Design Proposal: Unbalanced MZI for Group Index Extraction

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***Abstract*—The goal of this report is to simulate, design and experimentally characterize Mach-Zehnder interferometers (MZIs) to extract the group index of a silicon strip waveguide. The devices will be characterized after fabrication and the measured values will be compared to simulations made using Lumerical MODE and Lumerical INTERCONNECT. Furthermore, fabrication uncertainties will be investigated by analyzing the variability in the group index and interferometer performance for multiple MZIs of the same configuration.**

I. INTRODUCTION

Silicon photonics is a key enabling technology for high-bandwidth optical interconnects in data centers and high-performance computing [1]. It promises the integration of multiple function into a single package making use of the advanced fabrication technologies developed for micro-electronics promising high-complexity at low cost [2]. The Mach–Zehnder interferometer (MZI) specifically is an important building block for optical switches and modulators in silicon photonics [3], [4]. They operate based on converting a phase shift between two optical paths into an intensity change at the output. They can further be utilized to extract waveguide parameters such as the group index n_g and the waveguide dimensions [5]. In this work, multiple impalanced MZI with different path length differences ΔL between 30 µm and 200 µm will be designed and characterized to extract the group index of a quasi-TE mode in a silicon strip waveguide with 220 nm height and 500 nm width on silicon oxide. To check the fabrication reproducibility of the proposed photonic circuits, one interferometer design with ΔL= 90 µm will be fabricated three times. The group index will be calculated using the free spectral range (FSR) of the interferometer and be compared to simulations.

First, the theoretical background of the MZI will be discussed. Then, the waveguide will be simulated using Lumerical MODE to create a compact waveguide model. After that, the MZI will be constructed and simulated using Lumerical INTERCONNECT. Then, the proposed layout and fabrication will be discussed. After fabrication, the circuit will be experimentally characterized and the results will be compared to the simulations.

II. THEORY

In this section, the transfer function of an unbalanced MZI will be discussed following calculations from [2]. From that, the free spectral range (FSR) of the MZI will be calculated and the formula used for extracting the group index will discussed.

The unbalanced MZI consists of an input that is split into two branches including two waveguides of different lengths and then recombined. In this work, Y-branches are used to split and later recombine the signal.

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At the first Y-branch, the input intensity $I_i \sim |E_i|^2$ is split equally to the upper and lower branch of the interferometer with E_i describing the electric field. Therefore, both branches have the field $E_i/\sqrt{2}$ after the first Y-branch.

The propagation of the light through the waveguides is described by the propagation constant $\beta = \frac{2\pi n_{eff,j}(\lambda)}{\lambda} + i\frac{\alpha_j}{2}$ with wavelength λ, refractive index n_j and loss α_j of the respective waveguide with length L_j. Neglecting losses ($\alpha \approx 0$), the electric field at the end of each waveguide $E_{o,j}$ is

$$E_{0,j} = \frac{E_i}{\sqrt{2}} e^{-i\beta_j L_j}, j = 1, 2. \tag{1}$$

The two outputs are then combined at the second Y-branch so that the output at the end of the MZI can be described as

$$E_o = \frac{E_{o,1} + E_{o,2}}{\sqrt{2}} = \frac{E_i}{2}(e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2}), \tag{2}$$

or in terms of the intensity

$$\frac{I_o}{I_i} = \frac{1}{4} \cdot |e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2}|^2 = \frac{1}{2}(1 + \cos(\beta_1 L_1 - \beta_2 L_2)). \tag{3}$$

Due to the wavelenth-dependence of the propagation constant, output of the MZI is therefore a wavelength-dependent sinusoidally varying function. The period of this function is the FSR of the interferometer. Using the same waveguide material and dimensions ($\beta_1 = \beta_2$) in an unbalanced MZI ($L_1 \neq L_2$) with path lenght difference $\Delta L = L_2 - L_1$, equation (3) reduces to

$$\frac{I_o}{I_i} = \frac{1}{2}(1 + \cos(\beta(\lambda) \cdot \Delta L)). \tag{4}$$

The $FSR = \Delta\lambda = \lambda_{m+1} - \lambda_m$ can then be calculated knowing that the phase shift between two adjacent peaks is $\beta_m \Delta L - \beta_{m+1}\Delta L = 2\pi$. Assuming β varies linearly in λ, one can find $\frac{d\beta}{d\lambda} = -\frac{2\pi}{\lambda^2}(n - \frac{dn}{d\lambda}\lambda)$ [6]. The FSR can therefore be caculated using

$$FSR = \frac{\lambda^2}{\Delta L(n - \lambda\frac{dn}{d\lambda})} = \frac{\lambda^2}{\Delta L n_g}. \tag{5}$$

Finally, the group index n_g can be calculated for known path differences ΔL after measuring the FSR of the proposed MZIs according to

$$n_g = n - \lambda\frac{dn}{d\lambda} = \frac{\lambda^2}{FSR \cdot \Delta L}. \tag{6}$$

In the experiment, the group index can therefore be calculated by measuring the spectrum of the MZI, identifying adjacent maxima and computing the FSR. The latter can be averaged over multiple fringes to reduce the error and then inserted into equation (6).

III. Modeling and Simulation

Lumerical MODE [7] is used to extract the wavelength dependent effective index and group index of the silicon waveguide and develop a compact model for the waveguide. The data will then be exported to Lumerical INTERCONNECT [8] for the simulation of the optical circuit.

A. Waveguide simulations using Lumerical MODE

The waveguide-width was set to 500 nm and the height was set to 220 nm to follow common fabrication standards. The simulated mode profile of the first-order quasi-TE-mode is shown in figure 1.

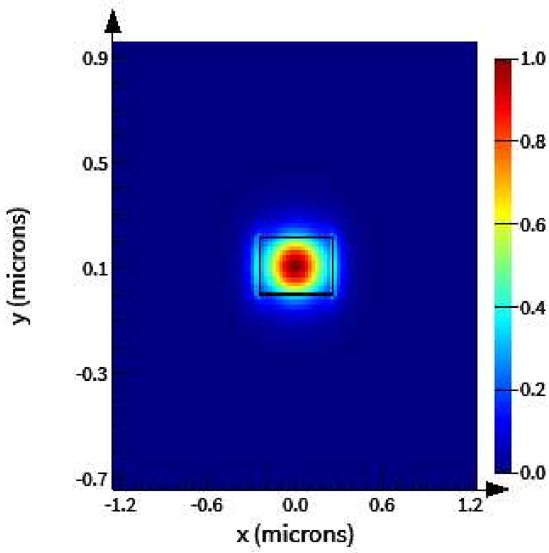

Fig. 1. Simulated waveguide mode profile of the first-order quasi-TE mode.

Then, a wavelength sweep between 1500 nm und 1600 nm according for material and waveguide dispersion was performed. The resulting effective index and group index are shown in figure 2 and figure 3.

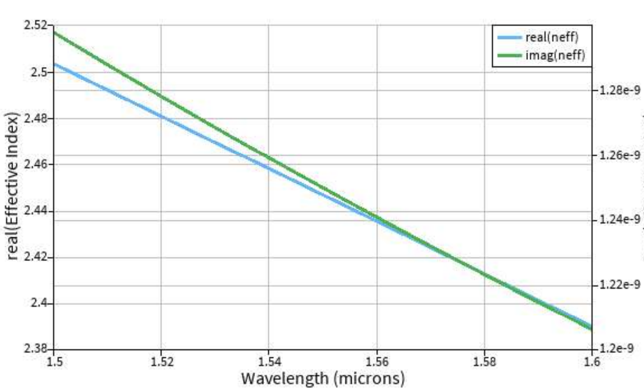

Fig. 2. Effective index n_{eff} vs. wavelength for the first-order quasi-TE mode (1500–1600 nm).

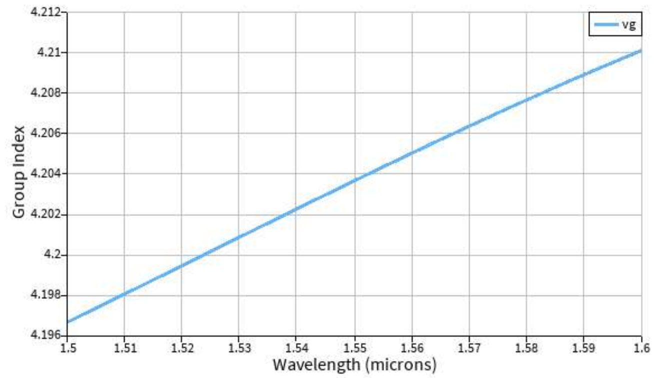

Fig. 3. Group index n_g vs. wavelength for the first-order quasi-TE mode (1500–1600 nm).

Afterwards, the compact model for the waveguide was derived according to [2]

$$n_{\mathrm{eff}}(\lambda) = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0)^2. \quad (7)$$

Fitting the data directly in Lumerical MODE and inserting them into equation (7) for $\lambda_0 = 1550\,\mathrm{nm}$ and for the first quasi-TE-mode leads to

$$n_{\mathrm{eff}}(\lambda) = 2.447 - 1.133(\lambda - 1.55) - 0.044(\lambda - 1.55)^2. \quad (8)$$

B. MZI simulation using Lumerical INTERCONNECT

The MZI was construed in Lumerical INTERCONNECT as shown in figure 4. The MZI consists of two Y-branches (ebeam_y_1550) whose S-parameters were taken from SiEPIC EBEAM INTERCONNECT Library and two waveguides which were imported from Lumerical MODE. The length of waveguide one was set to 100 µm whereas the length of waveguide two was varied between 130 µm and 300 µm to analyze the FSR for ΔL between 30 µm and 200 µm as shown in I. Furthermore, two grating couplers (GC_TE_1550_8degOxide_BB) from the SiEPIC EBEAM INTERCONNECT Library were added. An optical network analyzer (ONA) was included to simulate the expected FSR and transmission spectra of the device.

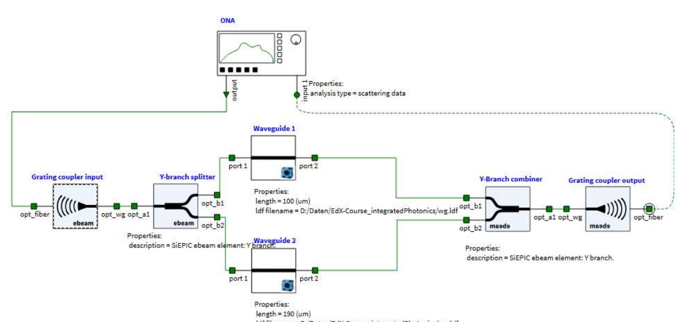

Fig. 4. Exemplary MZI-model implemented in Lumerical INTERCONNECT including the two grating couplers and the optical network analyzer (ONA) used to evaluate the circuit.

TABLE I
EXPECTED FSR AT 1550 NM FOR DIFFERENT ΔL. THE FSR WAS CALCULATED USING EQUATIONS (5) AND (8).

ΔL (µm)	FSR (nm)
30	19.05
60	9.52
90	6.35
120	4.76
150	3.81
200	2.86

Figure 5 shows two exemplary MZI gain spectra of the quasi-TE mode for 90 µm and 200 µm path difference. As expected, the FSR decreases for larger path length differences.

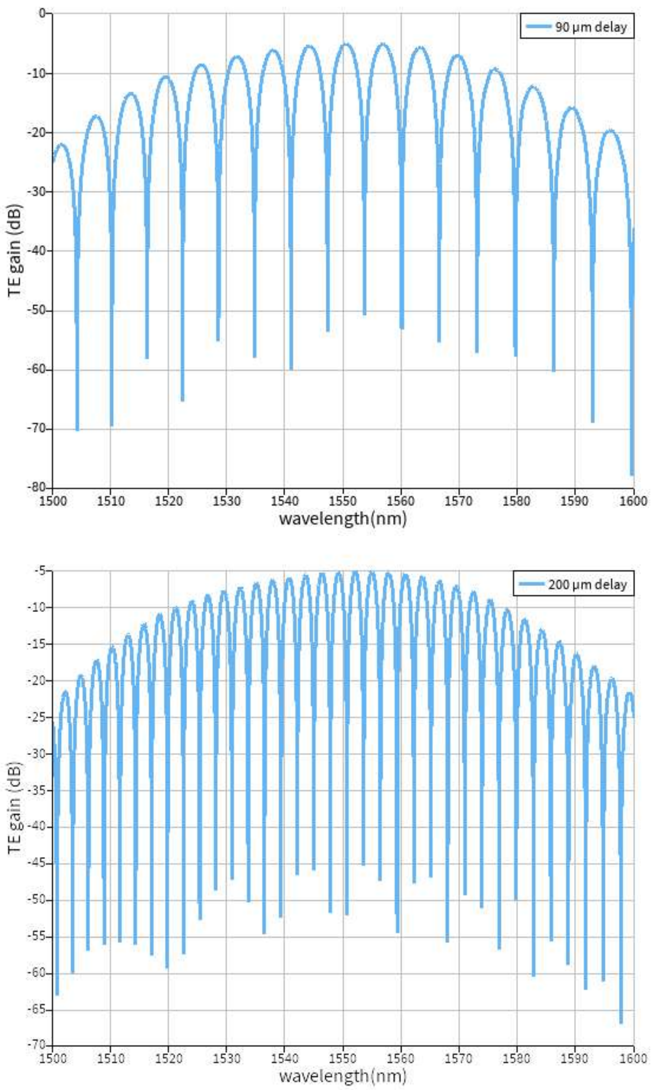

Fig. 5. Exemplary gain spectra of the proposed MZI with (top) 90 µm and (bottom) 200 µm path difference.

Figure 6 shows an exemplary MZI transmission of the quasi-TE mode for ΔL=90 µm.

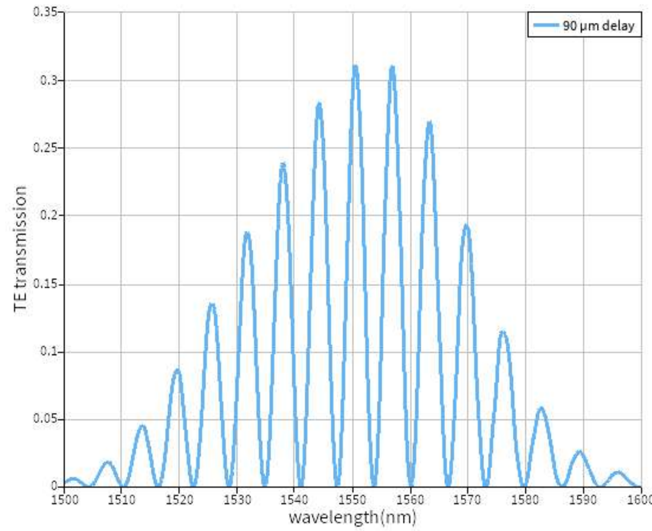

Fig. 6. Exemplary MZI transmission of the quasi-TE mode for ΔL=90 µm.

IV. FABRICATION

To be completed later.

V. EXPERIMENTAL DATA

To be completed later.

VI. ANALYSIS

To be completed later.

VII. CONCLUSION

To be completed later.

VIII. ACKNOWLEDGEMENTS

To be added.

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