# Silicon Mach-Zehnder Interferometer

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## 1. Introduction

On-chip Mach Zehender Interferometers (MZI) have attracted various applications ranging from biomedical sensing, optical switching, quantum computing, spectroscopy, and metrology [1-4]. Similar to the conventional MZI, the phase difference between the two light beams can be adjusted by creating an optical path difference between the two arms of the interferometer and further controlling the output using thermo-optic, electro-optic or refractive-index changes, making them suitable for different applications.

Here, a Mach-Zhender interferometer of different free spectral ranges (FSR) are designed. The theoretically calculated group index will be experimentally verified using measurements from the fabricated MZI. The next section describes the theory of MZI mostly adapted from [5].

## 2. Theory

A concept schematic of an MZI is provided in the Figure below. The input (complex) electric field **Ei** is equally divided into two at the first Y branch into **Ei1** and **Ei2** each having half the intensity of the incident light. Therefore,

$$Ei1 = \frac{Ei}{\sqrt(2)} \tag{1}$$

$$Ei2 = \frac{Ei}{\sqrt(2)} \tag{2}$$

At the time of recombining at the second Y branch, **Eo1** and **Eo2** evolve differently due to the difference in the optical path length difference. Assuming zero absorption and scattering losses, the two electric fields at the time of recombining becomes,

$$Eo1 = \frac{Ei}{\sqrt{2}} e^{i(\omega t - \beta L1)} \tag{3}$$

$$Eo2 = \frac{Ei}{\sqrt{2}} e^{i(\omega t - \beta L2)} \tag{4}$$

where $\beta$ is the propagation constant, $L1$ and $L2$ are the path lengths traversed in each arm of the MZI.

Upon recombination at the combining Y splitter, the output electric field,

$$Eo = \frac{Eo1 + Eo2}{\sqrt{2}} = \frac{Ei}{2}(e^{-i\beta L1} + e^{-i\beta L2}) \tag{5}$$

The output intensity,

$$Io = (\frac{Ei}{2}(e^{-i\beta L1} + e^{-i\beta L2}))^2 \tag{6}$$

$$Io = \frac{Ii}{4}(1 + Cos(\beta \Delta L)) \tag{7}$$

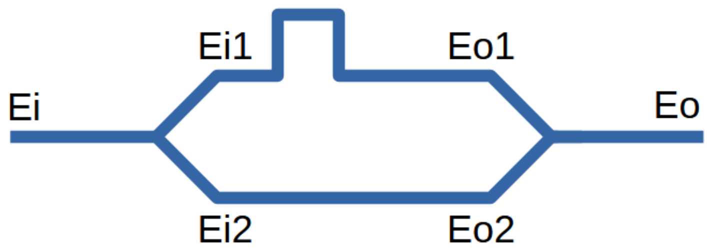


Fig. 1. Schematic of the MZI

The free spectral range (FSR) is the spectral difference between two consecutive peaks, which can be derived as

$$FSR = \frac{\lambda^2}{\Delta L * ng} \tag{8}$$

where ng is the group index. By measuring the FSR corresponding to different $\Delta L$ values, the group index can be calculated from the plot of FSR versus $\Delta L$.

## 3. Simulation and Design

| Length diff. (um) | FSR Theoretical (nm) | FSR Numerical (nm) |
|---|---|---|
| 30 | 17.8 | 18 |
| 60 | 9.53 | 9.68 |
| 90 | 6.36 | 6.32 |
| 120 | 4.77 | 4.77 |
| 150 | 3.81 | 3.79 |

The strip waveguide having 220 nm height and 500 nm width is chosen as the waveguide model. Figure 2 shows the quasi-TE mode of the waveguide at 1550 nm obtained using Lumerical MODE solver. The refractive index data corresponding to Si and SiO2 is chosen from Palik. The effective refractive index and the group index obtained after performing a wavelength sweep for the quasi-TE mode as a function of wavelengths are given in Figure 3 and Figure 4, respectively.

The Taylor series expansion of effective refractive index gives the expression:

$$neff(\lambda) = n1 + n2(\lambda - \lambda 0) + n3(\lambda - \lambda 0)^2 \tag{9}$$

Curve fitting of the effective refractive index versus wavelength in MATLAB gives the values of n1, n2 and n3 as 2.45, -1.13 and -0.04 respectively.

The group index value for the TE like mode at 1550 nm is estimated as 4.2. Based on this value, the following table summarizes the FSR values corresponding to different length deviations between the two arms of the MZI.

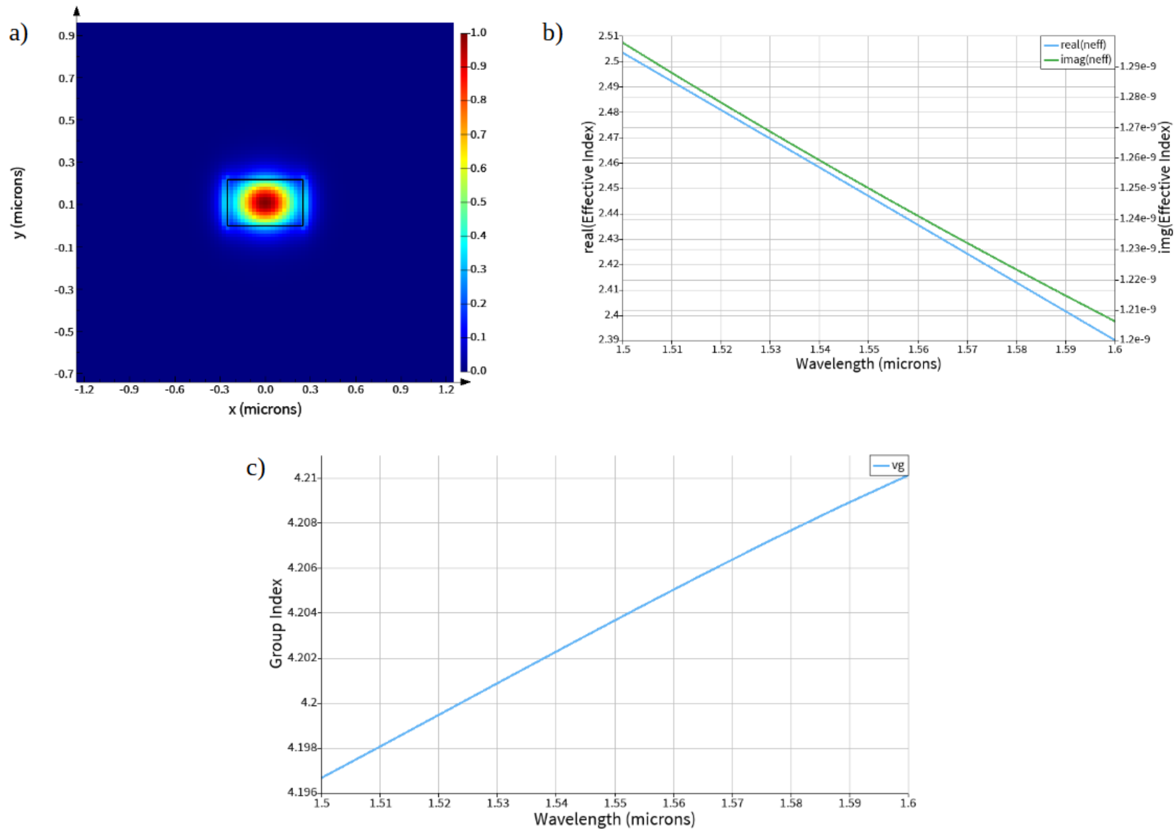


Fig. 2. a) The electric field intensity of the quasi-TE mode. b) The effective refractive index of the quasi-TE mode. c) The group index of the quasi-TE mode.

The FSR values obtained from the Lumerical INTERCONNECT simulations varies slightly compared to the values obtained based on the equation. The following figures show the output gain as a function of wavelength for the different length differences of the interferometer arms.

## 4. References

[1]. Marchisio, A., Da Ros, F., Curri, V. et al. Comprehensive model of MZI-based circuits for photonic computing applications. Commun Phys 8(277), 2025.

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[3]. Ultrafast Silicon MZI Optical Switch With Periodic Electrodes and Integrated Heat Sink. Journal of Lightwave Technology 39(15), 2021

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[5]. L. Chrostowski and M. Hochberg, “Silicon Photonics Design: From Devices to Systems”, Cambridge University Press, 2015.

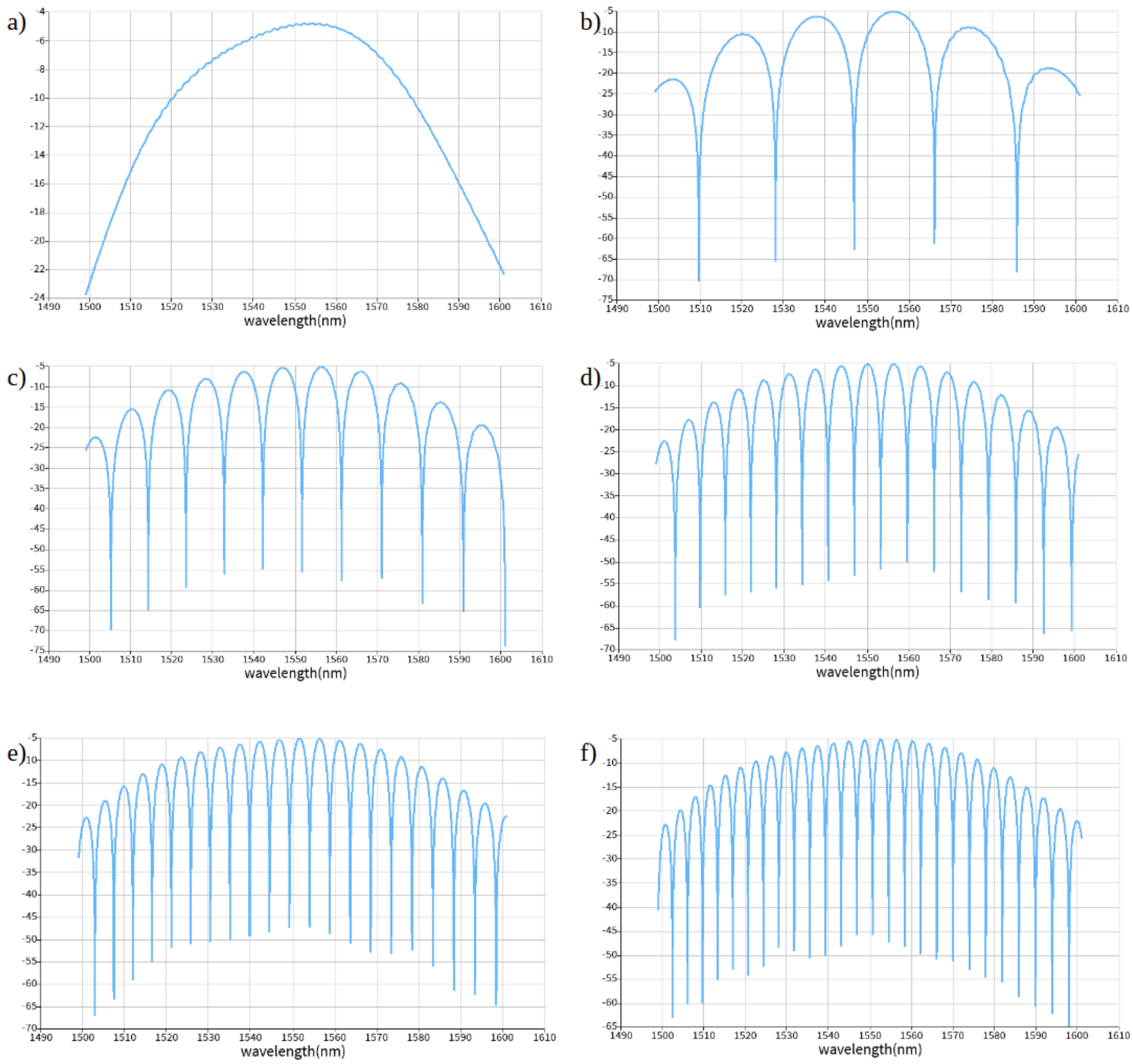


Fig. 3. Gain of the MZI as a function of wavelength a) grating coupler, b) $\triangle L$=30, c) $\triangle L$=60, d) $\triangle L$=90, e) $\triangle L$=120, f) $\triangle L$=150.