Design Proposal: Mach-Zehnder Interferometer

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Abstract: MZI devices were laid out and built. The simulated waveguide group index was compared to the test result of built devices. Process variability was also studied.

1. Introduction

The objective of the project is to design, fabricate, and then test MZIs (Mach-Zehnder interferometer) from which one can extract the waveguide group index. At the end, the test result of fabricated devices can be compared to simulations. MZI is a versatile device because it can measure a phase shift precisely, making it useful in applications such as an optical modulator in a high-speed optical network, a chemical and biochemical sensor, and a tool for classical experiments.

2. Theory

The MZIs designed have

1. A beam splitter: divides the incoming light into two separate, coherent beams of equal intensity
2. Two optical paths: have different lengths which result in a relative phase shift between the two beams
3. A beam combiner: combine the two beams to create constructive or destructive interference

In the MZI design, the beam splitter is a Y-branch waveguide, the two optical paths were two waveguides with two unequal lengths, and the beam combiner is another Y-branch waveguide.

The waveguide used in the design is a strip waveguide with 220nm height, and 500nm width. This waveguide geometry is chosen because it's what's provided by the foundry and also the maximum dimensions that support just one TE and one TM mode at 1550nm to avoid dispersion effect.

A Y-branch splitter will split the incoming light intensity 50%-50% between its two output ports. This means at each of the two output ports, electric field is 1/sqrt(2) of incoming electric field.

Given the imbalance MZI transfer function of

$$I_o/I_i = 1/2\ [1 + \cos(\beta \Delta L)]$$

where $\beta = 2\pi n/\lambda$ and ΔL is the path length difference between the two optical paths. In addition, the phase of a traveling wave is $\delta = \beta \Delta L$.

The FSR (free spectral range) is the difference between two adjacent peaks in a transmission vs. wavelength plot. This phase difference between the two adjacent peaks is just 2π because its where the next constructive interference therefore the peak occurs. Therefore,

$$\Delta\delta = 2\pi = \beta m\Delta L - \beta m{+}1\Delta L = \Delta\beta\Delta L$$

and so

$$\Delta\beta = 2\pi/\Delta L = \approx - d\beta/d\lambda * \Delta\lambda$$

Solving for $\Delta\lambda$, we get,

$$FSR = \Delta\lambda = \lambda^2/(\Delta L * ng)$$

where ng is the waveguide group index. It can be observed that FSR will decrease as ΔL increases[1].

3. Modelling and Simulation

3.1 Design Consideration

To design a MZI under the current process and measurement technologies, we have two constraints:

1. Grating coupler with a bandwidth limit of 50nm
2. Measurement laser with a smallest step size of 1pm

Since our grating coupler has a bandwidth of 50nm, we have to use it to find the ΔL range allowed. Assuming two oscillations within this 50nm range, then FSR is 25nm. Using equation below with λ=1550nm and assuming ng ~4.2, solving for the minimum ΔL,

$\Delta L = \lambda^2/(FSR * ng)$

The minimum ΔL is 22.9um, which sets the minimum ΔL.

The maximum path difference is limited by the 1pm laser step size. Assuming we want to have10 measurement points per oscillation, this means 10pm is the lower limit for FSR. Using the equation above again, the maximum ΔL is 57mm, which is very long and should not be a constraint in our case. For design and simulation purpose, six ΔLs larger than the required minimum of 22.9um were chosen: 25um, 30um, 35um, 40um, 45um, and 60um.

3.2 Waveguide Modelling

The 550nm wide and 220nm tall strip waveguide were simulated using Ansys Mode. The result is below.

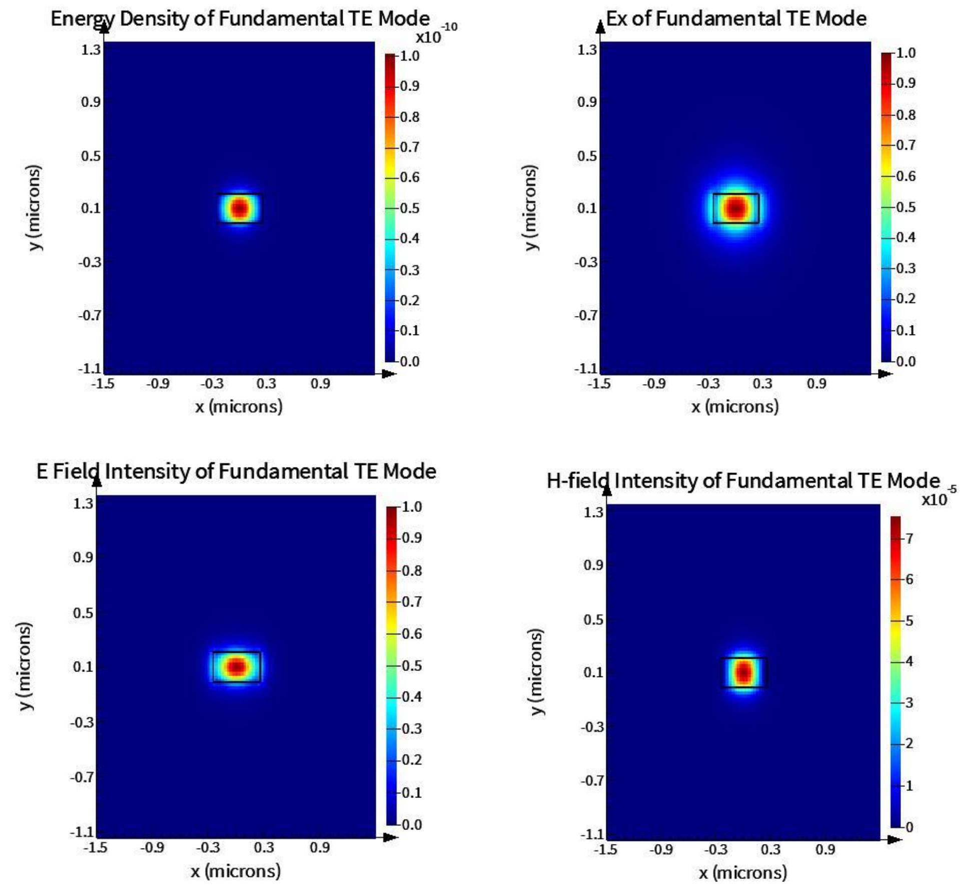


Figure 1. Mode profile for fundamental qusi-TE mode, 220nmx500nm waveguide at 1.5um wavelength

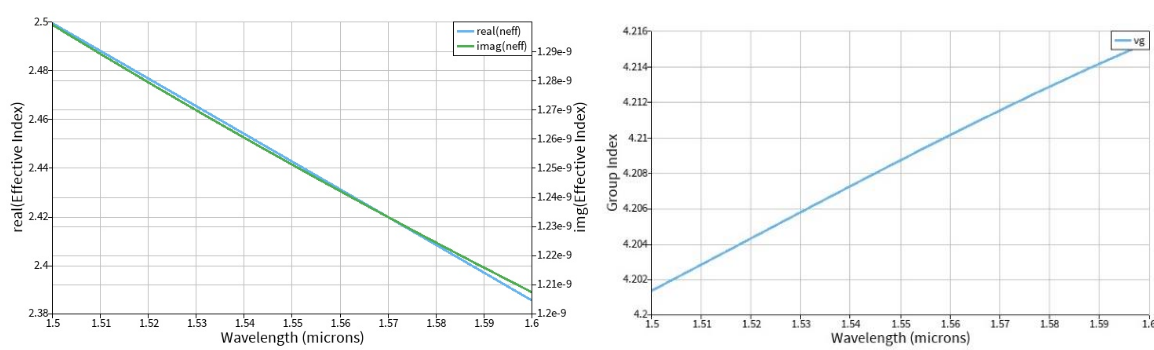


Figure 2. Effective and group index from Ansys Mode for 220nmx500nm waveguide

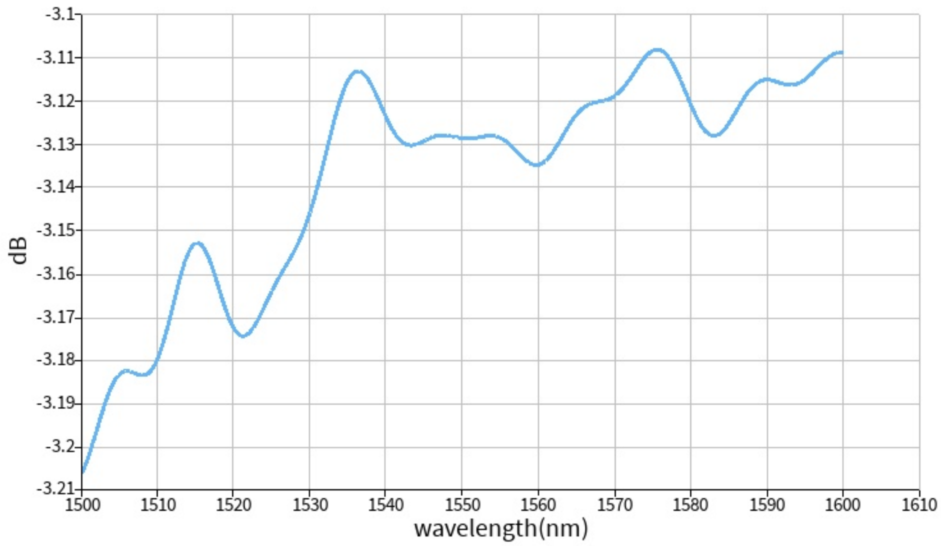


Figure 3. Y-Branch Transfer Function based on S-Parameters provided by the course, by Lumerical Interconnect

To set up MZI simulation in Ansys Interconnect, devices with ΔL=25um, 30um, 35um, 40um, 45um, 50um were laid out using Klayout. In addition, an insertion loss test die with two grating couplers connected by a waveguide were also included. The submitted layout is capture below.

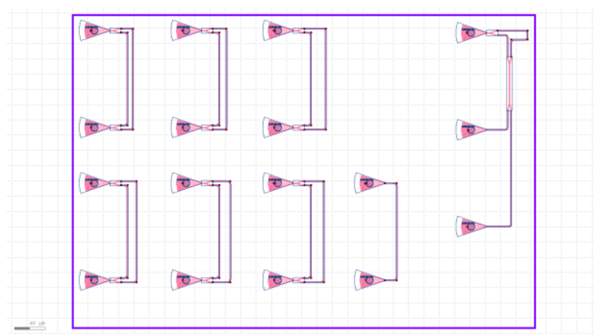


Figure 4 Klayout of submitted devices

The layout uses EBeam PKD as provided by the course and the devices were exported to Ansys Interconnect for simulation. The Interconnect schematic of one of the devices used is captured below as a reference.

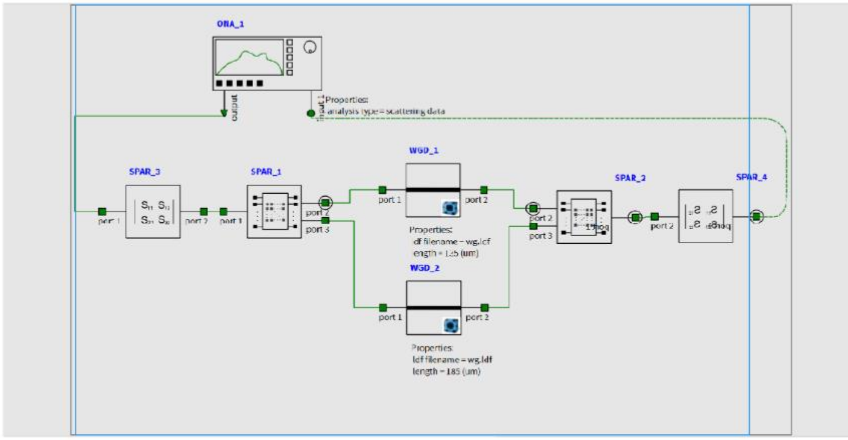
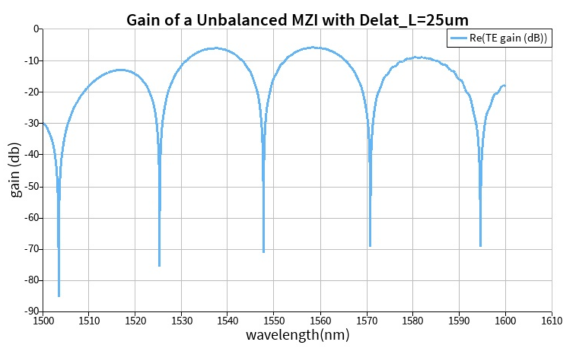
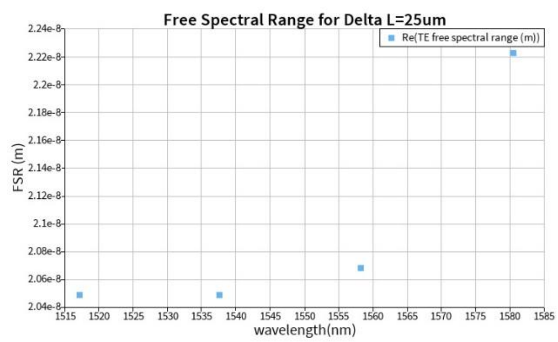
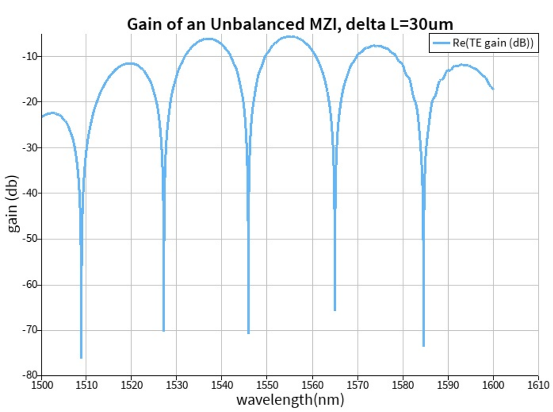


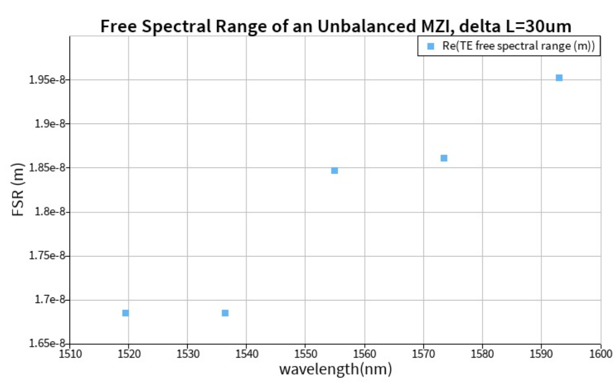
Figure5. Interconnect schematic of a MZI with ΔL=50um

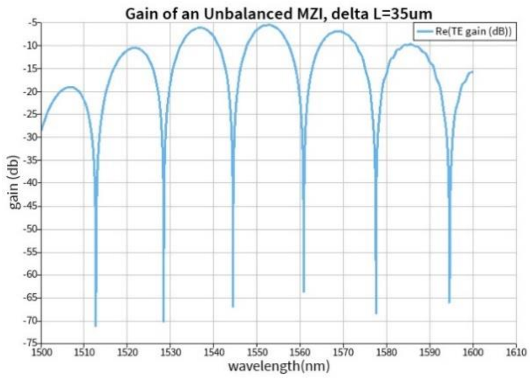
The simulation by Interconnect of the submitted devices with different ΔLs produce the transmission and FSR plots below.

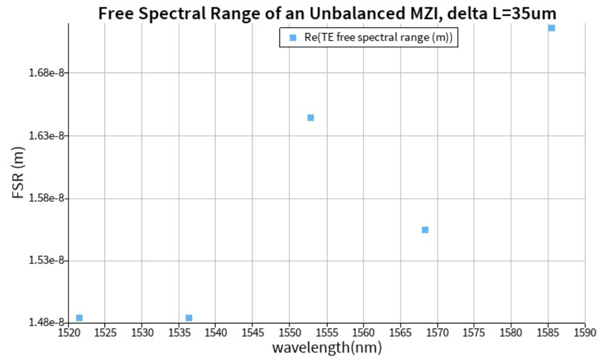


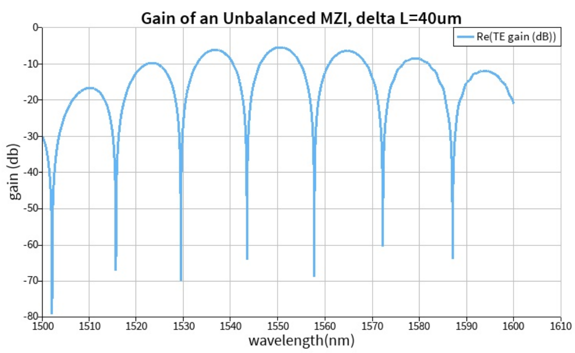


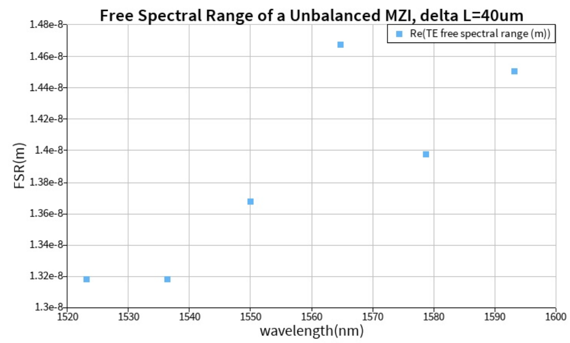


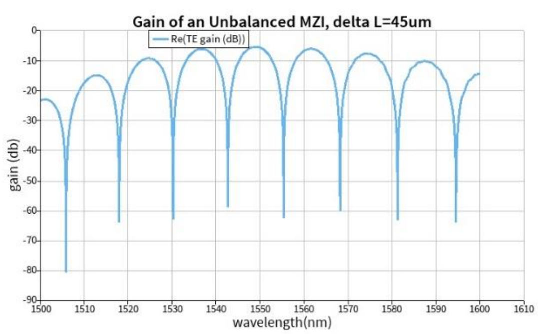


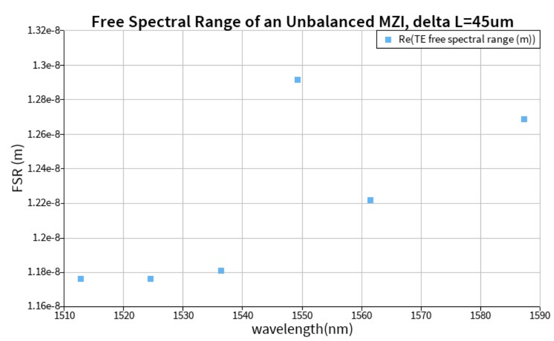

Gain of an Unbalanced MZI, delta L=35um
Re(TE gain (dB))
gain (db)
wavelength(nm)


Free Spectral Range of an Unbalanced MZI, delta L=35um
Re(TE free spectral range (m))
FSR (m)
wavelength(nm)


Gain of an Unbalanced MZI, delta L=40um
Re(TE gain (dB))
gain (db)
wavelength(nm)


Free Spectral Range of a Unbalanced MZI, delta L=40um
Re(TE free spectral range (m))
FSR(m)
wavelength(nm)


Gain of an Unbalanced MZI, delta L=45um
Re(TE gain (dB))
gain (db)
wavelength(nm)


Free Spectral Range of an Unbalanced MZI, delta L=45um
Re(TE free spectral range (m))
FSR (m)
wavelength(nm)

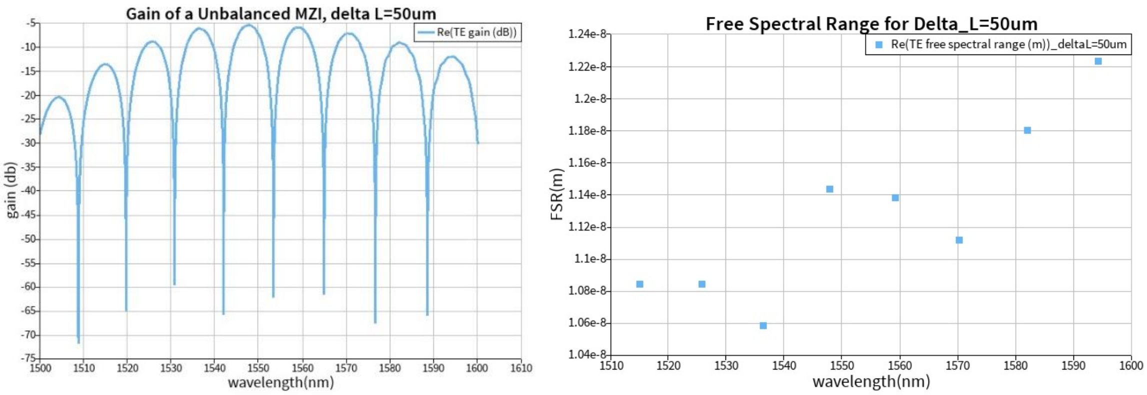


Figure 6. Transmission and FSR plots of MZI with ΔL=25um, 30um, 35um, 40um, 45um, 50um

The combined transmission plots can be seen below. It can be seen that the period of peaks for each ΔL is different and, therefore the FSRs, are different.

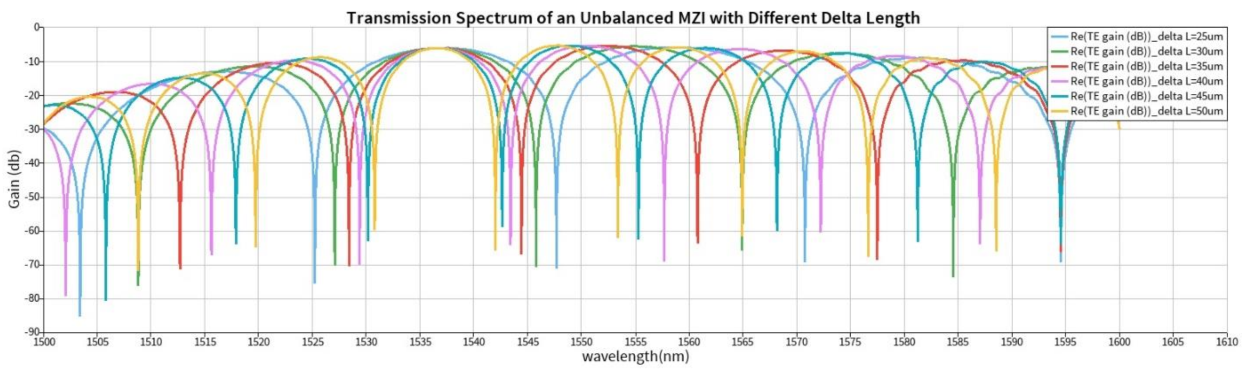


Figure 7. Transmission plot of MZI with ΔL=25um, 30um, 35um, 40um, 45um, 50um

Using the equation ng= λ^2/(ΔL*FSR), the group index can be calculated and is summarized in the table below.

waveguide Cross Section (nm)	Mode	λ (nm)	Delta L (um)	FSR (nm) - Interconnect	Ng from Interconnect
220x500	TE	1550	25	20.6	4.67
220x500	TE	1550	30	17.75	4.51
220x500	TE	1550	35	15.3	4.49
220x500	TE	1550	40	13.67	4.39
220x500	TE	1550	45	12.8	4.17
220x500	TE	1550	50	11.2	4.29

Table1. Group index from Interconnect simulation

In addition, a test design with just two grating couplers connected by waveguide is included to find out the loss from the input/output couplers themselves.

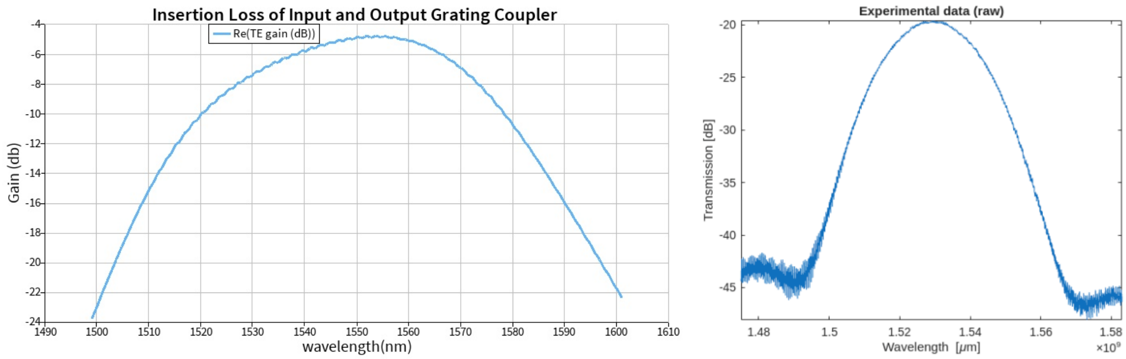


Figure 8. Transfer function of grating coupler test die a) simulation from Interconnect, b) test data from the fabricated devices

From the two plots, it can be observed that the insertion loss from the measured data, ~20dB, is much higher than the simulation result, ~5dB. A possible cause may be due to the test setup since the test setup loss is zero in the simulation. This data can be used to extract the group index of the waveguide without the impact of grating couplers.

4. Fabrication and Test

The devices were layout using Klayout and fabricated using the NanoSOI MPW fabrication process by Applied Nanotools Inc. (http://www.appliednt.com/nanosoi; Edmonton, Canada) which is based on direct-write 100 keV electron beam lithography technology. 20cm SOI wafers with a 220 nm device thickness and 2 μm buffer oxide were used as the base material for the fabrication[2]. The brief process steps are:

1. E-beam lithography to pattern the device layer
2. 220nm device layer etch
3. Silicon oxide deposition
4. Silicon oxide lithography
5. Silicon oxide etch

To characterize the devices, a custom-built automated test setup[2][3] with automated control software written in Python was used[4]. An Agilent 81600B tunable laser was used as the input source and Agilent 81635A optical power sensors as the output detectors. The wavelength was swept from 1500 to 1600 nm in 10 pm steps. A polarization maintaining (PM) fibre was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers[5]. A polarization maintaining fibre array was used to couple light in/out of the chip[6].

Process variation is likely the biggest contributor to variations in a same device performance on the same wafer as well as from wafer to wafer. Below is a Monte Carlo simulation on the same device for a 5 wafers run assuming 5 devices per wafer.

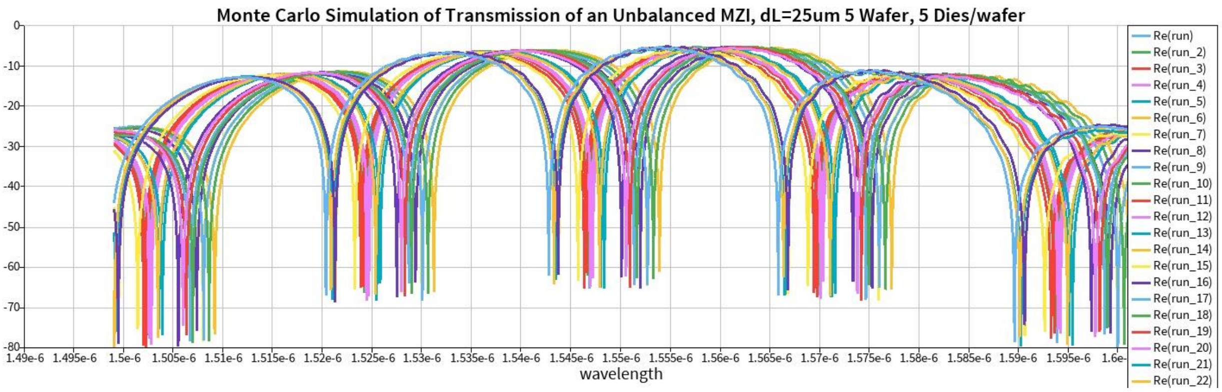


Figure 9. Monte Carlo simulation on transfer function the MZI with ΔL=25um for 5 wafers and 5 device/wafer

It can be observed that even with the same device, the shift in the peak and FSR can be expected across a wafer and from wafer to wafer.

5. Experimental Data

The MZI test data of fabricated devices were collected using automated test setup described above. The transfer functions of two ΔLs which represent the two extremes of ΔLs (25um and 50um) are shown below.

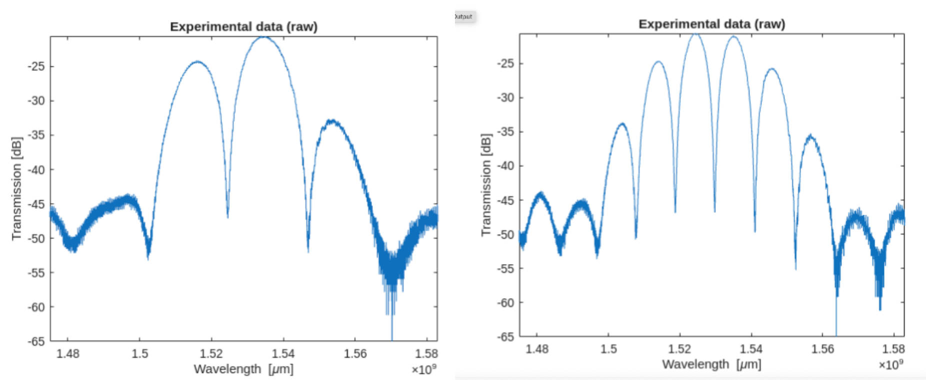


Figure 10. MZI Transfer function from measurement a)ΔL=25um , b) ΔL=50um

It can be observed that with a larger ΔL, there will be more peaks and easier to estimate the FSR. The MZI with ΔL=25um does not have enough peaks to make a good measurement of FSR. Thereore, MZI with ΔL=50um will be used in the subsequent analysis.

6. Analysis

The analysis will be based on the measurement data of MZI with ΔL=50um since it is the device with most peaks and therefore the extracted group index near 1550nm is more accurate. First the plot is compensated with loss from grating coupler. See the plots below.

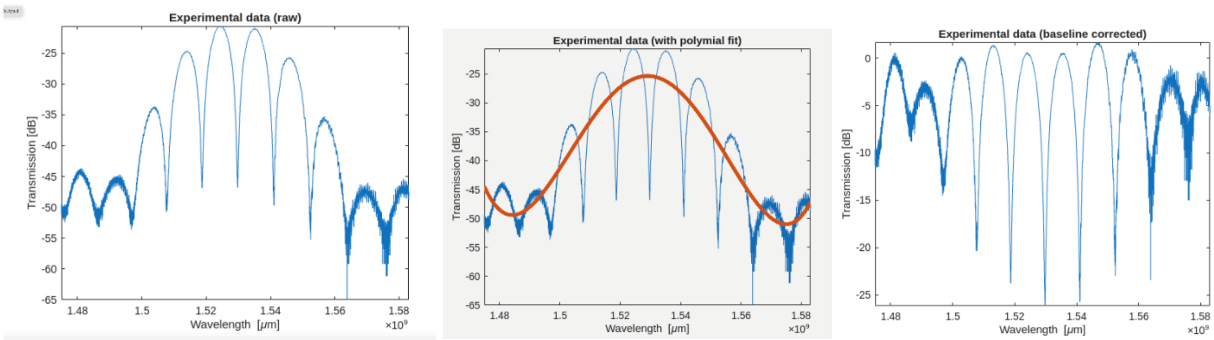


Figure 11. Transfer function lots of MZI test data with deltaL=50um a) raw data without compensation, b) grating coupler compensation plot, c) compensated with loss from grating coupler

From the compensated transfer plot, the FSR is ~11.77nm and using the equation ng=λ^2/(ΔL*FSR), with ΔL=50um, λ=1.55um, and FSR=11.77nm ,the group index is 4.08. From Table1 earlier, the group index from Interconnect simulation for MZI ΔL=50um is 4.29.

Since the variability in process will contribute to the different between simulation and measurement data. To analyze process variation impact, corner cases for waveguide width between 470nm and 510nm and height between 215.3nm and 223.1nm were analyzed. Below are the group indexes for the corner cases.

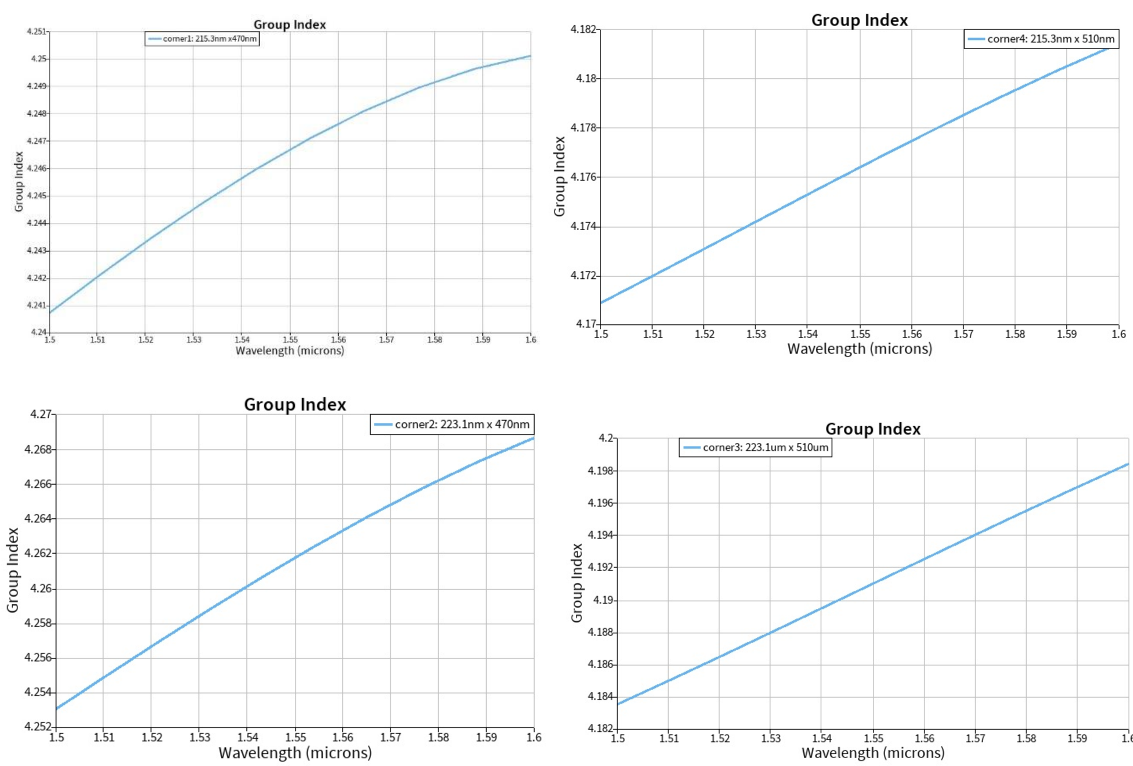


Figure 12. Group index of corner cases for 220nmx500nm waveguide a) 215.3nm x 470nm, b) 215.3nm x 510nm, c) 223.1nm x 470nm, d) 223.2nm x 510nm

corner case waveguide Cross Section (nm)	Mode	λ (nm)	Delta L (um)	Ng from Interconnect
215.3x470	TE	1550	50	4.247
215.3x510	TE	1550	50	4.177
223.1x470	TE	1550	50	4.262
223.1x510	TE	1550	50	4.191
nominal 220x500	TE	1550	50	4.209

Table 2. Summary of corner case group index

It can be observed that the group index can vary between 4.262 (223.1nm x 470nm) and 4.177 (215.3nm x 510nm). Since the measured group index 4.08 is even lower than the lowest simulated corner case of 4.177, it is very likely that the dimension of the waveguide is outside of the corner cases studies. Based on Table 2, in order to have a group index that is at or lower than 4.08, the width will need to be 565.0nm or higher if height is held at 215.3nm. If the height is held at 223.1nm, the width will need to be 572.7nm or higher.

7. Conclusion

MZI devices with different ΔLs were laid out, processed and measured. The measured group index was compared to the simulation. It was found that the measured group index, 4.08, is even lower than the lowest original simulated corner case, group index 4.177. Possible physical width dimensions that will result in the measured group index were proposed. In additions, to improve group index derivation, larger ΔLs than used in this project should be used in order to have more transmission peaks.

Acknowledgements

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The devices were fabricated by Cameron Horvath at Applied Nanotools, Inc. Mateo performed the measurements at The University of British Columbia. University of British Columbia. We acknowledge Lumerical Solutions, Inc., Mathworks, Mentor Graphics, Python, and KLayout for the design software.

References

[1] Lukas Chrostowski, Lectures notes from Fall 2025 Silicon Photonics Design, Fabrication and Data Analysis course on edX

[2] Lukas Chrostowski, Michael Hochberg. Chapter 12 in “Silicon Photonics Design: From Devices to Sytems”, Cambridge University Press, 2015

[3] http://mapleleafphotonics.com, Maple Leaf Photonics, Seattle WA, USA

[4] http://siepic.ubc.ca/proestation, using Python code developed by Michael Caverley.

[5] Yun Wang, Xu Wang, Jonas Flueckiger, Han Yun, Wei Shi, Richard Bojko, Nicolas A. F. Jaeger, Lukas Chrostowski, "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits", Optics Express Vol. 22, Issue 17, pp. 20652-20662 (2014) doi: 10.1364/OE.22.020652

[6] www.plcconnections.com, PLC Connections, Columbus OH, USA.