# Design Proposal: Mach-Zehnder Interferometer

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## I. Introduction

The Mach-Zehnder interferometer (MZI) is a fundamental building block in silicon photonics. A basic MZI consists of a beam splitter that divides the input light into two optical paths, two waveguides that have different lengths and a beam combiner that recombines the light from the two waveguides. The phase shift between the two beams can cause constructive or destructive interference.

This paper analyzes four design scenarios. First is the effect of varying the difference of lengths between the two optical paths (ΔL). Second is comparison of two designs with the same ΔL, but difference in geometry, the other having multiple waveguide bends. Third is a comparison between a Y-branch splitter and a directional coupler. And last is a check for manufacturing repeatability.

## II. Theory of MZI

The length difference between the two waveguides in the MZI causes the system to be imbalanced. One parameter for comparing the designs is the free spectral range (FSR) of the imbalanced interferometer which indicates the spacing between adjacent peaks. This is calculated as,

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

where $\lambda$ is the wavelength of interest, and $n_g$ is the group index which describes how fast the light travels through the waveguide. The group index is calculated as,

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

where n is the effective index of refraction of the waveguide. The effective index depends on the wavelength and the mode in which the light propagates.

## III. Modeling and Simulation

The waveguide used in the designs has width of 500nm, height of 220nm and bend radius of 5 microns. A calibration model is included in the design. To make measurements, each end of the waveguide is connected to a fiber grating coupler as shown in Figure 1. The design is done in KLayout software and simulation is done on Lumerical Interconnect software. The gain of the waveguide is shown in Figure 2 and Table 1, and the energy intensity is shown in Figure 3.

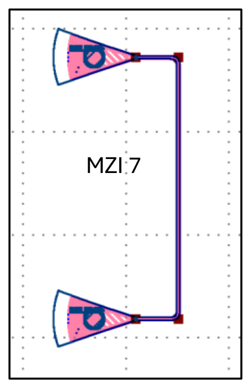


Fig. 1 – Calibration

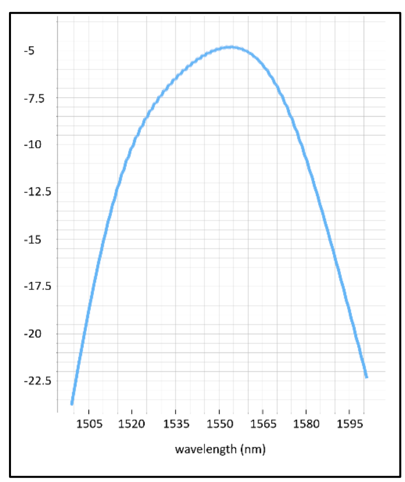


Fig. 2. Gain (dB) vs. wavelength of waveguide

| mode # | effective index | wavelength (µm) | loss (dB/cm) | group index | TE polarization fraction (Ex) |
|---|---|---|---|---|---|
| 1 | 2.444580+1.249232e-09i | 1.55 | 0.00043985 | 4.201897+2.633171e-09i | 98 |
| 2 | 1.783803+8.168373e-10i | 1.55 | 0.00028761 | 3.595479+4.485396e-09i | 4 |

Table 1. Gain (dB) vs. wavelength of waveguide

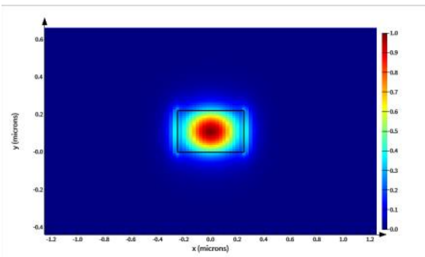


Fig. 3. Waveguide energy intensity

The base model of the MZI has two Y-branch splitters and two waveguides of lengths 165 micron and 190 micron as shown in Figure 4. The shortest length is kept constant, and the second waveguide is varied, as shown as MZ3, MZ4 and MZ5.

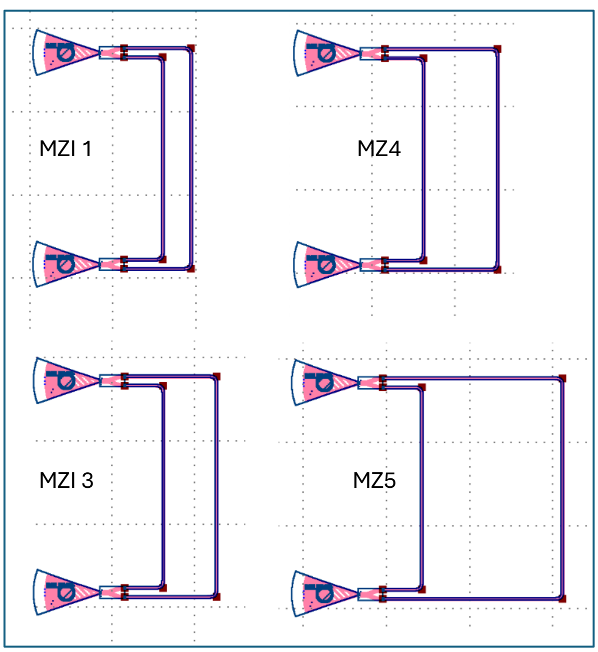


Fig. 4 – MZI model

Figure 5 shows the results of the simulations of the four different designs varying $\Delta L$.

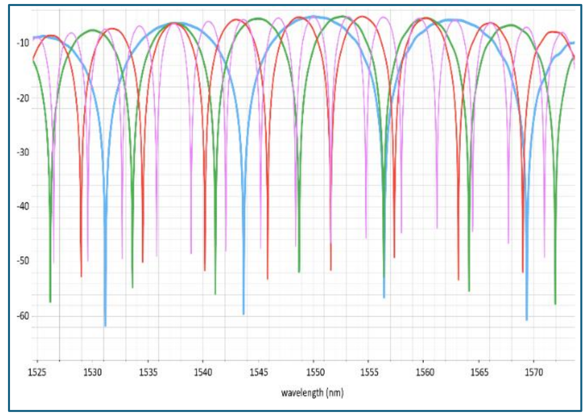


Fig. 5. Gain (dB) vs. wavelength

The bigger the length difference, the narrower the spacing between the adjacent peaks, which results in a smaller FSR as shown in Table 2.

| L1 (micron) | L2 (micron) | $\Delta L$ (micron) | FSR (nm) | Legend |
|---|---|---|---|---|
| 165 | 210 | 45 | 13.2 | Blue |
| 165 | 240 | 75 | 7.8 | Green |
| 165 | 265 | 100 | 6.03 | Red |
| 165 | 345 | 180 | 3.37 | Magenta |

Table 2. FSR for different $\Delta L$

The second analysis has the same $\Delta L$, but difference in geometry as shown in Figure 6. Both designs have 250 micron $\Delta L$.

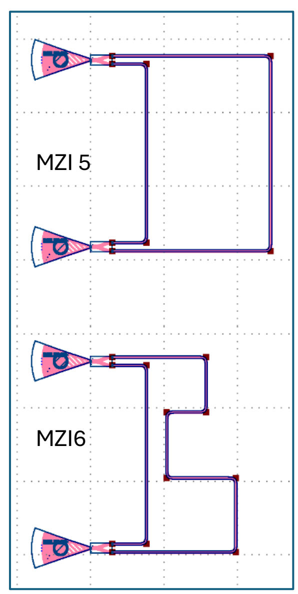


Fig. 6. Same $\Delta L$ but different geometry

Simulations show that the FSR between the two designs are the very close as shown in Figure 7.

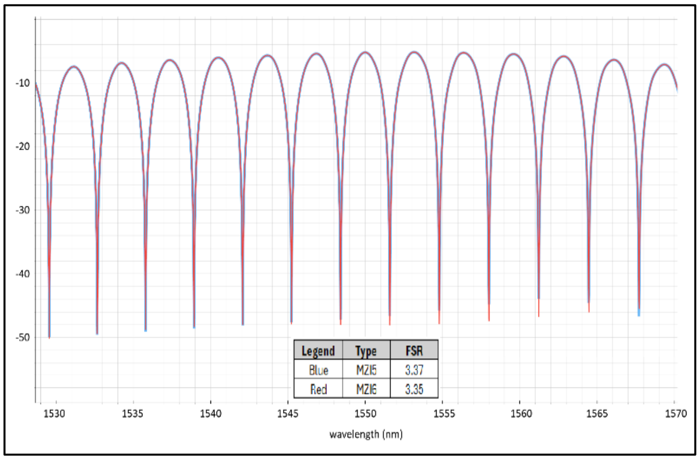


Fig. 7 – Effect of difference in geometry

The third analysis is comparing a Y-branch splitter and a directional coupler. Design is shown on Figure 8. The result of the simulation shows a closely matched gain for the Y-branch and the directional coupler as shown in Figure 9.

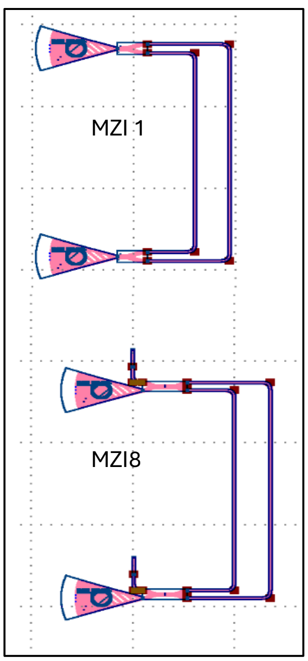


Fig. 8 – Design of y-branch splitter and directional coupler

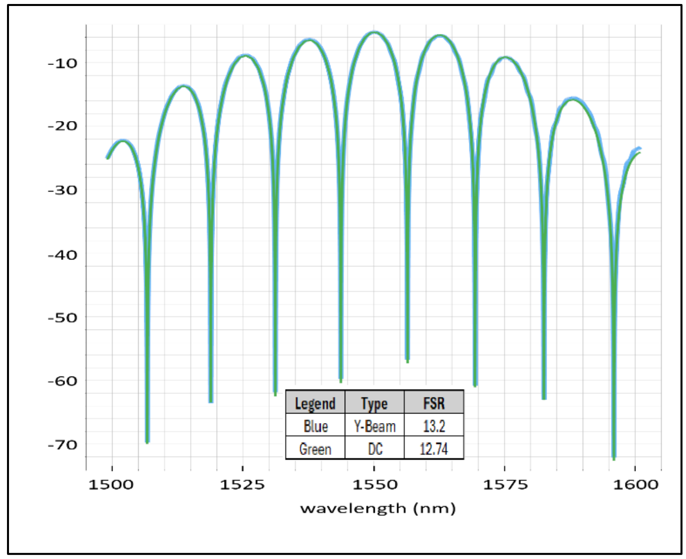


Fig. 9 – Gain (dB) vs wavelength of y-branch splitter and directional coupler

The last analysis compares the manufacturing repeatability. The MZI1 design in Figure 1 is duplicated. The simulation will show the same results. The fabrication environment will induce some difference. The results from the actual test will be compared to the simulations.

## IV. Corner Analysis

The manufacturing of the silicon photonics devices has challenges due to the variability of the wafer thickness and feature sizes. To take these variations into account, the simulations can be done through corner analysis as shown on Table 3. The simulations are run with different waveguide width and height which results in a varying effective index, group index, dispersion and FSR.

| | | | | | | MZI FSR (nm) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Corner | Width | Height | Effective Index | Group Index | Dispersion (s/m^2) | ΔL = 45 μm | ΔL = 75 μm | ΔL = 100 μm | ΔL = 180 μm |
| FS | 470 | 223.1 | 2.40205 | 4.2414 | 0.000432422 | 12.58756281 | 7.552537684 | 5.664403263 | 3.146890702 |
| FT | 470 | 220 | 2.38606 | 4.23049 | 0.00034179 | 12.62002484 | 7.572014904 | 5.679011178 | 3.15500621 |
| FF | 470 | 215.3 | 2.36859 | 4.22539 | 0.000220728 | 12.63525707 | 7.581154245 | 5.685865683 | 3.158814269 |
| TS | 500 | 223.1 | 2.4561 | 4.18763 | 0.000427645 | 12.74918961 | 7.649513766 | 5.737135325 | 3.187297403 |
| TT | 500 | 220 | 2.4404 | 4.17683 | 0.000352986 | 12.7821551 | 7.66929306 | 5.751969795 | 3.195538775 |
| TF | 500 | 215.3 | 2.42296 | 4.17285 | 0.00026126 | 12.79434652 | 7.676607914 | 5.757455935 | 3.198586631 |
| SS | 510 | 223.1 | 2.46951 | 4.17035 | 0.00040014 | 12.80201635 | 7.681209811 | 5.760907358 | 3.200504088 |
| ST | 510 | 220 | 2.45375 | 4.16027 | 0.00033651 | 12.83303461 | 7.699820765 | 5.774865574 | 3.208258652 |
| SF | 510 | 215.3 | 2.43648 | 4.15609 | 0.000247829 | 12.84594147 | 7.707564883 | 5.780673662 | 3.211485368 |

Table 3. Corner Analysis of MZI

Monte Carlo Simulation runs multiple executions of the simulation which incorporates randomness in each execution. Figures 10 to 13 are the results of the Monte Carlo Simulations for the MZI1 – with Y-branch splitter.

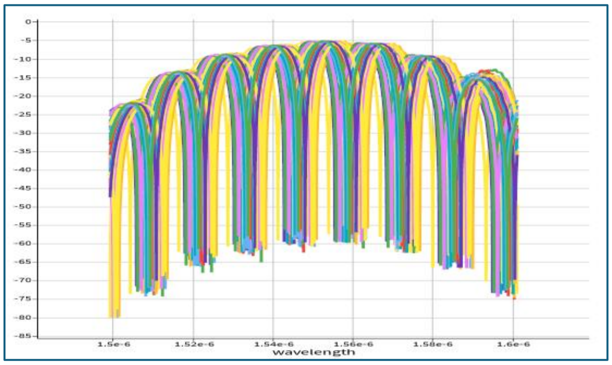

Fig. 10 – MZI1 Gain (dB) plot using Monte Carlo Simulation

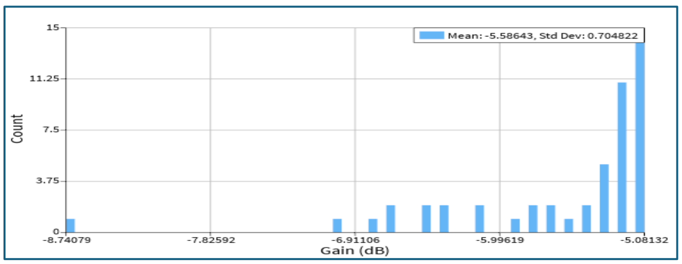


Fig. 11 – MZI1 Gain (dB) distribution using Monte Carlo Simulation

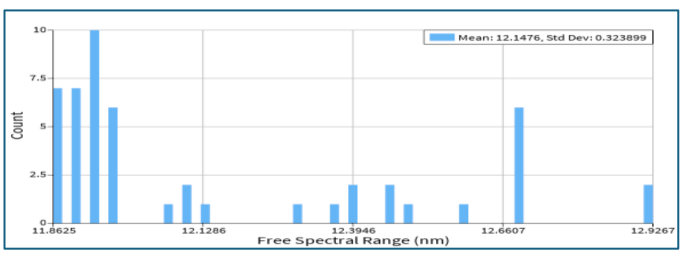


Fig. 12 – MZI1 FSR distribution using Monte Carlo Simulation

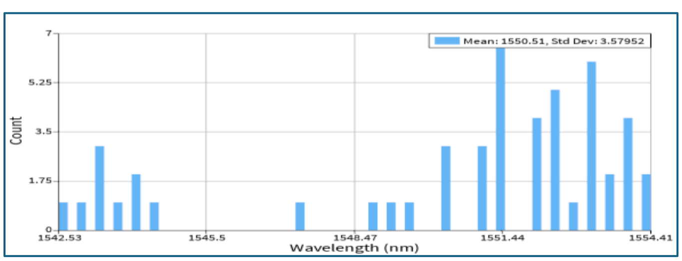


Fig. 13 – MZI1 wavelength distribution using Monte Carlo Simulation

Figures 14 to 17 are results of the Monte Carlo Simulations for the MZI8 – with directional coupler.

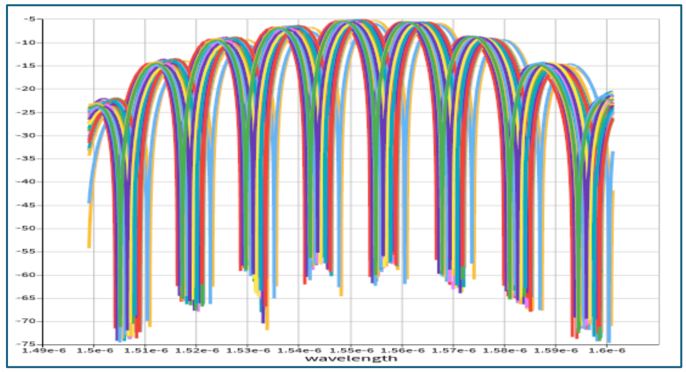

Fig. 14 – MZ8 Gain (dB) plot using Monte Carlo Simulation

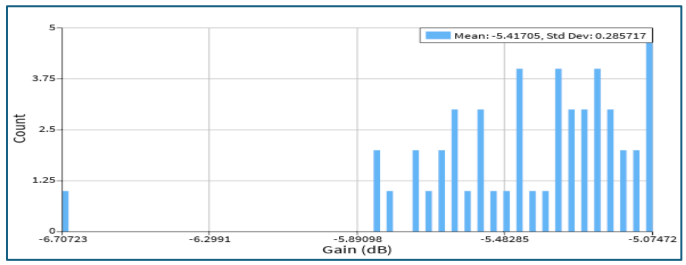


Fig. 15 – MZ8 Gain (dB) distribution using Monte Carlo Simulation

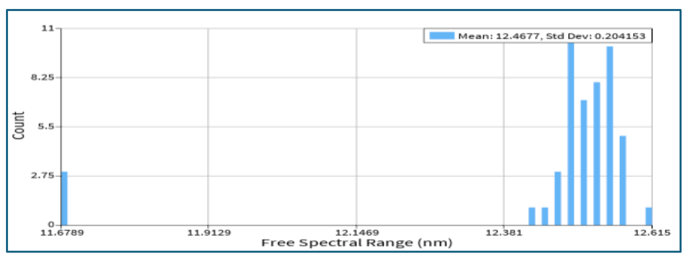


Fig. 16 – MZ8 FSR distribution using Monte Carlo Simulation

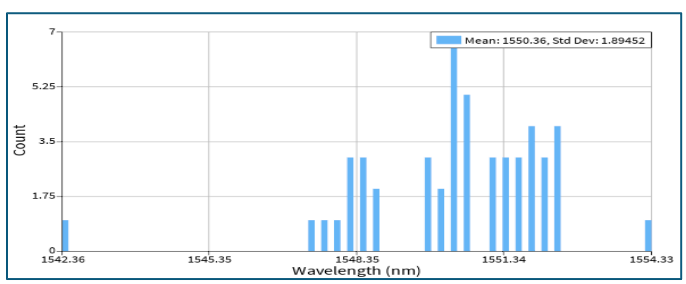


Fig. 17 – MZI8 wavelength distribution using Monte Carlo Simulation

## V. Measurement Data

After fabrication, actual measurements are taken from the die using an optical probe station. Optical fibers are used to send and receive light from the grating couplers of the devices.

Figure 18 is the measurement of the calibration circuit. The blue superimposed blue curve is the simulation of the calibration circuit with x-axis in scale, but with y-axis not in scale. The purpose is to show that the peak wavelength of the actual measurement is shifted to the left. This observation can be seen across all the designs.

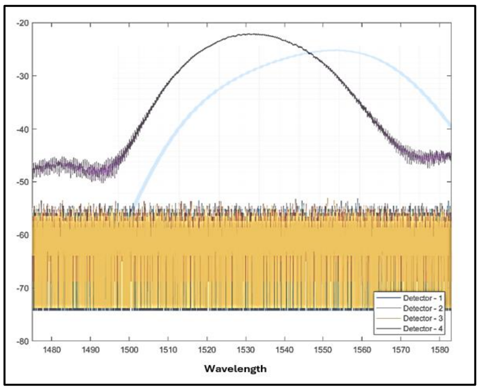


Fig. 18 – Gain of Calibration Waveguide

For the first analysis, Figure 19 validates that the varying $\Delta L$ results to different FSR. MZI1 has the smallest $\Delta L$ and has the widest spacing of the peaks. MZI4 has the largest $\Delta L$ and has the narrowest spacing of the peaks.

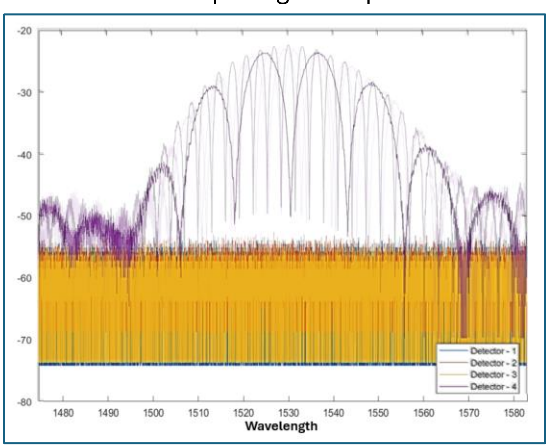


Fig. 19 – Gain of MZI with varying $\Delta L$

For the second analysis – MZI with the same $\Delta L$, but difference in bends, the measurement in Figure 20 shows the same results for both, which validates the simulations.

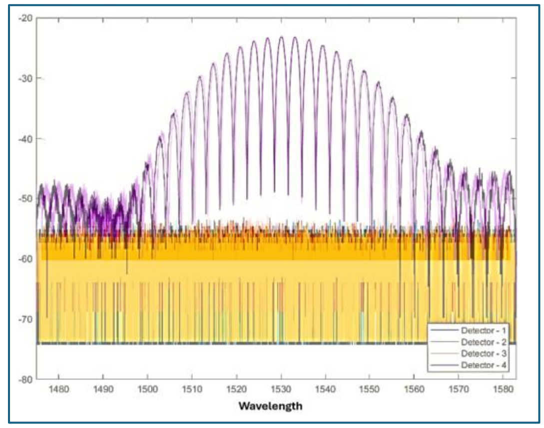


Fig. 20 – Gain of MZI5 and MZI6

The third analysis is the comparison of a Y-branch splitter and a directional coupler. Figure 21 shows that a directional coupler is lossy compared to a Y-branch splitter.

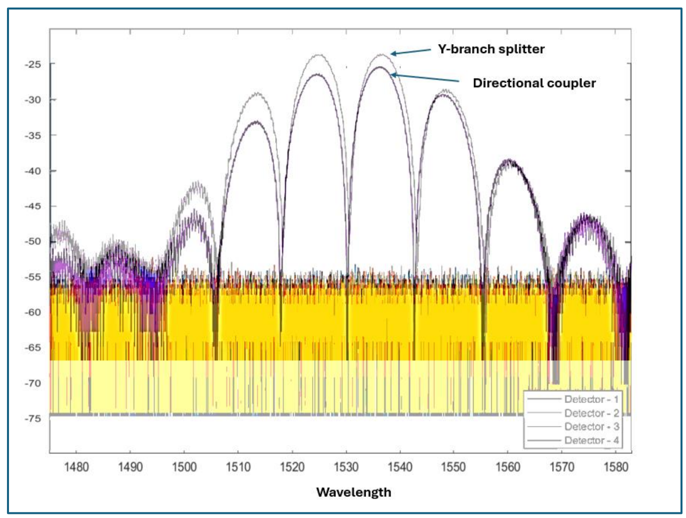


Fig. 21 – Gain of Y-branch splitter and directional coupler

The final analysis on the repeatability of the fabrication is shown in Figure 22. Although the two MZI's are the same, different gains are observed in some peaks. This validates that there can be die to die variation within a wafer.

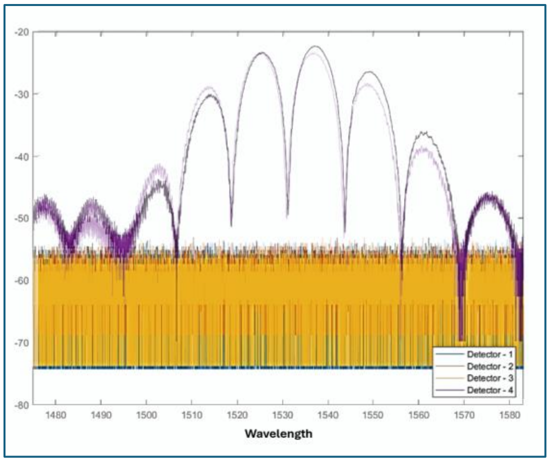


Fig. 22 – Gain the two same MZI designs

## VI. Conclusion

The simulation results of the different designs described in this paper confirm the theoretical behavior of the Mach-Zehnder interferometer given different lengths of the waveguide. The actual measurements validate the simulations. Further research though is needed to understand what causes the shift of the peak wavelength in the actual measurement versus the design simulations.

## VII. Reference

The main reference of this paper is the "Silicon Photonics Design" book by Lukas Chrostowski and Michael Hochberg.