Design Proposal of Mach-Zehnder Interferometer

edX username: tarjs

***Abstract*—We report a design, simulation and experimental data of waveguide imbalance Mach-Zehnder Interferometer on silicon-on-insulator platform.**

I. INTRODUCTION

Mach-Zehnder interferometer (MZI) is a fundamental optical device in which an input light beam is split into two paths and then recombined to produce interference pattern determine by the phase difference in two paths. The splitting and recombination operation can be done through Y-branch or directional coupler. The phase difference can achieved by introducing path length imbalance in two paths. In our work, we first explore the theory behind MZI, then design and fabricate MZI on silicon-on-insulator platform to investigate the effect of path difference in free spectral range (FSR).

II. MODELLING AND SIMULATION

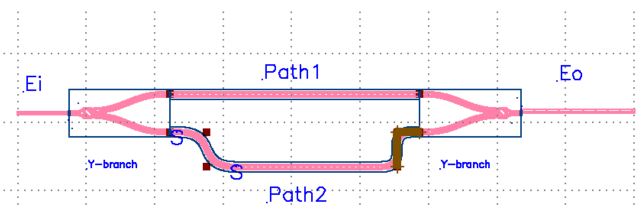

Figure 1. MZI, layout example Klayout

As mentioned before, MZI has an input light beam that is split into two path and later recombined. Figure 1 shows, input electric field E_i and output electric field E_o. The split and recombination is done through Y-branch. If we assume Y-branch is of equal split, then electric field in path 1 is $E_1 = \frac{E_i}{\sqrt{2}}$ and electric field in path 2 is $E_2 = \frac{E_i}{\sqrt{2}}$.
The output electric field is then defined by $E_o = \frac{E_1 + E_2}{\sqrt{2}}$. [1]

The electric field in each region is defined by plane-wave equation $E_i = E_i e^{j(wt-\beta z)}$ where β is propagation constant dependent on index of refraction n and wavelength λ and z is the length.
$\beta = \frac{2\pi n}{\lambda}$

Using plane-wave expression, electric field in each region can be written as such:

$$E_1 = \frac{E_i}{\sqrt{2}} e^{-j\beta_1 L_1}$$

$$E_2 = \frac{E_i}{\sqrt{2}} e^{-j\beta_2 L_2}$$

$$E_o = \frac{E_1 + E_2}{\sqrt{2}} = \frac{E_i}{\sqrt{2}}\left[e^{-j\beta_1 L_1} + e^{-j\beta_2 L_2}\right]$$

Where L_1 and L_2 are two path length in path 1 and path 2 respectively.

The intensity is proportional to the squared power of electric field. Output intensity is then

$$I_o = \frac{1}{4} I_i \left|e^{-j\beta_1 L_1} + e^{-j\beta_2 L_2}\right|^2$$

This can be simplified to

$$I_o = \frac{1}{4} I_i [1 + \cos(\beta_1 L_1 - \beta_2 L_2)]$$

The output of MZI is a sinusoidal with varying function of wavelength and dependent of path lengths L_1 and L_2. If we assume $\beta_1 = \beta_2 = \beta$, meaning same index of refraction for both paths then

$$I_o = \frac{1}{4} I_i [1 + \cos(\beta(L_1 - L_2))]$$

This is also known as the transfer function of MZI.

The free spectral range (FSR), which is the period between the peaks of transfer function is defined by

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

n_g is the waveguide group index and defined by

$$n_g(\lambda) = n_{eff}(\lambda) - \lambda * \frac{dn_{eff}(\lambda)}{d\lambda}$$

Before considering the complete MZI, we consider the properties of the waveguide itself. We have chosen silicon waveguide of with width of 500 nm and thickness of 200nm.

Figure below simulation using LUMERICAL MODE [2] shows that this geometry gives us fundamental TE mode.

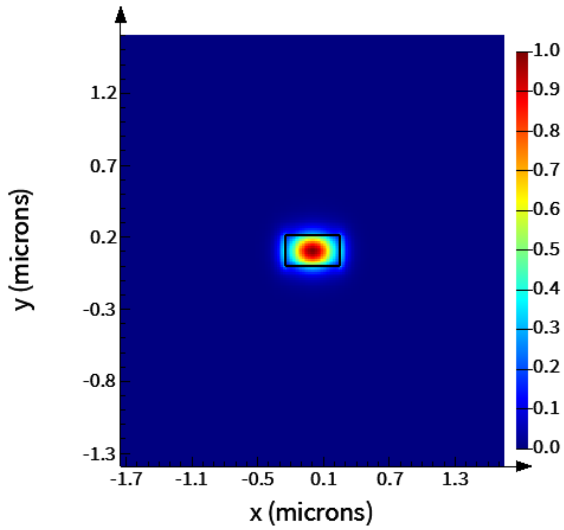

Figure 2- fundamental TE mode on waveguide

A wavelength swept from 1.5um to 1.6um was done to obtain waveguide's dispersion properties. The frequency sweep provides us with effective index and group index values. They are shown in Figure 3 and Figure 4, respectively.

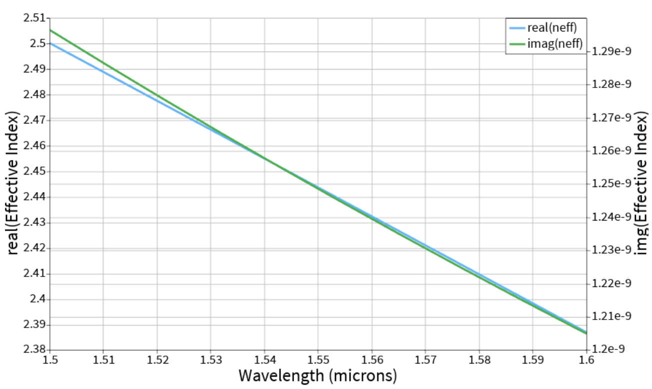

Figure 3 – effective index (real and imaginary) over wavelength

Observe that imaginary values of effective index are very small and can be ignored. Note that effective index decreases as the wavelength increases.

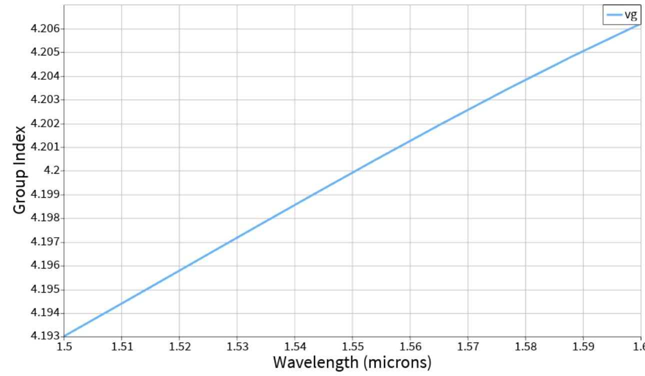

Figure 4 – group index over wavelength

The group index increases as the wavelength increases. This result is consistent with the fact that effective index over wavelength has a negative slope.

The effective index, $n_{eff}(\lambda)$ can modeled as a Taylor polynomial of 2nd second.

$$n_{eff}(\lambda) = n_1 + n_2(\lambda - \lambda_o) + n_2(\lambda - \lambda_o)^2$$

MATLAB was used to curve fit and solve for the coefficients.

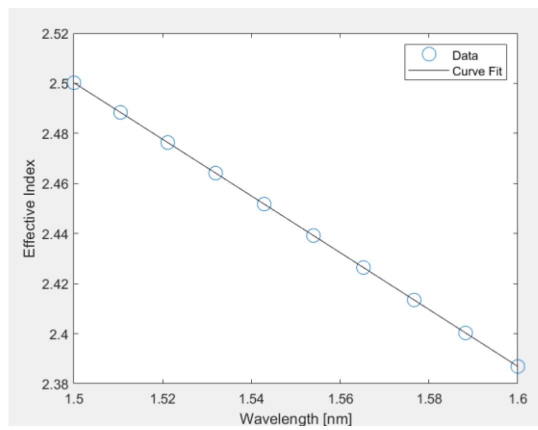

Figure 5 – effective index curve fit

$$n_{eff}(\lambda) = 2.44 - 1.33(\lambda - 1.55) - 0.043(\lambda - 1.55)^2$$

Using this waveguide model and with experimental S-parameters for grating coupler and Y-branch, a complete Mach-Zehnder interferometer was modeled using INTERCONNECT [3]. The simulation results showed transmission spectrum and gain profiles. Transmission and gain results are shown in Figure 7 and Figure 8, respectively.

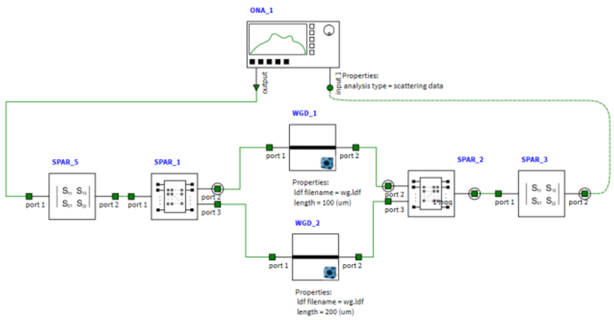

Figure 6 – MZI model in INTERCONNECT

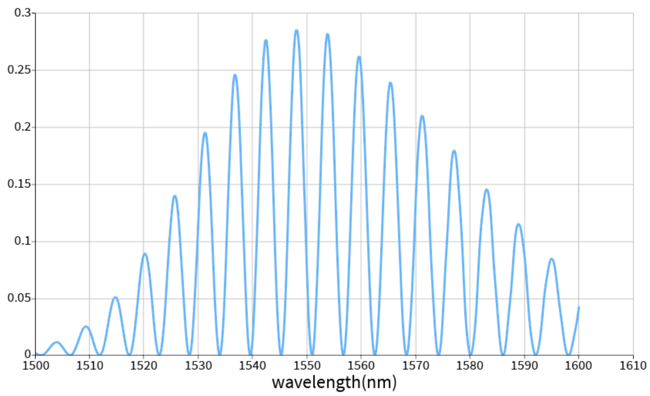

Figure 7 – transmission spectrum (abs)^2 with path difference of 100 um

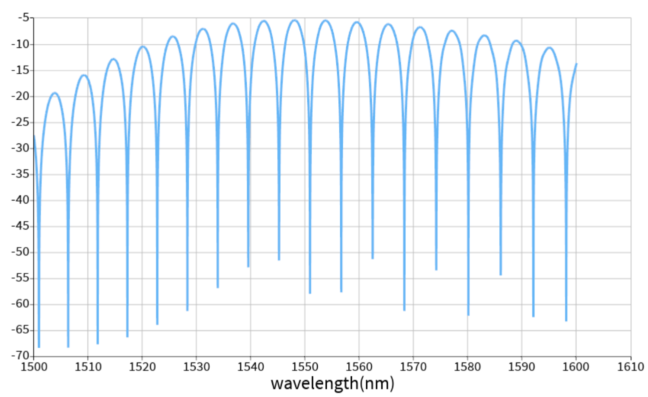

Figure 8- gain TE mode spectrum with path difference of 100 um

Theoretical FSR is given by

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

delta L (um)	FSR
75	7.63E-09
100	5.72E-09
125	4.58E-09
150	3.81E-09

Table 1

III. Fabrication

We wish to fabricate MZI using TE waveguides with dimensions provides in Section II on silicon wafer with path length differences shown in Table 1. We will simulate MZI in INTERCONNECT and match the results from experimental data. Layout verification will be done using KLayout [4].

IV. References

1. L. Chrostowski and M. Hochberg, "Silicon Photonics Design: From Devices to Systems", Cambridge University Press
2. https://www.ansys.com/products/optics/mode
3. https://www.ansys.com/products/optics/interconnect
4. https://www.klayout.de/