Design and analysis of a Mach-Zender interferometer (MZI) in integrated optics

Report by Aldo Camilo Martinez-Becerril for the course on Silicon Photonics imparted by Prof. Lukas Chrostowski and Mateo Branion-Calles.

1 General analysis of a MZI

First I report the analysis of a Mach Zender interferometer from a previosly designed and fabricated layout. Such a design corresponds to the file provided in the course. The model of a Mach-Zender interferometer (MZI from now on) is given by the following model:

$$f = 10\log_1 0\left(1/4\left|1+\exp\{-i2\pi n_{eff}/\lambda\Delta L - \alpha\Delta L/2\}^2\right|\right) + b, \tag{1}$$

where α is the waveguide loss, ΔL is the length mismatch within the MZI, b is the excess insertion loss and n_{eff} is the effective refractive index, which is given by the following expression:

$$n_{eff} = n_1 + n_2\left(\lambda - \lambda_0\right) + n_3\left(\lambda - \lambda_0\right)^2. \tag{2}$$

From which we define the group index $n_g = n_{eff} - \lambda\frac{dn_{eff}}{d\lambda} = n_1 - n_2\lambda_0$; and the group velocity dispersion $D = \alpha\frac{\lambda}{c}2n_3$.

The data analyzed is in the file LukasChrostowskiMZI1135Scan1. The optical path difference for such an interferometer is $\Delta L = 35\,\mu\text{m}$. The measured data and the corresponding fit to Eq. (1) is shown in Fig. 1. The obtained parameters are listed in Table. 1.

Parameter	Value
FSR	$2.1\,\mu\text{m}$
$\bar{n}_g$	0.84
r^2	0.75

Table 1: Obtained parameters, namely free spectral range (FSR), average index ($\bar{n}_g$) and correlation coefficient (r^2) for the fit, for a MZI with a path length mismatch equal to $\Delta L = 35\,\mu\text{m}$.

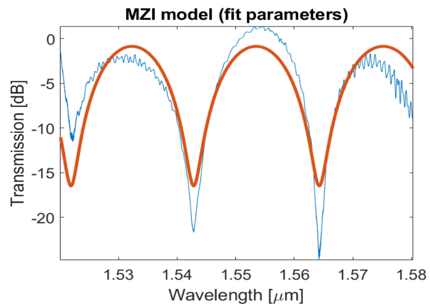

Figure 1: Measured amplitude upon transmission by a MZI with a path length difference equal to $\Delta L = 35\,\mu\mathrm{m}$. In blue I show the amplitude data after a baseline correction. The fit according to the model from Eq. (1) is shown in red. The fit was performed using the autocorrelation approach described during the lectures of the course.

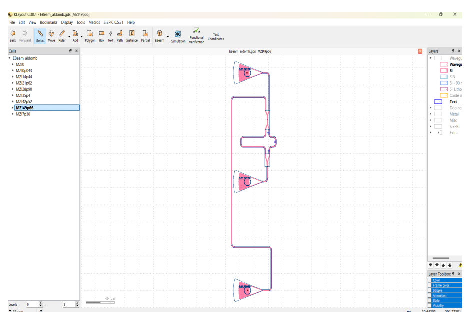

Figure 2: Layout of a MZI with a path length difference equal to $\Delta L = 49.66\,\mu\mathrm{m}$.

2 Own design of a MZI

2.1 Design

I designed a MZI, which is shown in Fig. 2. The design was performed in the klayout software utilizing the Siepic photonics libraries. The design is meant for TE light around 1550 nm and it consists of three Bragg gratings (coupling light into the chip is done at the second grating). A Y-branch is used to obtain two paths for the MZI. A directional coupler is then used for interfering the two paths. A detector is placed at the first and third Bragg gratings to measure the transmission of the MZI. Between the Y-branch and directional coupler, I opted to start off from a symmetric structure (similar to a trombone used in free-space photonics setups) of two identical waveguides. I then enlarged one of the waveguides achieving a length mismatch equal to $\Delta L = 49.66\,\mu\mathrm{m}$.

2.2 Fabrication

The photonic devices were 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. Silicon-on-insulator wafers of 200 mm diameter, 220 nm device thickness and 2 µm buffer oxide thickness are used as the base material for the fabrication. The wafer was pre-diced into square substrates with dimensions of 25x25 mm, and lines were scribed into the substrate backsides to facilitate easy separation into smaller chips once fabrication was complete. After an initial wafer clean using piranha solution (3:1 H2SO4:H2O2) for 15 minutes and water/IPA rinse, hydrogen silsesquioxane (HSQ) resist was spin-coated onto the substrate and heated to evaporate the solvent. The photonic devices were patterned using a JEOL JBX-8100FS electron beam instrument at The University of British Columbia. The exposure dosage of the design was corrected for proximity effects that result from the backscatter of electrons from exposure of nearby features. Shape writing order was optimized for efficient patterning and minimal beam drift. After the e-beam exposure and subsequent development with a tetramethylammonium sulfate (TMAH) solution, the devices were inspected optically for residues and/or defects. The chips were then mounted on a 4" handle wafer and underwent an anisotropic ICP-RIE etch process using chlorine after qualification of the etch rate. The resist was removed from the surface of the devices using a 10:1 buffer oxide wet etch, and the devices were inspected using a scanning electron microscope (SEM) to verify patterning and etch quality. A 2.2 µm oxide cladding was deposited using a plasma-enhanced chemical vapour deposition (PECVD) process based on tetraethyl orthosilicate (TEOS) at 300ºC. Reflectrometry measurements were performed throughout the process to verify the device layer, buffer oxide and cladding thicknesses before delivery.

2.3 Measurements

To characterize the devices, a custom-built automated test setup [2, 6] with automated control software written in Python was used [3]. 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 [4]. A 90º rotation was used to inject light into the TM grating couplers [4]. A polarization maintaining fibre array was used to couple light in/out of the chip [5].

2.4 Analysis

I now describe the analysis performed on the measured data of the designed device. Namely the MZI with a path imbalance equal to $\Delta L = 49.66\,\mu\text{m}$, which is shown in Fig. 2. The raw measured data of the transmission through the MZI is shown in Fig. 3.

I proceed to perform a fitting to Eq. (1) for this data. I used the advanced fitting routine based on autocorrelation. Such a method does identify the peaks (shown in Fig. 4) in the transmission spectrum. However it fails to provide a good set of initial conditions. Leading to a bad fitting result (Fig. 5). This shows performing a fitting to the MZI data is a challenging problem, which needs specific tuning of the model and initial conditions even when using a robust algorithm. I also tried using the advanced algorithm based on the *peaks* from MATLAB. The results were similar, i.e., the algorithm failed to perform a proper fit.

However, the correction (to account for the Bragg grating bandwidth) realized in the measured data shows a correspondence to the design data. Namely, the period of the oscillations is similar. However the low transmission wavelengths (resonances of the system) are not as sharp as the design. This is shown in Fig. 6. This suggests there is a good set of parameters for this fitting. I found out the main problem for the fit was the shift between the design and measured peaks. Manually corrected for such a shift by substracting 7.55 nm to the wavelength values. This is done to demonstrate a good fit is possible. With the shift in wavelength, I ran a scan of the initial parameters to find such a fit (using the poly fit MATLAB script provided in the course). The varying parameters are the values of n_1, n_2 and n_3 from Eq. (2). I set $n_3 = 0$, and scanned the looped over the other two parameters. The best initial conditions (Fig. 7) I found were $n_1 = 2$ and $n_2 = 2.3$. Fig. 7 shows the final fit obtained with an r^2 value of 0.86. The group index was determined to be -4.22.

I originally designed a few other interferometers. My goal is to find the one with zero path mismatch. This device could work as a beam combiner based on the constructive interference at a MZI. The fitting challenge I found took most of my time, however the analysis of the rest of the data remains to be done.

In summary, I presented the analysis of a general Mach-Zender interferometer. Using provided data, I showed results of such analysis and obtained physical parameters of the device (group index, free spectral range, bandwidth, transmission). Then I described an own design of a MZI; described their fabrication and experimental characterization. The experimental data was analyzed. In particular, I identified the need to match the peaks and valleys of the design and experimental data. Finally a good fit was performed and the group index of the device was determined.

For further details on the processes described in this report, the interested reader may consult the references [1–6].

3 Acknowledgements

I acknowledge the edX UBCx Phot1x Silicon Photonics Design, Fabrication and Data Analysis course, which is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Silicon Electronic-Photonic Inte-

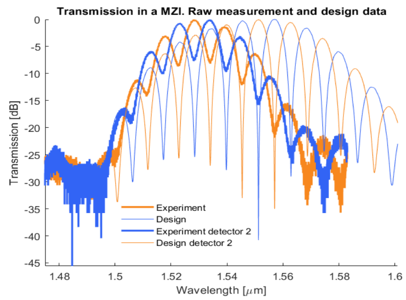

Figure 3: Raw transmission data (thick lines) and design data (lighter lines) for the MZI from Fig. 2 using one detector at each output port of the MZI. There is a shift of 0.04 μm in the best coupling wavelength probably due to manufacturing variability.

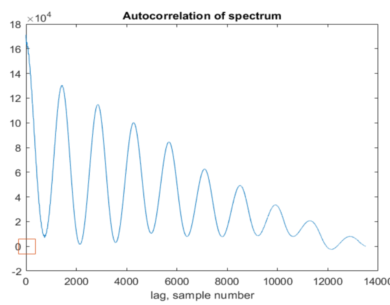

Figure 4: Autocorrelation analysis for the data of the MZI from the MZI from Fig. 2.

grated Circuits (SiEPIC) Program. The devices were fabricated by Richard Bojko at the University of Washington Washington Nanofabrication Facility, part of the National Science Foundation's National Nanotechnology Infrastructure Network (NNIN), and Cameron Horvath at Applied Nanotools, Inc. Omid Esmaeeli performed the measurements at The University of British Columbia. We acknowledge Lumerical Solutions, Inc., Mathworks, Mentor Graphics, Python, and KLayout for the design software.

References

[1] Richard J Bojko, Jing Li, Li He, Tom Baehr-Jones, Michael Hochberg, and Yukinori Aida. Electron beam lithography writing strategies for low loss, high confinement silicon optical waveguides. *Journal of Vacuum Science & Technology B*, 29(6), 2011.

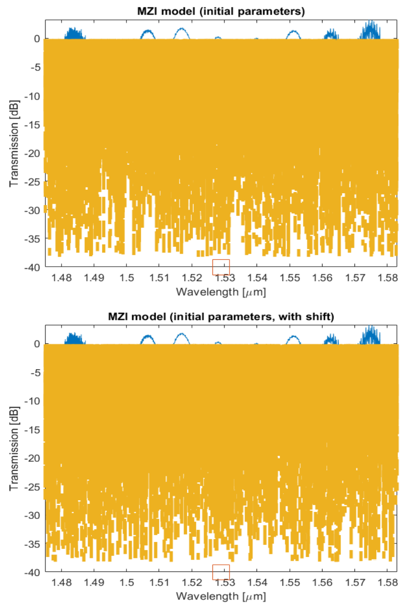

Figure 5: Initial conditions and final fitting of the MZI data (shown in Fig. 2) using the autocorrelation algorithm. Such amethod fails to set a good set of initial conditions, and thus a final fit.

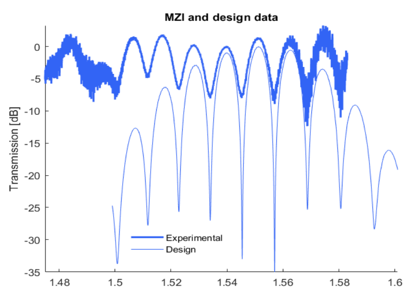

Figure 6: Calibrated data of the MZI and design data. The calibration does help to visualize a correspondence to the design data.

[2] Lukas Chrostowski and Michael Hochberg. *Silicon photonics design: from devices to systems*. Cambridge University Press, 2015.

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

[4] Yun Wang, Xu Wang, Jonas Flueckiger, Han Yun, Wei Shi, Richard Bojko,

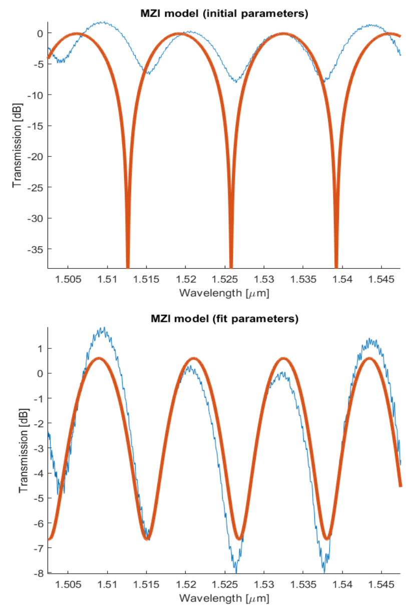

Figure 7: Manual initial conditions and obtained fit for the MZI in Fig. 2. Crucial to performing such a fit is the matching of the peaks in wavelength.

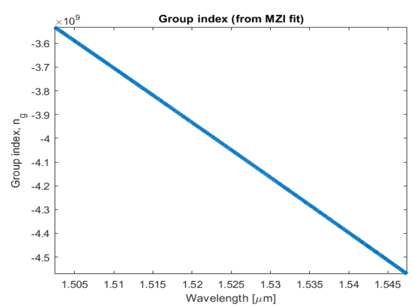

Figure 8: Plot of the refractive index for the MZI from Fig. 2. The group index is obtained as a result.

Nicolas AF Jaeger, and Lukas Chrostowski. Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits. *Optics express*, 22(17):20652–20662, 2014.

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

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