Phot1x Report:
Design of a 2x2 Photonic Switch in a SiPho PIC

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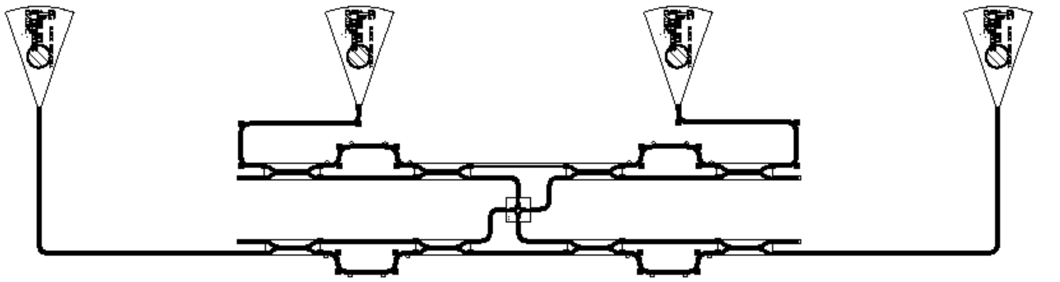

1. Introduction

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 (Section 2.1). I was also interested in learning more about the circuit-level engineering of PICs, since in my background I already covered some material/component simulation. In this regard, the first thing that caught my attention was the switch circuit mentioned in one of the lessons. Therefore, I decided to attempt to implement it by designing a 2x2 switch circuit operating at 1550 nm (Section 2.2).

Since I decided to focus more on circuit-level design for this project, the following variables were set for both the MZI design and the switch design:

- Waveguide type: strip waveguide.
- Waveguide dimensions: height of 220 nm, width of 500 nm, bend radius of 5 μm, and bend Bezier parameter of 0.2.
- Layout rules: spacing between waveguides and other devices above 6 μm, spacing between grating couplers above 65 μm.
- Polarization: quasi-TE.
- Interferometer short arm length, L_1/L_2 [μm]: 160/160, 160/180, 160/200, 160/250, 160/360, 160/480, 160/600.
- Interferometer imbalance length, ΔL [μm]: 0, 20, 40, 90, 200, 320, 440.
- 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 final circuits. The main approach used the ANSYS Lumerical products and KLayout. Section 2.1 covers the fundamental simulation results that were performed throughout the course lectures, namely covering the contents of: Passive Photonic Components, Photonic Circuits and Layout for Fabrication. I followed the basic workflow presented throughout the different sections, which established some the foundations for the project of my own proposed design: a 2x2 switch, in Section 2.2. Skip to Section 2.2 to read only the results of my final proposed design.

2.1. Generic Design Workflow

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.

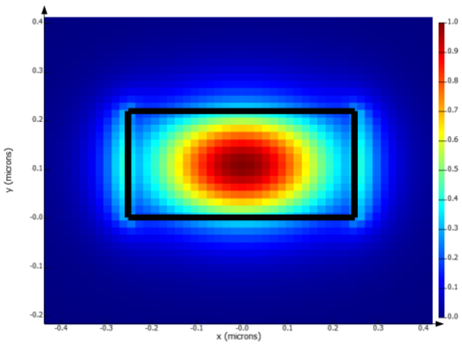

Figure 1 - E-field TE_0 mode profile at 1550 nm.

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.

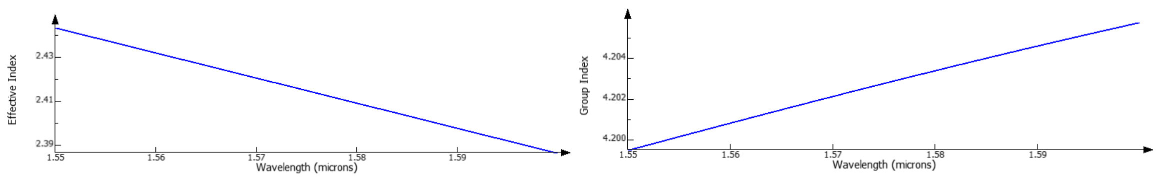

Figure 2 – Spectra for (left) n_{eff} and (right) n_g over 1500-1600 nm.

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

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

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

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

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

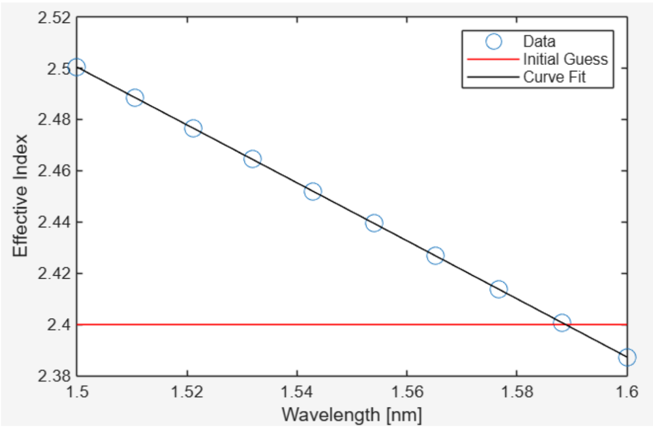

Figure 3 - WCM fit to the simulated n_{eff} spectrum data.

2.1.2. Y-Branch Splitter

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

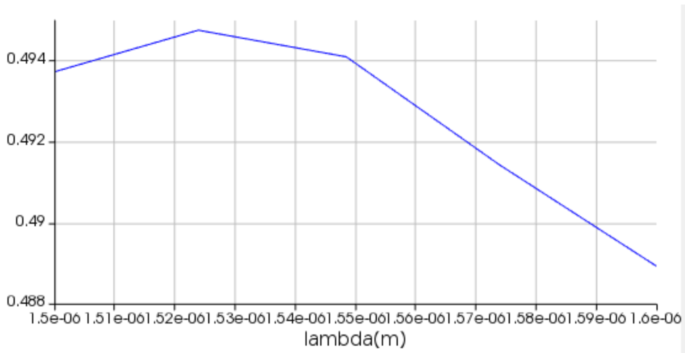

Figure 4 - Transmission Spectrum for the Y-Branch Splitter.

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.

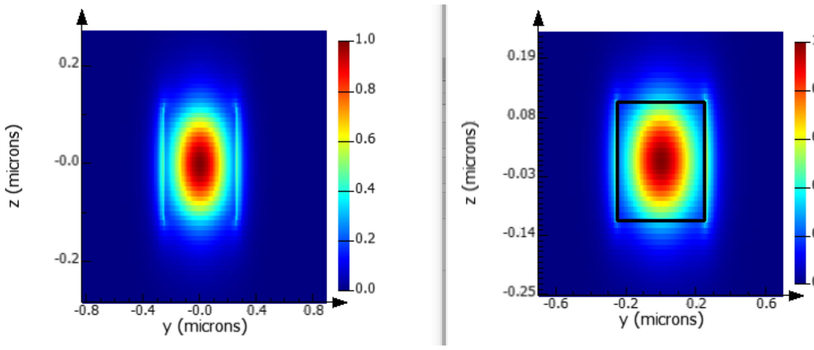

Figure 5 - E-field mode profiles for (left) straight waveguide and (right) bent waveguide.

2.1.4. Interferometer Circuit (Analytical)

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 (constructive interference) and a -30 dB transmission can be observed for λ = 1550 nm on the middle plot (destructive interference), where the utmost lowest transmission is redshifted to 1550 nm due to the addition of the propagation loss effect. By employing a ΔL = 100 μm, we see the characteristic MZI oscillations in the right plot.

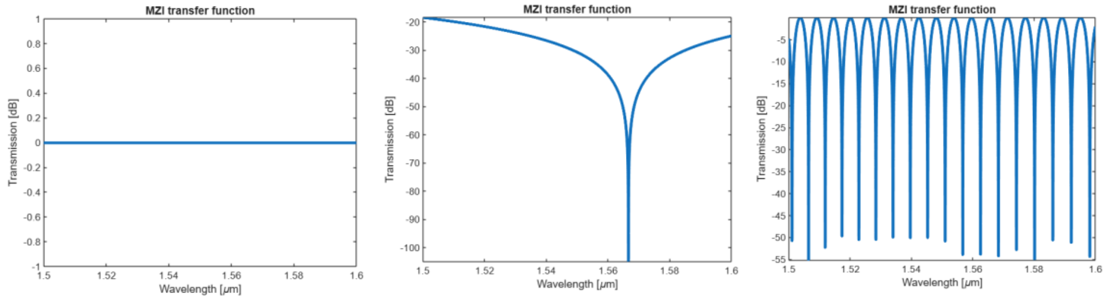

Figure 6 - MATLAB models for the MZI Transfer Function (H) for (left) ΔL = 0, (middle) ΔL = 323 nm and (right) ΔL = 100 μm.

2.1.5. Interferometer Circuit (Numerical)

To model the MZI numerically, I performed Lumerical INTERCONNECT simulations of an MZI circuit model. I started by simulating an ideal Y-Branch, as depicted in Figure 7, which resulted in a transmission of exactly -3.01 dB (50%) for one of the output ports, as expected. This was repeated for a real Y-Branch, meaning one whose s-parameters were simulated through FDTD, and imported into INTERCONNECT. This time, the transmission was even lower, with [-3.2; -3.1] dB, reflecting the real-device losses.

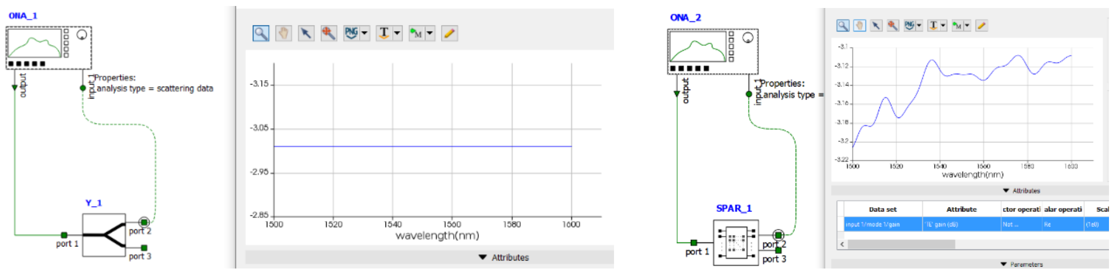

Figure 7 - Circuit model and transmission spectrum of (left) ideal and (right) real Y-Branch.

To model a full MZI circuit, I added a waveguide (MODE_Waveguide) to the Y-Branch output, which was set with: loss = 3 dB/cm, length = 100 μm, and mode profile from the file exported from MODE. By duplicating the waveguide and Y-Branch, changing the second waveguide length to 200 μm (ΔL = 100 μm), and connecting everything in an interferometer configuration, we get the results depicted in Figure 8. Therein, I obtained the expected oscillating transmission characteristic of MZI interference.

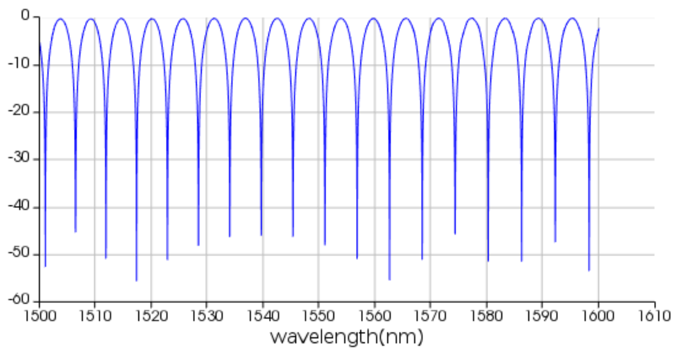

Figure 8 - Transmission of the basic interferometer configuration.

Lastly, I added grating couplers (GCs) by using the "Optical S Parameter" component, and importing FDTD data. The transmission is depicted in Figure 9, and we can observe how MZI with GCs (green) has a similar response to the previous circuit (blue, Figure 8), but lower transmission due to the GC's insertion loss (IL). Still, we can observe how the GCs are optimized to have the highest transmission at 1550 nm.

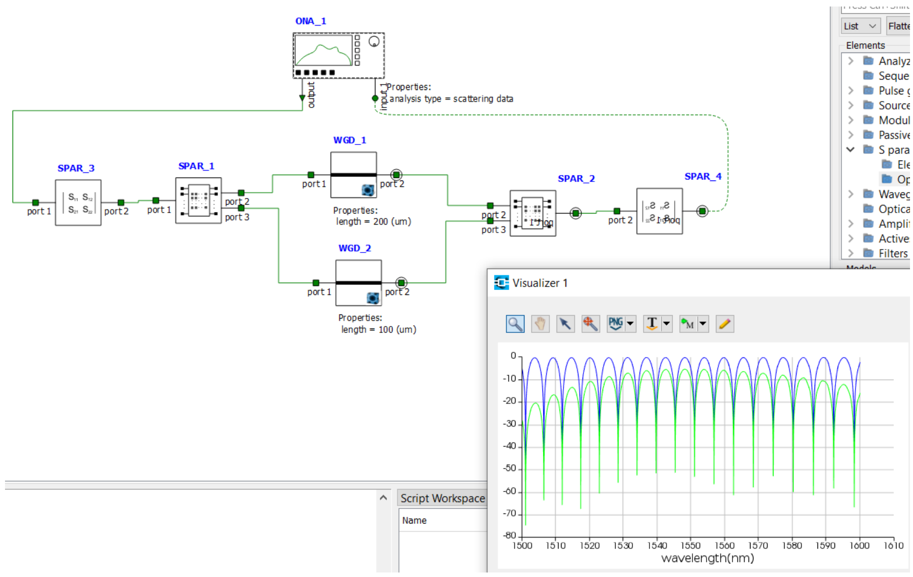

Figure 9 - Transmission of MZI circuit with GCs included.

To build a switch cell, I added directional couplers instead of Y-branches to the MZI circuit, creating a 2x2 MZI. The transmission spectrum of this circuit is depicted in Figure 10 in comparison to that of a regular Y-Branch 1x1 MZI. Notably, the extinction ratio of the 2x2 MZI is lower than that of the 1x1 MZI, and there is also a more prominent wavelength dependence, with the highest extinction ratio at the center wavelength.

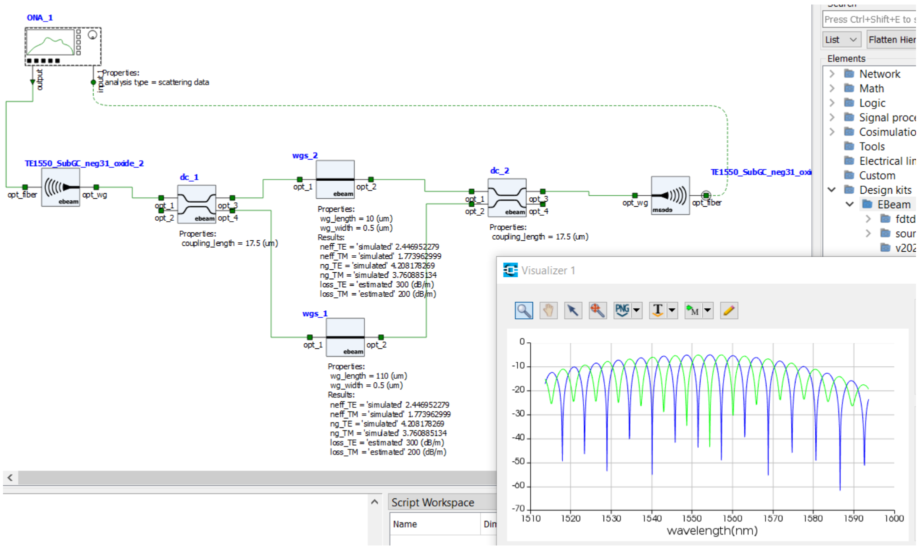

Figure 10 - Transmission of 2x2 MZI circuit (switch cell, in green) and a 1x1 MZI circuit (blue).

2.1.6. Layout

The following layout depicted in Figure 11 was designed as an initial test design, where the components: directional coupler, Y-branch, waveguide and grating coupler were tested. Simulating this layout in Lumerical INTERCONNECT with the mentioned components yielded the presented transmission spectrum, where we can observe the expected MZI behaviour for both output ports.

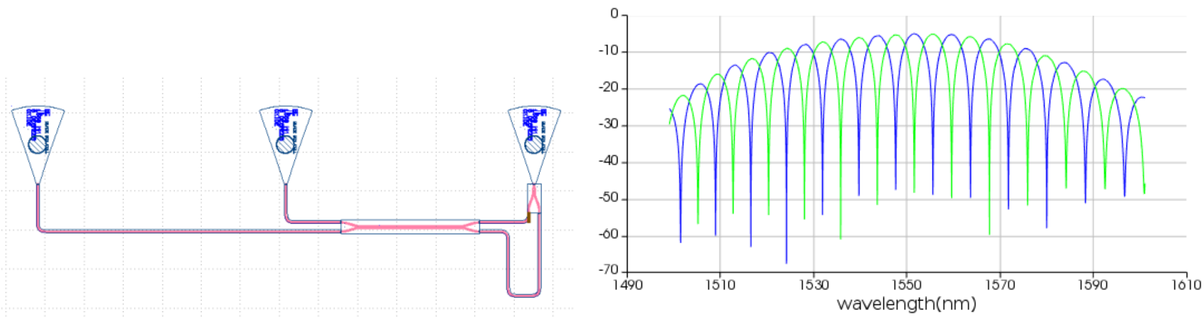

Figure 11 – Layout (left) and transmission spectrum (right) of the first MZI layout, comprised of the fundamental components: 3-dB broadband directional coupler, grating coupler (Dream Photonics), Y-branch splitter, waveguide arms (interferometer).

2.2. Design Proposal Project

In my project, I proposed the implementation of two types of structures, as shown in Figure 12. First, I implemented various MZI circuits with different parameters, since this was suggested in the course as the basic benchmark device for the project. Secondly, I left some space on my floorplan to develop my own proposed device: a 2x2 switch circuit.

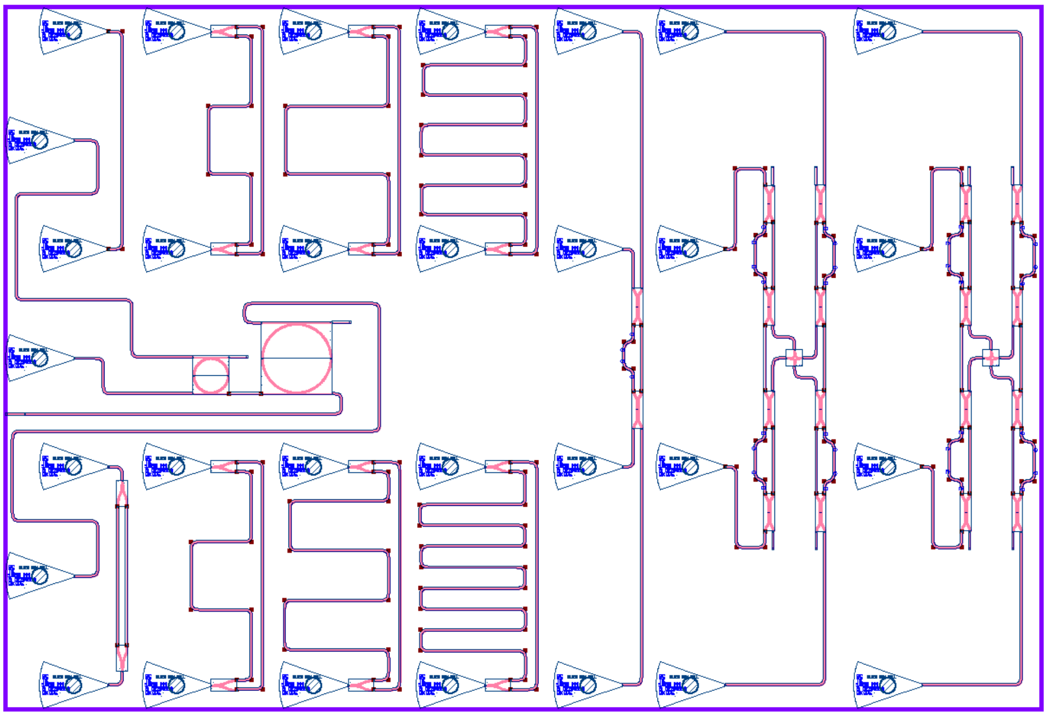

Figure 12 - Full layout of the proposed project design.

To begin with, I established and respected the following layout rules: spacing between waveguides and other devices above $d_{wg} = 6\ \mu m$, spacing between independent GCs above 65 um and spacing between linked GCs fixed at $d_{GC} = 127$ um. Then, I wanted to standardize the geometry of my structures, namely the length of waveguides. Considering that my waveguides are 500x220 nm with a bend radius $r_{bend} = 5\ \mu m$, I calculated the minimum waveguide length between 2 adjacent GCs (spaced 127 μm), which is limited by the bend radius, and given by

$$l_{min}^{GC-GC} = d_{GC} + (\pi - 2) \cdot r_{bend} = 132.708\ \mu m \qquad 5$$

which was standardized to 140 μm (see Figure 13). If we introduce a YB directly connected to the GC pin, it introduces some offset ($w_{offset,YB} = 2.75\ \mu m$) to the waveguide depending on the output, and the expression for the minimum length for the waveguide connected to the inner YB output pin (L_2) thus becomes

$$l_{min}^{YB-YB} = l_{min}^{GC-GC} - 2 \cdot w_{offset,YB} = 127.208\ \mu m \qquad 6$$

standardized to 130 μm (see Figure 13). Conversely, the minimum length for waveguide connected to the outer YB output pin (L_1) is not limited by the bend radius, but by the minimum waveguide spacing. It was thus measured empirically, yielding a minimum length of 154 μm, standardized to 160 μm.

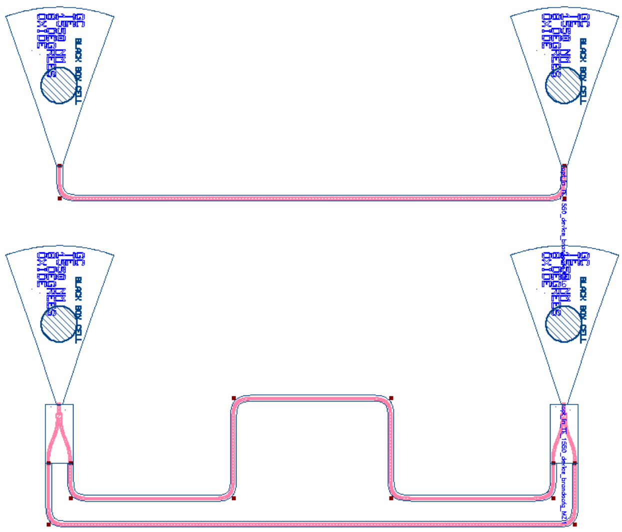

Figure 13 - Design concept (layout) of minimum waveguide length calculation: (top) GC-GC waveguide connection, (bottom) YB-YB waveguide connection.

2.2.1. MZI

The design of the MZI circuit variations exploited the empty space between GCs (see Figure 13), fixing the outer waveguide arm of the MZI at its minimum of 160 μm (L_1), and varying the length of the inner waveguide arm to become longer than 160 μm. To design the MZI lengths, I started with both the analytical and numerical modelling of the MZI circuits, by using the provided MATLAB script (Figure 6) and the Lumerical INTERCONNECT model (Figure 9), respectively. The established lengths for the inner arm were (L_2 [μm]): 180, 200, 250, 360, 480, 600; corresponding to the MZI imbalance lengths (ΔL [μm]): 20, 40, 90, 200, 320, 440. The comparison between both results is depicted in Figure 14, and shows how both approaches align precisely, with only the INTERCONNECT spectra having higher optical losses due to the consideration of losses from the GCs and YBs.

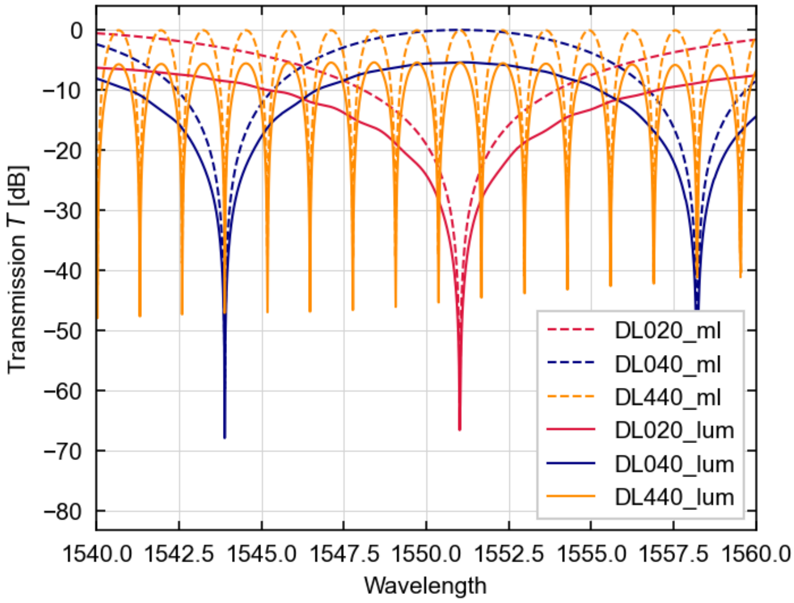

Figure 14 - Transmission spectra for the theoretical ("ml" – MATLAB) and numerical ("lum" – Lumerical INTERCONNECT, solid line) circuit model of the MZI, for the selected configurations: ΔL = 20/40/440 μm.

The layout of this proposed design was implemented in KLayout, and is depicted in Figure 15.

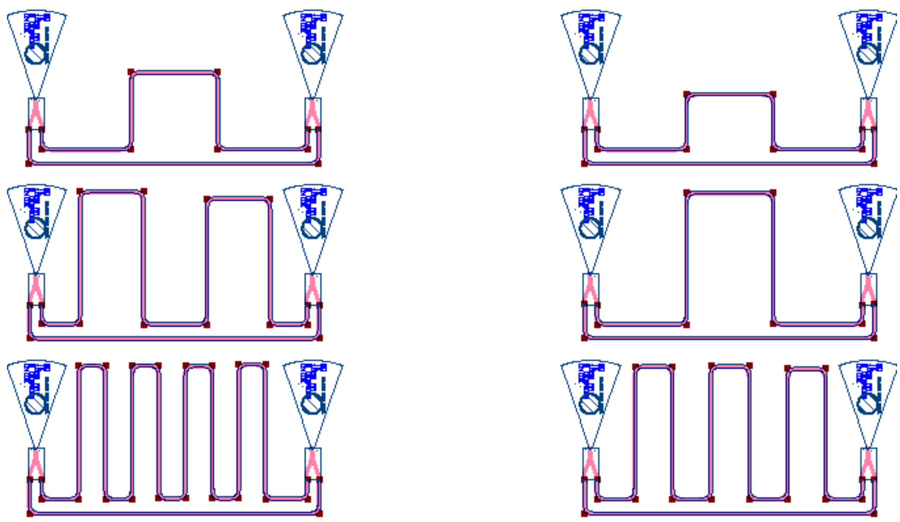

Figure 15 - Layout of the 6 imbalanced MZI configurations, with ΔL = 20-440 μm.

A basic balanced MZI (Figure 16), with a waveguide length of 81.25 μm, was also included in addition to the 6 imbalanced MZIs, resulting in a total of 7 variations. Finally, a calibration structure was also included (Figure 16), which was identical to the GC-GC waveguide connection with a length of 140 μm.

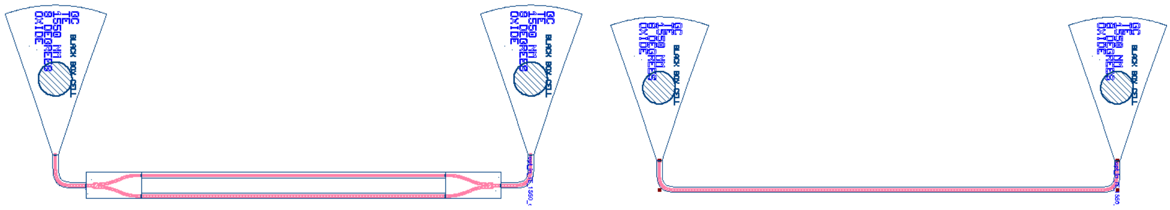

Figure 16 - Layout of (left) the balanced MZI variation and (right) calibration structure.

2.2.2. 2x2 Switch

My project proposal is to try and design a 2x2 switch circuit, inspired by the configuration proposed in Figure 17.[1]. The switch circuit consists of 4 switch cells that can route light into 1 of 2 outputs, similar to the circuit in Figure 11. While in a real PIC these switch cells would be an active component that integrated a phase shifter on one of the arms, since we are designing a passive PIC we use ΔL to control de phase shift, and implement both the bar-state and cross-state configurations in layout.

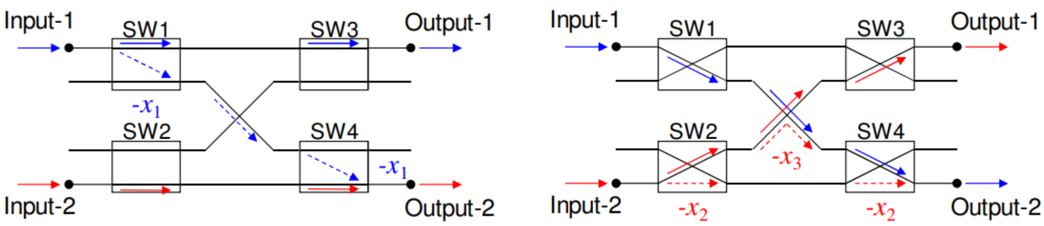

Figure 17 - Schematic 2x2 switch configuration in both (left) bar and (right) cross states.[1]

The switch cell is a 2x2 MZI where the two Y-Branch Splitters are substituted by two 3-dB Directional Coupler (DC) Splitters, wherein constructive/destructive interference will define whether the light is routed (coupled by the DC) to one of the two output waveguides. I started by implementing the fundamental switch cell in layout as presented in Figure 18, setting the spacing between DCs (and thus the straight waveguide length) to 38 μm. The second waveguide incorporated 2 bends to create the imbalanced interferometer configuration. I tried to use a relatively small ΔL to have a larger free spectral range (FSR), which makes it so the operation is more broadband and less sensible to fabrication variations.

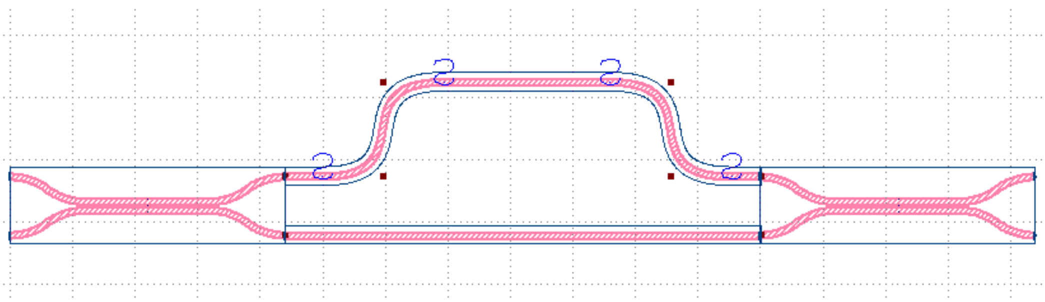

Figure 18 - Layout of the switch cell: a 2x2 MZI that uses 3-dB DC splitters.

The full 2x2 switch circuit presented in Figure 17 was implemented in KLayout, as depicted in Figure 19. This was done by linking 2 switch cells in series, and then cross-routing their inner waveguide arms through a waveguide crossing, to connect to another pair of switch cells. The open waveguides were capped with waveguide terminations (tapers).

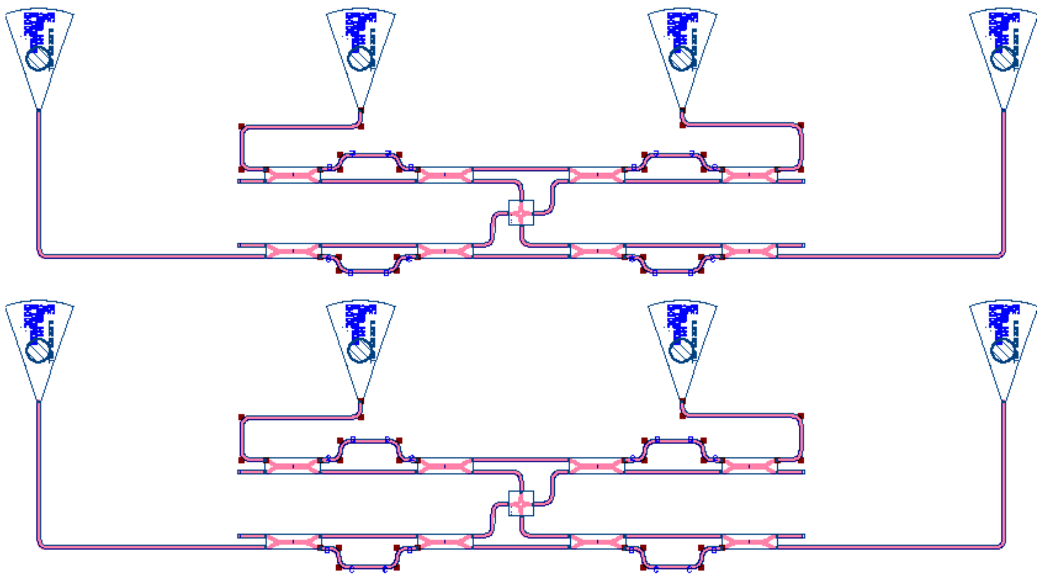

Figure 19 - Layout of a (top) cross-state 2x2 switch (cell "SW1") and (bottom) bar-state 2x2 switch (cell "SW0"). The I/O of the GCs is (left-to-right) $O_3/O_2/I/O_1$. Note that this figure is flipped -90º from the real layout.

In this layout, light will enter through the input (I), and be routed either to output 2 (O_2) or output 3 (O_3), depending on the configuration (ΔL). Meanwhile, output 1 (O_1) is not operational and should have no signal, it will therefore be used to measure backpropagation and crosstalk (unwanted coupling). For the bar-state, light should be routed I–O_3, while for the cross-state it will be routed I–O_2. Thus, I performed circuit simulations in INTERCONNECT directly from the layout, and optimized the ΔL of the switch cells to reach the desired operation. The optimized results were $\Delta L = 8.554$ µm for the bar-state and $\Delta L = 5.074$ µm for the cross-state, the transmission for these configurations are depicted in Figure 20.

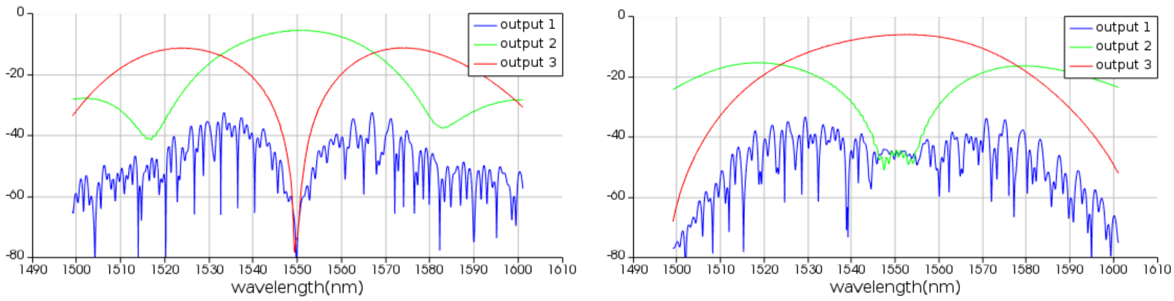

Figure 20 - Simulated transmission of the 2x2 switch in the (left) bar-state: I-O_2, and (right) cross-state: I-O_3.

We can observe that for the proposed configurations the switch works as supposed to, with the bar-state configuration providing the highest transmission around 1550 nm for O_2, and the cross-state providing the highest transmission for O_3 around the same wavelength. Notably, the transmission to O_1 is negligible for both cases, meaning that most light is being transmitted to either O_2 or O_3. In the final layout (Figure 12), a standalone switch cell in cross-state was also included for testing.

2.2.3. Ring Resonators

To make use of the leftover footprint inside the floorplan, I added an experimental circuit which consists of 2 rings, the first with r = 10 μm and the second with r = 20 μm, whose drop ports are each connected to a GC. The resulting layout and simulated transmission are depicted in Figure 21.

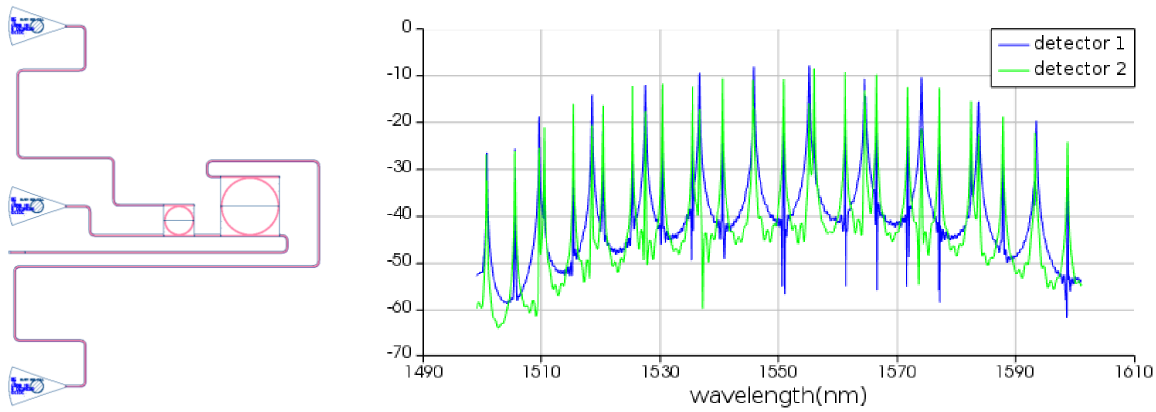

Figure 21 – (left) Layout of the ring circuit and (right) simulated transmission of the rings' drop port, for (detector 1, in blue) r = 10 μm and (detector 2, in green) r = 20 μm.

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