Simulation and design of photonic devices

Introduction

The photonic devices investigated in this study were the directional coupler and the Mach-Zehnder interferometer (MZI). The investigation was conducted to learn how the devices function, determine the accuracy of the simulation and predict the causes of inaccuracy. The design of the directional coupler was considered first, followed by the MZI.

The purpose of the directional coupler is to split a single input wave into two output waves with a desired intensity ratio. The device works by placing a second waveguide in the evanescent field of the input waveguide for a length, L_C, known as the coupling length. As the super modes propagate along the coupling length, the phase difference between them changes. This causes the super modes to periodically interfere with each other resulting in the intensity of light in each waveguide varying as a function of the coupling length. At the end of the coupling length (when the desired splitting ratio is present), the path of each waveguide is bent away from the other so that no more interference can take place.

The MZI is a photonic device designed to attenuate the amplitude of an input wave. An input wave is split into two different arms at a Y-junction. The light travels along the two arms until it reaches another Y-junction where the two waves recombine. The level of attenuation is determined by the path difference of the two arms. The path difference determines the phase difference between the waves when they recombine. As a result, the attenuation of the input wave is controlled by the interference at the combiner.

Directional coupler design and simulation in Lumerical MODE solutions

<u>Simulation setup</u>

Once the dimensions and materials of each layer of the device had been set, the model of the directional coupler was ready to be simulated. The eigenmode solver was used to determine how many modes could propagate through each of the waveguides. The height of each layer was given in the specification which meant the width of the etched core was the only variable used to control how many modes were supported. A waveguide width of 0.35um only supported the fundamental mode, so this width was used.

The 2.5D varFDTD solver was used to simulate the operation of the device. The span in all three dimensions needed to be entered to define the region of simulation. The full width and length of the device was declared along with the height being defined as the etch depth of the core. This meant that the behaviour of light in the silicon substrate, silicon core (below etch depth) and the top oxide weren't simulated. This reduced the simulation time dramatically. The inaccuracy caused by the reduction was negligible because the analysis from the eigenmode solver showed that the waveguides only supported a single mode which meant the total internal reflection condition had been met. Therefore, the light was confined within the waveguide core with some energy in the evanescent field. The energy in the evanescent field decayed exponentially as a function of distance from the waveguide core unless the coupling waveguide was nearby. The coupling length was within the simulation region, so the accuracy of the simulation was insensitive to the reduction. The simulated region was highlighted by orange boundaries as shown in figure 1. PML boundary conditions were used at all the boundaries. This meant that each boundary had a reflection coefficient equal to zero, so no light was reflected.

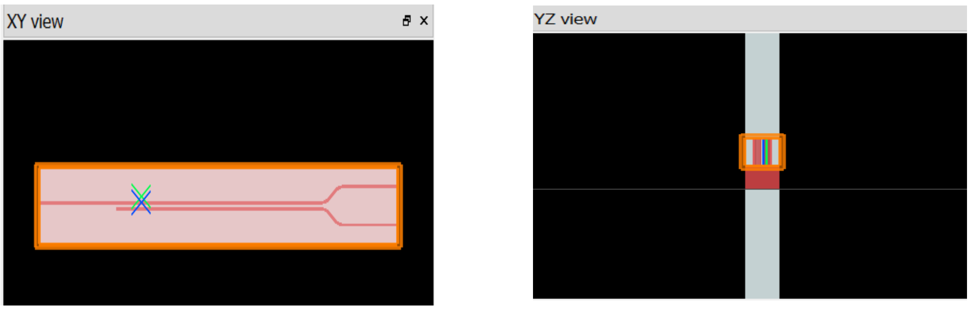

Figure 1: The simulated region from two perspectives. The left perspective shows the region included the full width and length. The right perspective shows the height was the etch depth.

Once the region was defined, the slab mode and test point positions needed to be chosen. The slab mode position was represented by the green cross (off waveguide) and the test point by the blue cross (on waveguide) in figure 1. These points reduced the analysis from a 3-d problem to a 2-d problem. It found the effective refractive index of the device along the z-axis at the test point (Si core only) and the slab point (SiO2 buried oxide only) which covered both effective refractive index states needed to simulate all the co-ordinates in the x-y plane.

<u>Structure of the directional coupler</u>

The rib waveguide structure was used for the device. The specification of the silicon platform with only one of the waveguides is shown in figure 2.

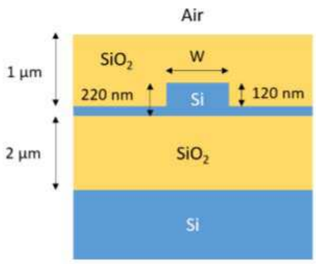

Figure 2: Dimensions of the silicon platform in the y-z plane

All the dimensions along the z-axis were fixed, but the dimensions along the y-axis and x-axis could be designed. Due to the fabrication tolerances, the minimum width of any feature in the design had to be 300nm and the gap between the waveguides had to be greater than 250nm. The total width was chosen to be 8um as this device width was used in previous experiments. The width of the waveguides, the distance between the waveguides and the coupling length were the variables.

The mask design of the device was produced in a 2016 version of L-edit (CAD software). The available standard objects included a 90° bend, so each waveguide used two of these to bend its path away from the other waveguide and then to bend the paths back towards the end of the chip as shown in figure 3.

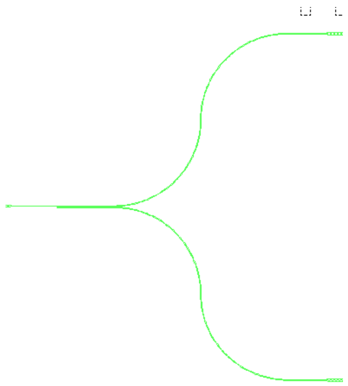

Figure 3: The bends used for the waveguide mask

These bends were different to the ones used in the directional coupler simulation model. However, as the light in that part of the guide wasn't being coupled, the bends could be simulated independently to ensure low loss bends were used. The only restriction on the bends was that they needed the same width as the other part of the waveguide. The loss of a waveguide bend is dependent on its bend radius. A parameter sweep simulated the loss of the waveguide bend with the radius varied between 15um and 40um. The range was limited to this range because many devices needed to fit on the chip. The results from the sweep showed a radius of 30um or above would produce a loss which tended to zero. This is shown by figure 4. A 40um radius was used in the mask design.

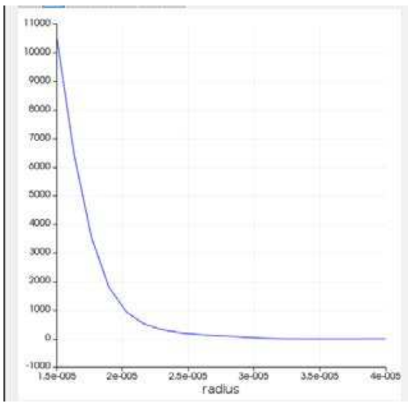

Figure 4: The loss in dB/90° as a function of radius (m)

<u>Optimization of the directional coupler</u>

The waveguide gap was kept at 0.3um. The electric field intensity at the output of the through waveguide (the one which the light entered from) and the output of the coupled waveguide were functions of the coupling length and wavelength. These results are shown in figures 5.

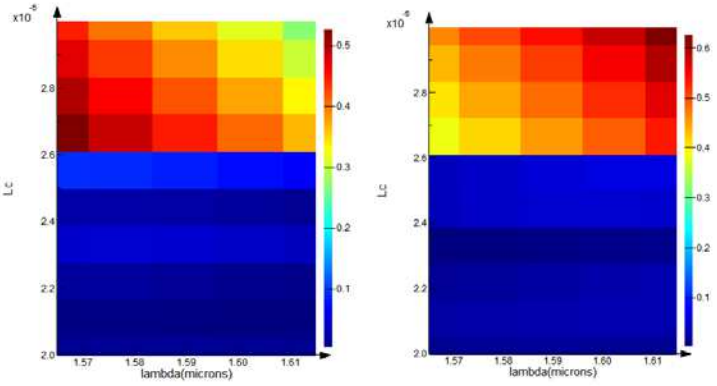

Figure 5: On the left, the electric field intensity at the output of the through waveguide is shown. On the right, the electric field intensity at the output of the coupled waveguide is shown. On both graphs, the wavelength is along the x-axis, the coupling length along the y-axis and colour is used to represent the electric field intensity

A 50:50 splitting ratio at a wavelength of 1590nm was specified. At this wavelength, the intensity was approximately equal between 26um and 27um (intensity scales were different). The accuracy was increased when the coupling length was manually varied between these limits until a 50:50 splitting ratio was achieved. The final coupling length used was 26.5um which produced the coupling shown in figure 6.

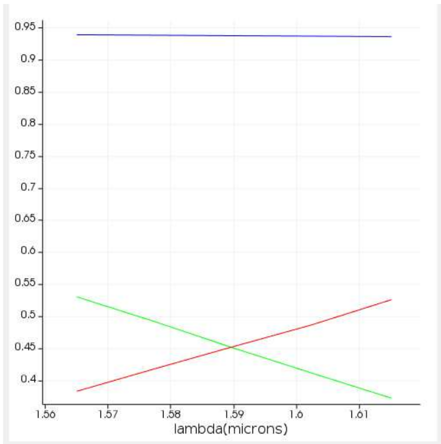

Figure 6: The blue line represents the intensity at the input, the green line represents the intensity at the output of the through waveguide and the red line represents the intensity at the output of the coupled waveguide

The output intensity of both waveguides intersected at 1590nm; thus a 50:50 splitting ratio was achieved. The expected insertion loss was calculated and converted into decibels to give an insertion loss of 0.18dB. The values of the variables which produced these results were:

Coupling length, L_C = 26.5um
Waveguide width, W = 0.35um
Bend radius, R = 40um
Gap, G = 0.3um

<u>Directional coupler variations and potential sources of simulation inaccuracy</u>

The simulated performance of the device was sensitive to a small change in the gap or waveguide width. Eight additional directional couplers were designed to account for fabrication error. Four were designed which accounted for fabrication errors in the waveguide width of 0.35um±0.01 and 0.35um±0.02. Another four were designed which accounted for a fabrication errors in the gap of 0.3um±0.01 and 0.3um±0.02. These devices were simulated to determine the coupling length which provided a 50:50 splitting ratio when each error occurred. In the mask design of the additional devices, the gap and the waveguide width were kept the same as the ideal device, but the simulated coupling lengths were used as it was expected these errors would be introduced during the fabrication process.

The 2.5D varFDTD solver reduced the simulation from 3-d to 2-d. It found the effective refractive index along the z-axis for every co-ordinate in the x-y plane of the simulation region [1]. A simulation of the device with no reductions would be more accurate. A mesh accuracy of 2 was used. This described a low resolution of the finite measurements. If the resolution of the finite measurements was increased, the model would more accurately represent the continuous fields. PML boundaries were used, these totally absorbed the light at the boundaries. Realistically, the interface between the device and its surroundings wouldn't behave like this and some reflection would occur. A customised model of the boundary would result in a realistic reflection coefficient.

Mask design

A normalisation structure was included in the mask design for each variation of the directional coupler. It provided a method to calculate the insertion loss. The normalisation structure had the same input and output coupling structures as the directional coupler; however, there was only one output. These coupling structures were connected directly to each other as shown in figure 7.

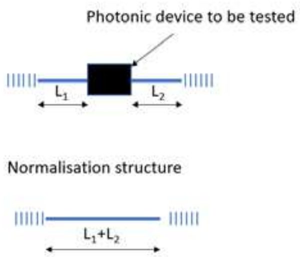

Figure 7: A generic comparison between a device with its coupling waveguides and its respective normalisation structure

If the circuit with the device and its corresponding normalisation structure have identical inputs, the insertion loss can be calculated. The insertion loss can be calculated by measuring the total output intensity from the device and the output intensity from the normalisation structure. The ratio of the two measurements eliminates the loss caused by the grating couplers and the waveguides guiding light to and from the device. This results in the loss induced by adding the device to the circuit.

To calculate the propagation loss of a directional coupler, the attenuation coefficient of a wave propagating through the device had to be calculated. The cut-back method was used to do this. A copy of the directional coupler was made but the length of the input of the device was increased without the coupling length being changed. The original device and its copy had a path length of L_1 and L_2 respectively. The attenuation coefficient could be calculated by finding the ratio of the total output intensity of the original device (I_1) and the copied device (I_2). This equation could be rearanged to make the attenuation coefficient the subject as shown in equation 1.

$$\alpha = (1/(L_1 - L_2))*\ln(I_2/I_1)$$

Equation 1: the propagation coefficient using the cut-back method

Conclusion

The simulation process of the directional coupler produced several potential sources of inaccuracy. The 2.5D varFDTD solver significantly reduced the required computation of the simulation by collapsing the problem into 2 dimensions. Since the slab and test points only passed through one material each along the z-axis, I expect this reduction to cause no simulation inaccuracy. To get a precise splitting ratio, the dimensions of the directional coupler need to be very accurate. As the dimensions of the directional coupler were in the order of micrometres, I think a higher resolution mesh accuracy should have been used because the device was very sensitive to small errors in the dimensions. This would have increased the amount of computation, but I expect it would reduce the inaccuracy. I predict the use of the PML boundaries to have little effect on the inaccuracy of the simulation. I expect this because the fields decay exponentially as the distance increases from the silicon waveguides. Therefore, after the light has travelled the distance to the boundary, I expect the energy in the waves to have dissipated. I expect the overall accuracy of the simulation to be very high, but the trade off between the level of accuracy and the computational power being used must be weighed up by the designer.

I think the main source of error will come from the difficulty in accurately realising the simulated device. Additional directional couplers were fabricated to account for the fabrication error in the width and gap. However, this assumed only one error would happen at a time. If a combination of these errors occurred, there wasn't a device fabricated which would perform as desired. The fabricated directional couplers which assumed an error needed the error accounted for to be realised on its corresponding device. The probability of that happening should be investigated to determine if there is any value in making devices which assume a fabrication error. Finally, the simulation model doesn't account for any misalignments between parts of the waveguide. This is a potential source of loss which is unaccounted for.

Due to time constraints, the MZI wasn't studied in this report. However, from my study of the directional coupler; I would expect similar results which suggest the inaccuracy lies with the difficulty in reproducing the simulation model. Further work should consider one of two pathways. Finding ways to reduce the sensitivity of the device's performance to common fabrication errors; or finding methods to increase the accuracy of the fabrication process.

References

[1] Lumerical, (N/a). Knowledge base- varFDTD. [Online] Available at: https://kb.lumerical.com/solvers_varfdtd.html [Accessed 23/04/2019]