Phot1x Report: Design and Simulation of an MZI

Fábio Gabriel Gameiro Brandão

Email: brandaofg@gmail.pt
edX Public Username: brandaofg

1. Introduction

This project will take the fundamental design objective of designing a Mach-Zehnder Interferometer (MZI), and obtain its waveguide group index by varying the ΔL of multiple MZI devices. For this project, the following variables were set:

- Waveguide type: strip waveguide.
- Waveguide dimensions: height of 220 nm and width of 500 nm.
- Polarization: quasi-TE.
- Interferometer imbalance length, ΔL [μm]: 50, 100, 150, 200, 250, 300, 350, 400, 450, 500.
- Interferometer type: MZI.
- Splitter type: Y-branch.
- Design variations: ΔL (to study FSR).

2. Modelling and Simulation

In this project I started with modelling the basic properties of fundamental components, building up to circuit simulations and layout of the MZI.

2.1. Design Workflow for a Mach-Zehnder Interferometer

2.1.1. Strip Waveguide

I started with the modelling of a strip waveguide. Through Lumerical MODE, I simulated the λ = 1550 nm mode profiles of a 500x220nm Si/SiO_2 waveguide, by using the FDE solver. The n_{eff} for the TE_0 mode was 2.443. The E-field mode profile can be observed in Figure 1.

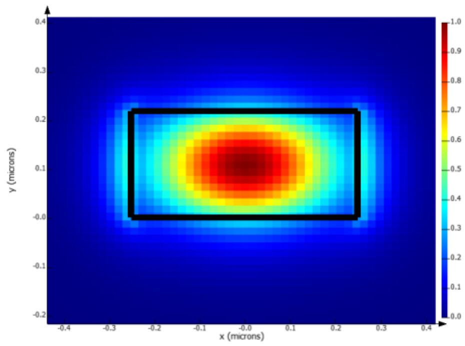

Figure 1 - E-field TE_0 mode profile at 1550 nm.

Then, I performed frequency sweeps for the TE_0 mode between λ = 1500–1600 nm to obtain the data for n_{eff} and n_g.

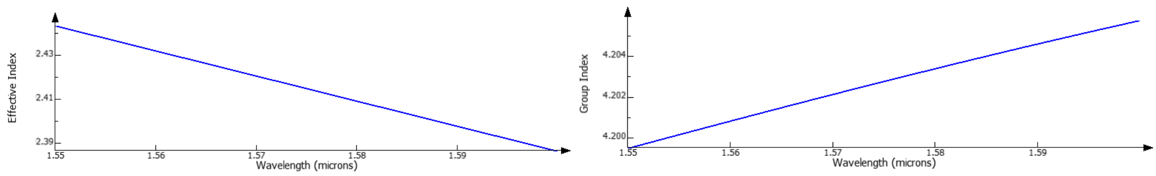

Figure 2 – Spectra for (left) n_{eff} and (right) n_g over 1500-1600 nm.

To create the Waveguide Compact Model (WCM), the n_{eff} data was exported into both MATLAB and INTERCONNECT formats. Through a MATLAB script, I performed curve fitting for the WCM, which was a Taylor expansion equation given by

$$n_{eff}(\lambda) = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0) \tag{1}$$

and obtained the following values for the fitting parameters (n_1, n_2, n_3)

$$n_{eff}(\lambda) = 2.444 - 1.131 \cdot (\lambda - \lambda_0) - 0.043 \cdot (\lambda - \lambda_0) \qquad 2$$

through the fit depicted in Figure 3. This is the model used for photonic circuit modelling.

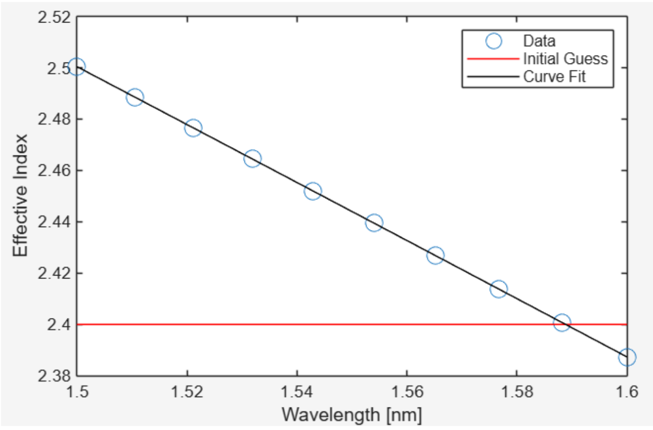

Figure 3 - WCM fit to the simulated n_{eff} spectrum data.

2.1.2. Y-Branch Splitter

To model the Y-Branch Splitter, I simulated the transmission of the Y-Branch geometry (provided in .gds format) over a λ = [1500; 1600] nm, obtaining the spectrum:

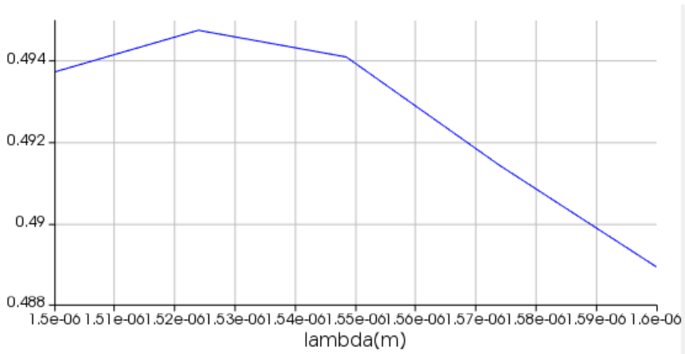

Figure 4 - Transmission Spectrum for the Y-Branch Splitter.

2.1.3. Waveguide Bend

To model the waveguide bend, I set up the FDE solver with perfectly matching layer (PML) boundary conditions (BCs), and simulated the mode overlap for a 5 μm bend radius, obtaining a value of 99.8621%. To test the influence of adopting an offset to the waveguide interface, I optimized the offset position and obtained the following: (x,y,z) = (0, 10, 0) nm, which resulted in an overlap of: 99.9492%, a minor improvement to the previous value. In terms of mode profile, we can observe in Figure 5 how the mode of the bent waveguide is more asymmetric, having the right evanescent tail more protrusive.

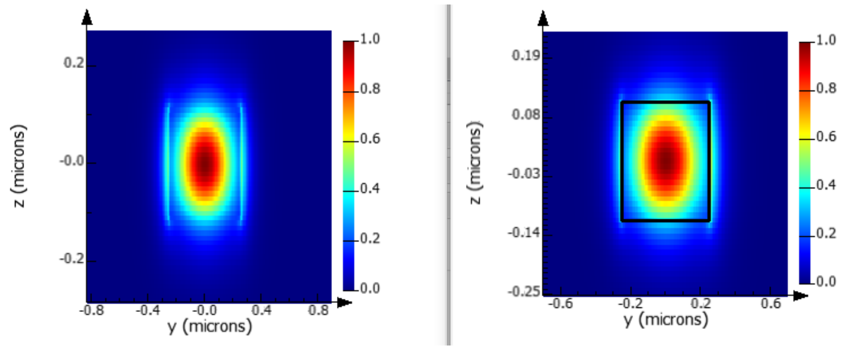

Figure 5 - E-field mode profiles for (left) straight waveguide and (right) bent waveguide.

2.1.4. Interferometer Circuit

The interferometer that was adopted in the project is the Mach-Zehnder Interferometer (MZI), particularly, the SiPho integrated variant from the free-space MZI. It consists of 2 waveguide arms of different lengths (L_1 and L_2), that differ in $\Delta L = L_2 – L_1$, which are connected through 2 Y-Branches on each end, whereupon light interferes leading to either destructive or constructive interference induced by the phase shift created due to ΔL. The transfer function for an imbalanced MZI with identical lossless waveguides is given by

$$H(\lambda) = \frac{1}{2}(1 + \cos(\beta \cdot \Delta L)), \qquad \text{where } \beta = \frac{2\pi}{\lambda} \tag{3}$$

where the following conditions define whether there is constructive or destructive interference:

$$H(\lambda) = \begin{cases} 1, & \text{if } \Delta L = \dfrac{\lambda}{n_{eff}} \cdot m \\ 0, & \text{if } \Delta L = \dfrac{\lambda}{2 \cdot n_{eff}} \cdot (m+1) \end{cases} \tag{4}$$

For the case of our waveguide, the first order (m = 0) ΔL for maximum and minimum transmission are 0 nm and 323 nm, respectfully. Equation 3 was modelled in MATLAB to demonstrate this, as depicted in Figure 6, where a broadband 0 dB transmission can be observed in the left plot and a

-30 dB transmission can be observed for λ = 1550 nm on the right plot, where the utmost lowest transmission is redshifted to 1550 nm due to the addition of the propagation loss effect.

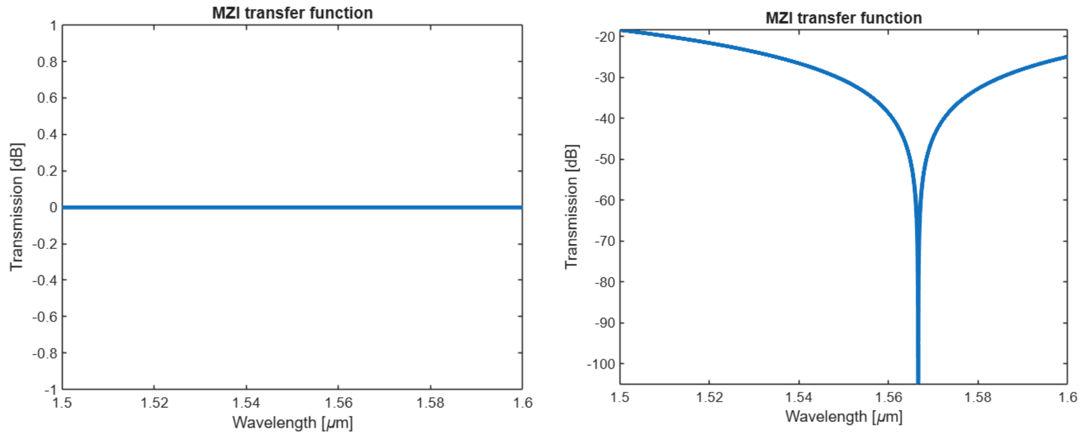

Figure 6 - MATLAB models for the MZI Transfer Function (H) for (left) ΔL = 0 and (right) ΔL = 323 nm.

In the case of a switch circuit, which consists of a 2x2 MZI connected to 2 3-dB directional couplers on each side, the constructive/destructive interference will define whether the light is routed to the output waveguide aligned with the shorter/longer MZI waveguide arm, respectfully.

2.1.5. Layout

The following layout was designed as an initial test design, where the components: directional coupler, Y-branch, waveguide and grating coupler were tested.

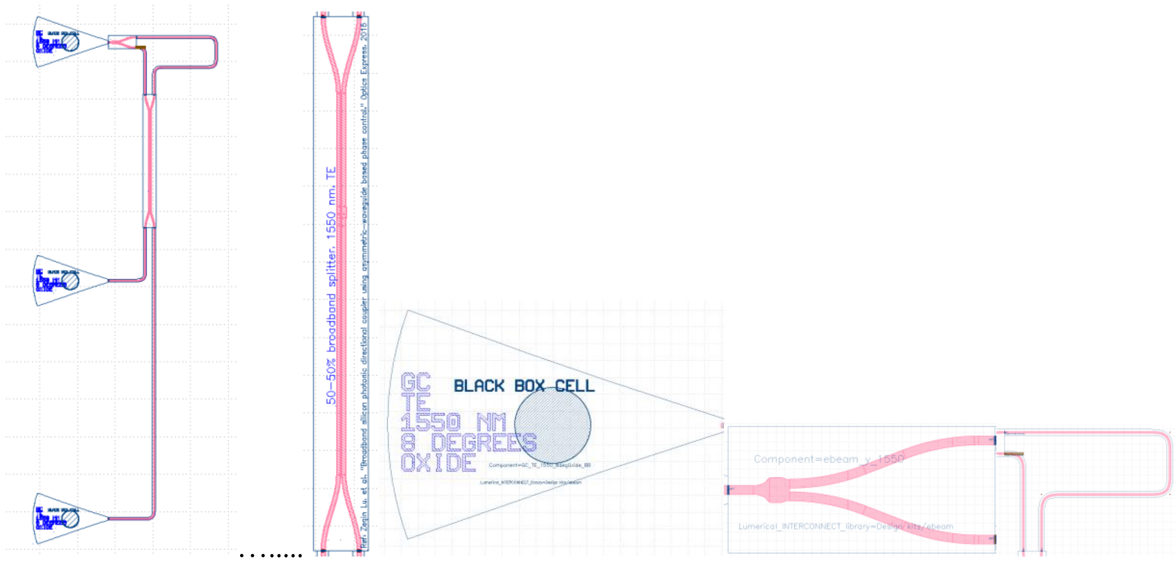

Figure 7 – Layout of the MZI (left-to-right): full MZI circuit layout, 3-dB broadband directional coupler, grating coupler (Dream Photonics), Y-branch splitter, waveguide arms (interferometer).

Simulating this layout in Lumerical INTERCONNECT with the mentioned components yielded the following transmission spectrum, where we can observe the MZI behaviour.

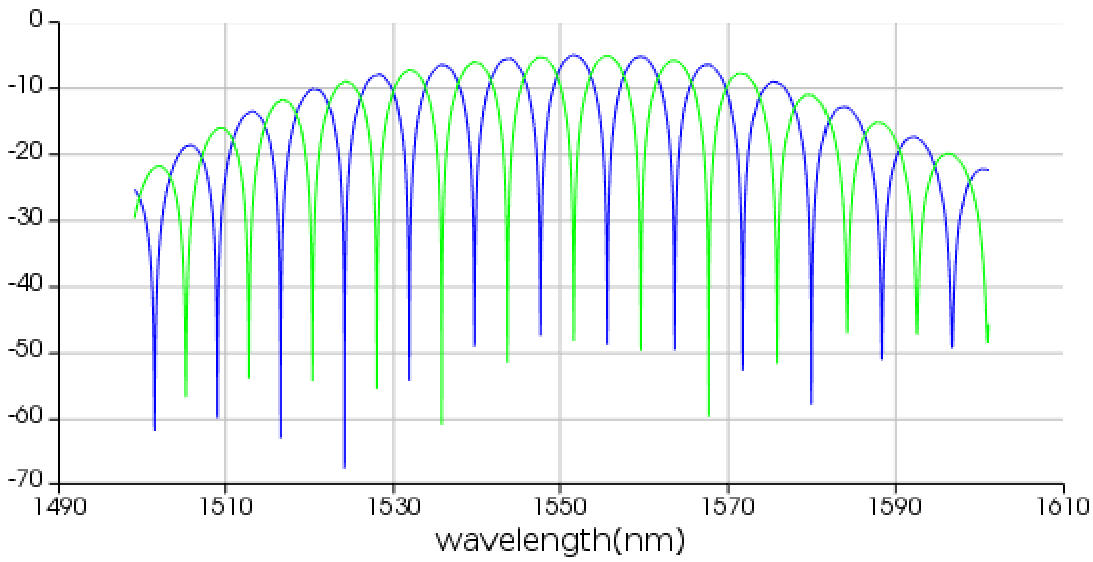

Figure 8 - Layout simulation for the first test design (L_2=178.138).

3. Conclusion

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Report Guidelines

Design Objectives

- The design objective is to make an interferometer circuit from which you can extract the waveguide group index. At the end of the course, you will compare your waveguide simulations with the experimentally extracted group index value(s) from your experiments.
- Within the constraints of the fabrication and test capabilities, you have freedom over:
    - **Waveguide type:** the strip waveguide is the default. Advanced students can consider sub-wavelength grating waveguides, photonic crystal waveguides, etc.
    - **Waveguide dimensions:** the default width is 500 nm. However, you can consider almost any width (e.g., 100 nm to 3 μm); changing the waveguide width requires an understanding of waveguide bend losses, connections with other components such as grating couplers and splitters, which can be achieved using tapers. The waveguide height is fixed in the fabrication process to be 220 nm.
    - **Polarization:** quasi-TE and/or quasi-TM. Fibre grating couplers are available for both. You can make designs for one or both polarizations.
    - **Interferometer imbalance length, ΔL = L2 - L1.** In order to be able to extract the waveguide group index, ensure that your design has an FSR that is smaller than the measurement bandwidth (which is about 50 nm); a design check is provided, "MZI Design Concept - Check", below.
    - **Interferometer type:** the default is the Mach-Zehnder Interferometer. You may also consider a Michelson interferometer. Advanced students can consider other interferometric devices including Fabry-Perot cavities (perhaps using Bragg gratings to create the Fabry-Perot), and even Michelson-Fabry-Pérot interferometers as those used by the LIGO experiments. Also, you can consider designing finite impulse response (FIR) filters using cascaded MZIs, which requires you to adjust both the coupling coefficient in the splitters and the phase shifts in the waveguides.
    - **Splitter type:** the default is the Y-branch. However, you can consider making interferometers using other splitters, including the provided adiabatic splitters, directional couplers, or broad-band directional coupler. You can consider making your own splitter (e.g., MMI).
    - **Design variations.** Based on the space allocation, I recommend choosing 5-10 designs. Consider different parameters so you can study trends (e.g., FSR varying

with ΔL, ng varying with waveguide width). You can also have the same design fabricated several times to test manufacturing variability.
    - **Note:** if your project devices/circuits go beyond the MZI considered in this course, or if you have additional designs, please include design information to help us understand, evaluate, and provide feedback on your design.

Report Requirements

- Your edX "Public Username" – the name that is used in discussion forums, etc., and found at the top-right of your browser.
- The waveguide geometry (height, width), polarization.
- The simulated waveguide mode profile (images from Lumerical MODE Solutions and/or MATLAB simulations)
- A plot of effective and group index of the waveguide, versus wavelength (graphs from MATLAB and/or Lumerical MODE Solutions)
- Compact model for the waveguide (polynomial expression)
- The transfer function of the interferometer vs. wavelength (a mathematical expression)
- A table listing your parameter variations (e.g., different values for path length difference ΔL, waveguide width, etc.), and expected performance for each (e.g., FSR). See below for a quick activity that checks if your ΔL values for the MZI make sense.
- The transmission spectrum of one or more photonic circuits (graphs from MATLAB and/or Lumerical INTERCONNECT)
- A derivation for an equation for the waveguide group index to be extracted from the free spectral range of an unbalanced interferometer. Test the equation using your simulation data and describe how you will obtain it from experimental data.

Report Format

- **Intro** – relevant application, your design objectives.
- **Theory**
- **Modelling and simulation** – this should have the compact equation for the waveguide, the transfer function of our device(s), simulation results, plots of neff/ng vs. lambda, table with parameter variation (i.e., how FSR is affected by ΔL), spectrum, waveguide, and circuit geometry.
- **Fabrication** – to be completed later to include your layout and details about fabrication
- **Experiment data** – to be completed later

- **Analysis** – to be completed later
- **Conclusion** – to be completed later
- **References** – provide citations to papers, notes, figures, etc., that you used in your report. Please avoid plagiarism in this report, and any others you write. Here are some resources that help explain how to avoid this: UBC's Avoiding Plagiarism page, and IEEE's plagiarism page.

References