Modelling, Design, Testing and Analysis of a Mach-Zender Interferometer

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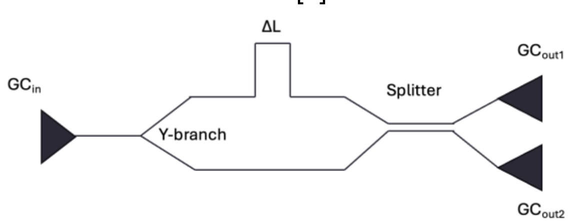
I. INTRODUCTION

Silicon photonics is a rapidly growing technology that leverages traditional CMOS semiconductor manufacturing to develop integrated optical circuits [2]. Several components serve as a building block to design of optical circuits with MZI being a key component. In this report, we model, design, test and analyze the circuit performance of a fabricated imbalanced MZI by varying the path lengths for both Quasi-TE and Quasi-TM modes by utilizing a mix of adiabatic splitters and broad-band directional couplers and compare post fabrication results with simulation results.

II. THEORY

Mach-Zehnder Interferometer (MZI) is one of the most versatile components in Silicon photonics that is used to build switches, filters and modulators. It consists of beam splitters (Y-branches) that splits light and recombine light. These splitters are connected to waveguides that have path length differences creating sinusoidal oscillations in the optical spectrum [3], making it easy to recognize constructive and destructive interference [1].



The optical transfer function of MZI is:

$$\frac{I_o}{I_i} = \frac{1}{2}\left[1 + cos(\beta\,\Delta L)\right]$$

FSR (free spectral range) is defined as the spacing between two adjacent peaks which is mathematically described as:

$$FSR[m] = \frac{\lambda^2}{\Delta L n_g}$$

where $n_g = n - \lambda\frac{dn}{d\lambda}$

III. MODELLING AND SIMULATION

First, we simulate the mode profile for quasi-TE and quasi-TM for the defined Si strip waveguide dimensions tabulated below using Lumerical MODE Eigenmode solver [4]. The materials used are Silicon for core and Silicon dioxide for cladding. The best fit for effective index is obtained and set using Lorentz fit model for a wavelength range of 1200nm to 1800nm.

Parameter	Dimensions
Width	500nm
Thickness	220nm
Polarization	Quasi-TE, Quasi-TM

Table1. ***Silicon strip waveguide dimensions***

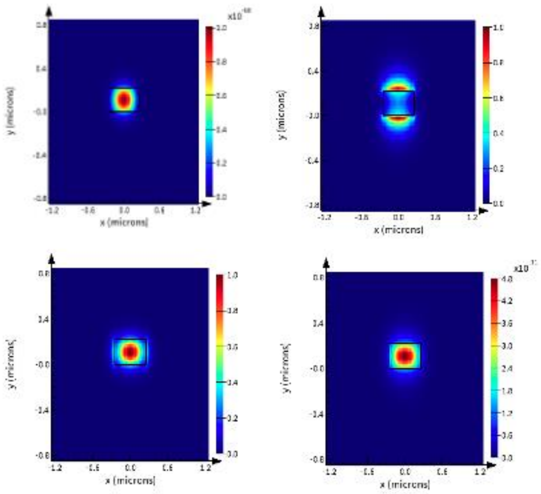


Figure1. Quasi-TE (left) and Quasi-TM (right) electric field intensity (top) and energy density (bottom) for 220nm thick 500nm wide waveguide

We use a Taylor expansion around the center wavelength to get a fitting model for effective index (N_{eff}).

$$n_{\mathrm{eff}}(\lambda) = n_1 + n_2\,(\lambda - \lambda_0) + n_3\,(\lambda - \lambda_0)^2$$

A simulated model from Lumerical MODE is eported to MATLAB and executed to get the compact model coefficients for the waveguide as shown below.

$$n_{\mathrm{eff}}(\lambda) = 2.444899 - 1.128185\,(\lambda - \lambda_0) - 0.042165\,(\lambda - \lambda_0)^2$$

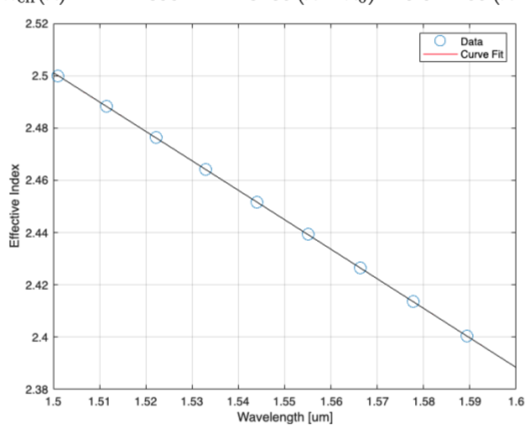


Figure2: TE1 mode Neff vs Wavelength [um]

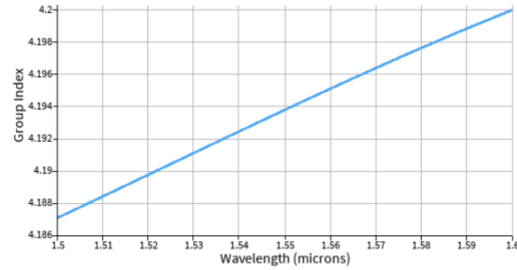


Figure3: TE1 mode Ng vs Wavelength [um]

For this experiment, we are using difference path lengths of the imbalanced MZI arms and expecting FSRs for the variations as listed below.

Waveguide dimensions (nm)	ΔL (um)	FSR (nm)(calculated)
500 x 220	25	TE:20.9, TM:27.16
500 x 220	50	TE:10.8, TM:13.5
500 x 220	75	TE: 7.78, TM:8.98

Table2: Path length differences and FSR

The following circuit was implemented using Lumerical INTERCONNECT. We have used grating couplers along with splitters and couplers to account for insertion and used an optical network analyzer to view results.

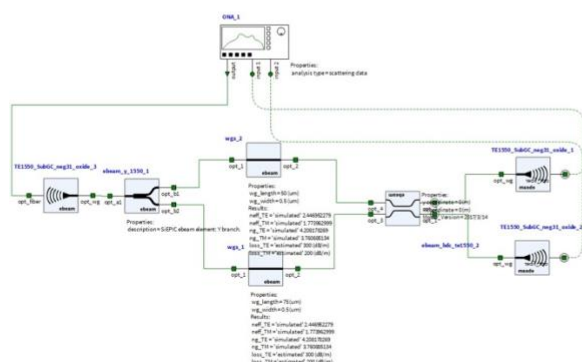


Figure4: Circuit of Mach-Zender Interferometer

The simulations based on the above Table for both quasi-TE and quasi-TM are shown below. We observed the sinusoidal oscillations to get denser as the path length difference is increased. FSR is inversely proportional to path length difference which has been shown in figure 7 and figure 10 below.

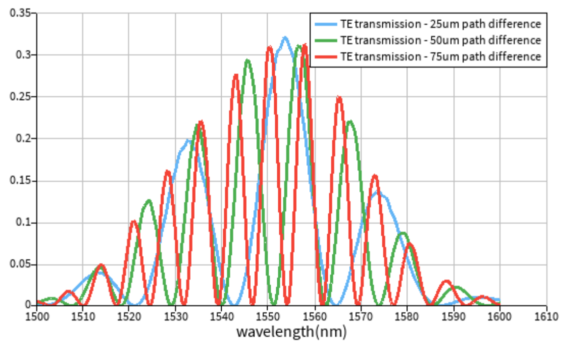


Figure5: TE transmission for different path lengths

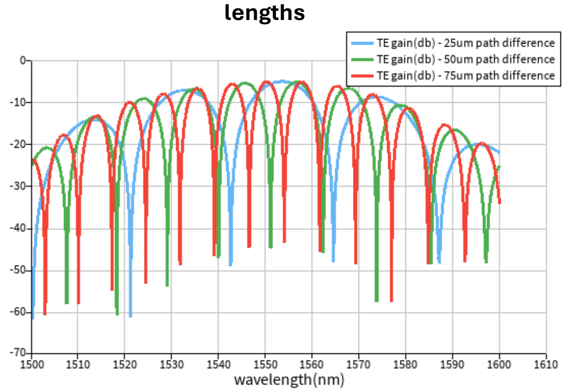


Figure6: TE gain in db for different path lengths

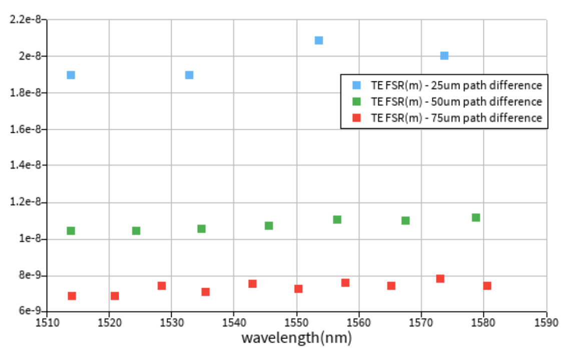


Figure7: TE FSR in meters for different path lengths

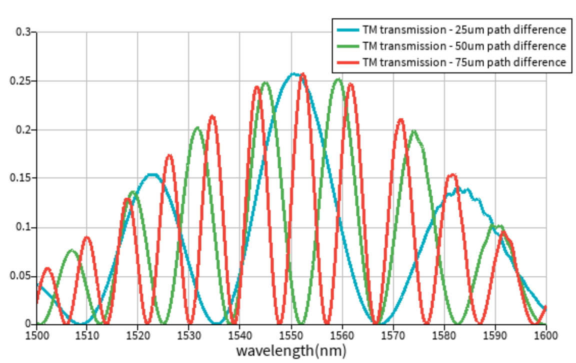


Figure8: TM transmission for different path lengths

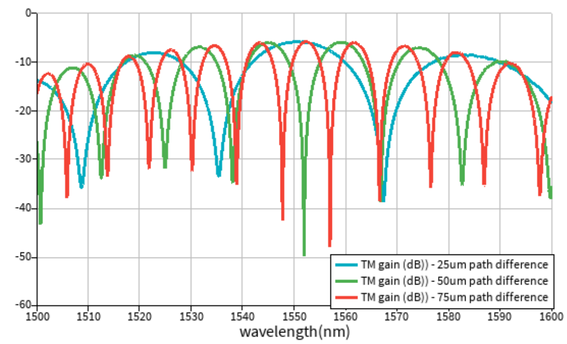


Figure9: TM gain in db for different path lengths

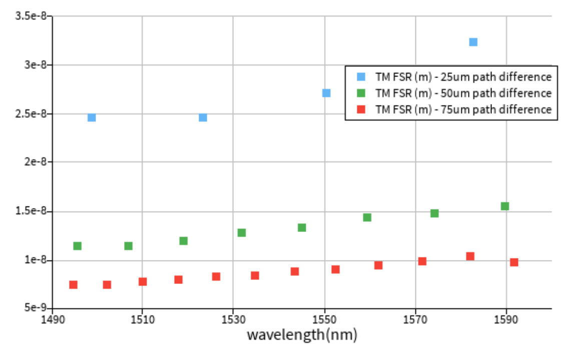


Figure10: TM FSR in meters for different path lengths

IV. FABRICATION, EXPERIMENTAL DATA AND ANALYSIS

The fabrication was performed at Applied nanotools using Electron beam lithography. The BOX (buffer oxide) thickness is 2um. The top cladding used a 2.2um SiO2 using PECVD (plasma enhanced chemical vapor deposition) process. The MZIs for both TE and TM configuration were all 500nm wide and 220nm thick. A corner analysis for group index and FSR estimation was done from a range of 470nm to 510nm wide Si waveguide and 215.3nm to 223.1nm thick waveguide.

Once the devices completed fabrication, automated measurements were done to obtain power spectra. Cycle time from tapeout to obtaining measurement results was approximately 5 weeks in total.

MATLAB was used for data analysis. The goal was to perform a fit of experimental data vs simulated data and extract group index and FSR (Free spectral range). Figure 11 and Figure 12 shows the power spectra for 75um path difference MZI for both TE and TM mode. The clipped wavelength range is from 1.54um to 1.57um. We can clearly see the peaks and minima match for both experimental and simulated spectra. The difference in power is due to effect of grating coupler losses included but this does not affect group index and FSR calculation.

Table 3 shows the group index and FSR differences between experiment and simulation.

ΔL (um)	FSR (nm) (Exp)	FSR (nm) (Sim)	Ng (Exp)	Ng (Sim)
75	TE: 7.62	TE: 7.57	4.2	4.22
75	TM:9	TM:8.98	3.56	3.55

Table2: FSR, Ng experiment vs simulation

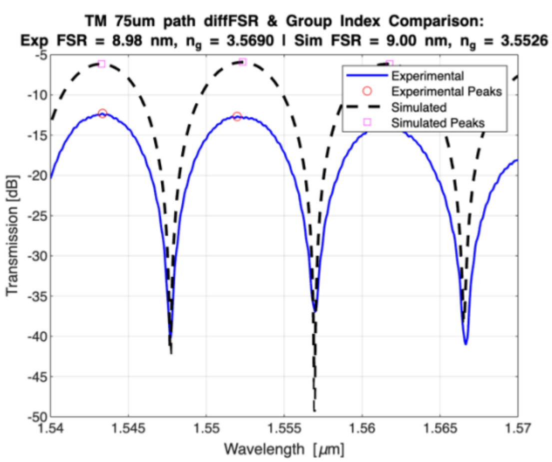


Figure11: TE 75um path difference power spectra, FSR and group index calculation

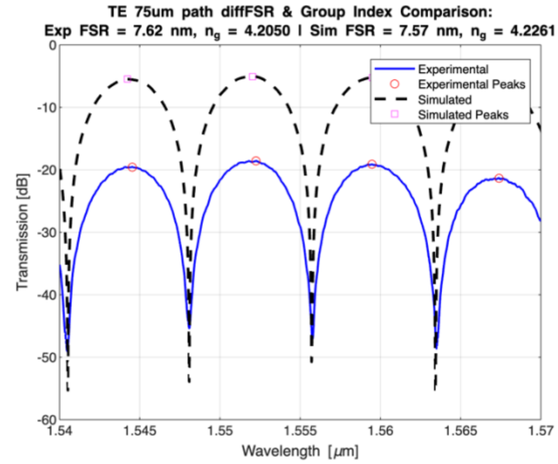


Figure11: TM 75um path difference power spectra, FSR and group index calculation

V. CONCLUSION

Overall, we studied and analyzed the MZI for both TE and TM mode. The layout was fabricated at Applied nanotools and experimental analysis shows the small delta that is well within corner analysis which we used for simulation. The FSR and group index comparison for the 75um path difference TE and TM MZI shows only < 0.01% variation w.r.t. simulation.

VI. REFERENCES

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