\text{high}}}{P_{\text{low}}}\right)$$  \hspace{1cm} (1.4)

where $P_{\text{high}}$ and $P_{\text{low}}$ are the transmission at the high power output and the low power output, respectively. For high performance switches, an ER of more than 20 dB is often required. According to theoretical analysis as presented in Appendix B, the cross state ER of a $2 \times 2$ MZI switch is determined by the cross-coupling ratio, $\kappa^2$, and through-coupling ratios, $t^2$, of the $2 \times 2$ couplers in the switch, as per Eq. B.8; the bar state ER is infinite, as per Eq. B.11. Figure 1.7 shows the calculated ER at the cross state of an MZI switch as a function of $\kappa^2$ and $t^2$. In principle, an infinite ER at the cross state can be obtained when $\kappa^2 = t^2$, i.e., the $2 \times 2$ couplers have 3-dB coupling.

Bandwidth

High performance photonic switches require a wide bandwidth in order to allow for a large number of ITU channels to be routed. For example, ITU-T Recommendation G.694.1 [27] suggests a channel spacing of 100 GHz for
1.2. Silicon Photonic Switches

**Figure 1.7:** Cross state extinction ratio (ER) of an Mach-Zehnder interferometer (MZI) switch versus the coupling ratios ($\kappa^2$ and $t^2$) of its $2 \times 2$ couplers. Inset illustrates the $\kappa^2$ and $t^2$ parameters for the $2 \times 2$ coupler.

**Figure 1.8:** Diagram that shows the 126 channels within a 100 nm bandwidth that are used in DWDM applications for a channel spacing of 100 GHz.

dense wavelength-division multiplexing (DWDM) applications, and accordingly, a switch with a 100 nm bandwidth can route more than 120 channels, as illustrated in Fig. 1.8.

The bandwidth of a photonic switch is typically defined as the wavelength range over which the ER is above a certain value, typically being 20 dB or
1.2. Silicon Photonic Switches

higher [21, 28]. As we’ve discussed, the ER of an MZI switch is determined by the coupling ratios of its 2×2 couplers; in other words, the bandwidth of an MZI switch is determined by the 3-dB coupling bandwidth of its 2×2 couplers. For the MZI switch shown in Fig. 1.4, the 2×2 couplers of the switch have wavelength-dependent coupling ratios, which lead to the switch having wavelength-dependent ER with a very limited bandwidth at the cross state that can meet the 20 dB ER requirement (see Fig. 1.4(c).

**Power Consumption**

For $N \times N$ switch matrices, the power consumption of each individual switch is desired to be as low as possible, in order to reduce the total energy cost of systems. The tuning efficiency of an MZI switch is commonly evaluated using mW/$\pi$ as a figure-of-merit, namely the power required to obtain an optical phase shift of $\pi$, which is required for switching between the bar and the cross.

**Switching Speed**

High-speed tuning capability is often desired for photonic switches. Typically, the switching speeds of carrier depletion, carrier injection, and thermo-optic phase shifters are on the scales of GHz, MHz, and kHz, respectively. In practice, the required switching speed is determined by the application.

**Insertion Loss**

The insertion losses of 2 × 2 couplers and phase shifters contribute to the total insertion loss of an MZI switch. Insertion loss is a significant figure-of-merit for large-scale switch matrices.

**Footprint**

Cost-of-fabrication is one of motivations for compact designs. The typical cost for a multi-project wafer (MPW) fabrication run in photonics global foundries (e.g. imec and IME) is around $500/mm^2$ to $2000/mm^2$ [29].
Taking a demonstrated 32×32 switches [30] as an example, which has a footprint of more than 150 mm², the fabrication cost of the switch chip at the prototyping stage is approximately 75,000$ (each prototype can produce hundreds to thousands chips). System footprint is limited by photonic device footprints, electrical I/Os, and optical I/Os. Another motivation for compact designs is to reduce the impacts of fabrication variations [31, 32]. Devices that are spatially close to each other tend to have correlated fabrication variations, and therefore have more consistent performance, as discussed in Ch. 7.

1.2.4 Remaining Issues

Although the research in silicon photonic switches has been making steady progress in recent years, commercialization of the technologies still has a long way to go. Much work is required to improve the switch performance at the component level to achieve satisfactory system performance.

Most of demonstrated MZI switches have limited operation bandwidths [26, 33–35] due to their 2 × 2 couplers having wavelength-dependent performance. The 3-dB operation bandwidth of 2 × 2 couplers need to be increased in order for broadband switching.

Many demonstrated thermo-optic MZI switches, although being compact in footprints, have high power consumption of more than tens of milliwatts [24–26, 33, 36–40]. To build N × N switch matrices that consist of hundreds switch elements, the power consumption of each element needs to be minimized.

MZI switches based on carrier injection phase tuning are superior for high-speed applications. However, the inherent loss modulation of carrier injection phase tuning breaks the power balance in the MZI structure, and therefore lead to the switch having a larger switching crosstalk. This is a long-existing and well-known problem in all the demonstrated carrier injection MZI switches [21–23, 28, 41, 42], which remains to be solved.

Silicon photonic “single-mode” waveguides support both fundamental transverse electric (TE₀) and fundamental transverse magnetic (TM₀) modes.
However, most silicon photonic switches are designed to operate using either the TE$_0$ mode or the TM$_0$ mode, and therefore they require polarization control.

Moreover, manufacturing variability is a major issue in photonics integrated circuit (PIC) designs. A successful PIC design requires prior knowledge of manufacturing variations and efficiently taking into account such variations in the design. Unfortunately, fabless designers typically do not have access to the variability assessment data of photonics MPW fabrications, and also there is currently no circuit simulation tool able to take into account layout-dependent correlated variations. These barriers make it difficult to design large-scale PICs, such as $N \times N$ switch matrices.

1.3 About This Thesis

1.3.1 Objectives and Contributions

The objectives of this thesis are to address the aforementioned issues, and further propel the development of silicon photonic switching technologies.

Contributions of this thesis include:

- Design and demonstration of a high-performance broadband 3-dB coupler with a 100 nm operation bandwidth, which is a fundamental building block for broadband switches.

- Demonstration of thermo-optic switches with state-of-the-art low power consumption of down to 50$\mu$W/$\pi$, which is approximately 10× lower than the power consumption of any thermo-optic switches in literature.

- Provided the first solution to the long-existing crosstalk issues of high-speed carrier injection switches.

- Proposed the first silicon photonic tri-state switch, which can be used for crosstalk suppression in $N \times N$ switch matrices.

- Demonstration of a high-performance polarization beamsplitter (PBS), which has a wider bandwidth and higher isolation strengths than other
demonstrated PBSs. Our device can be used for polarization control for photonic switches.

- Developed a novel characterization method for fabrication variations. As compared with other demonstrated methods that use two test structures for characterization, our method only use one test structure and has a sub-nanometer accuracy.

- Developed the first yield prediction method with layout-dependent correlation parameters for photonic integrated circuits. The proposed method has a significant improvement over the conventional Monte Carlo analysis, which has no correlation parameters in the analysis model. The proposed yield prediction method can be used to study the performance variations of silicon photonic switches.

Together, all of these contributions enable high-performance silicon photonic switch designs.

1.3.2 Thesis Organization

This thesis is organized as follows:

In Chapter 2, we focus on broadband MZI switch designs. First, we present design, modelling, and characterization of a TE$_0$ mode broadband 3-dB coupler. Then, we experimentally demonstrate a broadband MZI switch based on the demonstrated broadband 3-dB coupler.

In Chapter 3, we focus on designs of ultra-low power thermo-optic switches. We start from designs of novel thermo-optic phase shifters, which incorporate thermal isolation structures and folded waveguide structures to improve tuning efficiency. Based on the phase shifter designs, then we demonstrate ultra-low power thermo-optic switches.

In Chapter 4, we focus on designs of carrier injection switches with both high-speed and crosstalk-free performance. First, we propose a novel carrier injection tri-state (cross/bar/blocking) switch, and present its operation principles. Next, we analyze the cross/bar switching performance of the proposed switch, as compared with a regular carrier injection MZI cross/bar
1.3. About This Thesis

switch. Finally, we analyze the blocking ability of our proposed tri-state switch.

Chapter 5 discusses polarization control for silicon photonic switches. A broadband polarization beamsplitter (PBS) is designed and demonstrated for polarization control.

Chapter 6 demonstrates a novel characterization method for silicon photonics manufacturing. The principles for the characterization method is presented in details. Based on the proposed method, fabrication variations of a 200-mm-wafer is characterized.

In Chapter 7, we present how to predict performance of PICs with impacts of correlated manufacturing variability. We will describe the flow chart of our performance prediction method, and then present numerical models for the method. Finally, we perform performance prediction on several MZI switch designs.

The thesis is concluded in Chapter 8, where we summarize the contributions and significance of this research, and discuss future research directions.
Chapter 2

Broadband 3-dB Couplers for Broadband Switching

Optical power couplers are essential devices for splitting and combining light in photonic systems. In silicon photonics, directional couplers (DCs) have been widely used as power couplers due to their simple configurations and the ease with which they can be fabricated on SOI platforms. Figure 2.1 shows the schematic of a typical TE$_0$ mode DC, which consists of two parallel symmetric waveguides separated by a gap. The coupling behavior of a DC can be explained using supermode analysis [17]. In the two waveguide system of a DC, the TE$_0$ mode light entering one of the coupler inputs simultaneously excites the lowest order symmetric and anti-symmetric supermodes in the two waveguide system, as illustrated in Fig. 2.1, and the power intensity of the input light is the vector summation of these two supermodes. The two supermodes propagate at different velocities in the two waveguide system, which leads to a change in vector summation, i.e., a power exchange between two waveguides. Unfortunately, the velocity difference for the two supermodes are wavelength-dependent, and as a result, the power exchange between the two waveguides, i.e., coupling strength, of a DC is wavelength-dependent. As an illustrative example, Fig. 2.1(b) shows the performance of a typical 3-dB DC design having wavelength-dependent coupling ratios.

As we’ve discussed in section 1.2.3, in MZI switch designs, broadband 3-dB couplers are required for broadband switching performance. In the past two decades, much effort [8, 11, 43–50] has gone into developing broadband 3-dB couplers on SOI platforms. Among these works, adiabatic couplers
2.1 Broadband 3-dB coupler Designs

2.1.1 Schematic

Our broadband coupler design is based on SOI strip waveguides. Such a device, as shown in Fig. 2.2(a), is a multi-segment device that consists of two DCs and an asymmetric waveguide-based phase shifter. 1-µm-long linearly tapered waveguides are used to connect the phase shifter to the DCs. The cross-section schematics of the DCs and the phase shifter are shown.

Figure 2.1: (a) Schematic for a photonic directional coupler; (b) performance of a directional coupler design. The coupling length is 17.5 µm. The coupler waveguides are 500 nm wide by 220 nm height, and are separated by a 200 nm gap.
2.1. Broadband 3-dB coupler Designs

![Diagram of broadband 3-dB coupler designs]

Figure 2.2: (a) Schematic of the proposed broadband 3-dB coupler; (b) cross section schematic of the directional coupler (DC) segment; (c) cross section schematic of the phase shifter segment.

in Figs. 2.2(b) and 2.2(c), respectively. Each DC consists of two 500 nm wide waveguides separated by a 200 nm gap. The phase shifter consists of one 400 nm wide waveguide and one 600 nm wide waveguide separated by a 200 nm gap. The lengths for the waveguide segments, from left to right as shown in Fig. 2.2(a), are labeled as $L_1$, $L_2$, and $L_3$, respectively. The feature sizes of the broadband coupler design are well-compatible with the processes of photonics mass production foundries.

Our approach for broadband 3-dB coupling is introducing a wavelength-dependent phase shift between the two DCs, to engineer the wavelength-dependent propagation velocities of the supermodes in the coupler. By properly optimizing the coupling lengths of DCs and the delay length of the phase shifter, the wavelength-dependence in the velocity difference of the two supermodes can be eliminated, and therefore, broadband (wavelength-independent) 3-dB coupling is possible at the two outputs.
2.1. Broadband 3-dB coupler Designs

2.1.2 Design Principle

We use the transfer matrix method (TMM) to design the broadband 3-dB coupler. The supermode propagations in the device can be expressed as:

\[
\begin{bmatrix}
E_{+,\text{out}} \\
E_{-,\text{out}}
\end{bmatrix} = P_3 \cdot T^{-1} \cdot P_2 \cdot T \cdot P_1 \cdot \begin{bmatrix}
E_{+,\text{in}} \\
E_{-,\text{in}}
\end{bmatrix}
\]  \hspace{1cm} (2.1)

where \(E_{+,\text{in}}\) and \(E_{+,\text{out}}\) are the electric fields of the lowest order symmetric mode at the DC input and output, respectively; \(E_{-,\text{in}}\) and \(E_{-,\text{out}}\) are the electric fields of the lowest order anti-symmetric mode at the DC input and output, respectively. In this thesis, we use a commercial tool, Lumerical MODE Solutions [51], for all the mode calculations. The calculated mode profiles for the symmetric and the anti-symmetric modes are shown in Fig. 2.3(a). Matrices \(P_1\), \(P_2\), and \(P_3\) are the propagation matrices for the supermodes in the first DC, the phase shifter, and the second DC, respectively, and they are given by:

\[
P_1 = \begin{bmatrix}
e^{-j \frac{2\pi}{\lambda} n_+ (\lambda) L_1} & 0 \\
0 & e^{-j \frac{2\pi}{\lambda} n_- (\lambda) L_1}
\end{bmatrix}
\]  \hspace{1cm} (2.2)

\[
P_2 = \begin{bmatrix}
e^{-j \frac{2\pi}{\lambda} n_a (\lambda) L_2} & 0 \\
0 & e^{-j \frac{2\pi}{\lambda} n_b (\lambda) L_2}
\end{bmatrix}
\]  \hspace{1cm} (2.3)

\[
P_3 = \begin{bmatrix}
e^{-j \frac{2\pi}{\lambda} n_+ (\lambda) L_3} & 0 \\
0 & e^{-j \frac{2\pi}{\lambda} n_- (\lambda) L_3}
\end{bmatrix}
\]  \hspace{1cm} (2.4)

where \(n_+ (\lambda)\) and \(n_- (\lambda)\) are wavelength-dependent effective indices of the symmetric and anti-symmetric modes in the DCs, respectively; \(n_a (\lambda)\) and \(n_b (\lambda)\) are wavelength-dependent effective indices of mode a and mode b in the phase shifter, respectively. Here, as shown in Fig. 2.3(b), mode a refers to the fundamental mode of the phase shifter that is, in fact, primarily confined in waveguide a, and mode b refers to the next higher order mode of the phase shifter that is, in fact, primarily confined in waveguide b.

Matrix \(T\) and \(T^{-1}\) are transfer matrices for the 1-\(\mu\)m-long tapered waveg-
2.1. Broadband 3-dB coupler Designs

Directional couplers

Symmetric mode

Anti-symmetric mode

Phase shifter

Mode a

Mode b

Figure 2.3: (a) Supermode profiles in directional couplers; (b) Supermode profiles in phase shifter. wg a and wg b refer to waveguide a and waveguide b, respectively.

Here are the waveguide segments, which describe mode conversions between the supermodes in the DCs and those in the phase shifter. $T$ is given by:

$$T = \begin{bmatrix} a(\lambda) & b(\lambda) \\ c(\lambda) & d(\lambda) \end{bmatrix}$$

(2.5)

where coefficients $a(\lambda)$, $b(\lambda)$, $c(\lambda)$, and $d(\lambda)$ are obtained using a commercial tool, Lumerical FDTD (Finite-Difference Time-Domain) Solutions [51].

Assuming that a normalized TE$_0$ mode light is launched into the input 1 of the device, as shown in Fig. 2.2(a), it will simultaneously excite the symmetric and anti-symmetric modes with amplitudes $E_{+,in} = E_{-,in} = \frac{1}{\sqrt{2}}$.

To achieve broadband 3-dB coupling at the coupler outputs, the electric fields of the two supermodes at the outputs, i.e., $E_{+,out}$ and $E_{-,out}$, need to have a wavelength-independent phase difference of 90° (the results of vector summation make power intensity equally distributed in the two output waveguides). Based on such a goal, we then use the genetic optimization algorithm in Matlab [52] to optimize the segment lengths $L_1$, $L_2$, and $L_3$. Figure 2.4(a) shows the calculated phase difference of $E_{+,out}$ and $E_{-,out}$, i.e., $\Delta \phi(\lambda) = \phi_{E_{+,out}}(\lambda) - \phi_{E_{-,out}}(\lambda)$, for an optimized coupler design with
2.1. Broadband 3-dB coupler Designs

$L_1 = 33 \, \mu m$, $L_2 = 0.55 \, \mu m$, and $L_3 = 15 \, \mu m$. The power intensities at the two output ports of the device are respectively given by:

\[ P_{\text{output}1} = \left| \frac{1}{\sqrt{2}} (E_{+,\text{out}} + E_{-,\text{out}}) \right|^2 \]  \hspace{1cm} (2.6)

\[ P_{\text{output}2} = \left| \frac{1}{\sqrt{2}} (E_{+,\text{out}} - E_{-,\text{out}}) \right|^2 \]  \hspace{1cm} (2.7)

Figure 2.4(b) shows the calculated $P_{\text{output}1}$ and $P_{\text{output}2}$ for the optimized device. As we can see that broadband 3-dB coupling is possible.

![Figure 2.4: Transfer matrix method (TMM) simulation results for an optimized device with $L_1 = 33 \, \mu m$, $L_2 = 0.55 \, \mu m$, and $L_3 = 15 \, \mu m$. (a) Phase difference of the symmetric and anti-symmetric modes; (b) coupling ratios versus operation wavelength.](image)

Next, to physically split the coupler inputs and outputs, s-bent waveguides are added at the two ends of the broadband 3-dB coupler design, as shown in Fig. 2.5(a). Then, the broadband 3-dB coupler design is further confirmed using three-dimensional FDTD simulations, as shown in Fig. 2.5(b), and the simulation results are shown in Fig. 2.5(c). We evaluate the coupler performance based on the imbalance between cross-coupling ratios, $\kappa^2$, and through-coupling ratios, $t^2$, which is defined as: $|\kappa^2 - t^2|$. Accordingly, the FDTD simulation results indicate a maximum imbalance of 3.7% within a 100 nm bandwidth, from 1500 nm to 1600 nm.

23
2.1. Broadband 3-dB coupler Designs

Figure 2.5:  (a) Broadband 3-dB coupler design with s-bent waveguides as input and output ports; (b) FDTD simulation configuration; (c) FDTD simulation results.
2.1.3 Corner Analysis

Corner analysis [17] is a simple method to study impacts of fabrication variations on the performance of SOI devices. For our broadband 3-dB coupler design, we consider a ±10 nm variations for the width and the thickness of coupler waveguide, i.e., Δw and Δh, respectively. Figure 2.6(a) illustrates the 4 process corners in the analysis. For each process point, FDTD simulation is conducted; all simulation results are collected to understand the device’s tolerance to fabrication. Figure 2.6(b) shows corner analysis results for the coupling imbalance of the broadband 3-dB coupler design, which indicates a worst-case imbalance of 16.7% within a 100 nm bandwidth.

![Corner analysis for the broadband 3-dB coupler design. (a) Process corners; (b) corner analysis results for the coupling imbalance, $|\kappa^2 - t^2|$.](image)

2.1.4 Characterization Results

The broadband 3-dB coupler design was fabricated using an electron-beam lithography process at the University of Washington. We used an indirect measurement method to characterize the performance of the fabricated devices. As shown in Fig. 2.7, the indirect measurement structure is an imbalanced MZI circuit, which includes two identical under test couplers for splitting at the input and combining at the output, and two imbalanced
2.1. Broadband 3-dB coupler Designs

Figure 2.7: Block diagram illustrating the indirect measurement.

phase arms with a length difference, $\Delta L$, of 259.4 $\mu$m. Grating couplers (GCs) [53] were used to couple light into and out of the MZI circuit. The measurement structure also includes a pair of GCs connected by a short waveguide, which is intended for calibrating the insertion losses of GCs. In the measurements, an Agilent 81600B tunable laser was used as the optical input source, and an Agilent 81635A optical power sensor was used as the output detector for the MZI circuit.

The $\kappa^2$ and $t^2$ of the under test couplers can be extracted from the interference extinction ratio (IER) of the MZI output spectrum, which is discussed in Appendix C. We define IER as the difference on a logarithmic scale between the minima and maxima transmissions, as illustrated in Fig. 2.7. The wavelength-dependent IERs can be obtained by fitting the envelopes on the minima and maxima of the MZI spectrum. The extracted $\kappa^2$ and $t^2$ are given by:

$$\kappa^2 = \frac{1}{2}(1 \pm \frac{1}{\sqrt{10^{IER/10}}})$$

$$t^2 = 1 - \kappa^2$$

where we assume that the propagation losses of the two phase arms of the imbalanced MZI circuit are the same and the couplers are lossless. Due to the fact that IERs of the MZI spectrum are independent to the insertion loss of the MZI circuit (e.g., misalignment loss), the $\kappa^2$ and $t^2$ of couplers
2.2 Broadband Mach-Zehnder Interferometer Switch

2.2.1 Design

We have designed a $2 \times 2$, TE$_0$ mode, broadband MZI switch based on the demonstrated TE$_0$ mode, broadband 3-dB coupler. Figure 2.9(a) shows the schematic for such a switch design, which has a thermo-optic phase shifter on each phase arm and two broadband 3-dB couplers. We modeled the broad-
band MZI switch using a photonic circuit simulator, Lumerical INTERCONNECT [51], as shown in Fig. 2.9(b). The performance of the broadband 3-dB couplers is described using scattering parameters (S-parameters), which are extracted from FDTD simulations. The wavelength-dependent responses of waveguide phase arms are described using the effective refractive index, group index and group velocity dispersion at the central wavelength of operation bandwidth, as discussed in 7.2.2.1. In the simulations, switch input 1 was activated for optical source, as shown in Fig. 2.9(b). Figures 2.9(c) and 2.9(d) show the simulation results at the cross and bar states, respectively. According to the results, at both switching states, the switch can operate in a 100 nm bandwidth from 1500 nm to 1600 nm, with ERs of more than 25.6 dB.

2.2.2 Characterization Results

The silicon waveguide structures of our broadband MZI switch were fabricated using an electron-beam lithography process, and the electrical layers were defined using a metal deposition process, both of which were conducted by Applied Nanotools Inc., Canada. Figure 2.9(a) shows an optical image for the fabricated switch. On-chip GCs [54] coupled light into and out of the switch. A pair of GCs connecting by a short waveguide, being similar to the GC pair as illustrated in Fig. 2.7, was also fabricated on the same chip to calibrate the insertion losses of GCs. In our measurements, we used an Agilent 81600B tunable laser as the optical input source, both channels of an Agilent 81635A optical power sensor as the optical output detectors, and a Keithley 2602A dual-channel system source meter as the electrical power source for phase tuning.

Figures 2.10(b) and 2.10(c) show the measured spectral responses of the switch at the cross state and the bar state, respectively, where the insertion losses of GCs have been calibrated out. We can see that, at both switching states, the ERs are more than 23 dB within the 100 nm bandwidth from 1500 nm to 1600 nm, which is in good agreement with the simulation results that are shown in Figs. 2.9(c) and 2.9(d).
2.2. Broadband Mach-Zehnder Interferometer Switch

Figure 2.9: A 2×2 broadband MZI switch design. (a) Switch schematic; (b) INTERCONNECT simulation; (c) simulated cross state performance; (d) simulated bar state performance.
2.2. Broadband Mach-Zehnder Interferometer Switch

![Diagram of broadband Mach-Zehnder Interferometer Switch](image)

**Figure 2.10:** A fabricated 2×2 broadband MZI switch. (a) Optical image for the switch; (b) measured cross state performance; (c) measured bar state performance. Data in (b) and (c) were calibrated using a pair of GCs connecting by a short waveguide.

In this chapter, we have designed and demonstrated a compact, broadband 3-dB coupler for the TE\(_0\) mode, which has coupling ratio imbalances of less than 4.7%, in a 100 nm bandwidth from 1500 nm to 1600 nm. The principle behind our coupler design is engineering the dispersion of coupling strengths in two-waveguide coupler systems by using a multi-segment waveguide structure that includes dispersive couplers and dispersive phase shifters. Based on the broadband 3-dB coupler design, we have experimentally demonstrated a broadband MZI switch for the TE\(_0\) mode, which has a 100 nm bandwidth with ERs of more than 23 dB, at both the cross and bar states.
Chapter 3

Ultra-Low Power
Thermo-Optic Switches

Photonic switches with low-power consumption and compact size are highly desired in large-scale switch matrices. As discussed in section 1.2.2, thermo-optic phase shifters can be compact in footprint due to the efficient thermo-optic effect, and are appropriate for compact switch designs. In recent years, various thermo-optic switches [24–26, 33, 36–40] have been demonstrated with switching power consumption of typically more than tens of milliwatts. For large-scale switch matrix designs, it is always preferable to minimize the power consumption of individual switch elements, so as to reduce power budget of the matrix.

According to Eq. 1.3, the tuning strength of a thermo-optic phase shifter is proportional to the heating length, $L$, and the waveguide temperature change, $\Delta T$. Based on this rule, much work has been devoted to reducing the power consumption of thermo-optic switches [33, 55, 56]. Among the efforts working on increasing heating length, $L$, a Michelson interferometer (MI) configuration was demonstrated, which can double $L$ as light travel through the heated waveguide by twice, and therefore has lower power consumption than a regular MZI switch by a factor of two [55]. In [56], a demonstrated MZI switch with spiral waveguide configuration is able to increase $L$, and thus reduce power consumption down to 6.5 mW/π. Among the efforts working on increasing temperature change, $\Delta T$, using thermal

---

1Part of the contents in this chapter have been published in two journal papers listed in the Preface. In terms of academic contributions to the thermo-optic phase shifter designs presented in Section 3.1, I conceived the initial idea of combining both thermal isolation structures and folded waveguide structures to improve tuning efficiency. K. Murray contributed the idea of using dissimilar waveguides for crosstalk suppression.
isolation structures is a promising approach [57–60], which remove materials surrounding the tuning regions to eliminate thermal leakage pathways. Based on thermal isolation structures, switches with low power consumptions of down to 400 µW/π have been reported [60].

This chapter presents the design approach to further reduce the power consumption of silicon photonic thermo-optic switches. We present a novel thermo-optic phase shifter design featuring ultra-low power consumption. Based on this design, we demonstrate several ultra-low power thermo-optic switches.

3.1 Design of Ultra-Low Power Thermo-Optic Phase Shifter

![Schematics for the proposed ultra-low power phase shifter. (a) Cross section; (b) top view.](image)

Figure 3.1: Schematics for the proposed ultra-low power phase shifter. (a) Cross section; (b) top view.

Our approach to achieve ultra-low power phase tuning is to increase both the $\Delta T$ and $L$ of thermo-optic phase shifters. Figures 3.1(a) and 3.1(b) illustrate the cross section and top view schematics for our ultra-low power phase shifter design, respectively. As shown in Fig. 3.1(a), to increase $\Delta T$ in tuning, the phase shifter is isolated by etching away the adjacent SiO$_2$ and underlying Si materials of the tuning region, through 8-µm-wide etching windows designed on both sides of the phase shifter. The 12-µm-wide region between the etching windows is therefore suspended. Si waveguides and the TiN heater are both located in the suspended region. Mechanical support for the suspended region is through the west end and east end of the phase shifter, as illustrated in 3.1(b). Silicon photonics foundries, such as IME,
have standard fabrication processes to fabricate such a thermal isolation structure, and we choose design parameters for our thermal isolation structure based on specific design rules. We use a heat transport modelling solver [51] to simulate the temperature gradient at the cross section of the ultra-low power phase shifter, and the results are shown in Fig. 3.2(a), where the tuning power is 1mW/m in the 2D simulation. For purpose of comparison, we also investigate the temperature gradient of a regular phase shifter without thermal isolation structure, and the simulated results are shown in Fig. 3.2(b). It can be seen that a much higher $\Delta T$ can be achieved in the phase shifter with thermal isolation than the one without, for the same amount of tuning power.

![Figure 3.2: Heat transport modelling results for thermo-optic phase shifters with tuning power of 1mW/m. (a) A proposed design with thermal isolation structure; (b) a regular design without thermal isolation structure.](image)

In our phase shifter design, waveguides are folded by $N$ times in the suspended region, as shown in Figs. 3.1(a) and 3.1(b). Such a configuration can increase the heating length by a factor of $N$, because the dissipative heat from heater can heat up more waveguides. However, $N$ is limited by the width of the suspended region and the optical crosstalk between waveguides. In order to achieve a dense routing while keeping the crosstalk between waveguides sufficiently small, dimensions of folded waveguides are designed to be dissimilar with widths $w_1, w_2, \ldots, w_N$ (the evanescent coupling between dissimilar waveguides does not achieve the phase matching condition [61] so that the maximum power transfer between waveguides
3.2 Ultra-Low Power Thermo-Optic On/Off Switches

3.2.1 Design

Based on the ultra-low power phase shifter design, we have demonstrated ultra-low power on/off switches with Michelson interferometer (MI) configurations. Figure 3.4 shows the schematic for one of the demonstrated switches. The switch consists of a 2×2, 3-dB adiabatic coupler [43] as both the input power splitter and output power re-combiner for the switch, two balanced waveguide phase arms that are folded several times, and two waveguide loop mirrors operating as reflectors at the end of the phase arms. Phase arm 1 is designed for phase tuning using our ultra-low power phase shifter. Several etching windows are designed on both sides of the tuning arm to form the thermal isolation structure that is illustrated in Fig. 3.1(a), with
3.2. Ultra-Low Power Thermo-Optic On/Off Switches

Figure 3.4: An ultra-low power Michelson interferometer on/off switch. (a) Schematic of the switch; (b) block diagrams for switching states.

Each window being 8-µm-wide and 45-µm-long. The purpose of using several short etching windows with supporting bridges in between is to ensure the mechanical stability of the suspended region.

The MI switch is a $1 \times 1$ (1 input and 1 output) device. Figure 3.4(b) illustrates the operation principle of the MI switch. Ideally, the switch operates at the on-state by having a phase tuning, $\Delta \varphi$, of 0, which directs input signal to the output port; it operates at the off-state by having a phase tuning $\Delta \varphi$ of $\pi$, which reflects back the input signal. The phase tuning for such a MI switch is given by:

$$\Delta \varphi \propto \frac{2\pi}{\lambda} \frac{dn}{dT} \Delta T 2NL \quad (3.1)$$

where $\lambda$ is the operating wavelength; $\frac{dn}{dT} = 1.86 \times 10^{-4}K^{-1}$ is the thermo-optic coefficient of Si at room temperature, and $\Delta T$ is the temperature change for waveguides in the tuning region; $N$ is the folding turns for waveguides; $L=249 \, \mu m$ is heater length. The MI configuration doubles the phase tuning efficiency because light travels through each phase arm twice, and as a result, $2NL$ is the total heating length for the phase shifter.
3.2. Ultra-Low Power Thermo-Optic On/Off Switches

3.2.2 Characterization Results

The on/off switch designs were fabricated using a 248 nm deep ultra-violet (DUV) lithography process at the IME. Numerous switches with different design parameters were fabricated on the same wafer to investigate the contributions of the thermal isolation and the folded waveguides on the phase tuning efficiency. Table 3.1 lists the fabricated devices. Figures 3.5(a) and 3.5(b) respectively show optical images for the fabricated Device 5 and Device 6 in a lithography die.

To characterize spectral responses, we used an Agilent 81600B tunable laser as the optical input source, an Agilent 81635A optical power sensor as the optical output detectors, and a Keithley 2602A source meter as the electrical power source for thermal tuning, as illustrated in Fig. 3.6(a). To characterize switching speeds, we used an electrical square-wave generator as triggering source to the switches, and used a high-speed photodetector and an oscilloscope to measure the responses of switches.

Table 3.1: List for the fabricated on/off switches

<table>
<thead>
<tr>
<th>Device #</th>
<th>N</th>
<th>Thermal isolation</th>
<th>g (nm)</th>
<th>( w_i ) (nm)</th>
<th>2NL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>No</td>
<td>NA</td>
<td>( w_1 = 500 )</td>
<td>0.498</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Yes</td>
<td>NA</td>
<td>( w_1 = 500 )</td>
<td>0.498</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>No</td>
<td>1000</td>
<td>( w_{1,4,7} = 500, ) ( w_{2,5} = 600, ) ( w_{3,6} = 400 )</td>
<td>3.486</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>Yes</td>
<td>1000</td>
<td>( w_{1,4,7} = 500, ) ( w_{2,5} = 600, ) ( w_{3,6} = 400 )</td>
<td>3.486</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>No</td>
<td>430</td>
<td>( w_{1,4,7,10} = 500, ) ( w_{2,5,8,11} = 600, ) ( w_{3,6,9} = 400 )</td>
<td>5.478</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>Yes</td>
<td>430</td>
<td>( w_{1,4,7,10} = 500, ) ( w_{2,5,8,11} = 600, ) ( w_{3,6,9} = 400 )</td>
<td>5.478</td>
</tr>
</tbody>
</table>

\( g \) is the gap between waveguides, and \( w_i \) is the width of waveguide \( i \), as described in Fig. 3.1(a). 2NL is the waveguide heating length.
3.2. Ultra-Low Power Thermo-Optic On/Off Switches

Figure 3.5: Optical images for the fabricated ultra-low power thermo-optic on/off switches. (a) A switch without thermal isolation structure; (b) a switch with thermal isolation structure.

Figure 3.6: Block diagram illustrating the measurement setups. (a) Spectrum characterization; (b) switching speed characterization.
First, we present measurement results for Device 6, which is the best design in terms of tuning efficiency. Figure 3.7(a) presents the spectral responses at both the on-state and off-state for such a switch. The switch has an insertion loss of less than 5.1 dB in the entire optical C-band, which includes the round-trip optical propagation loss in the 4.27 mm long waveguide (about 3 dB), the insertion loss for the 32 waveguide bends with radii of 5 µm (about 0.01 dB per bend [17] and 0.64 dB for the round-trip loss), the insertion loss of the Y-junction [62] waveguide loop mirror (about 0.3 dB per device and 0.6 dB for the round-trip loss), and the optical propagation loss for a 1.3 mm long waveguide connecting the device to the input and output GCs in the layout (about 0.3 dB). The insertion loss of the switch was calibrated by using a pair of GCs connected by a short waveguide, which is similar to the calibration structure shown in Fig. 2.7. As shown in Fig. 3.7(b), at the operation wavelength of 1550 nm, the measured power consumption to switch from minimum to maximum output transmission is 50 µW, and the switching ER is over 25 dB. Figure 3.7(c) shows measured time-domain response for the switch triggered by a 100 Hz square-wave signal having a rise time of 300 ns. According to the result, the switch has a 10%–90% rise time of 551 µs.

For comparisons, measurement results for all switches are summarized in Table 3.2. According to the results, switching power consumption can be significantly reduced by increasing folding turns, $N$, and/or using thermal isolation structures, which are supported by Eq. 3.1. However, switches with thermal isolation structures have a much longer rise time (i.e., being slower) than those without. This observation demonstrates a good trade-off between switching power and switching speed in our switch designs. In practical deployments, the choice of switch design will be application dependent. Thermo-optic switches with thermal isolation structures are suitable for network reconfiguration within data center, where switching time of milliseconds is typical. For packet switching applications, which have typical switching time of nanoseconds to microseconds, carrier injection switches are suitable.
3.2. Ultra-Low Power Thermo-Optic On/Off Switches

Figure 3.7: Measurement results for Device 6. (a) on/off states transmission spectra; (b) transmission at 1550 nm versus tuning power; (c) time-domain response at 1550 nm.

Table 3.2: Performance comparison for the fabricated on/off switches

<table>
<thead>
<tr>
<th>N</th>
<th>Without thermal isolation</th>
<th>With thermal isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rise time (ms)</td>
<td>Power consumption (mW)</td>
</tr>
<tr>
<td>----</td>
<td>---------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>1</td>
<td>0.017</td>
<td>17.19</td>
</tr>
<tr>
<td>7</td>
<td>0.018</td>
<td>3.07</td>
</tr>
<tr>
<td>11</td>
<td>0.019</td>
<td>1.75</td>
</tr>
</tbody>
</table>
3.3 Ultra-Low Power Thermo-Optic Cross/Bar Switches

3.3.1 Design

Based on the proposed ultra-low power phase shifter design, we have also demonstrated ultra-low power, MZI cross/bar switches, which are the essential building blocks for large-scale switch matrices. The schematic of such a switch, as shown in Fig. 3.8, consists of two $2 \times 2$, 3-dB adiabatic couplers [43] and two phase arms based on folded waveguides. The phase arm 1 was designed for phase tuning using the proposed ultra-low power phase shifter. The thermo-optic phase tuning for such an MZI switch is given by:

$$\Delta \varphi \propto \frac{2\pi}{\lambda} \frac{dn}{dT} \Delta T NL$$

where $N$ is the folding turns for waveguides; $L$ is the heater length, and $NL$ is the total heating length for the phase shifter.

3.3.2 Characterization Results

The MZI cross/bar switches were fabricated together with the MI on/off switches. We used the same photonics testing setups shown in Fig. 3.6 to characterize the fabricated switches. In our measurements, we used input 1, as labeled in Fig. 3.8, for optical input source and measured the transmissions at the two switch outputs. Figure 3.9 presents measurement results for the best design in terms of power consumption. As shown in Fig. 3.9(a), at
3.4. Breakdown Test

- **Mechanical failures**, such as deformation and rupture, in the suspended region of our ultra-low power, thermo-optic phase shifters can cause optical

---

**Figure 3.9:** Measurement results for a fabricated ultra-low power MZI cross/bar switch. (a) Output transmissions at 1550 nm versus tuning power; (b) output spectra at the bar state; (c) output spectra at the cross state.

1550 nm operation wavelength, the power consumption to switch from one switching state to the other is only 84 μW, and the switching ER is over 20 dB. Figures 3.9(b) and 3.9(c) show the measured output spectra at the bar state and the cross state, respectively.
3.4. Breakdown Test

insertion loss, and hence degrade the switching ER. Mechanical strength of the demonstrated ultra-low power switches can be tested by measuring the optical output transmission of a switch versus electrical tuning power. As our demonstrated switches have similar design parameters for their thermal isolation structures, breakdown test was only performed on Device 2 that is listed in Table 3.1. Figure 3.10 shows breakdown test results for Device 2. We can see that the maximum output transmission of the switch decreases when the tuning power is greater than 37 mW, which indicates that mechanical failures start to happen at a tuning power of approximately 37 mW (being 71.5× of the cross/bar switching power consumption). Based on the number of switching cycles observed from Fig. 3.10, the temperature change ΔT that triggers mechanical failures can be inferred, which is approximately 670 K. Our breakdown test results are in good agreements with the results of a published report [63], which used a similar thermal isolation structure and suggested a reversible over-drive range up to 60× of switching power consumption.

![Figure 3.10](image_url)

**Figure 3.10:** Breakdown test results for a demonstrated ultra-low power thermo-optic switch.

In summary, in this chapter we have experimentally demonstrated ultra-efficient, thermo-optic on/off switches and cross/bar switches, which have extremely low power consumptions of down to 50 µW/π. The ultra-low power switching was realized by adopting both thermal isolation structures
3.4. Breakdown Test

and densely folded waveguides in the phase shifter designs. The power phases shifters can be further optimized to reduce the optical insertion loss while maintaining their tuning efficiency.
Chapter 4

Crosstalk-free Carrier Injection Tri-State Switches

As discussed in section 1.2.2, a common method to achieve high-speed phase tuning on SOI platforms is using P-i-N diodes operating in a carrier injection mode [21–23, 28, 41, 42]. While providing an efficient optical phase shift with a speed of up to hundreds of MHz, carrier injection also produces inherent insertion loss due to free-carrier absorption [18]. This is problematic for a MZI cross/bar switch that is operating at the bar state, where one of its phase shifters is tuned by a $\pi$ phase shift while the other is not, as illustrated in Fig. 1.4. In such a state, the optical power in the two waveguide arms of the switch is unbalanced, leading to a large crosstalk at the cross output port [21–23, 28, 42]. Theoretical analysis on the bar state switching crosstalk versus power imbalance in a MZI cross/bar switch has been reported in [41]. In order to suppress crosstalk, the optical power inside a MZI cross/bar switch needs to be balanced. Recently, a solution [64] using a nested MZI structure with a variable optical attenuator was proposed. Although this solution balances the optical power in the switch and therefore achieves low crosstalk performance, the optical bandwidth of the switch is strongly limited by its asymmetric interferometer structure. To the best of our knowledge, there is no efficient method that can balance the optical power in a carrier injection based MZI cross/bar switch to achieve low crosstalk performance while maintaining broadband operation.

In this chapter, we design a novel carrier injection switch that is both broadband and crosstalk-free, and additionally it offers three switching states: cross, bar, and blocking. We will present the design, operation principles,
4.1. Switch Design

4.1.1 Schematic

Figure 4.1(a) shows the schematic for a regular MZI cross/bar switch. Figure 4.1(b) shows the schematic for the proposed tri-state switch, which is a $2 \times 2$ device based on a balanced nested Mach-Zehnder interferometer (BNMZI) structure. Such a device consists of an input $2 \times 2$ coupler, an output $2 \times 2$ coupler, and two balanced main interference arms with each being a balanced $2 \times 2$ MZI, i.e., nested MZI A and nested MZI B as shown in Fig. 4.1(b). Each nested MZI has two identical carrier injection phase shifters. The BNMZI

**Figure 4.1:** (a) Schematic for a Mach-Zehnder interferometer (MZI) switch; (b) Schematic for the proposed balanced nested Mach-Zehnder interferometer (BNMZI) switch.
4.1. Switch Design

The switch has a balanced architecture, in which the optical path lengths through the two main interference arms are equal; as a result, optical broadband performance can be achieved.

4.1.2 Operation Principles

The transfer matrix method is used to analyze the operation principles of the proposed BNMZI switch. The relationship between the input and output electric fields for the two nested MZIs are given by:

\[
\begin{bmatrix}
E_c \\
E_d
\end{bmatrix} =
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
A_1 e^{-j\phi_1} & 0 \\
0 & A_2 e^{-j\phi_2}
\end{bmatrix}
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
E_a \\
E_b
\end{bmatrix}
\]

(4.1)

\[
\begin{bmatrix}
E_{c'} \\
E_{d'}
\end{bmatrix} =
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
A_3 e^{-j\phi_3} & 0 \\
0 & A_4 e^{-j\phi_4}
\end{bmatrix}
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
E_{a'} \\
E_{b'}
\end{bmatrix}
\]

(4.2)

where \(E_x=a,b,c,d...\) is the electric field at port \(x\) of the nested MZIs, as illustrated in Fig. 4.1(b); \(t\) and \(\kappa\) are through-coupling coefficient and cross-coupling coefficient for each \(2 \times 2\) coupler, respectively, and we assume that all of the \(2 \times 2\) couplers in the BNMZI switch are identical and lossless, i.e., \(t^2 + \kappa^2 = 1\); \(\phi_{i=1,2,3,4}\) is the modulated optical phase shift of phase shifter \(i\); \(A_{i=1,2,3,4}\) is optical field transmission factor of phase shifter \(i\), and it represents the optical field attenuation due to free-carrier absorption in phase tuning. In our switch design, ports \(a\) and \(b'\) are both terminated, i.e., \(E_a = E_{b'} = 0\), and accordingly we obtain the electric field transfer functions for the light paths from ports \(b\) to \(d\) and from ports \(a'\) to \(c'\), which are:

\[
\frac{E_d}{E_b} = -\kappa^2 A_1 e^{-j\phi_1} + t^2 A_2 e^{-j\phi_2}
\]

(4.3)

\[
\frac{E_{c'}}{E_{a'}} = -\kappa^2 A_4 e^{-j\phi_4} + t^2 A_3 e^{-j\phi_3}
\]

(4.4)
The relationship between the input and output electric fields of the BNMZI switch are given by:

\[
\begin{bmatrix}
E_{\text{out}1} \\
E_{\text{out}2}
\end{bmatrix} =
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
E_{\text{in}1} \\
E_{\text{in}2}
\end{bmatrix}
\] (4.5)

Assuming light is launched into input 1 of the switch, i.e., \(E_{\text{in}1} = 1\) and \(E_{\text{in}2} = 0\), the two outputs are thus given by:

\[|E_{\text{out}1}|^2 = |−t^2\kappa^2 A_1 e^{-j\phi_1} + t^4 A_2 e^{-j\phi_2} − t^2\kappa^2 A_3 e^{-j\phi_3} + \kappa^4 A_4 e^{-j\phi_4}|^2 (4.6)\]

\[|E_{\text{out}2}|^2 = |−j\kappa t(−\kappa^2 A_1 e^{-j\phi_1} + t^2 A_2 e^{-j\phi_2} + t^2 A_3 e^{-j\phi_3} − \kappa^2 A_4 e^{-j\phi_4})|^2 (4.7)\]

The nested MZIs A and B of the BNMZI switch can be driven in a balanced manner in order to balance the free-carrier absorption induced insertion loss in the switch, and therefore, the switch can be crosstalk-free. The operation principles of the BNMZI switch are described as follows:

**Cross State**

When \(\phi_1=\phi_4=0\) and \(\phi_2=\phi_3=\pi\), we have \(A_1=A_4=1\) and \(A_2=A_3=A_\pi\), where \(A_\pi\leq 1\) is optical field transmission factor for the \(\pi\) phase tuning and is dependent on the design parameters of the phase shifter, e.g., phase shifter length and optical confinement of the waveguide, which will be discussed in Section 4.1.3. In such phase tuning, the nested MZI A routes light from ports b to d (see Fig. 4.1(b)) with a digital \(\pi\) phase shift, and the nested MZI B routes light from ports a’ to c’ (see Fig. 4.1(b)) also with a digital \(\pi\) phase shift. As a result, the BNMZI switch operates in the cross state [17]. In addition, the insertion loss for the light path from ports b to d and that from ports a’ to c’ are balanced in such balanced phase tuning, and hence, the BNMZI switch can be crosstalk-free. Based on Eqs. 4.6 and 4.7, we calculate the optical output transmissions of the BNMZI switch as a function of \(\kappa^2\) and \(A_\pi\), and the results for output 1 and output 2 are shown in
4.1. Switch Design

Figs. 4.2(a) and 4.2(b), respectively. According to the results, light launched at input 1 is cross-switched to output 2. Ideally, when the $2\times2$ couplers of the BNMZI switch are perfect 3-dB couplers, i.e., $\kappa^2 = t^2 = 0.5$, the output transmissions are given by:

$$|E_{out1}|^2 = 0; \quad |E_{out2}|^2 = \frac{1}{4}(1 + A_\pi)^2$$

(4.8)

which shows crosstalk-free performance for any $A_\pi$.

![Figure 4.2: Cross state output transmissions as a function of $\kappa^2$ and $A_\pi$. (a) Output 1. (b) Output 2.](image)

**Bar State**

When $\phi_1=\phi_3=\pi$ and $\phi_2=\phi_4=0$, we have $A_1=A_3=A_\pi$ and $A_2=A_4=1$. In such phase tuning, the nested MZI A routes light from ports b to d (see Fig. 4.1(b)) with a digital 0 phase shift, while the nested MZI B routes light from ports a’ to c’ (see Fig. 4.1(b)) with a digital $\pi$ phase shift. As a result, the BNMZI switch operates in the bar state. And more, the insertion loss for the light path from ports b to d and that from ports a’ to c’ are balanced in such balanced phase tuning, and hence, the BNMZI switch can be crosstalk-free. Based on Eqs. 4.6 and 4.7, we calculate the optical output transmissions of the switch as a function of $\kappa^2$ and $A_\pi$, and the results for output 1 and output 2 are shown in Figs. 4.3(a) and 4.3(b), respectively. As can be seen from the results, light launched at input 1 is routed to output
4.1. Switch Design

1. Ideally, when $\kappa^2 = t^2 = 0.5$, the output transmissions are given by:

$$|E_{out1}|^2 = \frac{1}{4}(1 + A\pi)^2; \quad |E_{out2}|^2 = 0 \quad (4.9)$$

In this case, the switch is crosstalk-free for any $A\pi$.

![Figure 4.3: Bar state output transmissions as a function of $\kappa^2$ and $A\pi$. (a) Output 1. (b) Output 2.](image)

**Blocking State**

When no phase tuning is applied, i.e., $\phi_1 = \phi_2 = \phi_3 = \phi_4 = 0$, we have $A_1 = A_2 = A_3 = A_4 = 1$. In such a state, the nested MZI A routes light from ports b to c (see Fig. 4.1(b)) and the nested MZI B routes light from ports a’ to d’ (see Fig. 4.1(b)), as each nested MZI operates in a cross state. No light is routed to the switch outputs. Both the ports c and d’ can be terminated using waveguide terminators. Figures 4.4(a) and 4.4(b) show the optical transmissions at output 1 and output 2 as a function of $\kappa^2$ at such a state, which are calculated based on Eqs. 4.6 and 4.7, respectively. According to the results, the optical transmissions at the two outputs are both low, indicating that the input light is blocked from reaching the two outputs. Ideally, when $\kappa^2 = t^2 = 0.5$, we obtain:

$$|E_{out1}|^2 = |E_{out2}|^2 = 0 \quad (4.10)$$
4.1. Switch Design

Figure 4.4: Blocking state output transmissions as a function of $\kappa^2$.
(a) Output 1. (b) Output 2.

which shows that the switch is completely blocked.

Table 4.1 summarizes the phase tunings for the three switching states. Note that for all of the three switching states, the deviation of $\kappa^2$ ($\kappa^2 \neq 0.5$) breaks the balance of power in the switch and consequently causes switching crosstalk, which are shown in Figs. 4.2(a), 4.3(b), 4.4(a) and 4.4(b). However, this is an issue due to the imperfect performance of $2 \times 2$ 3-dB couplers rather than a performance limitation of the proposed BNMZI switch.

Table 4.1: Phase tuning for the switching states of BNMZI switch.

<table>
<thead>
<tr>
<th>Switching state</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
<th>$\phi_3$</th>
<th>$\phi_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross</td>
<td>0</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>0</td>
</tr>
<tr>
<td>Bar</td>
<td>$\pi$</td>
<td>0</td>
<td>$\pi$</td>
<td>0</td>
</tr>
<tr>
<td>Blocking</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.1.3 Carrier Injection Phase Shifter Design

4.1.3.1 Free-carrier Absorption Loss

Figure 4.5 illustrate the schematic for a carrier injection phase shifter that is designed based on the 220 nm SOI platform. The optical phase tuning
4.1. Switch Design

Figure 4.5: Schematic of a carrier injection phase shifter design on a silicon-on-insulator (SOI) platform.

\[ \Delta \varphi = \frac{2\pi}{\lambda} \frac{\partial n_{\text{eff}}}{\partial n} \Delta n L \]  

(4.11)

where \( \Delta n \) is the change of refractive index of Si; \( \frac{\partial n_{\text{eff}}}{\partial n} \) is susceptibility, i.e., a mode-dependent coefficient, and \( \frac{\partial n_{\text{eff}}}{\partial n} \Delta n \) represents the change of effective index of the waveguide; \( L \) is the phase shifter length.

Based on Eqs. 1.1, 1.2, and 4.11, the change of waveguide absorption, \( \Delta \alpha \), versus phase shifter length, \( L \), for a \( \pi \) phase shift can be calculated, and the results are shown in Fig. 4.6(a). Accordingly, the optical field transmission factor, \( A_\pi \), which describes waveguide loss due to free-carrier absorption in a \( \pi \) phase shift, is given by:

\[ A_\pi = e^{-\Gamma \frac{\Delta \alpha}{\pi} L} \]  

(4.12)

where \( \Gamma \) is optical field confinement factor for the light in waveguide. For example, the TE\(_0\) mode light propagating in the phase shifter design shown in Fig. 4.5 has an optical field confinement factor of 0.7, which is calculated using an Lumerical MODE Solutions [51]. Figure 4.6(b) shows the calculated \( A_\pi \) versus \( L \) for \( \Gamma = 0.7 \). It is found that the free-carrier absorption loss of a carrier injection phase shifter is dependent on its phase shifter length.
4.1. Switch Design

Figure 4.6: Performance of the carrier injection phase shifter with a π phase shift. (a) Change of waveguide absorption, $\Delta \alpha$, versus phase shifter length, $L$; (b) optical field transmission factor, $A_\pi$, versus phase shifter length, $L$. Waveguide propagation loss is not included in the $A_\pi$ calculation.

For low loss carrier injection phase shifter designs, $L \geq 200 \ \mu m$ is typically required, and such a design rule was deployed in many demonstrated designs [21–23, 28, 41, 42]. Note that the data presented in Fig. 4.6(b) does not include the waveguide propagation loss. However, for very long phase shifters, the propagation loss (scattering, e.g., 3 dB/cm) will dominate and lead to the switch having a large insertion loss.
4.1. Switch Design

4.1.3.2 Power Consumption

We assume that every electron and hole recombine in the intrinsic Si region with a non-radiative recombination time constant $\tau_n$. For carrier injection effect, the change of carrier concentration, $\Delta N$, in the intrinsic Si region versus the injection current, $I$, is given by:

$$\Delta N = \frac{I\tau_n}{qSL} \quad (4.13)$$

where $q$ is the electrical charge; $S$ is the area of the intrinsic region. For a $\pi$ phase shift, the injected current, $I$, versus the phase shifter length, $L$, can be calculated based on Eqs. 1.1, 4.11, and 4.13, and the results are shown in Fig. 4.7(a). In the calculation, $\tau_n = 4$ ns is used according to [42]. The current-voltage (I-V) relation for the carrier injection phase shifter is described by the Shockley diode equation:

$$I = I_s (e^{\frac{qV}{nKT}} - 1) \quad (4.14)$$

where $k$ is Boltzmann’s constant; $T$ is absolute temperature; $n = 1$ is ideality factor; $I_s$ is reverse bias saturation current for the P-i-N diode shown in Fig. 4.5, which can be calculated based on diode equations. Based on Eq. 4.14 and the results shown in Fig. 4.7(a), the $\pi$ phase shift power consumption versus $L$ can be thus determined, which is shown in Fig. 4.7(b). It is found that the power consumption of a carrier injection phase shifter decreases with the increase of the phase shifter length.

Based on the analysis in above, we can conclude that a long carrier injection phase shifter design has benefits of both low absorption loss and low power consumption.

4.1.3.3 Tuning Speed

Tuning speeds of carrier injection phase shifters are primarily limited by the carrier recombination lifetime in the intrinsic Si region, which is in the scale of a few nanoseconds [42] and cannot be engineered via the layout, except
4.2. Performance

Figure 4.7: Electrical responses of the carrier injection phase shifter for a $\pi$ phase shift. (a) Injected current, $I$, versus phase shifter length, $L$; (b) power consumption versus phase shifter length, $L$.

by changing the doping concentration of the waveguide.

4.2 Performance

We compare the BNMZI switch shown in Fig. 4.1(b) with the MZI switch shown in Fig. 4.1(a) by investigating the impacts of $\kappa^2$ variations on their cross/bar switching performance. Simulations are performed using a photonic circuit simulator, Lumerical INTERCONNECT [51], as shown in Fig.
4.2. Performance

4.8. In the simulations, each carrier injection phase shifter of the two switches is 250 $\mu$m long with an optical field confinement factor of 0.7, which is similar to many demonstrated designs [21–23, 28, 41, 42]. According to the analysis results shown in Fig. 4.6(b), such a phase shifter design has an $A_\pi$ of 0.8613. The tuning responses of each phase shifter are implemented as a script within the component model in Lumerical INTERCONNECT.

Figure 4.8: Circuit simulation schematics. (a) BNMZI switch; (b) MZI switch.

We assume that the $2 \times 2$ couplers in each switch have identical coupling strength due to a uniform fabrication variation across the switch. Figure 4.9(a) compares the simulated cross state performance of the two switches, and it is found that the BNMZI switch has slightly lower crosstalk than the MZI switch. Figure 4.9(b) compares the simulated bar state performance of the two switches. According to the results, the crosstalk of the MZI switch is greater than -23 dB for the $\kappa^2$ range from 0.4 to 0.6. Meanwhile, the crosstalk of the BNMZI switch is well below -37 dB in the same $\kappa^2$ range, being much lower than the crosstalk of the MZI switch. For a BNMZI switch design using high performance 3-dB couplers [65] which have $\kappa^2$ in between 0.48 and 0.52, the crosstalk at the bar state can be reduced to below -50 dB. According to the results in above, the proposed BNMZI switch exhibits better performance than the MZI switch.

In practice, the $2 \times 2$ couplers in switches may have different coupling strengths due to random fabrication errors. Such an effect can be taken
4.2. Performance

Figure 4.9: Performance comparison for the BNMZI switch and the MZI switch, when the $2 \times 2$ couplers in the switches have identical $\kappa^2$. (a) Cross state performance; (b) bar state performance.

into account in our performance comparison by using simple Monte Carlo (MC) simulations. In the MC simulations, each $2 \times 2$ coupler has a random $\kappa^2$ in between 0.48 and 0.52. Figures 4.10(a) and 4.10(b) show the cross state and the bar state performance of the BNMZI switch, respectively, in 200 MC simulation trials; Figs. 4.10(c) and 4.10(d) present the cross state and the bar state performance of the MZI switch, respectively, in 200 MC simulation trials. By comparing the results, we can find that both switches have variations in their switching crosstalk due to the random variations of $\kappa^2$. At the cross state, both switches have similar switching crosstalk, as shown in Figs. 4.10(a) and 4.10(c); at the bar state, the worst crosstalk of the BNMZI switch is almost 10 dB lower than that of the MZI switch, as shown in Figs. 4.10(b) and 4.10(d). Overall, the proposed BNMZI switch exhibits better performance than the MZI switch.

It should be noted that the BNMZI switch requires two-fold tuning power consumption as compared with the MZI switch. However, the power consumption can be reduced by increasing the phase shifter length, as per Fig. 4.7(b).
4.3. Crosstalk Suppression Functionality

According to Eqs. 4.8, 4.9, and 4.10, ideally the BNMZI switch can be crosstalk-free if its $2 \times 2$ couplers have perfect 3-dB coupling ratios. However, most SOI based $2 \times 2$ couplers exhibit unbalanced coupling ratios due to either imperfect designs or fabrication variations, and as a result, crosstalk will exist for a BNMZI switch in practice. According to the analytical calcu-
4.3. Crosstalk Suppression Functionality

Crosstalk results shown in Figs. 4.2, 4.3 and 4.4, Table 4.2 presents performance of an example BNMZI switch having $A_\pi$ of 0.8613 for a $\pi$ phase tuning and $\kappa^2$ of 0.48 for its imperfect 2×2 couplers (based on the performance of the demonstrated broadband 3-dB coupler presented in Fig. 2.8(b)).

Table 4.2: Performance of an example BNMZI switch with $k^2 = 0.48$ and $A_\pi = 0.8613$.

<table>
<thead>
<tr>
<th></th>
<th>Cross</th>
<th>Bar</th>
<th>Blocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through-port trans. (dB)</td>
<td>-28.61</td>
<td>-0.62</td>
<td>-55.92</td>
</tr>
<tr>
<td>Cross-port trans. (dB)</td>
<td>-0.65</td>
<td>-51.14</td>
<td>-27.97</td>
</tr>
</tbody>
</table>

For a $N \times N$ photonic switch matrix built on imperfect switching elements, crosstalk can be accumulated along a connection route from an input to an output, which degrades the performance of the $N \times N$ switch matrix. The unique blocking state of the BNMZI switch is capable of suppressing crosstalk in $N \times N$ switch matrices, such as dilated Banyan [66, 67], hybrid dilated Benes [68], and route-and-select [69] architectures. The strength of crosstalk suppression depends on both the architecture and the connection loading of the switch matrix.

4.3.1 Crosstalk Suppression for Partially-Loaded Switches

For dilated Benes [66, 67] and hybrid dilated Benes [68] architectures, idle switches exist in a partially-loaded switch matrix. The first order crosstalk in these architectures can be eliminated by constraining connection routing to one signal per switching element [68], as illustrated in Fig. 4.11; the second and higher order crosstalk can be suppressed by assigning blocking state to the idle switching elements in the matrix. As an illustrative example, we simulate the performance of a half-loaded 8×8 dilated Benes switch, which uses the 2×2 BNMZI switch presented in Table 4.2 as its switching elements, and we compare the switching crosstalk in the cases with and without assigning blocking states to the idle switches. Figure 4.12(a) shows the schematic of the 8×8 dilated Benes switch with established connections: I1-O5, I4-O4, I6-O1, and I7-O7, where idle switches can be seen in the
4.3. Crosstalk Suppression Functionality

connections. In our simulations, waveguide crossings in the 8×8 switch are assume to be lossless and crosstalk-free in order to isolate the impacts of the BNMZI switch on the performance of the 8×8 switch. Figure 4.12(b) shows the simulated output transmissions of the 8×8 switch when the idle switches are randomly at the cross or bar state. As a comparison, Fig. 4.12(c) presents the simulated output transmissions of the 8×8 switch when the idle switches are assigned to the blocking state. It can be seen that the worst output crosstalk of the 8×8 switch is drastically suppressed by more than 25 dB, from -32.4 dB in the case of without blocking the idle switches, as shown in Fig. 4.12(b), down to -59.8 dB in the case of blocking the idle switches, as shown in Fig. 4.12(c).

4.3.2 Crosstalk Suppression for Fully-Loaded Switches

A fully loaded dilated Banyan architecture has a total of \(2N(N-1)\) switching elements but only uses \(2N \cdot \log_2 N\) switching elements for connections. Idle switches in the matrix can be blocked for crosstalk suppression. As an illustrative example, we simulate the performance of a fully loaded 8×8 dilated Banyan switch, which uses the 2×2 BNMZI switch presented in Table 4.2 as its switching elements, and we compare the switching crosstalk in the cases with and without assigning blocking states to the idle switches. Figure 4.13(a) illustrates the schematic of the 8×8 dilated Banyan switch with established connections: I1-O3, I2-O7, I3-O5, I4-O1, I5-O6, I6-O2, I7-O4, and I8-O8. In our simulations, waveguide crossings in the 8×8 switch are assumed to be lossless and crosstalk-free in order to isolate the impact of the BNMZI switch on the performance of the 8×8 switch. Figure 4.13(b) show
4.3. Crosstalk Suppression Functionality

Figure 4.12: (a) Schematic of an example 8×8 dilated Benes switch fabric with established connections: I1-O5, I4-O4, I6-O1, and I7-O7. (b) Output transmissions of the 8×8 switch without blocking the idle switches (idle switches are randomly at the cross or bar states). (c) Output transmissions of the 8×8 switch with blocking the idle switches.

The simulated output transmissions of the 8×8 switch where idle switches are randomly at the cross or bar state. Figure 4.13(c) presents the simulation results of the 8×8 switch where the idle switches are set to the blocking state. Obviously, we can see that the worst output crosstalk for the 8×8 switch is drastically suppressed by more than 50 dB, from -59.8 dB in the case of without blocking the idle switches, as shown in Fig. 4.13(b), down to -114.4 dB in the case of blocking the idle switches, as shown in Fig. 4.13(c).

In summary, in this chapter we have designed a high-performance tri-state switch based on a novel BNMZI structure. The switch has a balanced architecture, in which the optical path lengths are equal in its interferometer arms, so that broadband switching can be achieved. High-speed switching
4.3. Crosstalk Suppression Functionality

Figure 4.13: (a) Schematic of an example 8×8 dilated Banyan switch fabric with established connections: I1-O3, I2-O7, I3-O5, I4-O1, I5-O6, I6-O2, I7-O4, and I8-O8. (b) Output transmissions of the 8×8 switch without blocking the idle switches (idle switches are randomly at the cross or bar states). (c) Output transmissions of the 8×8 switch with blocking the idle switches.

can be achieved using carrier injection phase tuning. The insertion loss of carrier injection phase tuning is balanced in the BNMZI structure due to the balanced phase tuning to the switch, and hence the switch can be crosstalk-free in operation, which can not be achieved by regular carrier injection MZI switches [21–23, 28, 41, 42]. As compared with regular carrier injection MZI switches, the proposed BNMZI switch not only exhibits better performance but also provides a unique blocking functionality, the later of which can be applied to crosstalk suppression in N × N switch matrices.
Chapter 5

Polarization Control for Switches

Edge coupling [17], as illustrated in Fig. 5.1(a), is a common solution to couple light from optical fibres to silicon waveguides on chips. This approach couples both TE and TM polarizations, and it has both broadband and low loss performance. Depending on the polarization of the light in the fibre, the light coupled into a silicon “single-mode” waveguide can be in the TE$_0$ mode and/or the TM$_0$ mode. Edge coupling efficiency can be determined by performing mode overlap calculations for the fibre Gaussian beam with the waveguide modes. As an example, Fig. 5.1(b) shows the simulated electric field distribution of a fibre Gaussian beam with a waist radius of 2.5 µm and a polarization angle, $\theta$; Figs. 5.1(c) and 5.1(d) respectively show the electric field distributions for the TE$_0$ mode and TM$_0$ mode in a 180 nm × 220 nm edge coupler waveguide [17]; Fig. 5.1(e) shows the transmission power for the coupled TE$_0$ mode and TM$_0$ mode in the waveguide, as a function of $\theta$. According to Fig. 5.1(e), as $\theta$ increase, the transmission of the TE$_0$ mode decrease while that of the TM$_0$ mode increase. For optical systems using polarization-maintaining (PM) fibres for connections, $\theta$ is determined by the alignment for the slow axis of the PM fibre to the horizontal surface of the silicon waveguide. For optical systems using regular single-mode fibres (SMFs) for connections, $\theta$ may vary in time due to changes of environment conditions, such as temperature and stress.

Silicon photonic devices are mode-sensitive. Most silicon photonic switches are designed to operate using only the TE$_0$ mode or the TM$_0$ mode. In such switches, if both modes are present, crosstalk will typically increase.
Figure 5.1: (a) Edge coupling solution in silicon photonic integrated circuits; (b) fibre Gaussian beam with a waist radius of 2.5 µm; (c) TE\(_0\) mode profile in a 180 nm \(\times\) 220 nm edge coupler waveguide; (d) TM\(_0\) mode profile in a 180 nm \(\times\) 220 nm edge coupler waveguide. (e) Power transmission for the coupled TE\(_0\) and TM\(_0\) modes versus polarization angle, \(\theta\), of the fibre Gaussian beam.
5.1. Broadband Polarization Beamsplitter

As a result, silicon photonic switches require polarization control at switch inputs. One simple solution to polarization control is using polarization beamsplitters (PBSs) to filter away the undesired mode the switch inputs, as illustrated in Fig. 5.2. In such a solution, PBSs are required to have low loss and broadband performance since MZI switches are designed to be broadband.

In this chapter, we present design and characterization results of a high-performance PBS that is broadband (i.e., operate over a wide wavelength range), low loss, easy to fabricate, and has a large modal isolation (i.e., efficiently separate the two mode types). The demonstrated PBS is integrated with a broadband MZI switch for polarization control.

5.1 Broadband Polarization Beamsplitter

In PICs, the PBS, which splits or combines the orthogonal TE modes and TM modes, is a fundamental component for polarization control. Ideally, a PBS should be broadband, low loss, compact in size, easy to fabricate, and has high isolation. In recent years, various PBS designs [70–83] have been reported on SOI platforms. However, most demonstrated devices have disadvantages such as large excess loss (more than 1 dB), narrow operating...
5.1. Broadband Polarization Beamsplitter

bandwidth (less than 50 nm), and low extinction ratio (less than 15 dB), being incompatible with our proposed solution for polarization control, which requires broadband and low loss performance.

5.1.1 Principles

5.1.1.1 Approach to Split TE$_0$ and TM$_0$ Modes

In properly designed SOI directional couplers, the TM$_0$ mode has much stronger coupling strength than the TE$_0$ mode due to a dramatic difference in their mode confinements. For a coupler with a crossover length (i.e., the length to achieve 100% coupling) designed for the TM$_0$ mode, it can crossover couple the TM$_0$ mode while leaving the TE$_0$ without being significant coupled. As a result, the two modes can be separated at the coupler outputs.

5.1.1.2 Approach for Broadband Crossover Coupling

In order to achieve broadband polarization beamsplitting, broadband crossover coupling is needed for the TM$_0$ mode. In section 2.1, we have presented a design methodology for broadband 3-dB couplers; however, such methodology is unable to achieve broadband 100% cross-coupling. To design a broadband 100% coupler, we cascade two easy to achieve, broadband 3-dB couplers in a point-symmetric way [84].

Figure 5.3(a) shows the schematic of a point-symmetric network consisting of two components. The component on the left is an arbitrary $2 \times 2$ coupler and the component on the right is the point-symmetry-transformed version of the coupler on the left. The unitary transfer matrix for the arbitrary $2 \times 2$ coupler is given by [84, 85]:

$$T = \begin{bmatrix} t(\lambda) & -\kappa^*(\lambda) \\ \kappa(\lambda) & t^*(\lambda) \end{bmatrix}$$ (5.1)

where $t(\lambda)$ and $\kappa(\lambda)$ are the complex straight-through coupling coefficient and the cross-coupling coefficient, respectively, and $t^*(\lambda)$ and $\kappa^*(\lambda)$ are their
5.1. Broadband Polarization Beamsplitter

**Figure 5.3:** (a) Schematic of a point-symmetric network; (b) responses of a 3-dB, 2×2 coupler and its point-symmetric network. The shadow regions mark out the variations of their respective cross-coupling powers.

Given a normalized input electric field at the input 1 shown in Fig. 5.3(a), i.e., $E_1 = 1$ and $E_2 = 0$, we have:

$$
\begin{bmatrix}
E_3 \\
E_4
\end{bmatrix} = T \cdot \begin{bmatrix} 1 \\
0
\end{bmatrix}, \quad
\begin{bmatrix}
E_5 \\
E_6
\end{bmatrix} = T \cdot T_{\text{point-symmetric}} \cdot \begin{bmatrix} 1 \\
0
\end{bmatrix}
$$

complex conjugates. $\lambda$ is the wavelength. The transfer matrix for the point-symmetry-transformed coupler is given by [84]:

$$
T_{180^\circ} = \begin{bmatrix}
t^*(\lambda) & -\kappa^*(\lambda) \\
\kappa(\lambda) & t(\lambda)
\end{bmatrix}
$$

(5.2)

Therefore, the transfer matrix for the point-symmetric network, which is shown in Fig. 5.3(a), can be expressed as:

$$
T \cdot T_{180^\circ} = \begin{bmatrix}
t(\lambda)t^*(\lambda) - \kappa(\lambda)\kappa^*(\lambda) & -2t(\lambda)\kappa^*(\lambda) \\
2t(\lambda)\kappa(\lambda) & t(\lambda)t^*(\lambda) - \kappa(\lambda)\kappa^*(\lambda)
\end{bmatrix}
$$

(5.3)
5.1. Broadband Polarization Beamsplitter

and accordingly have:

\[ E_3(\lambda) = t^*(\lambda) \] (5.5)
\[ E_4(\lambda) = \kappa(\lambda) \] (5.6)
\[ E_5(\lambda) = t(\lambda)t^*(\lambda) - \kappa(\lambda)\kappa^*(\lambda) \] (5.7)
\[ E_6(\lambda) = 2t^*(\lambda)\kappa(\lambda) \] (5.8)

where \( E_3 \) and \( E_4 \) are the electric fields at the through port and cross port of the 2×2 coupler, respectively. \( E_5 \) and \( E_6 \) are the electric fields at the through port and cross port of the point-symmetric network, respectively. \( P_3(\lambda) \) and \( P_4(\lambda) \) are the through-coupling and cross-coupling power of the 2×2 coupler, respectively, and for convenience they are taken to be:

\[ P_3(\lambda) = |E_3(\lambda)|^2 = t(\lambda)t^*(\lambda) \] (5.9)
\[ P_4(\lambda) = |E_4(\lambda)|^2 = \kappa(\lambda)\kappa^*(\lambda) \] (5.10)

Assuming that there is no coupling loss (i.e., \( |t(\lambda)|^2 + |\kappa(\lambda)|^2 = 1 \)) and according to Eqs. 5.7, 5.8, 5.9, and 5.10, we obtain the through-coupling power, \( P_5(\lambda) \), and the cross-coupling power, \( P_6(\lambda) \), of the point-symmetric network:

\[ P_5(\lambda) = |E_5(\lambda)|^2 = |P_3(\lambda) - P_4(\lambda)|^2 = |\Delta P(\lambda)|^2 \] (5.11)
\[ P_6(\lambda) = 1 - P_5(\lambda) = 1 - |\Delta P(\lambda)|^2 \] (5.12)

where \( \Delta P(\lambda) \) is the coupling imbalance for the 2×2 coupler. According to Eqs. 5.11 and 5.12, when \( \Delta P(\lambda) = 0 \), we have \( P_5(\lambda) = 0 \) and \( P_6(\lambda) = 1 \), which achieves crossover-coupling. When the deviation of \( \Delta P(\lambda) \) from 0 is small, then the deviation of \( P_6(\lambda) \) from 1 is also small due to their quadratic relationship; in other words, the cross-coupling power \( P_6(\lambda) \) is less sensitive to unbalanced coupling in the 3-dB 2×2 coupler. As an example, Fig. 5.3(b) shows the cross-coupling power of a 3-dB 2×2 coupler for the TM\(_0\) mode and that of its point-symmetric network. Over a large wavelength span, the \( \Delta P(\lambda) \) varies by ±0.1, as indicated by the red shadow in Fig. 5.3(b), while
5.1. Broadband Polarization Beamsplitter

$P_6(\lambda)$ remains between 0.96 and 1, as indicated by the blue shadow in Fig. 5.3(b).

At this point, we have seen that broadband crossover-coupling can be obtained by cascading two 3-dB 2×2 couplers in a point-symmetric configuration, which is shown in Fig. 5.3. The principle of using the point-symmetric network for broadband crossover-coupling is similar to that of the $\Delta \beta$ reversal couplers [86, 87] well-known in LiNbO$_3$ photonics.

5.1.2 Device Design

In above, we have discussed the approach for polarization beamsplitting based on directional coupling and the approach to achieve broadband crossover-coupling. By combining the two approaches, we can design a broadband PBS that crossover-couples the TM$_0$ mode into the cross port over a broad bandwidth while leaving the TE$_0$ mode to propagate to the through port without being significantly coupled.

![Diagram of broadband PBS](image)

**Figure 5.4:** (a) Schematic of our broadband PBS; (b) schematic of the first broadband 3-dB coupler in the PBS.
5.1. Broadband Polarization Beamsplitter

Our PBS design is based on the 220 nm SOI platform as depicted in Fig. 1.3. As shown in Fig. 5.4(a), the PBS consists of two identical TM$_0$ mode broadband 3-dB couplers that are cascaded in a point-symmetric network. Figure 5.4(b) shows the schematic for the first broadband 3-dB coupler. The second broadband 3-dB coupler is identical to the first coupler but is flipped around both axis, i.e., it is the point-symmetry-transformed version of the first coupler.

![Figure 5.5: FDTD simulation results of the broadband 3-dB coupler operating at the (a) TE$_0$ mode and (b) TM$_0$ mode.](image)

We design the PBS in a 2 steps process. To begin with, we design broadband 3-dB couplers for the TM$_0$ mode using the methodology as described in section 2.1. The geometric parameters of the broadband 3-dB couplers are detailed in Fig. 5.4(b). In the design, we optimize geometric parameters of the coupler to achieve 3-dB coupling for the TM$_0$ mode over a large wavelength span. A large waveguide spacing of 500 nm is used in the broadband 3-dB coupler design to achieve a weak coupling strength for the TE$_0$ mode; as a result, the TE$_0$ mode can propagate through the coupler without significant cross-coupling. Using a FDTD solver [51], we simulate the spectral responses for the broadband 3-dB coupler design operating at the TE$_0$ and TM$_0$ modes, and simulation results are shown in Figs. 5.5(a) and 5.5(b), respectively. As shown in Fig. 5.5(a), the cross-coupling power for the TE$_0$ mode is less than -22 dB across a wavelength range from 1480 nm to 1580 nm.
nm, whereas, in the same wavelength range the TM<sub>0</sub> mode coupling ratios are close to 3-dB, as shown in Fig. 5.5(b).

![Diagram of polarization beamsplitter](image)

**Figure 5.6:** FDTD simulation results for the PBS. (a) Spectral responses for the TE<sub>0</sub> mode; (b) spectral responses for the TM<sub>0</sub> mode; (c) modal isolation at the through port; (d) modal isolation at the cross port.

Then, using the FDTD solver we model the PBS design, which is configured by cascading the two identical broadband 3-dB couplers in a point-symmetric manner, as shown in Fig. 5.4(a). Figures 5.6(a) and 5.6(b) show the simulated output spectral responses for the TE<sub>0</sub> mode and TM<sub>0</sub> mode, respectively. As we can see, over a wide wavelength range most of the TE<sub>0</sub> mode light propagates through the device and exits from the through port, while most of the TM<sub>0</sub> mode light is coupled to the cross port. Hence,
broadband polarization beamsplitting is possible.

We use modal isolation and bandwidth to evaluate the performance of our PBS. The isolation at the through port and cross port are defined as follows:

\[
\text{(Isolation at the through port)} = P_{TE_0,\text{through}} - P_{TM_0,\text{through}} \tag{5.13}
\]

\[
\text{(Isolation at the cross port)} = P_{TM_0,\text{cross}} - P_{TE_0,\text{cross}} \tag{5.14}
\]

where \(P_{TE_0,\text{through}}\) and \(P_{TE_0,\text{cross}}\) are the output powers, in logarithmic scale, for the TE\(_0\) mode at the through port and cross port, respectively, as shown in Fig. 5.6(a). Similarly, \(P_{TM_0,\text{through}}\) and \(P_{TM_0,\text{cross}}\) are the output powers, in logarithmic scale, for the TM\(_0\) mode at the through port and cross port, respectively, as shown in Fig. 5.6(b). The bandwidth of device is defined as the wavelength span over which the isolation is above a certain value, here we use 20 dB. Figures 5.6(c) and 5.6(d) show the modal isolation at the through port and cross port, respectively, which are extracted from the simulated spectral responses. According to the results, our PBS has a 20 dB modal isolation at both the through and cross ports, for a 105 nm bandwidth from 1465 nm to 1570 nm.

To illustrate how the behaviours of TE\(_0\) and TM\(_0\) modes within the PBS, in Figs. 5.7(a) and 5.7(b) respectively, we show the normalized field intensities of 1550 nm wavelength in the waveguide cores of the PBS. The TE\(_0\) mode coupling along the propagation length shows reversal behaviour and the total cross-coupled power is suppressed due to its low coupling strength in the first half of the PBS, as shown in Fig. 5.7(a). The TM\(_0\) mode coupling also shows reversal behaviour but the input power is completely cross-coupled due to its strong coupling strength in the first half of the PBS, as shown in Fig. 5.7(b). Such coupling behaviours are similar to the operation of \(\Delta\beta\) reversal couplers [86, 87].
5.1. Broadband Polarization Beamsplitter

Figure 5.7: Normalized field intensities of 1550 nm wavelength in the PBS waveguide cores along propagation length. (a) TE\textsubscript{0} mode; (b) TM\textsubscript{0} mode.

5.1.3 Characterization Results

Our PBSs were fabricated using an electron-beam lithography process at the University of Washington. Figure 5.8 shows scanning electron microscope (SEM) images for one of our fabricated PBSs.

Figure 5.8: Scanning electron microscope (SEM) images for one of the fabricated broadband polarization beamsplitters.

Figure 5.9 shows a sketch of our measurement setup. Our test devices include two identical PBSs separated by a 20 µm spacing on the SOI wafer. For such a small spacing, fabrication variation for the two identical PBSs is negligible. As illustrated in Fig. 5.9, one of the PBSs is used for character-
5.1. Broadband Polarization Beamsplitter

Figure 5.9: Sketch of measurement setup. The yellow and pink triangles are the on-chip grating couplers for the TE0 mode and TM0 mode, respectively.

izing the TE0 mode responses, while the other is used for the TM0 mode responses. On-chip grating couplers (GCs), which also work as TE0-pass or TM0-pass polarizers due to their strong polarization dependence, were used to couple light into and out of our test devices. We also fabricated a pair of TE0 mode and a pair of TM0 mode GCs, connected by short waveguides for calibrating the insertion losses. In the characterizations, we used an Agilent 81600B broadband laser as the input source and both channels of an Agilent 81635A optical power sensor as the output detectors, as illustrated in Fig. 5.9. The laser output is TE-polarized. The slow-to-slow PM fibre keeps the polarization state of the light, and the slow-to-fast PM fibre rotates the polarization state of the light by 90 degrees at the outputs of fibres that were used to inject light into the GCs.

Devices were measured over the wavelength range from 1460 nm to 1635 nm, with a measurement resolution of 10 pm and an input power at 0 dBm. Figures 5.10(a) and 5.10(b) present the measured output spectra for the TE0 mode and TM0 mode, respectively, in which the insertion losses introduced by the GCs have been calibrated out. It is found that the insertion loss of our PBSs is less than 0.5 dB across the C-band for both the TE0 and TM0 modes. In Figs. 5.10(c) and 5.10(d), we plot the extracted modal isolation at the through port and cross port, respectively. For comparison purposes, the modal isolation from simulation results are also plotted in the figures. According to Figs. 5.10(c) and 5.10(d), good agreement is seen between the simulated and the measured results. The measured PBS has a 20 dB modal isolation at both the cross port and through port, for a bandwidth
of 120 nm, i.e., from 1482 nm to 1602 nm.

Figure 5.10: Measurement results for the fabricated PBS. (a) Spectral responses for the TE\(_0\) mode; (b) spectral responses for the TM\(_0\) mode; (c) modal isolation at the through port; (d) modal isolation at the cross port.
5.2 Polarization Control for Switches using Polarization Beamsplitters

As discussed, most silicon photonic switches are designed to operate using only one mode. Taking the TE\textsubscript{0} mode, broadband MZI switch that was demonstrated in section 2.2 as an example, here we model its performance in a multi-mode operation condition. As shown in Fig. 5.11(a), in our simulations the input source to the switch is a mixture of 80% TE\textsubscript{0} mode and 20% TM\textsubscript{0} mode. Figures 5.11(b) and 5.11(c) show the simulated output transmission spectra of the switch at the cross state and bar state, respectively. As compared to the switch performance in the single-mode (TE\textsubscript{0} only) operation condition that is shown in Fig. 2.9, the multi-mode operation causes a huge degradation to the switching ERs at both two switching states.

**Figure 5.11:** (a) A broadband MZI switch without polarization control; (b) simulated cross state performance of the switch; (c) simulated bar state performance of the switch.
5.2. Polarization Control for Switches using Polarization Beamsplitters

The demonstrated broadband PBS can be used as a front-end mode filter for the broadband MZI switch, as illustrated in Fig. 5.12(a). Figure 5.12(b) and 5.12(b) show the simulated output transmission spectra of the switch operating at the cross state and the bar state, respectively. It can be found that the switch with polarization control has great improvements in the switching ERs at both switching states, as compared the switch without. However, the improvements are at the expense of polarization dependent loss (PDL). Polarization control without PDL can be realized by using an automated polarization receiver [88], and our demonstrated broadband PBS is a critical building block in the receiver design.

Figure 5.12: (a) A broadband switch having polarization control; (b) simulated cross state performance of the switch; (c) simulated bar state performance of the switch.
Chapter 6

Wafer-Scale Manufacturing Variation Characterization

The high refractive index contrast of SOI photonics enables tight confinement of light in sub-micrometer waveguides and sharp waveguide bends, making SOI promising for developing PICs with high integration densities. In applications such as WDM, PICs often require precise matching of the central wavelength and the waveguide propagation constant between components on a chip (e.g., ring modulators and optical filters). However, manufacturing variability is a challenge [89] in PIC designs. Fabrication errors in waveguide width and height have significant impacts on the propagation constant of light in waveguides; therefore, circuits such as interferometers are highly sensitive to manufacturing. For designers, it is critical to be aware of such variations so as to take them into account in PIC designs.

Unfortunately, characterizing manufacturing variations in a wafer scale is challenging in SOI photonics. Although the widths and heights of fabricated SOI waveguides can be characterized by using SEM imaging [90] and atomic force microscope (AFM) mapping [91], respectively, they are rather costly and time-consuming. A more efficient method is to extract waveguide widths and heights from the spectral responses of fabricated SOI devices (e.g., micro-disk resonators [31] and Bragg gratings [92, 93]). However, most demonstrated methods require either dual-polarization measurement [31] or complex spectrum reflection measurement [92]. Therefore, more efforts are required to simplify the characterization methods.

In this chapter, we propose a simple and accurate method to characterize photonics manufacturing variations, which is based on the spectral response
6.1 Characterization Methodology

6.1.1 Principle

As we know, manufacturing variations in waveguide width, \( w \), and height, \( h \), both affect the waveguide effective index, \( n_{\text{eff}}(\lambda) \), and consequently result in photonic interferometric devices having variations in their spectral responses. In turn, it is possible to extract \( w \) and \( h \) from the spectral responses of fabricated interferometric devices.

Based on this, we have designed an all-pass racetrack resonator based on the 220 nm SOI platform, as the test device to extract waveguide geometry variations. The schematic layout for such a device is shown in Fig. 6.1(a). Silicon waveguides of the racetrack resonator have a nominal \( w \) of 500 nm and a nominal \( h \) of 220 nm. The radius, coupling length and coupling gaps of the device are 12 \( \mu \)m, 4.5 \( \mu \)m, and 200 nm, respectively. Figure 6.1(b) shows the calculated through-port transmission spectrum of such a device, which is given by [94]:

\[
\frac{E_{\text{thru}}}{E_{\text{in}}} = e^{i\left(\pi + \frac{2\pi}{\lambda} n_{\text{eff}}(\lambda)L\right)} \frac{a - te^{-i\frac{2\pi}{\lambda} n_{\text{eff}}(\lambda)L}}{1 - tae^{i\frac{2\pi}{\lambda} n_{\text{eff}}(\lambda)L}}
\]  

(6.1)

where \( t=0.9592 \) is the self-coupling coefficient of the ring coupler at a wavelength of 1550 nm and is obtained from FDTD simulation results; \( L \) is the round-trip length of the resonator; \( a=0.9811 \) is the round-trip amplitude factor contributed by waveguide propagation loss in the resonator (assumed to be 10 dB/cm [95]) and coupling loss in the coupler.

Manufacturing variations have a direct impact on the resonance wavelengths, \( \lambda_{\text{res}} \), of racetrack resonators. As an example, Fig. 6.2(a) shows transmission spectra for racetrack resonators with various waveguide width, \( w \), where resonance shifts can be directly observed. Manufacturing varia-
6.1. Characterization Methodology

Figure 6.1: (a) Schematic layout of the racetrack resonator test device; (b) transmission spectrum for such a device without fabrication variations. FSR is free-spectral-range.

tions also affect the waveguide group index, \( n_g \), at each resonance wavelength \( \lambda_{res} \). The \( n_g \) can be extracted from the spectral response and is determined by [17, 96]:

\[
    n_g = \frac{\lambda_{res}^2}{FSR \cdot L}
\]  

(6.2)

where FSR is free-spectral-range and is defined as wavelength spans between two adjacent resonances, as illustrated in Fig. 6.1(b). By quantifying (via simulations) the variations of \( \lambda_{res} \) and \( n_g \) versus the variations of \( w \) and \( h \) (i.e., \( \frac{\partial \lambda_{res}}{\partial w} \), \( \frac{\partial \lambda_{res}}{\partial h} \), \( \frac{\partial n_g}{\partial w} \) and \( \frac{\partial n_g}{\partial h} \)), waveguide dimensions of a racetrack resonator can be extracted from its spectral response by:

\[
    \begin{bmatrix}
    \Delta n_g \\
    \Delta \lambda_{res}
    \end{bmatrix}
    =
    \begin{bmatrix}
    \frac{\partial n_g}{\partial w} & \frac{\partial n_g}{\partial h} \\
    \frac{\partial \lambda_{res}}{\partial w} & \frac{\partial \lambda_{res}}{\partial h}
    \end{bmatrix}
    \begin{bmatrix}
    \Delta w \\
    \Delta h
    \end{bmatrix}
\]  

(6.3)

\[
    \begin{bmatrix}
    \Delta w \\
    \Delta h
    \end{bmatrix}
    =
    \begin{bmatrix}
    \frac{\partial n_g}{\partial w} & \frac{\partial n_g}{\partial h} \\
    \frac{\partial \lambda_{res}}{\partial w} & \frac{\partial \lambda_{res}}{\partial h}
    \end{bmatrix}^{-1}
    \begin{bmatrix}
    \Delta n_g \\
    \Delta \lambda_{res}
    \end{bmatrix}
\]  

(6.4)

where \( \Delta w \) and \( \Delta h \) are deviations of waveguide width and height relative to their nominals, respectively; \( \Delta n_g \) and \( \Delta \lambda_{res} \) are variations of group index and resonance wavelength relative to their nominals at a resonance mode, respectively.
6.1. Characterization Methodology

Figure 6.2: Simulation results for racetrack resonators with a nominal waveguide height, $h$, of 220 nm and various waveguide widths, $w$. (a) Transmission spectra; (b) group indices at resonances; (c) resonance wavelength versus waveguide width for a selected resonance mode; (d) group index versus waveguide width for a selected resonance mode.
Using Eq. 6.2, we extract \( n_g \) from the spectral responses of racetrack resonators with various \( w \) and a nominal \( h \) of 500 nm. The extracted \( n_g \) results are shown in Figure 6.2(b). It is found that \( n_g \) decreases with an increase of \( w \) whereas its corresponding \( \lambda_{res} \) increases. According to [96], the data points forming a downward diagonal line are in the same resonance mode. Based on this relationship, it is possible to identify the data points that belong to one mode and accordingly determine their resonance shifts even if the shifts are greater than a FSR. Here, we analyze the resonance mode having a nominal \( \lambda_{res} \) of 1544.25 nm and \( n_g \) of 4.1899, as shown in 6.2(b). For this mode, we plot the \( \lambda_{res} \) versus \( w \) and \( n_g \) versus \( w \) in Figs. 6.2(c) and 6.2(d), respectively, both of which can be approximated using linear fits. From the fitting slopes, we obtain:

\[
\frac{\partial \lambda_{res}}{\partial w} = 0.585911 \ (nm/nm) \quad (6.5) \\
\frac{\partial n_g}{\partial w} = -0.001650 \ (/nm) \quad (6.6)
\]

Similarly, we simulate racetrack resonators having a nominal \( w \) of 500 nm and various \( h \), and part of the simulated results are shown in Fig. 6.3(a). We extract the \( n_g \) at resonances from each simulated spectrum, as shown in Fig. 6.3(b). It is found that the data points for each resonance mode change in a upward diagonal direction, with an increase in \( h \). For the resonance mode having a nominal \( \lambda_{res} \) of 1544.25 nm and a nominal \( n_g \) of 4.1899, the \( \lambda_{res} \) versus \( h \) and \( n_g \) versus \( h \) are plotted in Figs. 6.3(c) and 6.3(d), respectively. Both the \( \lambda_{res} \) versus \( h \) and the \( n_g \) versus \( h \) can be approximated using linear fits, and according to the fitting slopes we obtain:

\[
\frac{\partial \lambda_{res}}{\partial h} = 1.36330 \ (nm/nm) \quad (6.7) \\
\frac{\partial n_g}{\partial h} = 0.001091 \ (/nm) \quad (6.8)
\]

Given the results of Eqs. 6.5, 6.6, 6.7, and 6.8, the deviations of waveguide dimensions can be extracted from the variations of resonance wavelength and group index, base on Eq. 6.4.
6.1. Characterization Methodology

Figure 6.3: Simulation results for racetrack resonators with a nominal waveguide width, $w$, of 500 nm and various waveguide heights, $h$. (a) Transmission spectra; (b) group indices at resonances; (c) resonance wavelength versus waveguide height for a selected resonance mode; (d) group index versus waveguide height for a selected resonance mode.
6.1. Characterization Methodology

By measuring the spectral responses for a large number of fabricated, identical test devices spread over a wafer, which is easy to achieve using a wafer-scale automated testing setup [17], statistical results for the variations of waveguide width and height can be obtained. While here the test device for the proposed characterization method is based on a racetrack resonator, ring resonators can also be used as test devices. As compared to traditional characterization methods using SEM imaging and AFM mapping, which are time-consuming and costly (SEM typically cost $20/picture), our propose method is efficient and cost-free (including test devices in a layout makes no change to the fabrication cost).

6.1.2 Characterization Errors

As the results of Eqs. 6.5, 6.6, 6.7 and 6.8 are based on linear approximations, there are numerical errors in our proposed variation extraction method, and these errors can be quantified by using the following calibration procedures. First, the transmission spectrum of a racetrack resonator is simulated with given waveguide width and height deviations, i.e., $\Delta w_{given}$ and $\Delta h_{given}$, respectively. Second, the $\lambda_{res}$ for each resonance mode is obtained from the simulated spectrum, and its corresponding $n_g$ is extracted by using Eq. 6.2. Third, the $\Delta \lambda_{res}$ and $\Delta n_g$ are calculated for the resonance mode having a nominal $\lambda_{res}$ of 1544.25 nm and a nominal $n_g$ of 4.1899. Finally, base on Eq. 6.4, the deviations of waveguide width, $\Delta w_{extracted}$, and waveguide height, $\Delta h_{extracted}$, are extracted. The width extraction error, $Error_\Delta w$, and height extraction error, $Error_\Delta h$, are given by:

$$ Error_\Delta w = |\Delta w_{given} - \Delta w_{extracted}| $$

(6.9)

$$ Error_\Delta h = |\Delta h_{given} - \Delta h_{extracted}| $$

(6.10)

For most of 193-nm and 248-nm DUV lithography processes, waveguide etching linewidth is typically controlled to an accuracy of within $\pm 20$ nm, and the wafer thickness uniformity is controlled to an accuracy of within $\pm 10$ nm. In our error tests, extraction errors are investigated in the same ranges. Figures 6.4(a) and 6.4(b) show the calibrated $Error_\Delta w$ and $Error_\Delta h$, respect-
6.2 Characterization Results

Using the proposed characterization method, we’ve characterized a 200-mm-wafer that was fabricated by a 248-nm DUV lithography process through IME’s silicon photonics foundry. A total number of 2013 identical racetrack resonators were fabricated in 33 lithography dies in the wafer. The size of each die is 7.6 mm × 6 mm (being 1/16 of the size of each 30.4 mm × 24 mm lithography reticle), and each die has 61 identical devices. Figure 6.5(a) shows the schematic layout for a fabricated racetrack resonator, the design parameters of which are the same as those of the design shown in Fig. 6.1(a). Figure 6.5(b) shows the layout distributions for the racetrack resonators on each die, and Fig. 6.5(c) shows the wafer map for the fabricated 200-mm-wafer. All of the fabricated racetrack resonators were measured using an automated photonics testing setup, and the temperature of the setup was stabilized with a control stability of 1 mK.
6.2. Characterization Results

Figure 6.5: (a) Schematic layout for the racetrack resonator test device; (b) distribution of racetrack resonators on each wafer die; (c) wafer map for the fabricated multi-project-wafer.

6.2.1 Within-Die Variations

Figure 6.6(a) shows the measured spectra of the devices in die #20, which is located close to the centre of the wafer. Using Eq. 6.2, we extracted the \( n_g \) of the devices in die #20, and the results are shown in Fig. 6.6(b). Each cluster of data points in Fig. 6.6(b) represents a resonance mode. The data points for the mode being closest to 1544.25 nm is selected for \( \Delta w \) and \( \Delta h \) extractions. In the extractions, the \( \Delta \lambda_{\text{res}} \) and \( \Delta n_g \) for each selected data point are calculated, relative to a nominal \( \lambda_{\text{res}} \) of 1544.25 nm and a nominal \( n_g \) of 4.1899 for the selected mode. Then, \( \Delta w \) and \( \Delta h \) are extracted using Eq. 6.4. Figures 6.6(c) and 6.6(d) respectively show the extracted \( \Delta w \) and \( \Delta h \) versus coordinates on the die #20. It is found that \( \Delta w \) varies from 3.15 nm to 9.14 nm, and \( \Delta h \) varies between -0.44 nm and -3.03 nm.

Using the same approach, we’ve characterized the \( \Delta w \) and \( \Delta h \) for all of the 33 wafer dies, and the results for \( \Delta w \) and \( \Delta h \) are shown using scatter plots in Figs. 6.7(a) and 6.7(b), respectively. Each data point in the figures corresponds to the characterized results of a test device. We used normal distribution functions to fit the characterized \( \Delta w \) and \( \Delta h \) of each die, and summarized the fitting results in Table 6.1.
6.2. Characterization Results

Figure 6.6: Characterization results for die #20. (a) Measured spectra for the 61 identical test devices; (b) extracted $n_g$ for the 61 devices; (c) distribution map for extracted $\Delta w$; (d) distribution map for extracted $\Delta h$. 
6.2. Characterization Results

![Characterization Results](image)

**Figure 6.7:** Characterization results for all of the fabricated wafer dies. (a) Waveguide width variations, $\Delta w$; (b) waveguide height variations, $\Delta h$. 
## 6.2. Characterization Results

Table 6.1: Statistical results for the characterized variations for all of the wafer dies.

<table>
<thead>
<tr>
<th>Die #</th>
<th>Width variations, $\Delta w$</th>
<th>Height variations, $\Delta h$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (nm)</td>
<td>Standard deviation (nm)</td>
</tr>
<tr>
<td>2</td>
<td>9.15</td>
<td>1.30</td>
</tr>
<tr>
<td>5</td>
<td>7.28</td>
<td>2.60</td>
</tr>
<tr>
<td>6</td>
<td>9.43</td>
<td>1.24</td>
</tr>
<tr>
<td>7</td>
<td>8.29</td>
<td>0.94</td>
</tr>
<tr>
<td>8</td>
<td>9.05</td>
<td>1.32</td>
</tr>
<tr>
<td>10</td>
<td>5.37</td>
<td>1.49</td>
</tr>
<tr>
<td>11</td>
<td>2.79</td>
<td>2.84</td>
</tr>
<tr>
<td>12</td>
<td>8.36</td>
<td>1.23</td>
</tr>
<tr>
<td>13</td>
<td>3.50</td>
<td>1.03</td>
</tr>
<tr>
<td>14</td>
<td>8.36</td>
<td>0.95</td>
</tr>
<tr>
<td>17</td>
<td>7.55</td>
<td>1.26</td>
</tr>
<tr>
<td>18</td>
<td>-0.12</td>
<td>2.15</td>
</tr>
<tr>
<td>19</td>
<td>-1.69</td>
<td>3.06</td>
</tr>
<tr>
<td>20</td>
<td>6.68</td>
<td>1.65</td>
</tr>
<tr>
<td>21</td>
<td>7.37</td>
<td>1.41</td>
</tr>
<tr>
<td>22</td>
<td>13.33</td>
<td>1.29</td>
</tr>
<tr>
<td>24</td>
<td>9.81</td>
<td>1.33</td>
</tr>
<tr>
<td>25</td>
<td>7.99</td>
<td>1.02</td>
</tr>
<tr>
<td>26</td>
<td>8.10</td>
<td>1.67</td>
</tr>
<tr>
<td>27</td>
<td>3.75</td>
<td>1.83</td>
</tr>
<tr>
<td>28</td>
<td>7.00</td>
<td>1.23</td>
</tr>
<tr>
<td>29</td>
<td>9.75</td>
<td>1.71</td>
</tr>
<tr>
<td>31</td>
<td>9.41</td>
<td>1.16</td>
</tr>
<tr>
<td>32</td>
<td>9.65</td>
<td>1.15</td>
</tr>
<tr>
<td>33</td>
<td>5.48</td>
<td>1.07</td>
</tr>
<tr>
<td>34</td>
<td>6.05</td>
<td>2.41</td>
</tr>
<tr>
<td>35</td>
<td>3.86</td>
<td>4.31</td>
</tr>
<tr>
<td>38</td>
<td>10.59</td>
<td>1.24</td>
</tr>
<tr>
<td>39</td>
<td>10.55</td>
<td>1.13</td>
</tr>
<tr>
<td>40</td>
<td>7.48</td>
<td>1.32</td>
</tr>
<tr>
<td>41</td>
<td>8.37</td>
<td>1.76</td>
</tr>
<tr>
<td>43</td>
<td>12.36</td>
<td>1.61</td>
</tr>
<tr>
<td>44</td>
<td>15.78</td>
<td>1.67</td>
</tr>
</tbody>
</table>
6.2. Characterization Results

6.2.2 Within-wafer Variations

Figures 6.8(a) and 6.8(b) show the histograms for the characterized $\Delta w$ and $\Delta h$ across the 200-mm-wafer. We fit the histograms using normal distributions to estimate the variations across the 200-mm-wafer, and list the fitting results in Table 6.2. According to the results, standard deviations for $\Delta w$ and $\Delta h$ are 3.89 nm and 1.36 nm, respectively.

![Histograms for the characterized variations across the 200-mm-wafer. (a) Width variations, $\Delta w$; (b) height variations, $\Delta h$.](image)

Figure 6.8: Histograms for the characterized variations across the 200-mm-wafer. (a) Width variations, $\Delta w$; (b) height variations, $\Delta h$.

Table 6.2: Statistical results for the characterized variations across the 200-mm-wafer.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta w$ (nm)</th>
<th>$\Delta h$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (nm)</td>
<td>7.60</td>
<td>-1.69</td>
</tr>
<tr>
<td>Standard deviation (nm)</td>
<td>3.89</td>
<td>1.36</td>
</tr>
</tbody>
</table>

6.2.3 Literature Results

In recent years, there has been studies investigating manufacturing variations [32, 90–92, 97–100] and correlations [96, 101] of various photonics fabrication processes. In these reports, many techniques including SEM, ellipsometry, AFM, and indirect measurements were used for characterizations. Here, we summarize the reported wafer-to-wafer and within-wafer
6.2. Characterization Results

Table 6.3: Literature results for wafer-to-wafer fabrication variations

<table>
<thead>
<tr>
<th>Process</th>
<th>Wafer-to-wafer variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>imec 193-nm dry lithography [91]</td>
<td>σ_{Δw} 1.26 nm</td>
</tr>
</tbody>
</table>

Table 6.4: Literature results for within-wafer fabrication variations

<table>
<thead>
<tr>
<th>Process</th>
<th>Within-wafer variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>imec 193-nm dry lithography [90, 91]</td>
<td>σ_{Δw} 2.59 nm, σ_{Δh} 2 nm</td>
</tr>
<tr>
<td>imec wafer-scale corrective etching [97]</td>
<td>σ_{Δw} 0.83 nm</td>
</tr>
<tr>
<td>imec wafer-scale corrective etching [98]</td>
<td>σ_{Δw} 3.64 nm</td>
</tr>
<tr>
<td>imec 193-nm immersion lithography [7]</td>
<td>σ_{Δw} 2.53 nm</td>
</tr>
<tr>
<td>200-mm-wafer, 193-nm dry lithography [99]</td>
<td>σ_{Δw} 0.78 nm</td>
</tr>
<tr>
<td>300-mm-wafer, 193-nm immersion lithography [99]</td>
<td>σ_{Δw} 2.65 nm</td>
</tr>
<tr>
<td>248-nm lithography [101]</td>
<td>σ_{Δw} 4.17 ± 0.42 nm</td>
</tr>
<tr>
<td>IME 248-nm lithography [96]</td>
<td>σ_{Δw} 5 mm</td>
</tr>
<tr>
<td>imec 193-nm lithography [93]</td>
<td>σ_{Δw} 2.4 nm</td>
</tr>
<tr>
<td>248-nm lithography [100]</td>
<td>σ_{Δw} 2 nm, σ_{Δh} 4.16 nm</td>
</tr>
</tbody>
</table>

variations in Tables 6.3 and 6.4, respectively. The wafer-to-wafer variations evaluate the drifts for the mean of waveguide linewidth and height. As demonstrated in [91], standard deviation for the mean of waveguide height, σ_{Δh}, is 1.26 nm. For within-wafer variations, standard deviations for waveguide linewidth, σ_{Δw}, range from 0.78 nm to 2.65 nm; standard deviations for waveguide height, σ_{Δh}, range from 0.83 nm to 4.16 nm. According to [96, 101], within-wafer variations are correlated over short distance scales, and the characterized correlation length, l_{cor}, is around 4 mm to 5 mm.

From these summarized results, it can be found that fabrication variations vary from foundry to foundry, from process to process, and even from run to run. Worse, according to our practical experience, officially released
results for manufacturing variability lack of timely updates. For photonics designers, the capability to characterized manufacturing variations in a cost-efficient and accurate way can be helpful for yield prediction analysis, and our proposed characterization method can satisfy such a need.

6.3 Summary

In this chapter, we have proposed a simple and accurate method for manufacturing variation characterization. In our method, each characterization only requires a single measurement on the transmission spectrum of a single racetrack resonator. Waveguide dimension variations are extracted from the variation of waveguide group index, $\Delta n_g$, and the variation of resonance shift, $\Delta \lambda_{\text{res}}$, both of which are directly obtained from the measured transmission spectrum. In practice, the racetrack resonators for characterization can be fabricated together with other photonic devices in the same photonics wafer for no extra-cost, and can be measured together with other photonic devices using an automated photonics test setup [17] for no extra-cost; as a result, the proposed characterization method is very cost-efficient. Based on the proposed characterization method, we have experimentally characterized the variability of a 200-mm-wafer that was fabricated using a 248-nm DUV lithography process. As compared to other published results on manufacturing variability, which are summarized in Tables 6.3 and 6.4, our characterized results show a larger standard deviation for waveguide linewidth, which is reasonable since a 248-nm lithography process typically has lower accuracy than a 193-nm lithography process. Our characterized standard deviation for waveguide height is within the scope of other published results.
Chapter 7

Layout-Dependent Yield Prediction for Photonics Integrated Circuits

Photonics manufacturing variations are spatially-correlated [96, 101]. Efficiently taking such correlated variations into account in PIC designs is challenging for designers, and unfortunately, there is currently no simulation tool that can support such simulations. In fact, correlated manufacturing variations also exist in electronics, and the well-developed electronics has sophisticated solutions in their simulation tools, which can be references to photonics. In electronics simulations, Monte Carlo (MC) analysis [102], which assigns random variations with correlation constraints to circuit components, is typically used for yield prediction. As lengths of electrical devices are typically small as compared with operation wavelengths, phase errors caused by variations are small; therefore, correlation are only applied to critical components that require matching, typically device pairs. For example, the resistor pair of a differential amplifier requires matching as it affects the common-mode-rejection-ratio of the amplifier. However, the lengths of photonic devices are much longer than the operating wavelength; as a result, a small variation in waveguide dimensions can cause a dramatic phase error [7, 32]. Therefore, in photonics manufacturing analysis, correlations are required for all of the circuit components. Simply applying the electronics MC analysis to photonics will face serious scaling issues (e.g., it requires $N^2$ correlation parameters for $N$ components). Additionally, it is difficult to determine correlation parameters from photonics physical lay-
This chapter presents a statistical yield prediction method for photonics, which can efficiently take into account the layout-dependent correlated manufacturing variations. The analysis approach and simulation models will be detailed. As examples, we will perform yield prediction analysis for a MZI switch design based on the proposed method.

### 7.1 Methodology

#### 7.1.1 Approach

![Diagram showing simulation approach](image)

**Figure 7.1:** Proposed simulation approach for photonics yield prediction. Primary simulation steps include: (1) layout-to-schematic transformation, (2) virtual wafer simulation and mapping, (3) components’ performance update, and (4) circuit simulation.

Figure 7.1 sketches our simulation approach for photonics yield prediction. Our approach uses an open-source netlisting tool [103] to extract component information as well as connectivity of a photonic circuit from its physical layout, and transfers the extracted information into a circuit
7.1. Methodology

Correlated manufacturing variations for waveguide widths and thicknesses are modeled as virtual wafers. Then, the generated virtual wafers information is transferred to the photonic circuit by assigning each component’s physical variations based on its layout coordinates. All circuit components are parameterized to be continuous functions of width and height so that their performance can be automatically updated according to the obtained physical variations, without having to run any physical-level simulation. Finally, the circuit performance is simulated multiple times (MC analysis), each time with new virtual wafers, to obtain statistical results for the performance variations of the circuit.

7.1.2 Simulation Flow Chart

Figure 7.2: (a) Detailed simulation flow chart for the proposed approach; (b) and (c) illustrate the simulated virtual wafers for waveguide width and height variations, respectively.

The simulation flow chart for the proposed yield prediction approach is
7.1. Methodology

detailed in Fig. 7.2(a). Procedures are as follows:

- **Layout-to-schematic transformation**: First, the layout of the silicon photonic circuit under test are created (in the example presented here, they are designed using KLayout [104], an open-source layout tool). The netlist of the layout, which provides coordinates and design parameters for primitive components, path and dimension information of waveguides, and connectivity between components, is extracted from the layout using a developed open-source netlisting tool [103], and is then imported into a circuit simulator, Lumerical INTERCONNECT [51]. As an example, Fig. 7.3(a) shows the physical layout of a photonic circuit consisting of two grating couplers connected by a strip waveguide, and Fig. 7.3(b) shows the imported circuit simulation schematic for such a layout. The extracted netlist of such a layout is:

```plaintext
*Checking layout for errors:
*Number of errors found: 0.
*Grating coupler 1 N$0 N$2 ebeam_gc_te1550 library="
  Design kits/ebeam_v1.2" lay_x=0 lay_y=0 sch_x=0
  sch_y=0
*Grating coupler 2 N$1 N$3 ebeam_gc_te1550 library="
  Design kits/ebeam_v1.2" lay_x=50.0E-6 lay_y=0 sch_x
  =1.2E0 sch_y=0 sch_r=180
*waveguide 1 N$2 N$3 ebeam_wg_integral_1550 library="
  Design kits/ebeam_v1.2" wg_length=50.0E-6 wg_width
  =500.0E-9 sch_x=600.0E-3 sch_y=0 sch_r=0 path
  =[[0,121.250],[50000,121.250]]
```

- **Virtual wafer simulation**: Second, in the circuit simulator, we create a virtual wafer for waveguide width variations, $\Delta w$, and a virtual wafer for waveguide height variations, $\Delta h$, as illustrated in Figs. 7.2(b) and 7.2(c), respectively. Each virtual wafer is characterized by a standard deviation amplitude and a correlated length, both of which are based on experimental results [32, 90–92, 96–101]. The virtual wafer model will be described in section 7.2.1.
7.1. Methodology

Figure 7.3: An example circuit consisting of two grating couplers connected by a waveguide. (a) Physical layout; (b) simulation schematic in the circuit simulator.

- **Variation mapping**: The simulated virtual wafers, as illustrated in Figs. 7.2(b) and 7.2(c), can be divided into numerous lithography dies with identical size. The virtual maps for one of the dies is selected and mapped to the photonic circuit under test. As an example, Fig. 7.4 illustrates the die selection and variation mapping for a ring resonator circuit. Each circuit component obtains its local $\Delta w$ and $\Delta h$ according to its layout coordinates.

- **Performance interpolation**: The performance of each circuit component is updated according to the obtained $\Delta w$ and $\Delta h$, which is performed using interpolation in the circuit simulator. The parameterized component models will be described in section 7.2.2.

- **Circuit simulation**: Finally, the photonic circuit, with updated components’ performance, is simulated.

The proposed method provides two categories of statistically analysis: within-wafer analysis and wafer-to-wafer analysis. The within-wafer analysis iterates the steps of "variation mapping", "performance interpolation", and "circuit simulation", to study the circuit performance variations across various lithography dies, as shown in Fig. 7.2(a). Figure 7.4 illustrates
the die selection and variation mapping for the within-wafer analysis. The wafer-to-wafer analysis includes the within-wafer analysis, and each of its iteration generates a new $\Delta w$ virtual wafer and a new $\Delta h$ virtual wafer for the within-wafer analysis, as illustrated in Fig. 7.5. The iteration numbers for the within-wafer analysis and wafer-to-wafer analysis, i.e., $N$ and $M$ respectively as shown in Fig. 7.2(a), can be defined by users.

![Figure 7.4: Illustration for the die selection and variation mapping in the within-wafer analysis.](image)

7.2 Models

7.2.1 Virtual Wafer Model

We model the within-wafer manufacturing variations using a correlated surface roughness function [105]. Firstly, we generate an uncorrelated random distribution map, $z(x, y)$, based on discrete mesh of points in x-y plane, and the value at each discrete point is a random number following a normal distribution with a mean of 0 and a standard deviation of $\sigma$. Then, the random distribution map, $z(x, y)$, is convolved with a Gaussian filter, $g(x, y)$, which
7.2. Models

is given by:

\[ g(x, y) = \frac{1}{\sqrt{\pi l^2}} e^{-\left(\frac{x^2}{l^2} + \frac{y^2}{l^2}\right)} \]  (7.1)

in which, \( l \) is correlation length for variations. The convolved wafer, \( m(x, y) \), which has correlated distributions, is given by:

\[ m(x, y) = \mathcal{F}^{-1} [ \mathcal{F}[g(x, y)] \cdot \mathcal{F}[z(x, y))] \]  (7.2)

where \( \mathcal{F} \) and \( \mathcal{F}^{-1} \) are denotations for the fast Fourier transform and the inverse fast Fourier transform, respectively. As an example, Figs. 7.6(a), 7.6(b), and 7.6(c) show a random distribution map, \( z(x, y) \), a Gaussian filter map, \( g(x, y) \), and a correlated variation wafer map \( m(x, y) \), respectively.

Wafer-to-wafer variations are included in our virtual wafer model by adjusting the mean of the correlated variation wafer map, which is given by:

\[ m(x, y) = \mathcal{F}^{-1} [ \mathcal{F}[g(x, y)] \cdot \mathcal{F}[z(x, y))] + c \]  (7.3)

where \( c \) is a random number following a normally distribution with a mean of 0 and a standard deviation \( \sigma^* \). In total, there are three input parameters

Figure 7.5: Illustration for the manufacturing variation simulations of wafer-to-wafer analysis.
7.2. Models

to our virtual wafer model, which are $\sigma$, $l$, and $\sigma^*$. To increase computation efficiency, virtual wafers are simulated using a coarse simulation mesh of 500 $\mu$m $\times$ 500 $\mu$m in the "virtual wafer simulation" step. In the "variation mapping" step, the simulated width and height variations of the selected die are interpolated using a high resolution mesh of 5 $\mu$m $\times$ 5 $\mu$m. The interpolated high resolution variation maps are then mapped to photonic circuits. As an example, Fig. 7.7 illustrates the variations maps before and after the interpolation.

![Coarse simulation mesh](image1)

**Figure 7.6:** (a) A 100 mm $\times$ 100 mm random distribution map $z(x,y)$ generated with $\sigma=2$; (b) a Gaussian filter map $g(x,y)$ generated with $l=4$ mm; (c) the correlated variation wafer map $m(x,y)$.

![Correlated variation wafer map](image2)

**Figure 7.7:** (a) A 100 mm $\times$ 100 mm correlated variation wafer map $m(x,y)$, which is simulated using a coarse simulation mesh; (b) and (c) are the variation maps of a 10 mm $\times$ 10 mm die located at the top right corner of the wafer, before and after interpolation, respectively.
7.2. Parameterized Component Models

In order to consider fabrication variations in circuit simulations, we require parameterized component models that are continuous with width variations, $\Delta w$, and height variations, $\Delta h$. In addition, wavelength-dependency is necessary in order to model a circuit over a wavelength range of interest. This section describes how waveguides and components are modeled.

7.2.2.1 Waveguide Compact Model

Waveguides are fundamental building blocks in PICs. Waveguide properties can be described using a waveguide loss and a wavelength-dependent effective refractive index, $n_{\text{eff}}(\lambda)$. In our waveguide model, the waveguide loss is based on empirical results (e.g. 2-6 dB/cm for 500 nm $\times$ 220 nm waveguides), and it can be defined by the user. The $n_{\text{eff}}(\lambda)$ is described using a third-order Taylor expansion, which is given by [17]:

$$n_{\text{eff}}(\lambda) = n_{\text{eff}}(\lambda_0) + (\lambda - \lambda_0) \frac{dn_{\text{eff}}}{d\lambda} \bigg|_{\lambda=\lambda_0} + (\lambda - \lambda_0)^2 \frac{d^2n_{\text{eff}}}{d\lambda^2} \bigg|_{\lambda=\lambda_0}$$  \hspace{1cm} (7.4)

where $\lambda_0$=1550 nm is the central wavelength of operation bandwidth; $\frac{dn_{\text{eff}}}{d\lambda}$ and $\frac{d^2n_{\text{eff}}}{d\lambda^2}$ are determined by the group index, $n_g$, and group velocity dispersion, $D$, respectively:

$$n_g(\lambda_0) = n_{\text{eff}}(\lambda_0) - \lambda_0 \frac{dn_{\text{eff}}}{d\lambda} \bigg|_{\lambda=\lambda_0}$$  \hspace{1cm} (7.5)

$$D(\lambda_0) = -\frac{\lambda_0}{c} \frac{d^2n_{\text{eff}}}{d\lambda^2} \bigg|_{\lambda=\lambda_0}$$  \hspace{1cm} (7.6)

The $n_{\text{eff}}(\lambda_0)$, $n_g(\lambda_0)$ and $D(\lambda_0)$ can be obtained from eigenmode simulations.

To parameterize the $n_{\text{eff}}(\lambda)$ as a continuous function of waveguide width, $w$, and waveguide height, $h$, we perform eigenmode simulations for waveguides with various geometries (e.g. sweeping $w$ from 300 nm to 1000 nm with a 20 nm step, and sweeping $h$ from 200 nm to 240 nm with a 2 nm step), and
we generate a look-up table for the simulated $n_{\text{eff}}(\lambda_0)$, $n_g(\lambda_0)$ and $D(\lambda_0)$ for each waveguide geometry. According to the look-up table, we use a multi-dimensional spline interpolation method to interpolate the $n_{\text{eff}}(\lambda_0)$, $n_g(\lambda_0)$ and $D(\lambda_0)$ for any waveguide geometry, and accordingly obtain the $n_{\text{eff}}(\lambda)$ using Eq. 7.4. The look-up table and the interpolation are implemented within our waveguide compact model in Lumerical INTERCONNECT.

In our waveguide model, the impacts of the spatially dependent $\Delta w$ and $\Delta h$ on a waveguide are averaged along its layout path. The waveguide path information is extracted from the layout, as discussed in section 7.1.2, and is imported into our waveguide model. With the path information, a waveguide is mathematically meshed into pieces by the simulated virtual wafers, and each waveguide piece automatically obtains the $\Delta w$ and $\Delta h$ at its mesh point, as illustrated in Fig. 7.8. The average waveguide width and height along the path, i.e., $w_{\text{avg}}$ and $h_{\text{avg}}$, are given by:

\[
    w_{\text{avg}} = w_0 + \frac{1}{N} \sum_{n=1}^{N} \Delta w_n, \quad h_{\text{avg}} = h_0 + \frac{1}{N} \sum_{n=1}^{N} h_n \tag{7.7}
\]

where $N$ is total number of waveguide pieces; $\Delta w_n$ and $\Delta h_n$ are width and height variations for the waveguide section $n$, respectively. The averaging is implemented as a script within our waveguide model. Based on $w_{\text{avg}}$ and $h_{\text{avg}}$, the $n_{\text{eff}}(\lambda_0)$, $n_g(\lambda_0)$ and $D(\lambda_0)$ are determined as described above.

### 7.2.2.2 S-parameter Component Models

All of the primitive components, such as y-junction splitter [62], grating couplers [53], and directional coupler [65], are described using optical S-parameters [17, 51], which can be obtained by using FDTD solvers, e.g., Lumerical FDTD Solutions [51]. The optical S-parameters include the amplitude and phase responses of a primitive component (indicating both transmission and reflection parameters). Since these simulations do not provide propagation loss result from waveguide sidewall roughness, we need to add this separately to the compact model. To parameterize the primitive component model as a function of $\Delta w$ and $\Delta h$, first, we obtain S-parameters
for the nominal design and the four process corners of manufacturing variations. We consider a maximum $\Delta w$ of $\pm 20$ nm and a maximum $\Delta h$ of $\pm 10$ nm for a photonics process. Accordingly, the four corners are $(20$ nm, $10$ nm), $(-20$ nm, $10$ nm), $(-20$ nm, $-10$ nm) and $(20$ nm, $-10$ nm), and the nominal design is $(0$ nm, $0$ nm), as illustrated in Fig. 7.9(a). Then, for a desired $(\Delta w, \Delta h)$ input, we use a multi-dimensional spline interpolation method to interpolate the amplitude and phase of the S-parameters. After interpolation, the S-parameters' passivity and reciprocity are tested and enforced [17], to avoid violating energy conservation laws. We implement the S-parameter data and interpolation as a script within the component model in Lumerical INTERCONNECT. As an example, Figs. 7.9(b) and 7.9(c) show the $S_{31}$ amplitudes and phases of a TE$_0$ mode 2×2 directional coupler, respectively. The example directional coupler has a coupling length of 17.5 $\mu$m, a coupling gap of 200 nm, waveguide widths of 500 nm, and waveguide heights of 220 nm.
7.2. Models

7.2.2.3 Sub-Circuit Component Models

Sub-circuit components can be described using both the S-parameter model and the waveguide model. One example of a sub-circuit component is a 2×2 MZI, which can be decomposed into two 2×2 couplers described by the S-parameter model and two waveguides described by the waveguide model, as illustrated in Fig. 7.10. The performance of the MZI, such as extinction ratio and insertion loss, will vary with the width and height variations introduced into the directional coupler model and the waveguide model.

Figure 7.9: S-parameter component model. (a) Process corners for two process parameters: waveguide width variation, Δw, and height variation, Δh; (b) and (c) are S31 amplitude and phase of a 2×2 directional coupler, respectively.
7.3 Yield Prediction for Mach-Zehnder Interferometer Switches

7.3.1 Switch Layout

Using the proposed yield prediction method, this section studies the performance variations of several MZI switch designs. Figure 7.11(a) shows the layout of a 2×2 thermo-optic MZI switch, which is generated using Klayout [104]. The MZI switch consists of two broadband 3-dB couplers (i.e., the coupler design presented in section 2.1) and two balanced waveguide phase arms that are separated by a spacing \( d \) of 50 \( \mu \text{m} \). The silicon waveguides are 220 \( \text{nm} \) height. The waveguides of the two phase arms are both 500 \( \text{nm} \) wide. One of the phase arms has a 200 \( \mu \text{m} \) long thermo-optic phase shifter.

Figure 7.11(b) shows the circuit simulation schematic of the switch, which is loaded from its physical layout using the netlist extraction tool [103] as discussed in section 7.1.2. All of the circuit components have been parameterized using the methods as described in section 7.2.2. In our simulation settings, input 1 is activated for optical source and both switch outputs are monitored, as illustrated in Fig. 7.11(b). For simulations at the cross state, the heater applies no phase shift to the waveguide arm; while at bar state, the heater applies a wavelength-dependent phase shift \( \Delta \phi(\lambda) \) to
7.3. Yield Prediction for Mach-Zehnder Interferometer Switches

Figure 7.11: A thermo-optic MZI switch. (a) Physical layout; (b) circuit simulation schematic in Lumerical INTERCONNECT.

the waveguide arm with $\Delta \phi = \pi$ at 1550 nm wavelength.

7.3.2 Input Parameters for Manufacturing Variability

The input parameters to the virtual wafer model of our yield prediction are listed in Table 7.1. The wafer size and die size are 100 mm $\times$ 100 mm and 5 mm $\times$ 5 mm, respectively. In total, the wafer includes 400 dies. Standard deviations for the waveguide width and height, i.e., $\sigma_{\Delta w}$ and $\sigma_{\Delta h}$, are set to 3.89 nm and 1.36 nm, respectively, which are based on the characterized variations of the 200-mm-wafer as presented in section 6.2.2. The correlation lengths for the width and height variations, i.e., $l_{\Delta w}$ and $l_{\Delta h}$, are both 4 mm, based on [96, 101]. Note that simulation results to be shown in this
section depend on the input parameters to the virtual wafer model, and these parameters can be defined by the user according to the variability of a specific fabrication process.

### Table 7.1: Input parameters for the virtual wafer model

<table>
<thead>
<tr>
<th></th>
<th>100 mm × 100 mm</th>
<th>5 mm × 5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wafer size</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Die size</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Within-wafer variations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\Delta w}$</td>
<td>3.89 nm</td>
<td></td>
</tr>
<tr>
<td>$l_{\Delta w}$</td>
<td>4 mm</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\Delta h}$</td>
<td>1.36 nm</td>
<td></td>
</tr>
<tr>
<td>$l_{\Delta h}$</td>
<td>4 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Wafer-to-wafer variations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma^*_{\Delta w}$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\sigma^*_{\Delta h}$</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

### 7.3.3 Yield Prediction Results

First, we perform a circuit simulation without introducing fabrication variations. Figures 7.12(a) and 7.12(b) respectively show the simulated spectral responses of the switch at the cross state and bar state, without fabrication variation. We use bandwidth to evaluate the switch performance, and we define it as the wavelength span over which the ER is greater than 25 dB. Ideally, the switch has a bandwidth of 132 nm in the wavelength range from 1480 nm to 1612 nm at the cross state, and a bandwidth of 112 nm in the wavelength range from 1496 nm to 1608 nm at the bar state. At 1550 nm, the switch has an insertion loss of 0.1 dB for both two switching states.

Manufacturing variations affect the switch performance in numerous ways. Waveguide dimension variations can vary the coupling ratios of the broadband 3-dB couplers, and therefore vary the switching ER, as discussed in Section 1.2.3. In addition, the two phase arms may experience differential variations in waveguide geometries, which leads to the switch having imbalance phase arms with wavelength-dependent phase errors, $\Delta \phi_{\text{error}}(\lambda)$. As $\Delta \phi_{\text{error}}(\lambda)$ cannot be completely trimmed in a wide bandwidth by using thermo-optic phase tuning, the switch can only achieve 0 or $\pi$ phase shift in a narrow wavelength range, and therefore its operation bandwidth
7.3. Yield Prediction for Mach-Zehnder Interferometer Switches

![Diagram of transmission spectra for cross and bar states of a Mach-Zehnder interferometer switch]

Figure 7.12: Ideal performance for the 2×2 Mach-Zehnder interferometer switch. (a) Cross state; (b) bar state.

The phase trimming for $\Delta \phi_{\text{error}}(\lambda)$ also increases the power consumption of the switch.

Next, we perform a within-wafer analysis to study the performance variations of switch circuit, which simulates the switch performance on each of the 400 wafer dies. In each simulation, the phase shifter model is able to detect the $\Delta \phi_{\text{error}}(\lambda)$ caused by manufacturing variations, and automatically apply phase trimming with a target for 1550 nm. Figures 7.13(a) and 7.13(b) show the simulated transmission spectra at the cross state and bar state, respectively. It can be found that the cross state performance is quite sensitive to manufacturing variations, while the bar state performance is comparatively stable. Figures 7.13(c) and 7.13(c) show the histograms for the cross state bandwidth and the bar state bandwidth, respectively.

According to the results, the cross state bandwidth vary in between 70.8 nm and 140 nm, and the bar state bandwidth vary in between 105.7 nm and 137.0 nm. It is surprising that both the cross state and the bar state bandwidths under manufacturing variations can be larger than their results in the ideal case, which might be the outcome of multiple impacts. Figure 7.13(e) and 7.13(f) show the statistical results for the insertion loss at 1550 nm, at the cross state and bar state, respectively. Based on these results in above, designers can estimate the performance stability of the MZI.
7.3. Yield Prediction for Mach-Zehnder Interferometer Switches

![Graphs showing spectral variations and histograms for cross and bar states.](image)

**Figure 7.13:** Within-wafer yield prediction results for the 2×2 Mach-Zehnder interferometer switch. (a) Spectral variations at the cross state; (b) spectral variations at the bar state; (c) histograms for the cross state bandwidth; (d) histograms for the bar state bandwidth; (e) histograms for the cross state insertion loss; (f) histograms for the bar state insertion loss.
switch, and accordingly improve the design, e.g., using 3-dB couplers that is less sensitive to manufacturing variations and using a smaller spacing $d$ for the two phase arms to reduce the impacts of differential manufacturing variations.

As demonstrated in many reports [96, 101], fabrication variations are correlated over short distance scales, leading to adjacent components in a layout having similar performance variations. As a result, compact layout is a significant design rule for applications where performance matching is required. Such a rule also applies to MZI switch designs. For a MZI switch, the $\Delta \phi_{\text{error}}(\lambda)$ is dependent on the correlation of the two phase arms. Here, we study the variations of $\Delta \phi_{\text{error}}(\lambda)$ for switch designs with various spacings between its two phase arms, which are $d=30 \, \mu\text{m}$, $d=50 \, \mu\text{m}$, and $d=100 \, \mu\text{m}$. We perform within-wafer yield prediction analysis on each switch design. Figure 7.14 shows and compares the phase errors at 1550 nm, $\Delta \phi_{\text{error}}(1550)$, for the three different designs. We fit the histograms using normal distributions, and the fitting results are listed in Table 7.2. According to the results, a larger spacing leads to a larger variation to the phase error, since fabrication variations of two phase arms are less correlated when they are further apart. Based on the statistical results shown in Fig. 7.14, the power consumption for phase trimming can be estimated.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7_14.png}
\caption{Histograms for phase errors at 1550 nm, for switch designs with $d=25 \, \mu\text{m}$, $d=50 \, \mu\text{m}$, and $d=100 \, \mu\text{m}$.}
\end{figure}
Table 7.2: Statistical results for the phase errors at 1550 nm for switch designs with $d = 25 \, \mu m$, $d = 50 \, \mu m$, and $d = 100 \, \mu m$.

<table>
<thead>
<tr>
<th></th>
<th>$d = 25 , \mu m$</th>
<th>$d = 50 , \mu m$</th>
<th>$d = 100 , \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean for $\phi_{\text{error}}$</td>
<td>-0.0001 $\pi$</td>
<td>-0.0004 $\pi$</td>
<td>-0.0007 $\pi$</td>
</tr>
<tr>
<td>Standard deviation for $\phi_{\text{error}}$</td>
<td>0.020 $\pi$</td>
<td>0.048 $\pi$</td>
<td>0.093 $\pi$</td>
</tr>
</tbody>
</table>

To minimize phase errors $\Delta \phi_{\text{error}}(\lambda)$, the waveguide spacing, $d$, needs to be small; however, reducing $d$ will increase thermal crosstalk from one phase arm to the other, which in turns reduce the efficiency of phase tuning. Heat transport simulations are needed to obtain a small $d$ while having sufficiently small thermal crosstalk.

7.4 Summary

In this chapter, we have presented methodologies and mathematical models that enable layout-dependent yield prediction for silicon photonics integrated circuits. Our approach models spatially-correlated manufacturing variations as virtual wafers and assigns each component’s physical variations based on its layout coordinates so that circuit simulations can capture layout-dependent, correlated variations. Using the proposed yield prediction method, we have analyzed the performance variations of several MZI switch designs.
Chapter 8

Conclusion and Future Work

8.1 Conclusion

This thesis have developed and demonstrated novel SOI components for high-performance silicon photonic switches, and have investigated manufacturing variability issues associated with the switch designs. Each chapter discusses one significant aspect towards high-performance switch designs. Major contributions of this research includes:

• Design and demonstration of a high-performance, TE\(_0\) mode, broadband 3-dB coupler. Our demonstrated 3-dB coupler has an operation bandwidth of 100 nm, with coupling imbalance of less than 4.7%. The demonstrated device is a fundamental building block for broadband switching.

• Demonstration of state-of-the-art low-power thermo-optic switches, with power consumption of down to 50 \(\mu\)W/\(\pi\). Our results is almost 10\(\times\) lower than the power consumption of any thermo-optic switch in literature. The ultra-low power switching is realized by adopting both thermal isolation structures and densely folded waveguides in the phase shifter designs.

• First realization of a tri-state switch based on a novel BNMZI structure. As compared with regular dual-state (cross/bar) MZI switches, the proposed tri-state switch has great advantages in \(N \times N\) switch applications. As a switching element, the tri-state switch can operate at the cross state and the bar state for signal switching, as well as at the blocking state for crosstalk suppression.
8.1. Conclusion

- First efficient solution to the long-existing crosstalk issues of high-speed switches. MZI switches using carrier injection phase tuning can perform in high-speed but have large switching crosstalk due to the imbalanced absorption loss in the carrier injection phase tuning. Our proposed carrier injection BNMZI switch has a balanced phase tuning scheme, and therefore can have both high-speed and crosstalk-free performance.

- Design and demonstration of a high-performance PBS, which has a 20 dB modal isolations for the TE$_0$ and TM$_0$ modes and a 120 nm operation bandwidth. As compared to many PBSs demonstrated by other research groups, our device has a wider operation bandwidth. The demonstrated broadband PBS can be used for polarization control for silicon photonic switches.

- Investigation on silicon photonics manufacturing variations:
  
  (a) We have demonstrated a ring resonator based method to characterize photonics manufacturing variations. Our method has a sub-nanometer characterization accuracy, and has simpler test structure and testing approach as compared with other demonstrated methods.

  (b) We have developed a novel yield prediction method for PICs, which is the first approach in silicon photonics able to take into account layout-dependent, correlated manufacturing variations. Before our report, Monte Carlo yield analysis for photonics has no correlation constrains in its parameter models, and therefore can not truly reflect the impacts of manufacturing variations.

The components and design methodologies developed in this thesis have both benefits and limitations. Table 8.1 compares the performance of our demonstrated broadband 3-dB coupler with several representative 3-dB couplers [43, 44, 48, 106] that were demonstrated on the same 220 nm SOI platform. According to the comparison, our coupler exhibits best performance in terms of balanced coupling, and is competitive in feature size and operation bandwidth. In terms of fabrication requirements, our coupler and the
8.1. Conclusion

adiabatic coupler demonstrated in [43] are both compatible with CMOS fabrication processes; while other devices [44, 48, 106] require high-resolution electron beam lithography process due to the small features in their waveguide structures. However, according to the corner analysis results presented in Fig. 2.6, the performance of our coupler is sensitive to fabrication variations. Our broadband 3-dB coupler design can be optimized to improve its tolerance to fabrication, which is discussed in Section 8.2.

Table 8.2 summarizes the performance of SOI thermo-optic switches [24–26, 33, 37–40, 55–60, 107] that were demonstrated in recent years. According to the results, our demonstrated switches have state-of-the-art low power consumption, but at the expense of a larger insertion loss. In this research, we focused on investigating the contributions of thermal isolation structures and folded waveguide designs to the reduction of switching power. For practical applications, our ultra-low power phase shifter designs can be optimized to achieve low loss performance, e.g., by reducing the number of folded waveguides.

Table 8.3 compares our demonstrated PBS with several representative, high-performance PBSs demonstrated on SOI platforms. According to the results, our device has superior broadband performance but its device footprint is at a disadvantage.

The yield prediction method presented in Ch. 7 does not take into account the correlated variations within devices. For devices having large footprints, such an effect should be considered.

**Table 8.1:** Comparisons of high-performance 3-dB couplers demonstrated on the 220 nm SOI platform.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Device length (µm)</th>
<th>Bandwidth (nm)</th>
<th>Maximum imbalance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[48]</td>
<td>14</td>
<td>100</td>
<td>16.2</td>
</tr>
<tr>
<td>[43]</td>
<td>155</td>
<td>80</td>
<td>14.24</td>
</tr>
<tr>
<td>[106]</td>
<td>≈14</td>
<td>140</td>
<td>≈10</td>
</tr>
<tr>
<td>[44]</td>
<td>50</td>
<td>130</td>
<td>6.93</td>
</tr>
<tr>
<td>This report</td>
<td>48.55</td>
<td>100</td>
<td>4.7</td>
</tr>
</tbody>
</table>
8.1. Conclusion

Table 8.2: Summary of SOI based thermo-optic switches that were experimentally demonstrated in recent years.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Power consumption (mW/π)</th>
<th>Rise time (μs)</th>
<th>Insertion loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[24]</td>
<td>2003</td>
<td>50</td>
<td>3.5</td>
<td>32</td>
</tr>
<tr>
<td>[25]</td>
<td>2004</td>
<td>210</td>
<td>50</td>
<td>≈2</td>
</tr>
<tr>
<td>[107]</td>
<td>2004</td>
<td>6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>[38]</td>
<td>2005</td>
<td>120</td>
<td>120</td>
<td>≈3</td>
</tr>
<tr>
<td>[39]</td>
<td>2005</td>
<td>90</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>[37]</td>
<td>2007</td>
<td>78</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>[55]</td>
<td>2008</td>
<td>10.6</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>[59]</td>
<td>2008</td>
<td>0.6</td>
<td>3600</td>
<td>≈4.6</td>
</tr>
<tr>
<td>[56]</td>
<td>2009</td>
<td>6.5</td>
<td>14</td>
<td>≈6</td>
</tr>
<tr>
<td>[57]</td>
<td>2010</td>
<td>0.54</td>
<td>141</td>
<td>≈2.8</td>
</tr>
<tr>
<td>[26]</td>
<td>2010</td>
<td>40</td>
<td>30</td>
<td>≈4</td>
</tr>
<tr>
<td>[58]</td>
<td>2011</td>
<td>0.49</td>
<td>144</td>
<td>0.3</td>
</tr>
<tr>
<td>[60]</td>
<td>2012</td>
<td>0.4</td>
<td>1700</td>
<td>1.1</td>
</tr>
<tr>
<td>[33]</td>
<td>2013</td>
<td>12.7</td>
<td>2.4</td>
<td>≤2.5</td>
</tr>
<tr>
<td>[40]</td>
<td>2014</td>
<td>24.77</td>
<td>2.69</td>
<td>0.23</td>
</tr>
<tr>
<td>This report</td>
<td>2015</td>
<td>0.05</td>
<td>551</td>
<td>≤5.1</td>
</tr>
</tbody>
</table>

Table 8.3: Summary of representative, high-performance PBSs demonstrated on SOI platforms.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Insertion loss (dB)</th>
<th>Modal isolation (dB)</th>
<th>Bandwidth (nm)</th>
<th>Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[108]</td>
<td>&lt;1</td>
<td>17</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>[109]</td>
<td>1</td>
<td>20</td>
<td>29</td>
<td>27.5</td>
</tr>
<tr>
<td>[110]</td>
<td>&lt;1</td>
<td>20</td>
<td>57</td>
<td>15</td>
</tr>
<tr>
<td>[111]</td>
<td>1</td>
<td>20</td>
<td>60</td>
<td>22.5</td>
</tr>
<tr>
<td>[112]</td>
<td>0.35</td>
<td>20</td>
<td>135</td>
<td>20</td>
</tr>
<tr>
<td>This report</td>
<td>&lt;0.5</td>
<td>20</td>
<td>120</td>
<td>97.4</td>
</tr>
</tbody>
</table>
8.2 Future Work

With the accomplished works in this dissertation, suggested future work includes:

- Experimental demonstrations of the proposed BNMZI tri-state switch.

- Developing low loss switches. Insertion loss is a challenge for large-scale silicon photonic switch matrices. For example, a demonstrated $32 \times 32$ switch has on-chip insertion loss of 23 dB to 28 dB over the optical C-band [30], and as a result, in practical applications optical amplifiers will be required to compensate the insertion loss, which bring both cost and power penalties. The insertion loss of components (such as 2×2 couplers, optical phase shifters, routing waveguides, and waveguide crossings) need to be reduced in order to avoid the requirement of amplifiers. In this thesis, our research has only focused on silicon photonics switches operating at the TE$_0$ mode. Alternatively, it is possible to design switches operating at the TM$_0$ mode, which have lower insertion loss due to the mode field having a lower overlap with waveguide sidewall roughness. Besides, TM$_0$ mode broadband 3-dB couplers could be designed shorter than TE$_0$ mode couplers, due to the fact that the TM$_0$ mode has a stronger coupling strength; as a result, TM$_0$ mode switches could be more compact in footprints than TE$_0$ mode switches.

- A more thorough study on 2×2 broadband coupler designs. The design approach for the broadband 3-dB coupler presented in Section 2.1 can be applied to design broadband couplers having other power splitting ratios (such as 10%/90%) or operating at other waveguide modes (such as TE$_1$ mode). In addition, using multiple coupling segments and phase shifter segments to design broadband couplers can potentially improve the devices’ tolerance to fabrication, which is well worth of investigation.

- Improving the component models of the proposed yield prediction
method, to include the effects of intra-device correlated variations. For example, the broadband 3-dB coupler design presented in Ch. 2 can be decomposed into three sub-components (two DCs and one phase shifter), with each having layout-dependent physical variations and being described by a S-parameter component model.

- Thermal stabilization for switches. MZI switches are susceptible to local temperature fluctuation, which may cause differential phase errors and therefore deteriorate switching ERs. Thermal stabilization for MZI switches requires local temperature monitoring and feedback control. Figure 8.1(a) shows a proposed solution. A temperature sensing diode (TSD), which is an integrated PN junction doped in silicon waveguide, can be used for on-chip temperature measurement, as the voltage across the diode is temperature-dependent according to the diode equation. The measured temperatures can be fed back for phase tuning so as to compensate the phase errors induced by differential temperature fluctuations. The integrated TSDs, as shown in Fig. 8.1(b), are connected in series for temperature measurement along waveguide phase arms, with each being doped in a 90-nm-high silicon slab layer. The p and n regions are lightly doped; while the p++ and n++ regions are heavily doped, and are intended for metal contacts. Feedback control of the stabilization can be performed using a computer, similar to the approach used for ring resonator temperature stabilization in [12].
8.2. Future Work

Figure 8.1: A proposed temperature stabilization solution for MZI switches; (a) Schematic for a MZI switch with feedback control; (b) schematic for series connected temperature sensing diodes (TSD).
Bibliography


Bibliography


Bibliography


Appendices

Appendix A

Publications

A.1 Patents


A.2 Journal Publications


A.3 Conference Proceedings


### A.3 Conference Proceedings


Appendix B

Derivation of the Transfer Functions of a MZI Switch

Figure B.1: Schematic for a typical Mach-Zehnder interferometer (MZI) circuit.

Here, we derive the output transfer functions of a MZI switch using the transfer matrix method. Considering a typical MZI circuit as shown in Fig. B.1, the relationship between the input and output electric fields of the MZI circuit can be expressed by:

\[
\begin{bmatrix}
E_{out1} \\
E_{out2}
\end{bmatrix}
= \begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
e^{-j\phi_1} & 0 \\
0 & e^{-j\phi_2}
\end{bmatrix}
\begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\begin{bmatrix}
E_{in1} \\
E_{in2}
\end{bmatrix}
\]

(B.1)

where \( E_{in1} \) and \( E_{in2} \) are the electric fields at the two inputs, and \( E_{out1} \) and \( E_{out2} \) represent the electric fields at the two outputs; \( t \) and \( \kappa \) are the through-coupling coefficient and cross-coupling coefficient, respectively, for each 2×2 coupler, and the 2×2 couplers in the MZI are assumed to be identical; \( \phi_1 \) and \( \phi_2 \) are the optical phase shifts of the two phase arms.

Assuming light is launched into the input 1 only, i.e., \( E_{in1} = 1 \) and \( E_{in2} = 0 \), the output transfer functions become:

\[
\begin{bmatrix}
E_{out1} \\
E_{out2}
\end{bmatrix}
= \begin{bmatrix}
t \cdot e^{-j\phi_1} & -\kappa \cdot e^{-j\phi_1} \\
-\kappa \cdot e^{-j\phi_2} & t \cdot e^{-j\phi_2}
\end{bmatrix}
\begin{bmatrix}
1 \\
0
\end{bmatrix}
\]

(B.2)

where \( E_{out1} \) and \( E_{out2} \) are the output electric fields of the MZI switch.
Appendix B. Derivation of the Transfer Functions of a MZI Switch

$E_{in2} = 0$, the output electric fields of the circuit are given by:

$$E_{out1} = t^2 e^{-j\phi_1} - \kappa^2 e^{-j\phi_2} \quad (B.2)$$

$$E_{out2} = -j\kappa t e^{-j\phi_1} - j\kappa t e^{-j\phi_2} \quad (B.3)$$

And accordingly, output transmissions are given by:

$$P_{out1} = |E_{out1}|^2 = (\kappa^4 + t^4 - 2\kappa^2 t^2 \cos(\Delta\phi)) \quad (B.4)$$

$$P_{out2} = |E_{out2}|^2 = 2\kappa^2 t^2 (1 + \cos(\Delta\phi)) \quad (B.5)$$

where $\Delta\phi = |\phi_1 - \phi_2|$ is the phase difference between the two waveguide arms. The input light to the MZI circuit can be selectively switched to either of the outputs depending on the phase difference, $\Delta\phi$.

For a $\Delta\phi$ of 0, Eqs. B.4 and B.5 can be simplified as:

$$P_{out1} = (\kappa^2 - t^2)^2 \quad (B.6)$$

$$P_{out2} = 4\kappa^2 t^2 \quad (B.7)$$

Due to the fact that the 2×2 couplers are designed for balanced coupling, i.e., $\kappa^2$ and $t^2$ are equal or close to 0.5, we have $P_{out2} > P_{out1}$, i.e., the switch operates in the cross switching state and routes the input light to the output 2. In such a state, we define the switching ER as:

$$ER_{cross} = 10 \log_{10}(\frac{P_{out2}}{P_{out1}}) = 10 \log_{10}(\frac{4\kappa^2 t^2}{(\kappa^2 - t^2)^2}) \quad (B.8)$$

As it is shown that the cross state ER is dependent to the coupling ratios, $\kappa^2$ and $t^2$, of the 2×2 couplers in the MZI circuit.

For a $\Delta\phi$ of $\pi$, Eqs. B.4 and B.5 can be simplified as:

$$P_{out1} = (\kappa^2 + t^2)^2 \quad (B.9)$$

$$P_{out2} = 0 \quad (B.10)$$

In this case, the switch operates in the bar state, which routes the input
Appendix B. Derivation of the Transfer Functions of a MZI Switch

light to the output 1. We define the switching ER at the bar state as:

\[ ER_{\text{bar}} = 10 \log_{10}(\frac{P_{\text{out1}}}{P_{\text{out2}}}) = 10 \log_{10}(\frac{(\kappa^2 + t^2)^2}{0}) = \infty \]  
(B.11)

As we can see that the bar state ER is infinite and is independent to the coupling ratios, \( \kappa^2 \) and \( t^2 \), of the 2\( \times \)2 couplers in the MZI circuit. Note that the bar state results given in Eqs. B.9, B.10, and B.11 are based on the assumption that \( \Delta \phi \) has no wavelength-dependence. For a wavelength-dependent phase shift, \( \Delta \phi(\lambda) \), which has a \( \pi \) phase shift for the central wavelength, \( \lambda_0 \), we have:

\[ \Delta \phi(\lambda_0) = \pi = \frac{2\pi}{\lambda_0} \Delta n L \]  
(B.12)

where \( \Delta n \) is the change of waveguide refractive index required for the \( \pi \) phase shift for \( \lambda_0 \); \( L \) is waveguide length. Accordingly, \( \Delta \phi(\lambda) \) can be given by:

\[ \Delta \phi(\lambda) = \frac{2\pi}{\lambda} \Delta n L = \frac{\lambda_0}{\lambda} \pi \]  
(B.13)

where \( \lambda \) is operation wavelength. By substituting Eq. B.13 into Eqs. B.4 and B.5, wavelength-dependent performance at the bar state can be calculated. As \( \frac{\lambda_0}{\lambda} \) is close to 1 (considering a 100 nm wavelength span centred at 1550 nm), we obtain:

\[ P_{\text{out1}}(\lambda) \approx (\kappa^2 + t^2)^2 \]  
(B.14)
\[ P_{\text{out2}}(\lambda) \approx 0 \]  
(B.15)
\[ ER_{\text{bar}}(\lambda) = 10 \log_{10}(\frac{P_{\text{out1}}(\lambda)}{P_{\text{out2}}(\lambda)}) \approx \infty \]  
(B.16)

which indicates that the wavelength-dependent bar state ER is insensitive to \( \kappa^2 \) and \( t^2 \).
Appendix C

Derivation of Coupling Ratios Extractions for 2×2 Couplers

As per Appendix B, the responses of a MZI circuit are sensitive to the coupling ratios, $\kappa^2$ and $t^2$, of its 2×2 couplers. Conversely, the responses of a MZI circuit can be used to characterize the $\kappa^2$ and $t^2$ of 2×2 couplers.

For a MZI circuit with imbalanced phase arms, as illustrated in Fig. B.1, each output transmission will go through minima and maxima when sweeping the operation wavelength, due to the wavelength-dependent phase delay, $\Delta\phi(\lambda)$. Based on the output transmission functions given by Eqs. B.4 and B.5, we define interference extinction ratio (IER) for each output port, which is the difference on a logarithmic scale between minima and maxima transmissions, as given by:

$$ IER_{out1} = 10 \log_{10} \left( \frac{P_{out1,\text{max}}}{P_{out1,\text{min}}} \right) = 10 \log_{10} \left( \frac{(\kappa^2 + t^2)^2}{(\kappa^2 - t^2)^2} \right) \quad (C.1) $$

$$ IER_{out2} = 10 \log_{10} \left( \frac{P_{out2,\text{max}}}{P_{out2,\text{min}}} \right) = 10 \log_{10} \left( \frac{4\kappa^2t^2}{0} \right) = \infty \quad (C.2) $$

where $P_{out1,\text{max}}$ and $P_{out1,\text{min}}$ are maxima and minima transmissions at the output 1, respectively; $P_{out2,\text{max}}$ and $P_{out2,\text{min}}$ maxima and minima transmissions at the output 2, respectively. According to the results, $IER_{out1}$ is dependent to $\kappa^2$ and $t^2$, and therefore the spectral responses at output 1 can be used to characterize $\kappa^2$ and $t^2$; however, $IER_{out2}$ is independent to $\kappa^2$ and $t^2$, and hence the spectral responses at output 2 is invalid for
Appendix C. Derivation of Coupling Ratios Extractions for 2×2 Couplers

characterization.

Assuming the 2×2 couplers are lossless, i.e., $κ^2 + t^2 = 1$, based on Eq. C.1, the extracted coupling ratios are given by:

$$κ^2 = \frac{1}{2} \left( 1 \pm \frac{1}{\sqrt{10^{IEF_{out1}}} \sqrt{10}} \right) \quad (C.3)$$

$$t^2 = 1 - κ^2 \quad (C.4)$$