Mach-Zehnder Interferometer Design, Fabrication and Data Analysis

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Abstract—**This proposal outlines the design and characterisation of silicon photonics Mach-Zehnder interferometer (MZI) on a 220 nm Silicon on Insulator (SOI) platform. Theoretical modelling and simulations are used to understand and analyse the transmission response of multiple imbalanced MZI.**

Index Terms—**Group Index, Group Delay, Free spectral range, Mach-Zehnder Interferometer, Silicon photonics, Transmission Response, Waveguide, Y branch Splitter/Coupler**

I. INTRODUCTION

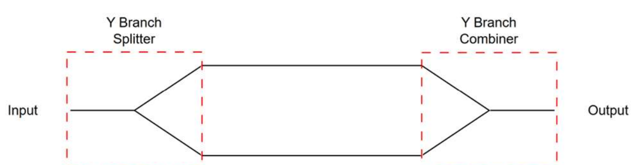
SILICON Photonics enables integration of optical components onto silicon chips using standard semiconductor fabrication process. The Mach-Zehnder interferometer (MZI) is a key building block in silicon photonics and is widely used in devices such as optical switches and modulators. An MZI in this case is works by splitting optical light into two paths, introducing a phase difference between the branches and recombine them to produce constructive or destructive interference.

In this proposal we focus on the design and characterization of an MZI. The behaviour of these components is simulated using the Lumerical simulation software and later validated using fabrication and measurement analysis.

II. THEORY

An MZI in silicon photonics can be constructed using three main optical components:

1. Waveguides
2. Grating Couplers
3. Y branch splitters/combiners



Let's explore each individual component:

Waveguide

Wave guides are fundamental blocks in silicon photonics. They work by confining and guiding the light through the silicon layer. We will design waveguide with silicon core, which has high refractive index, and is surrounded by silicon dioxide cladding with low refractive index.

Light propagation in a silicon waveguide can be described using electromagnetic wave theory

$$E = E_0 \cdot e^{j(\omega t - \beta z)}$$

Where:

$Angular\ frequency\ (\omega) = \frac{2\pi c}{\lambda}$,

$Propogation\ constant\ (\beta) = \frac{2\pi n_{\text{eff}}}{\lambda}$ and

n_{eff} is the effective refractive index.

Y Branch Splitters and Combiners:

Y branches can be used to either split the light or recombine them. Let's say, light with intensity I_i and electric field E_i enters a Y-branch splitter, it gets equally divided between the two output branches and this can be expressed as

$$I_1 = I_2 = \frac{I_i}{2}$$

Since the intensity is proportional to the square of the electric field magnitude

$$I \propto |E|^2$$

$$|E_1|^2 = |E_2|^2 = \frac{|E_i|^2}{2}$$

Therefore, the electric field amplitudes are:

$$E_1 = E_2 = \frac{E_i}{\sqrt{2}}$$

When light from two input waveguides with electric fields E_1 and E_2 enters a Y-branch combiner the output electric field becomes a vector superposition of the inputs, scaled by $1/\sqrt{2}$:

$$E_{out} = \frac{1}{\sqrt{2}}(E_1 + E_2)$$

The output intensity depends on both the magnitude and phase relationship between E_1 and E_2:

$$I_{out} = |E_{out}|^2 = \frac{1}{2}|E_1 + E_2|^2$$
$$= \frac{1}{2}(|E_1|^2 + |E_2|^2 + 2\text{Re}(E_1 E_2^*))$$

If both inputs have equal intensity ($|E_1| = |E_2| = E_0$):

$$I_{out} = \frac{1}{2}(E_0^2 + E_0^2 + 2E_0^2 \cos(\phi)) = E_0^2(1 + \cos(\phi))$$

where ϕ is the phase difference between E_1 and E_2.

This yields two extreme cases: Constructive Interference where we see maximum transmission and Destructive Interference, where we see complete extinction.

Grating couplers:
Grating couplers enable light coupling between external optical fibres to on chip waveguides.

Mach-Zehnder Interferometer Transfer Function
For an imbalanced MZI with identical waveguides ($\beta_1 = \beta_2 = \beta$) but different arm lengths, light propagating through each arm accumulates different phases. After propagating through arms of length L_1 and L_2, the fields at the end of each arm are:

$$E_{o1} = \frac{E_i}{\sqrt{2}} e^{-i\beta L_1}, E_{o2} = \frac{E_i}{\sqrt{2}} e^{-i\beta L_2}$$

The combiner output becomes:

$$E_{out} = \frac{1}{\sqrt{2}}(E_{o1} + E_{o2}) = \frac{E_i}{2}(e^{-i\beta L_1} + e^{-i\beta L_2})$$

The output intensity in the lossless case is:

$$I_{out} = |E_{out}|^2 = \frac{I_i}{4}|e^{-i\beta L_1} + e^{-i\beta L_2}|^2$$

After trigonometric simplification, the normalized transmission spectrum becomes:

$$T(\lambda) = \frac{I_{out}}{I_{in}} = \frac{1}{2}[1 + \cos(\beta(\lambda).\Delta L)]$$

$$T(\lambda) = \frac{1}{2}\left[1 + \cos\left(\frac{2\pi n_{eff}(\lambda)}{\lambda} \cdot \Delta L\right)\right]$$

where $\Delta L = L_1 - L_2$ is the path length imbalance.

Free Spectral Range and Group Index Extraction
The free spectral range (FSR) is the wavelength spacing between adjacent transmission peaks, defined as

$$\mathrm{FSR} = \lambda_{m+1} - \lambda_m.$$

Given the imbalanced interferometer transfer function

$$\frac{I_o}{I_i} = \frac{1}{2}(1 + \cos(\beta\Delta L))$$

we define the phase term as $\beta\Delta L$, where the propagation constant is

$$\beta = \frac{2\pi n}{\lambda}$$

The phase difference between adjacent peaks is 2π. At adjacent peaks, the propagation constants are β_m and β_{m+1}, giving

$$(\beta_m - \beta_{m+1})\Delta L = 2\pi$$

Approximating β as varying linearly over the small wavelength step FSR, we use

$$\beta_m - \beta_{m+1} \approx \frac{d\beta}{d\lambda}\,\mathrm{FSR}$$

Combining equations above yields

$$\mathrm{FSR} = \frac{2\pi}{\Delta L\,\frac{d\beta}{d\lambda}}$$

Using $\beta = \frac{2\pi n}{\lambda}$, the derivative is

$$\frac{d\beta}{d\lambda} = \frac{2\pi}{\lambda^2}\left(\lambda\frac{dn}{d\lambda} - n\right)$$

Substituting equation into equation gives

$$\mathrm{FSR} = \frac{\lambda^2}{\Delta L\left(n - \lambda\frac{dn}{d\lambda}\right)} = \frac{\lambda^2}{\Delta L\, n_g}$$

where the group index is defined as

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

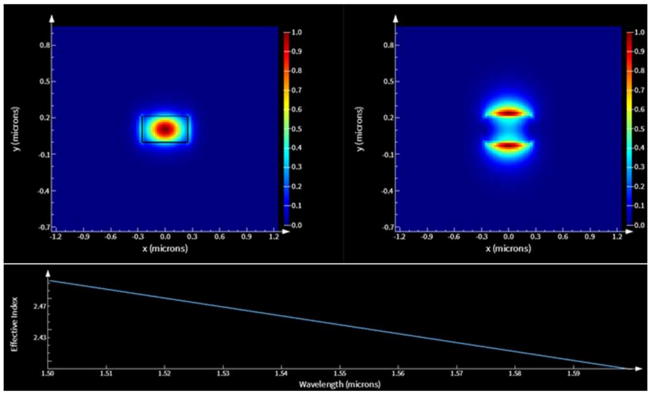
Rearranging equation, the group index can be extracted from a measured FSR and known imbalance length ΔL via

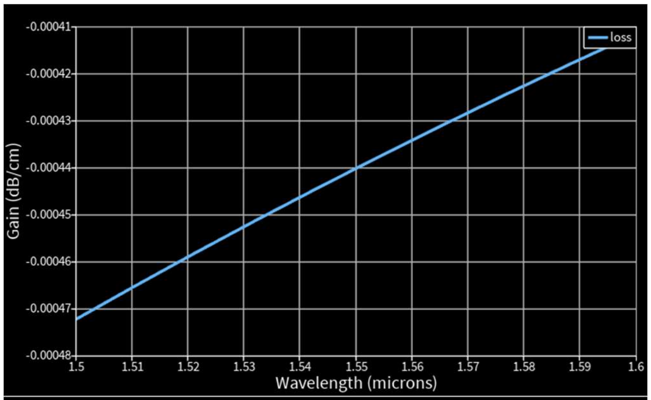
$$n_g = \frac{\lambda^2}{\Delta L \cdot \mathrm{FSR}}$$

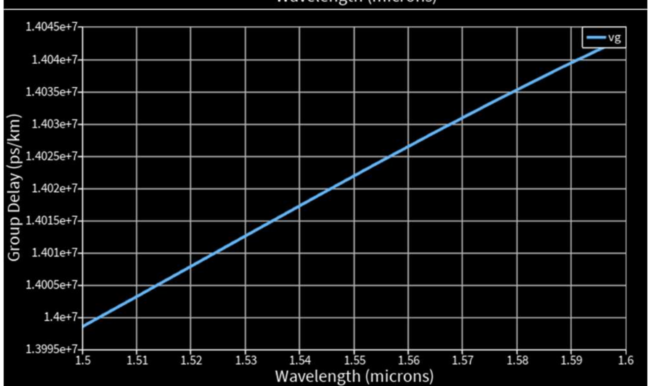
III. Modelling and simulations

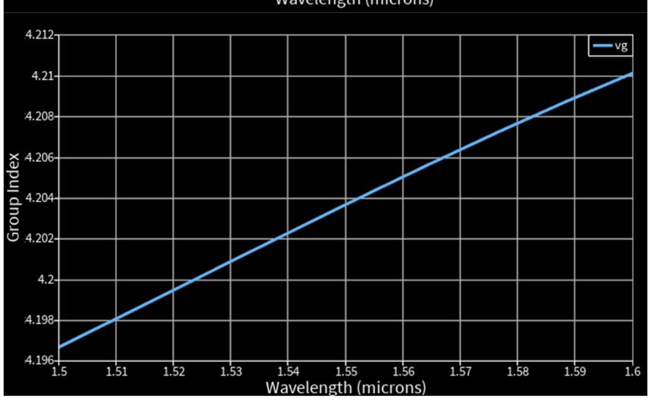
Design parameters:
1. We will be designing 10 MZI using the layout software Klayout.
2. 5 MZI's will be identical in design, and the rest will have varying arm lengths. This helps us in verifying the repeatability of measurement.
3. The allocated design space is 605 x 401 um.
4. We will use using 1550 nm as centre frequency
5. The wavelength span of 1500 to 1600 nm will be considered.
6. Strip waveguide will be used in this design.
7. Only Quasi-TE mode MZI's will be designed.
8. All waveguides will have same cross section of 220 x 500 nm.
9. Waveguide effective index and group indices are computed using the eigenmode solver in Lumerical mode solutions.
10. Material refractive indices Si = 3.47 and SiO2 = 1.44 will be used.

Let's simulate the waveguide in Lumerical mode simulation software.
The silicon waveguide was simulated using Lumerical MODE Solutions to evaluate its optical properties. The simulation results include the electromagnetic energy density profiles for both quasi-TE and quasi-TM modes, confirming single-mode operation for the target geometry. The effective refractive index was calculated as a function of wavelength across the operating band. In addition, key dispersive parameters including gain, group delay, and group index were extracted to support Mach-Zehnder Interferometer modelling and free spectral range analysis.

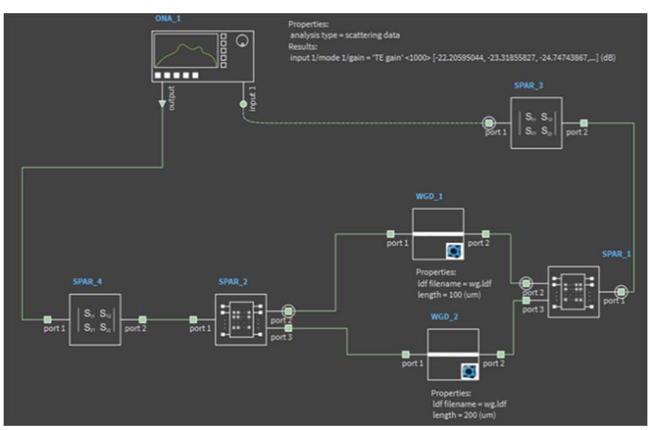




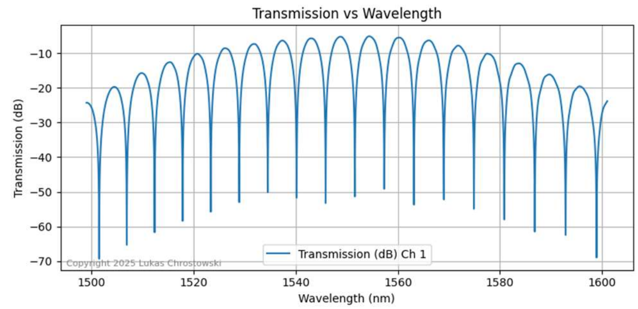


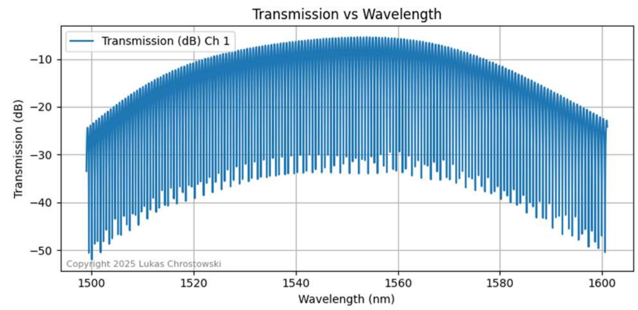


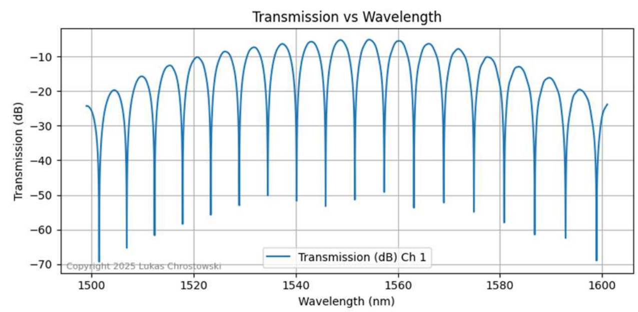
Then we simulated, imbalanced MZI's in Lumerical Interconnect and transmission plots are displayed below:

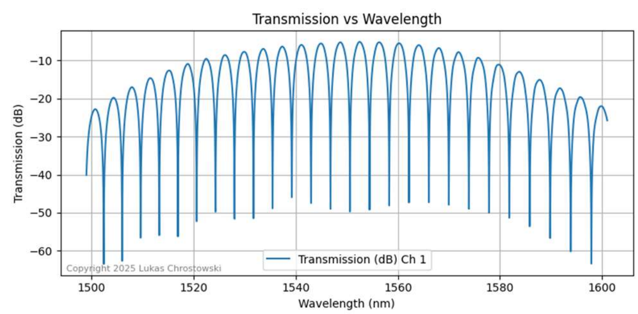


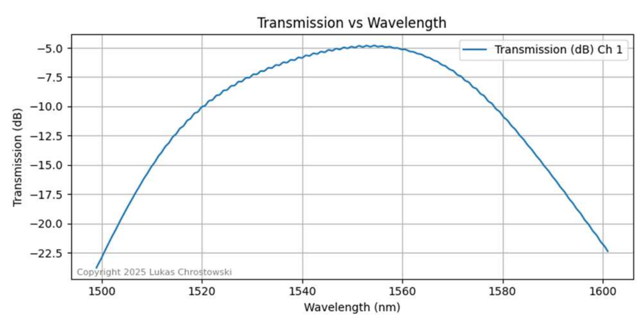
A branch length difference ranging from 20 µm to 950 µm was considered. A wavelength sweep was performed and the transmission vs wavelength data was plotted.

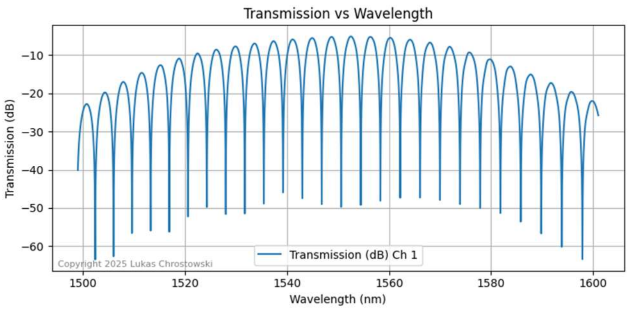












The designs were created on Klayout and once the fabrication of the following MZI is done, devices will be measured using the available test setup and tested data will be compared against the simulation data.