Mach-Zehnder Interferometer Design

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1 Introduction

This report focuses on the design and development of a Mach-Zehnder Interferometer (MZI), with the goal of creating an interferometer which generates a 25GHz output spacing when a wavelength of 1310 nm is used. The report will cover my design considerations of waveguide geometries, path difference, and waveguide routing. The report will explore two manufacturing techniques, one with a silicon waveguide core and silicon dioxide cladding, and one where the silicon rests on top of a silicon dioxide layer, but the air acts as a cladding. The second chip design will have an on-chip laser. The goal of this experiment is to compare multiple manufacturing techniques and laser classes, and observe how their properties impact the performance.

2 Background Information

This section will be used to provide some background information about how to simulate waveguides theoretically.

3 Chip Designs

3.1 Chip 1 Design

To determine a variety of path length differences, a variety of waveguides were simulated using the LUMERICAL MODE software. The following procedure was followed to determine the group index of a waveguide, and then the required path length difference to achieve the necessary FSR for this group index.

3.1.1 Procedure

1. Create waveguide in LUMERICAL MODE by changing the size of a silicon rectangle within the silicon dioxide cladding.

2. Set test wavelength to 1310 nm and simulate the modes for a TE polarized wave.

3. Look at the output table to determine the value of the group index for the given waveguide.
4. Calculate the necessary path length difference to achieve a FSR of 25 GHz (From Python Calculation).
5. Create a waveguide model by running a frequency sweep from 1270 nm to 1330 nm and export this model for future INTERCONNECT simulations.
6. Repeat these steps for a variety of waveguide sizes based on manufacturing tolerances, and determine a variety of path length differences.

The path differences below were calculated using the formula:

$$\Delta L = \frac{c}{n_g FSR}$$

where $FSR = 25$ GHz

3.1.2 Results

Design #	**Waveguide Size**	**Group Index**	**Path Difference**
1	350 x 220	4.507478	2660.40
2	360 x 230	4.469343	2683.10
3	360 x 210	4.466558	2684.77
4	340 x 230	4.525866	2649.59
5	340 x 210	4.518220	2654.08

Table 1: Waveguide Path Difference Calculation

3.1.3 Designs

Based on the results from my simulations above, I identified 3 key path length differences, to capture a variety of possible waveguide sizes: 2660 nm, 2684 nm, and 2652 nm. For my Chip 1, I chose to design three similar waveguides using a spiral but with these 3 variations in waveguide length, and then I wanted to test out two alternative designs which incorporated a different routing style, and for these two chips I designed for a 2660 nm and a 2684 nm path length difference. The final layout of my chip 1 design can be found in figure 1 below.

After creating the designs, I chose to measure their exact path length differences, and from this construct a table of the expected FSR values for each design. This information is in table 2 below.

3.2 Chip 2 Design

The process for designing chip 2 was very similar to chip 1, but the main discrepancy between the two designs was that chip 2 uses air as its waveguide cladding.

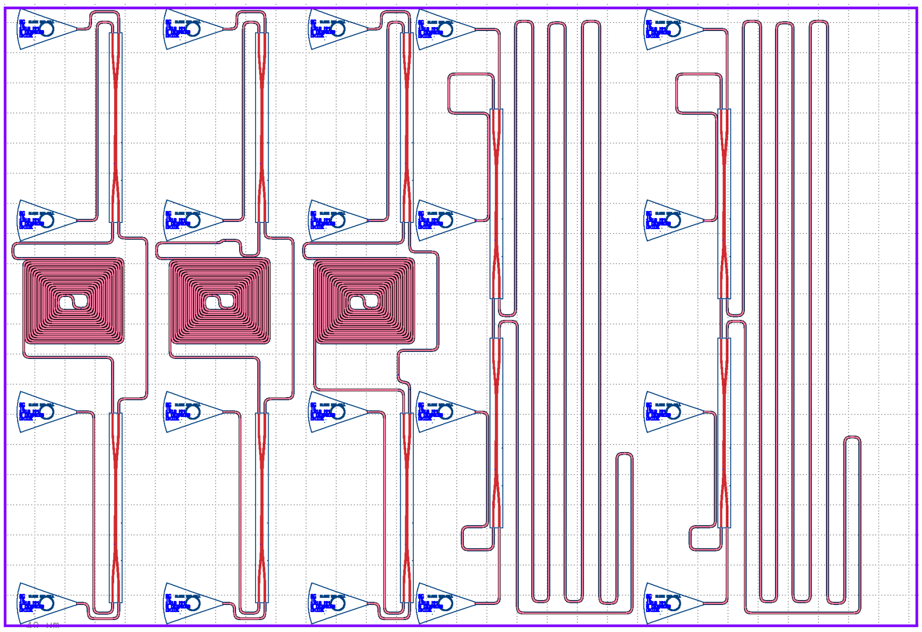


Figure 1: Final chip 1 design with five experiments.

Table 2: Theoretical vs Simulated FSR Values

Design #	Δ L (um)	Expected FSR (GHz)	Simulated FSR (GHz)
1	2664.16	24.96	
2	2683.86	25.01	
3	2652.15	24.97	
4	2660.16	24.94	
5	2684.93	25.02	

3.2.1 Procedure

1. Create waveguide in LUMERICAL MODE by putting a rectangle of silicon with dimensions 350nm x 220 nm on top of a large rectangle of Silicon Dioxide.

2. Set test wavelength to 1310 nm and simulate the modes for a TE polarized wave.

3. Look at the output table to determine the value of the group index for the given waveguide.

4. Calculate the necessary path length difference to achieve a FSR of 25 GHz (From Python Calculation).

5. Create a waveguide model by running a frequency sweep from 1270 nm to 1330 nm and export this model for future INTERCONNECT simulations.

6. Create a waveguide design in KLayout with the calculated path length difference and simulate the design to find the FSR.

The path differences below were calculated using the formula:

$$\Delta L = \frac{c}{n_g FSR}$$

where $FSR = 25$ GHz.

3.2.2 Results

From the LUMERICAL MODE simulation, the group index for the calculated wave was found to be 4.78668, and so the path length difference was found to be 2505.22 um.

$$\Delta L = \frac{c}{n_g FSR} = \frac{2.99e8}{(4.78668)(25e9)} = 2505.22 \mu m$$

3.2.3 Design

Due to the constraint of there only being one on-chip laser, I chose to create an interferometer with a path length difference of 2505.22 um, as this should give me the highest likelihood of achieving a 25 GHz spacing. My design can be found in figure 2.

4 Experimental Testing

4.1 Procedure

4.2 Results

5 Results and Analysis

6 Conclusion

7 Future Work

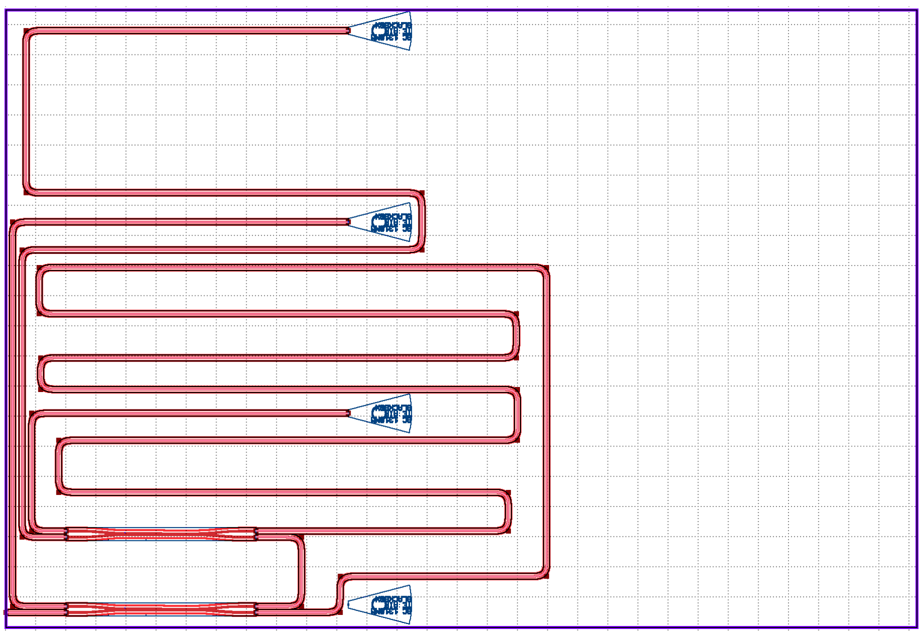
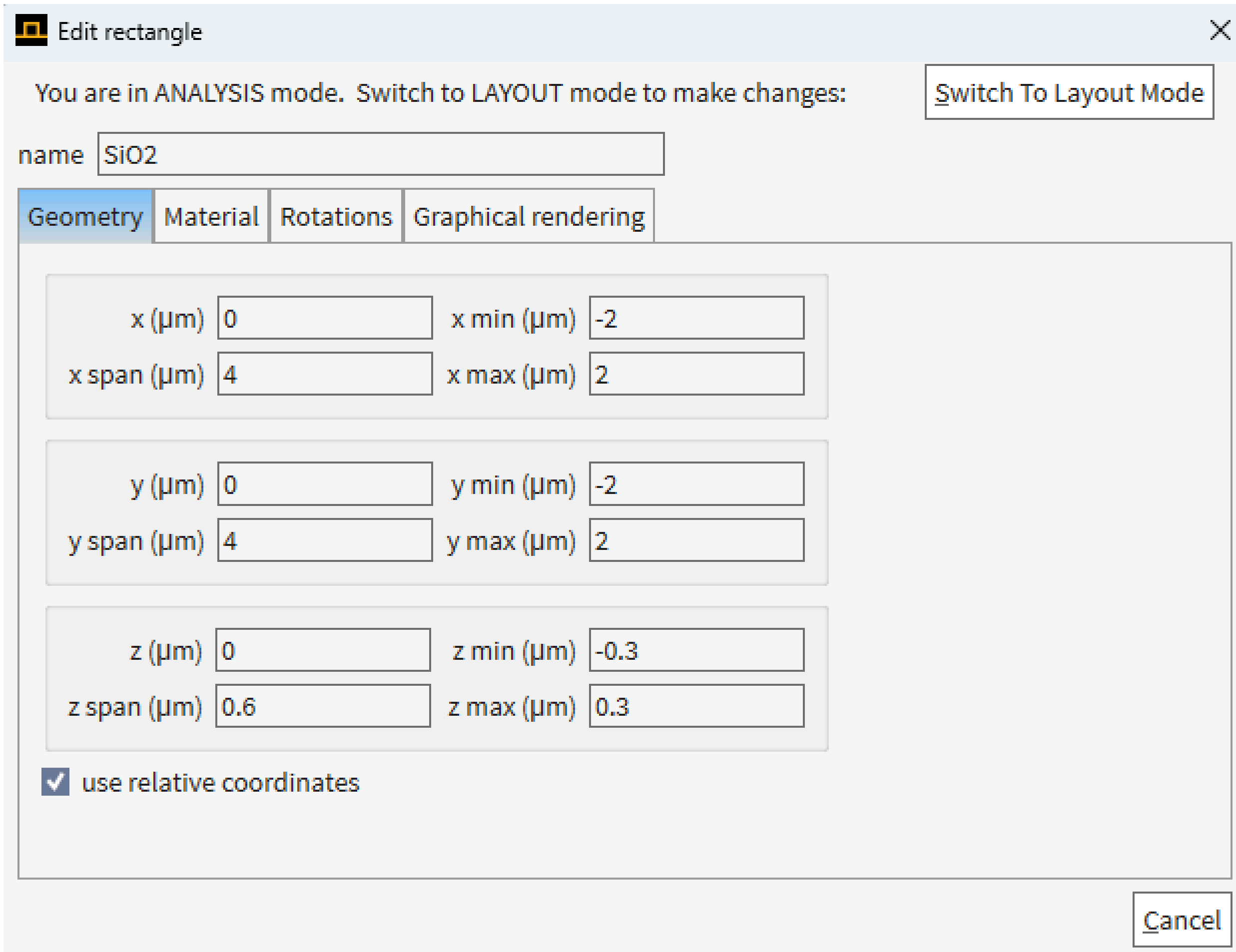


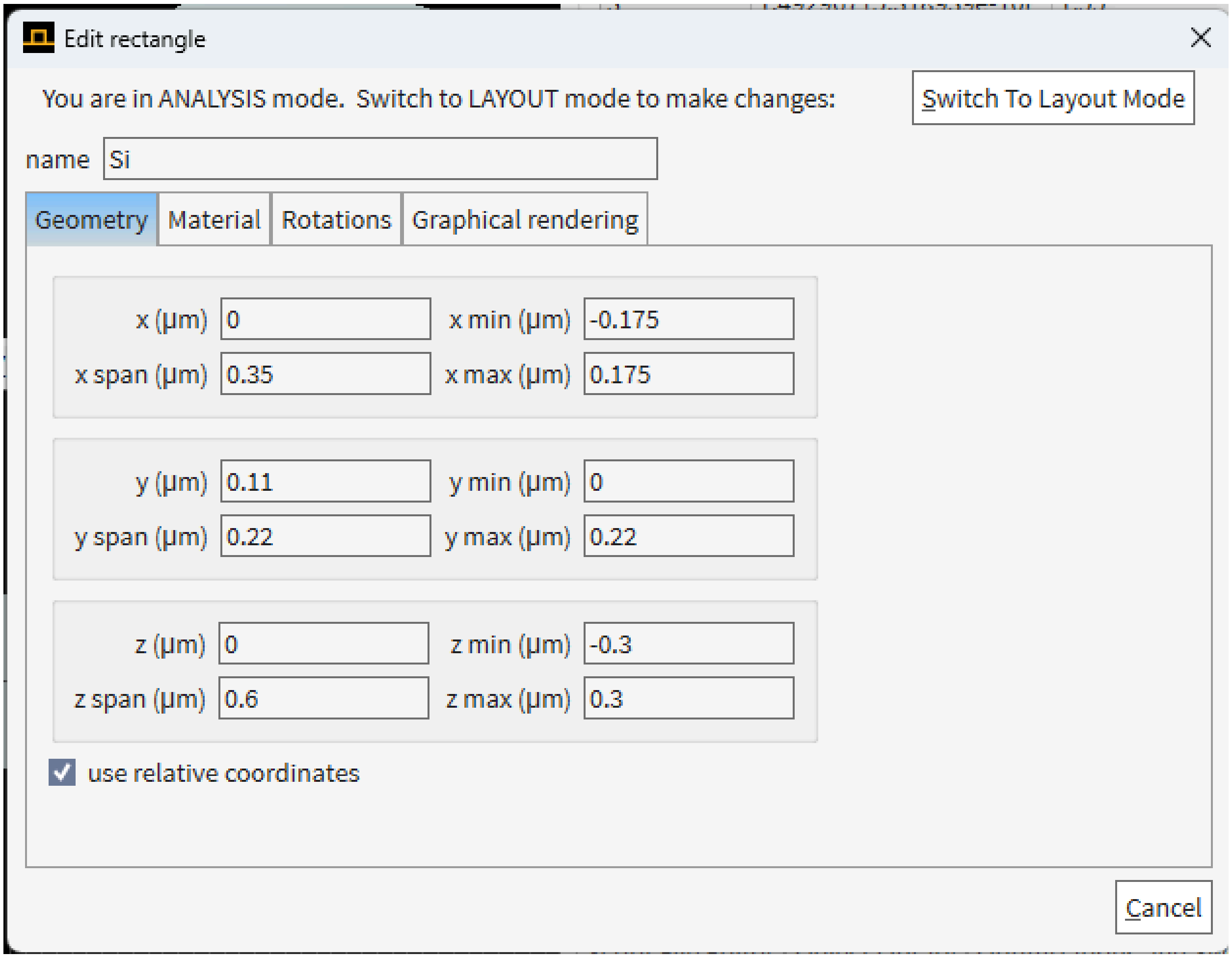
Figure 2: Chip 2 KLayout Design

Lumerical Mode Simulation

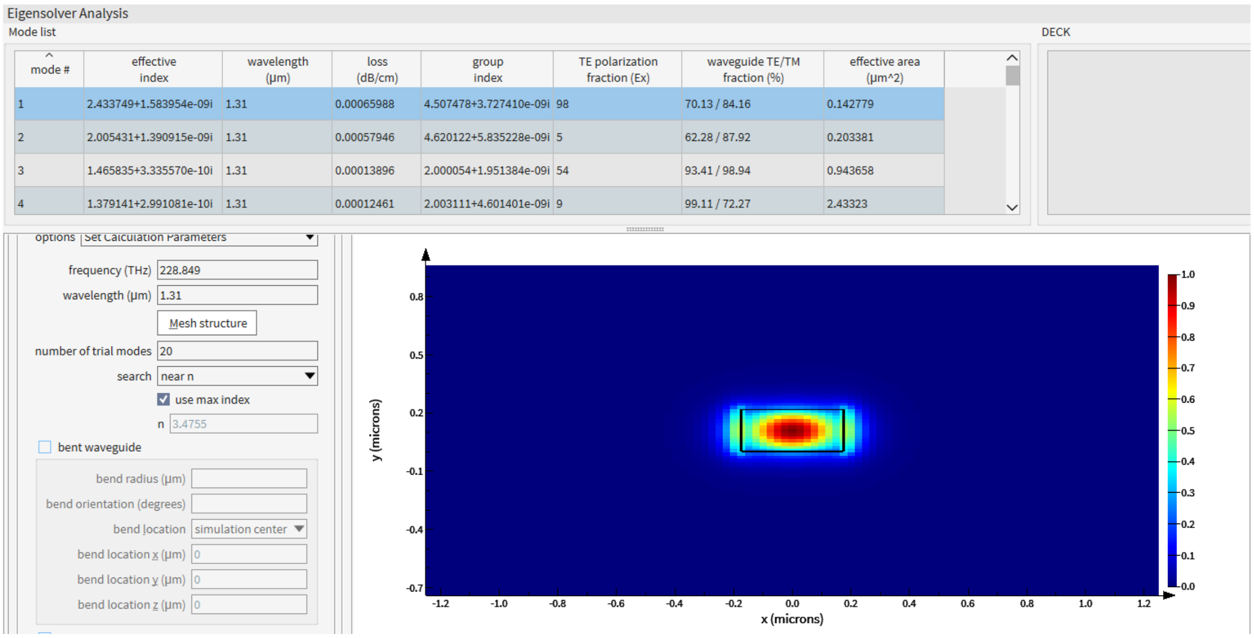
I kept the SiO2 material to be the same size with the settings from the videos on MODE.



Because our project deals with a 350 nm waveguide rather than a 500nm waveguide, I changed the Si geometry to have a 350nm x span. I kept the y span the same as we are not changing the waveguide thickness, just its width.

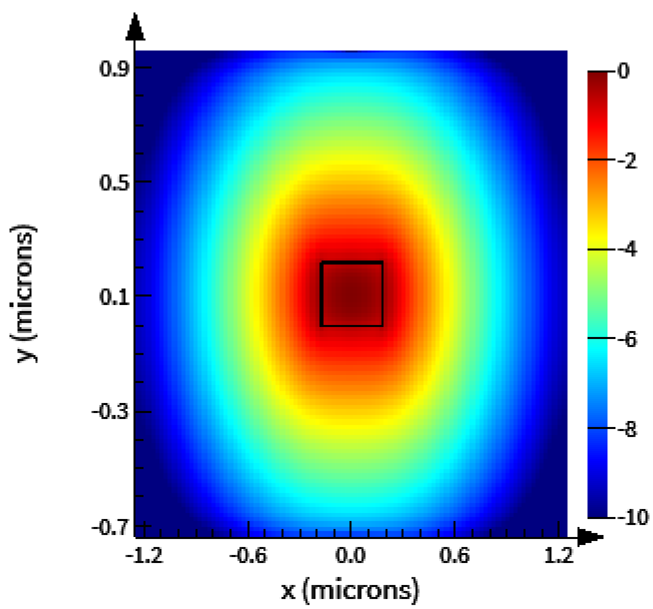


When simulating with the 1310 nm wavelength, we need to change the wavelength parameter in the modal analysis tab.

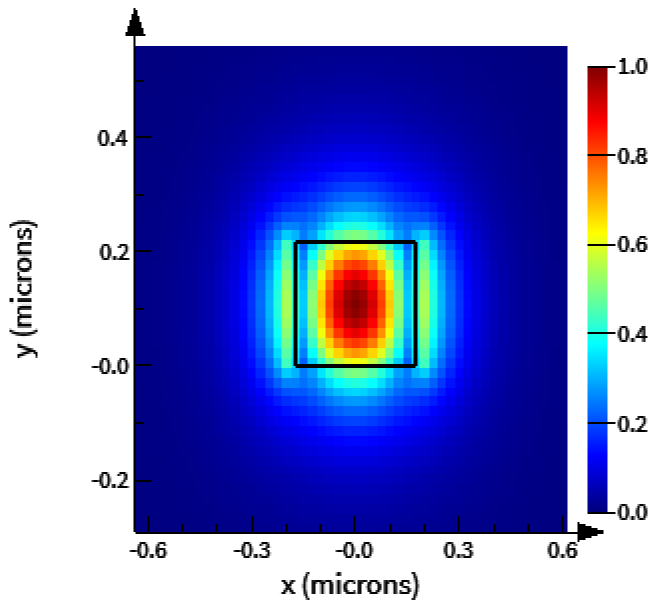


The effective Index after simulation is 2.434. With a group index of 4.507.

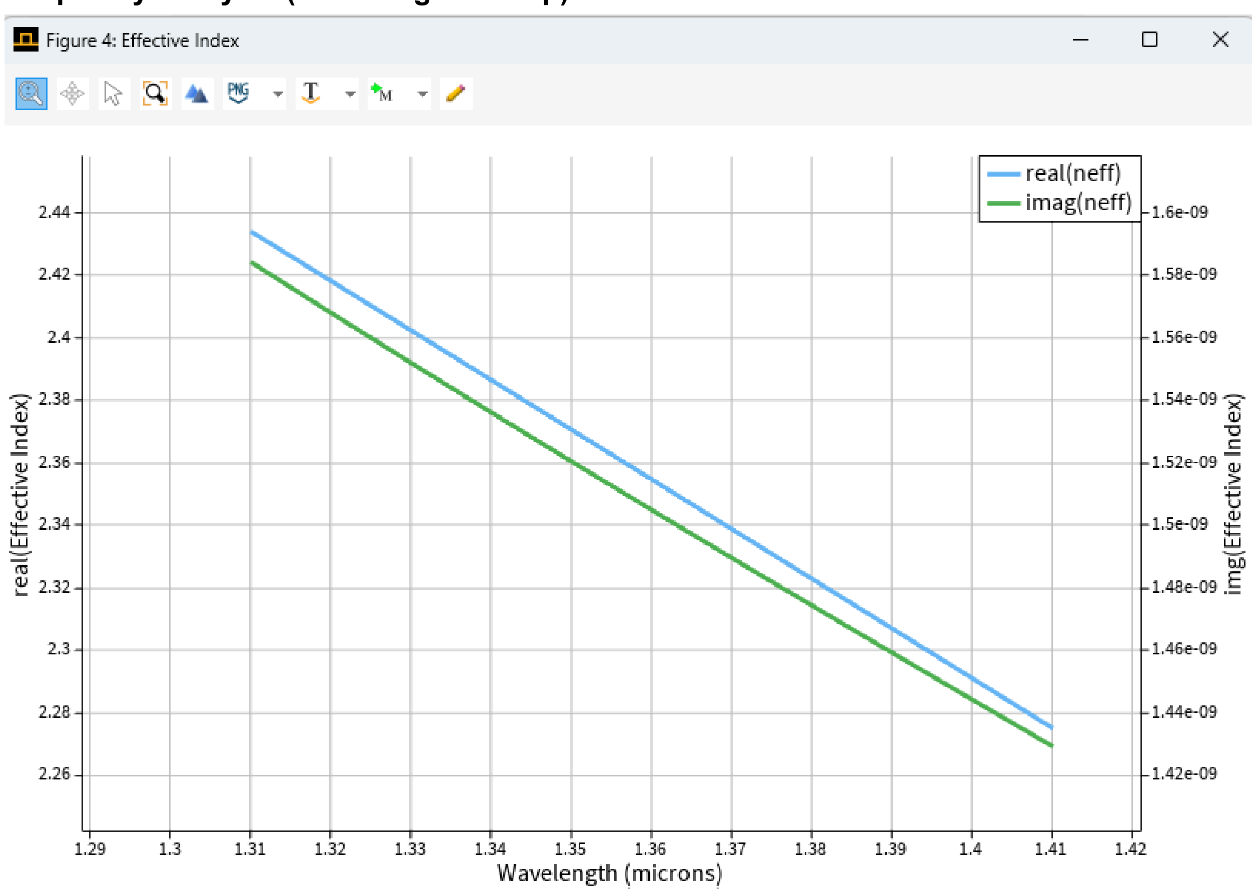
Here is the electric field intensity plotted on the log scale.



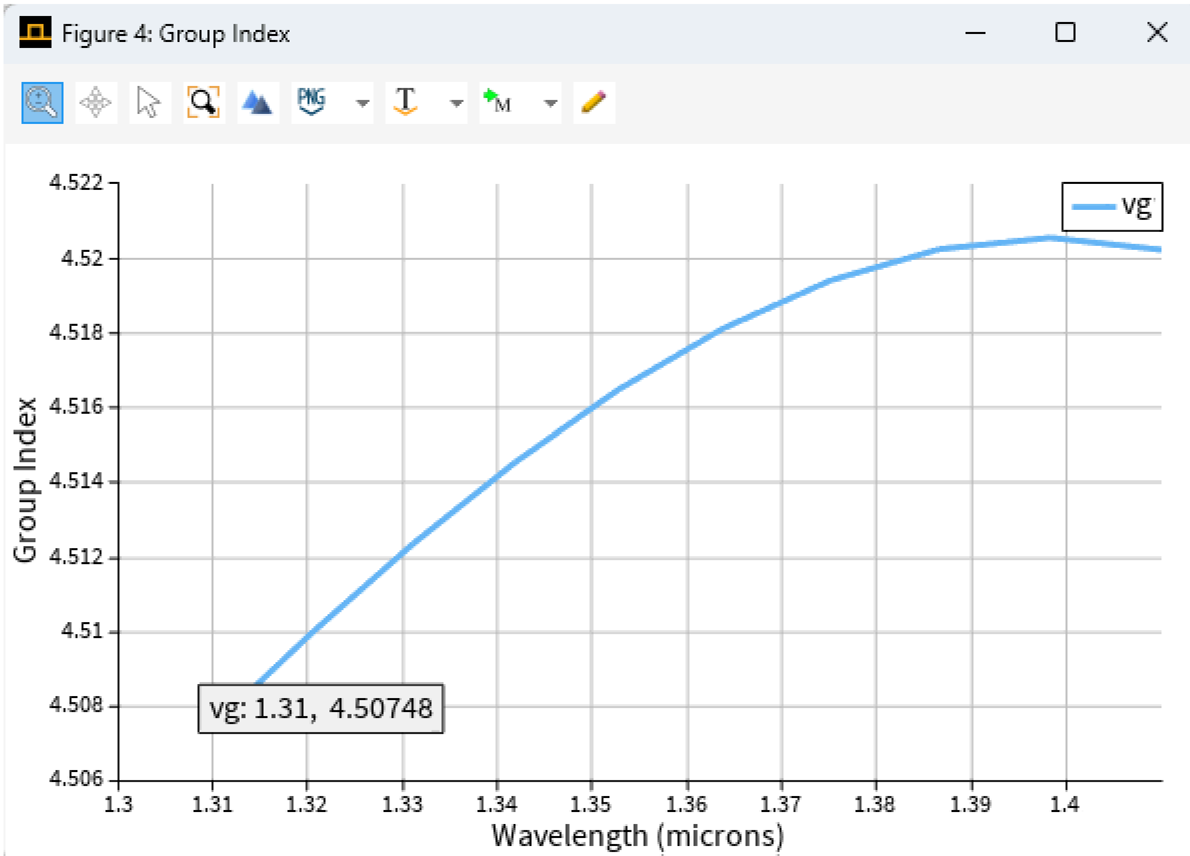
And here is the X component of the electric field.



Frequency Analysis (Wavelength Sweep)

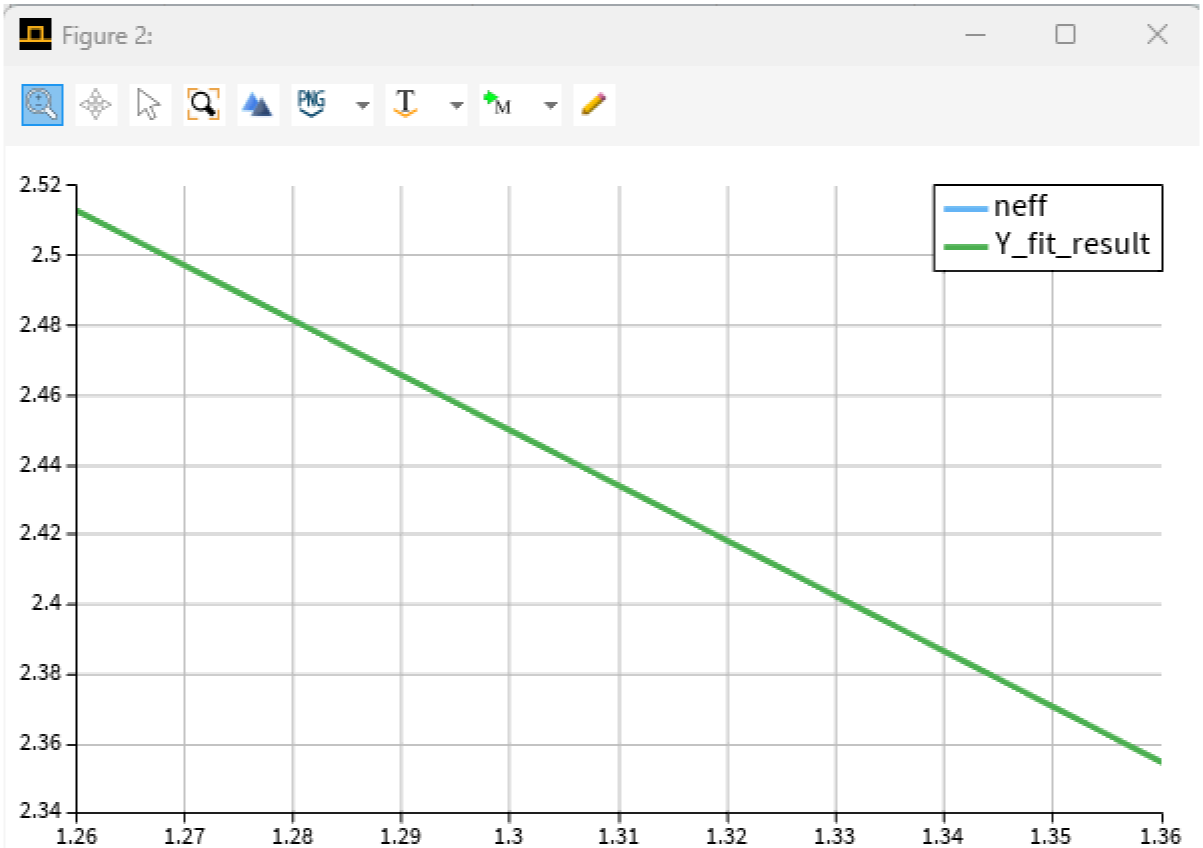


The effective index at 1310 nm for this waveguide is about 2.434, and the group index increases with wavelength and is approximately 4.50.

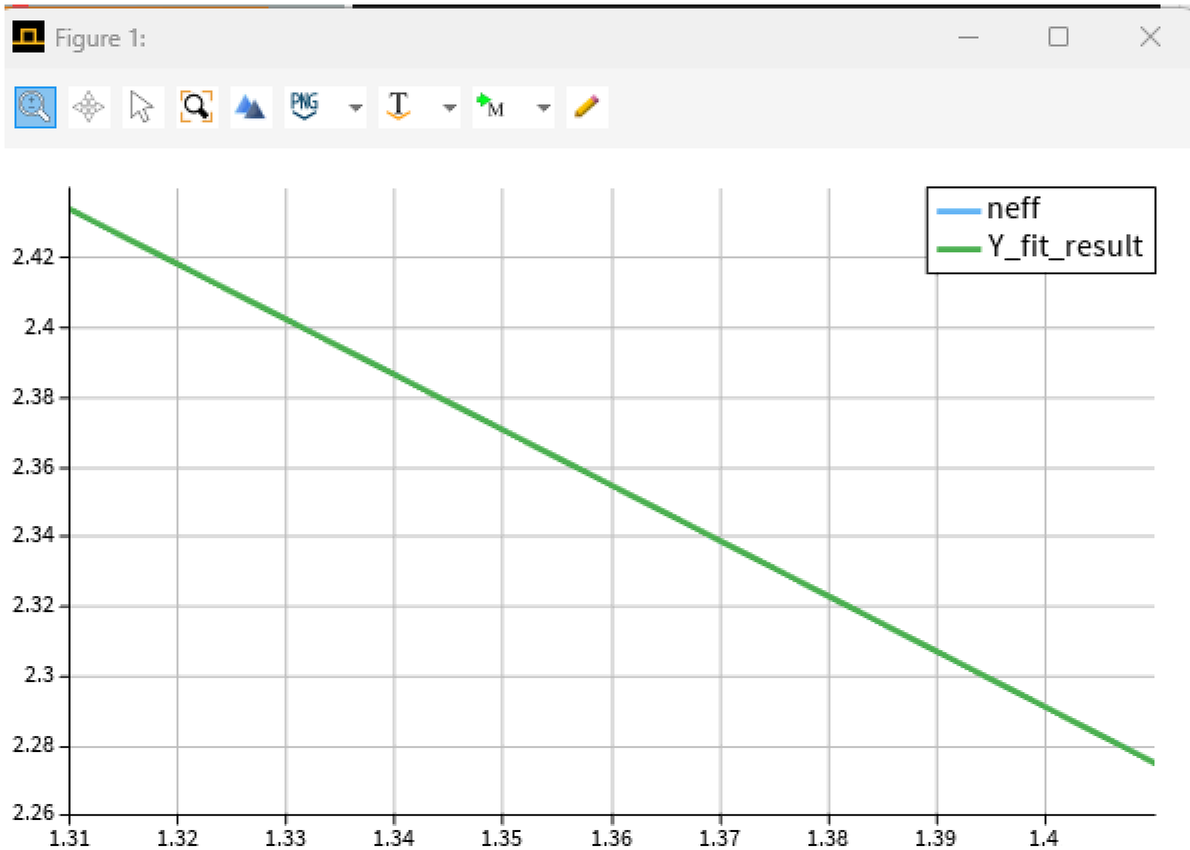


After running the script to model the wave guide's effective index, I got the following equation.

```
plot (lambda, neff, Y_fit_result);  # plot the result;
result:
2.0505
-1.60896
-0.0501316
```

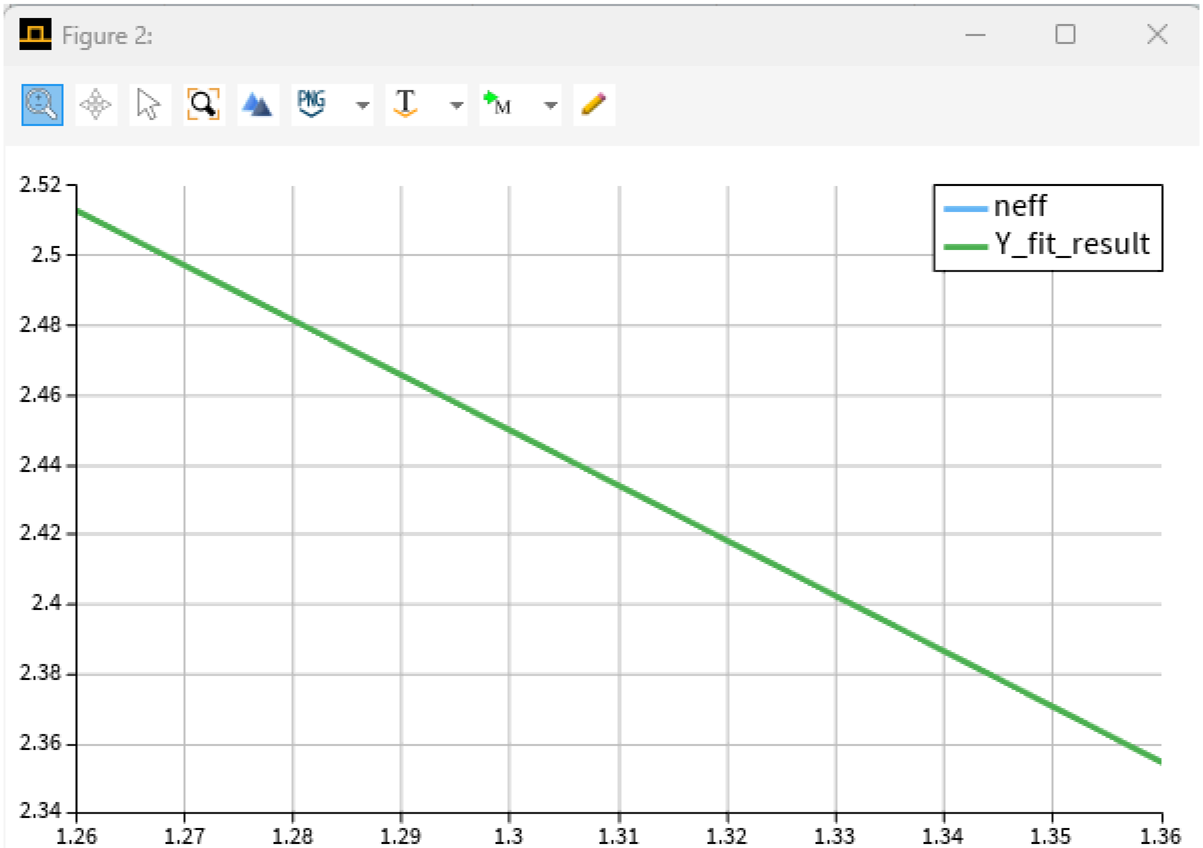


When using this method, the effective index is 2.04861, which varies quite substantially from the direct situation at 1310 nm.



Since we are operating at 1310 nm, I am also going to do a test from a 1260-1360 nm in order to double check the effective index.

```
plot (lambda, neff, Y_fit_result);  # plot the result;
result:
2.04861
-1.62683
-0.0920119
>
```



The effective index is around 2.04861 at the wavelength of 1.31nm.

Given a group index of 4.507, we can calculate the path length difference from the FSR, using the equation:

Delta L = c / (ng * FSR)

$$c = 299\,792\,458$$

−10 2.997925×10^{8}

$$n_g = 4.507$$

−10 10

$$F_{SR} = 25 \cdot 10^{6}$$

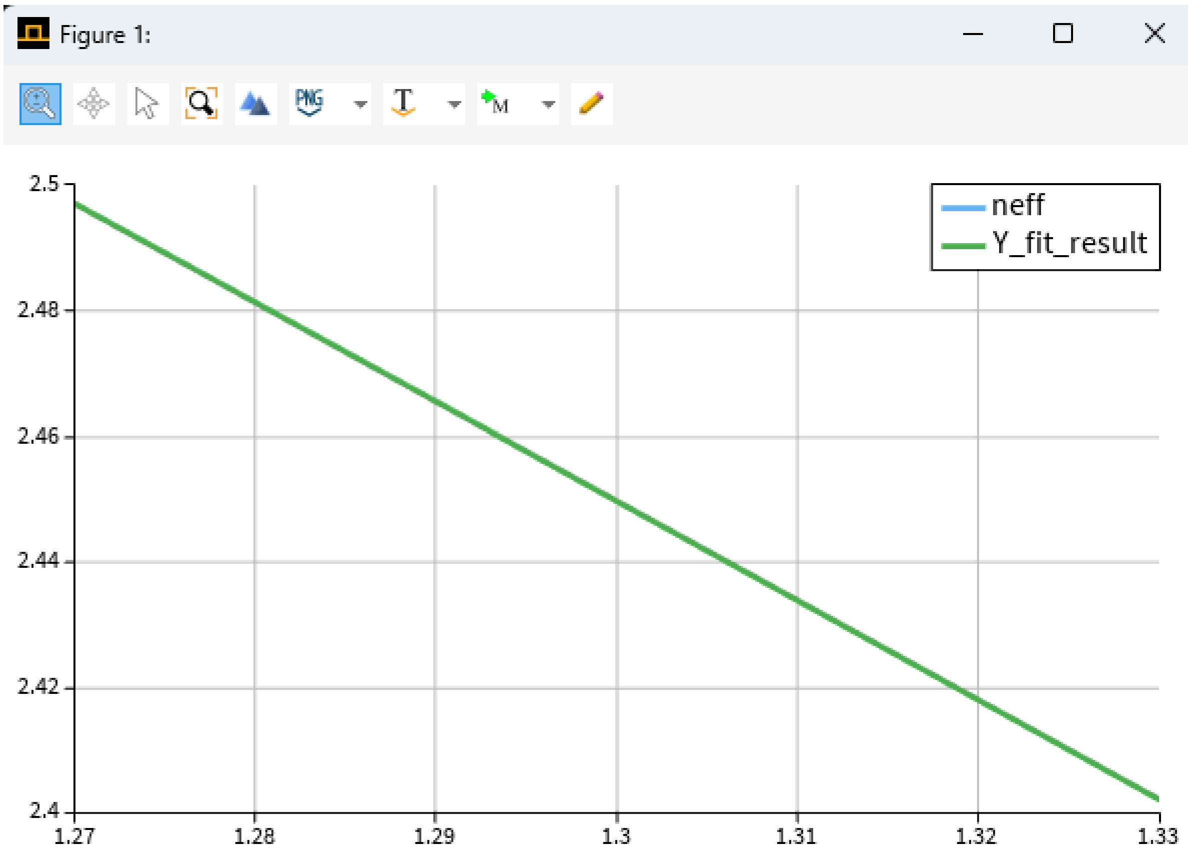
$= 25\,000\,000$

$$L = \frac{c}{n_g \cdot F_{SR}}$$

$= 2.66068300865$

I calculate that the path length difference of the interferometer needs to be 2.66 mm. Now I will make this in KLayout.

I also did a frequency sweep from 1270-1330 nm, as this aligns with the range that we are testing in, and
The effective index sweep looked like this:



And the equation for effective index was:

```
plot (lambda, neff, Y_fit_result);  # plot the result;
result:
2.04818
-1.63017
-0.0984098
>
```

And at 1.27nm, the group index was 4.49.

So using a group index of 4.5 in my calculations is good and I will aim for a path difference of 2.66mm.

I made this design in KLayout.

$L_1 = 155.254$

−10 155.254

$L_2 = 90.285$

−10 90.285

$L_{SPIRAL} = 2578.429$

−10 2578.429

$L_3 = 151.971$

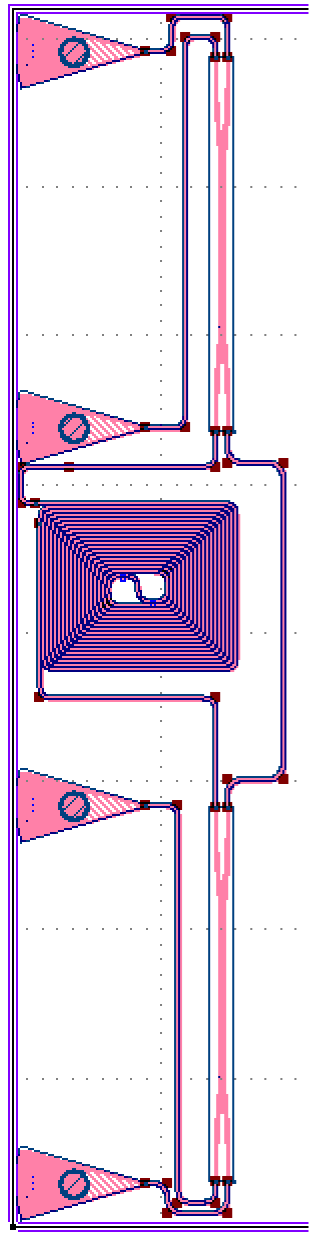
−10 151.971

$L_{Total} = L_2 + L_3 + L_{SPIRAL}$

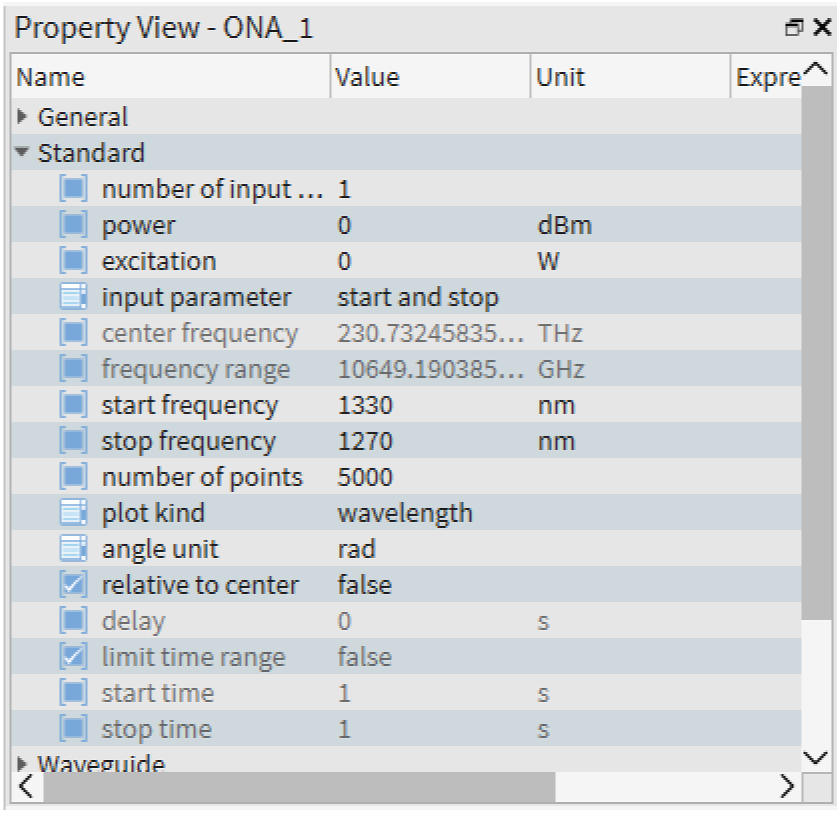
$= 2820.685$

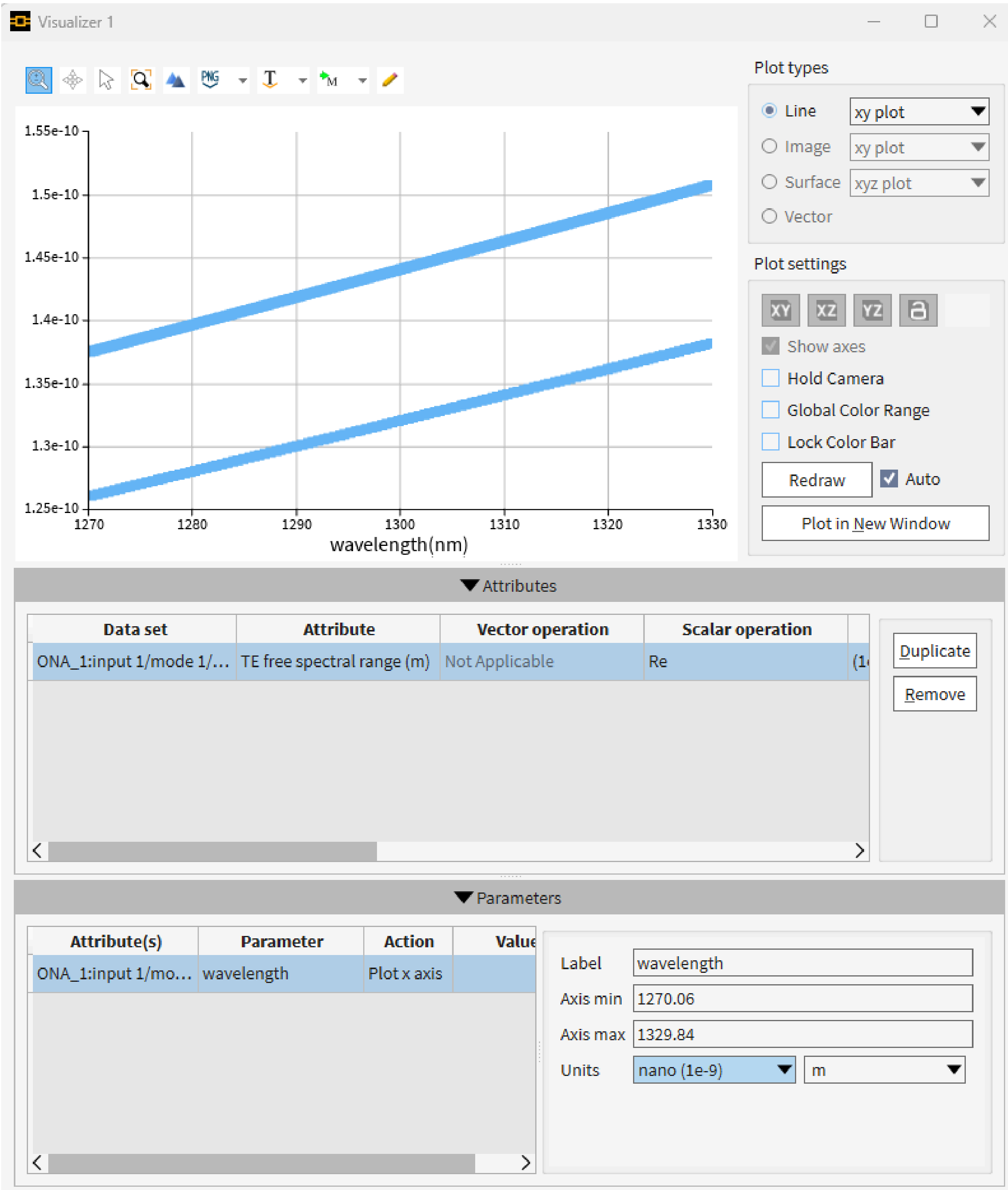
$D = L_{Total} - L_1$

$= 2665.431$

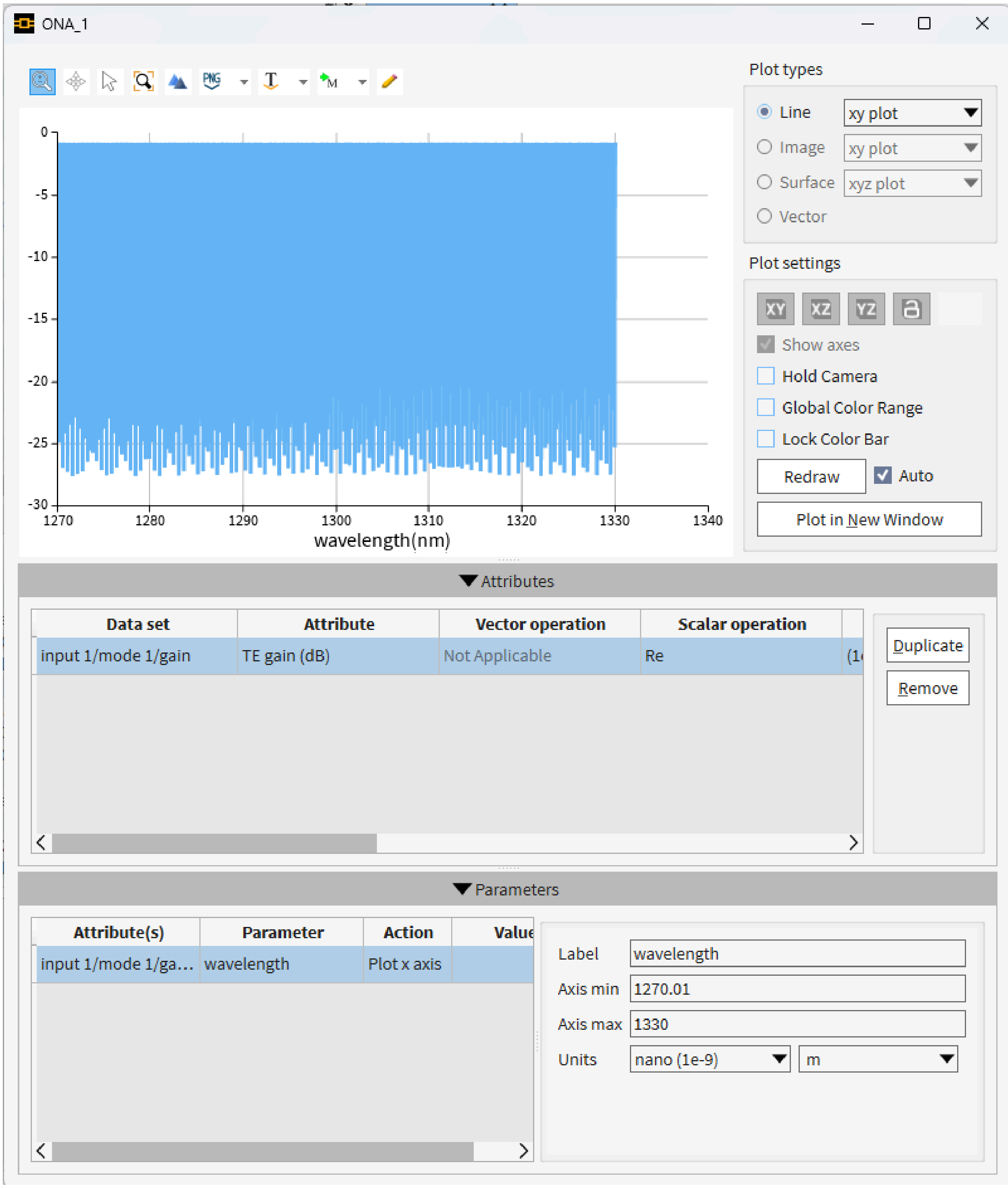


I am running the network analyzer from 1270nm to 1330nm

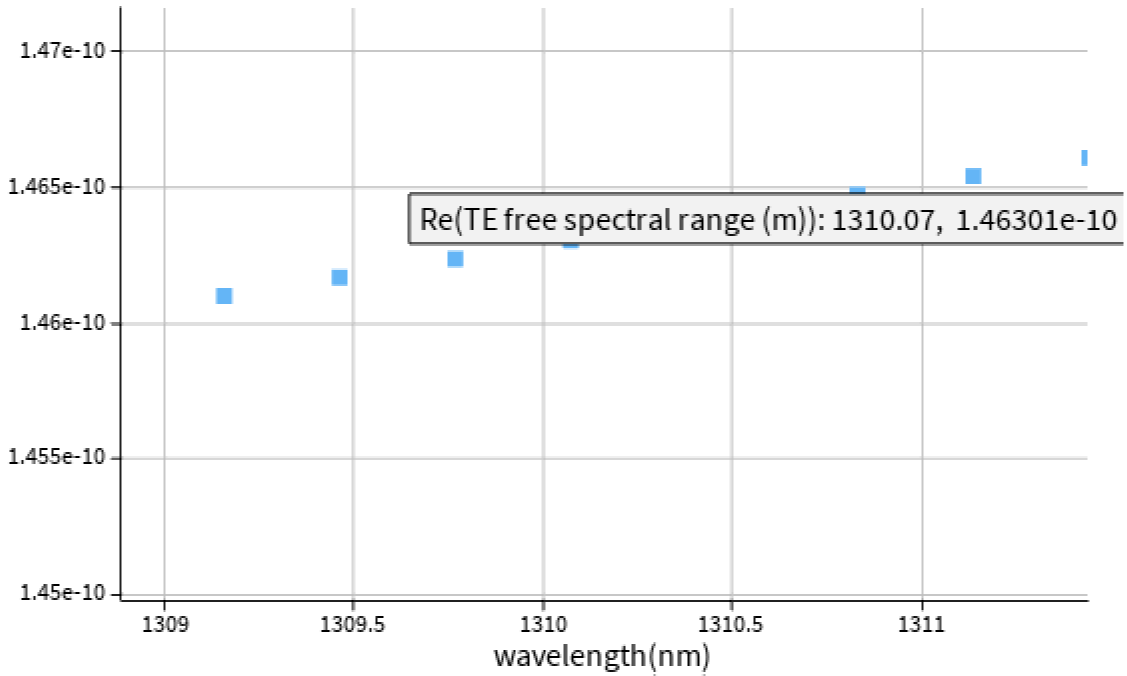




Above is the plot of the free spectral range.



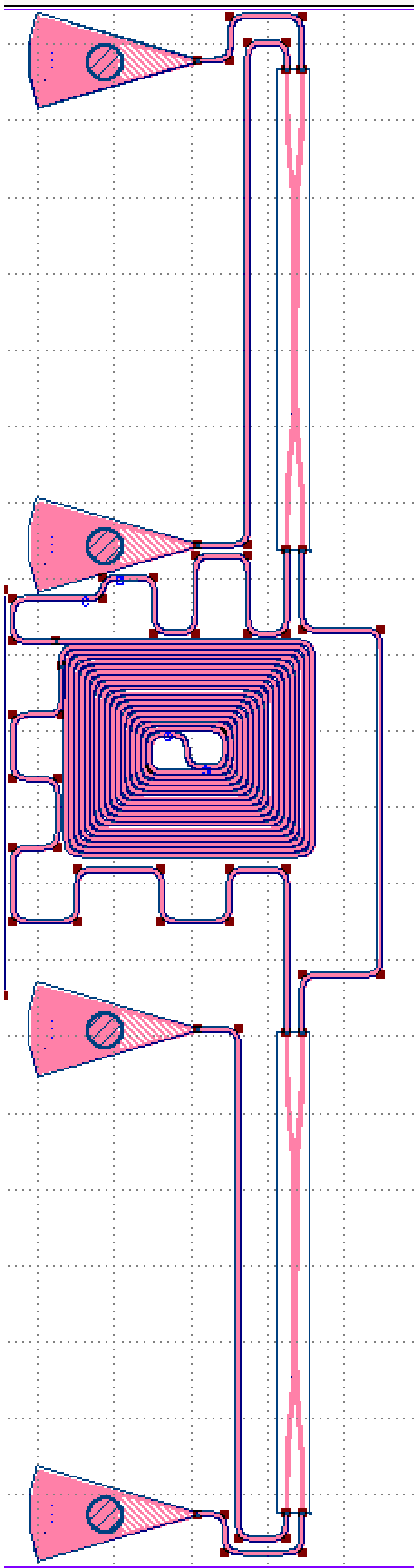
This was the plot for the output of the interferometer.



Here the FSR is 0.14nm, which is what it should be, as this is a 25 GHz FSR. To convert from nm to hertz of the FSR you use the equation:

$$\boxed{\Delta\nu \approx -\frac{c\Delta\lambda}{\lambda^2} = \frac{c}{\Delta L n_g}}$$

I was able to simulate these expected output frequencies for different path lengths as well, and I made a chip design with a 23GHz spacing.



```python
c = 299792458 # m/s
ng = 4.507478

FSR_GHz = 25.0e9 # GHz

wavelength = 1310e-9 # nm

FSR_wavelength_spacing = FSR_GHz * wavelength**2 / c
# Print spacing to 2 decimal places
print("Wavelength Spacing = {:.2f}".format(FSR_wavelength_spacing * 1e9), "nm")
```

✓ 0.0s

```
Wavelength Spacing = 0.14 nm
```

```python
path_length_difference_1 = c / (FSR_GHz * ng)
# Print path length difference to 2 decimal places
print("Path Length Difference = {:.2f}".format(path_length_difference_1*1e3), "mm")
```

✓ 0.0s

```
Path Length Difference = 2.66 mm
```

```python
def calc_path_diff_from_spacing(desired_spacing):
    L = wavelength**2 / (desired_spacing*1e-9 * ng)
    return L

lambda_diff = 0.8 # nm
for lambda_diff in [0.08, 0.10, 0.12, 0.14, 0.16]:
    print(f"Path Length Difference for {lambda_diff}nm = " + "{:.2f}".format(calc_path_diff_from_spacing(lambda_diff) * 1e6), "um")
    print(f"Resulting FSR = "+"{:.2f}".format(c / (calc_path_diff_from_spacing(lambda_diff) * ng) * 1e-9), "GHz")
```

✓ 0.0s

```
Path Length Difference for 0.08nm = 4759.04 um
Resulting FSR = 13.98 GHz
Path Length Difference for 0.1nm = 3807.23 um
Resulting FSR = 17.47 GHz
Path Length Difference for 0.12nm = 3172.69 um
Resulting FSR = 20.96 GHz
Path Length Difference for 0.14nm = 2719.45 um
Resulting FSR = 24.46 GHz
Path Length Difference for 0.16nm = 2379.52 um
Resulting FSR = 27.95 GHz
```

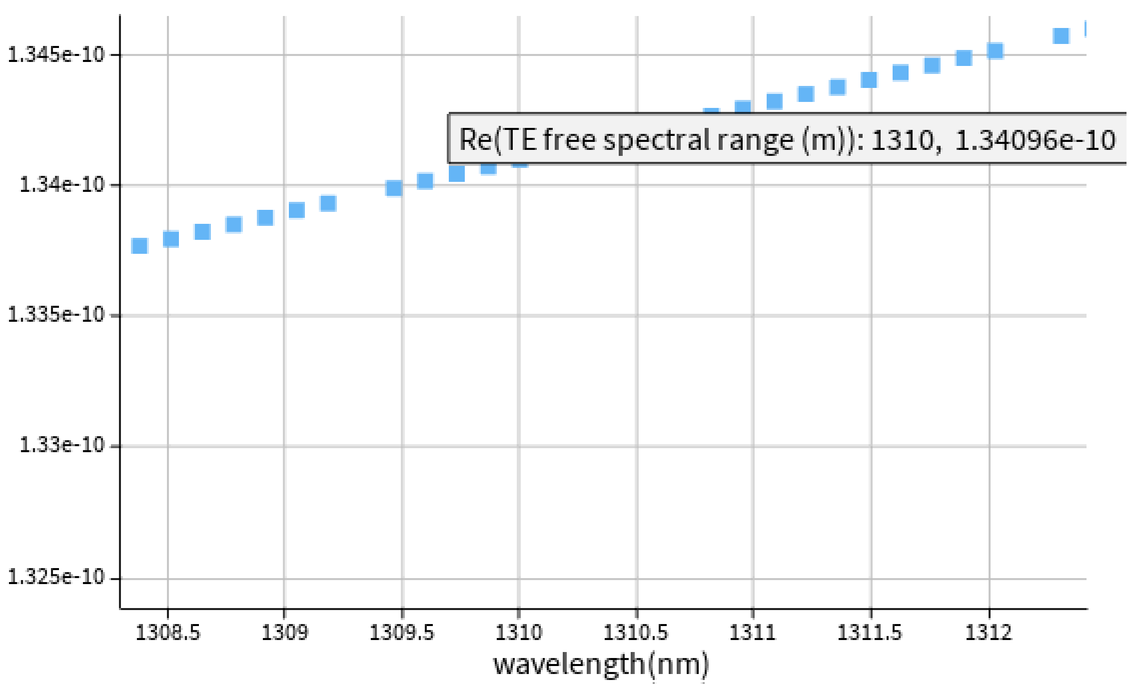
```python
def calc_FSR_from_path_diff(path_diff):
    return c / (path_diff * ng)

L1 = 160.693e-6
L2 = 237.315e-6
L_Spiral = 2578.429e-6
R1 = 161.323e-6

LTotal = L1 + L2 + L_Spiral
R_Total = R1

L_Diff = LTotal - R_Total
FSR = calc_FSR_from_path_diff(L_Diff)
print("FSR_GHz = ", FSR * 1e-9, "GHz")
print("FSR_nm = ", FSR * wavelength**2 / c * 1e9, "nm")
```

✓ 0.0s

```
FSR_GHz =  23.626049014977255 GHz
FSR_nm =  0.1352424373351062 nm
```

The function above calculated the expected FSR in GHz for the path length difference that I had in the second circuit.

This matches the INTERCONNECT simulation.



- Consider fabrication variations (width +/- 10 nm, thickness +/- 10 nm, process bias Δw, range of propagation loss values) and how they will impact the filter performance. Start with identifying the process corners, simulating the waveguide for each corner, then simulating the circuit for each corner.

Corners:

Design #	Waveguide Size	Group Index	Path Difference	File_name
1	350 x 220	4.507478	2660.40	350x220_wg.ldf
2	360 x 230	4.469343	2683.10	360x230_wg.ldf
3	360 x 210	4.466558	2684.77	360x210_wg.ldf
4	340 x 230	4.525866	2649.59	340x230_wg.ldf
5	340 x 210	4.518220	2654.08	340x210_wg.ldf

```python
def calc_necessary_path_diff(ng):
    FSR = 25e9 # GHz
    return c / (FSR * ng)

print("Path Length Difference for ng = 4.5: ", calc_necessary_path_diff(4.5) * 1e6, "um")
```

✓ 0.0s Python

```
Path Length Difference for ng = 4.5:  2664.821848888889 um
```

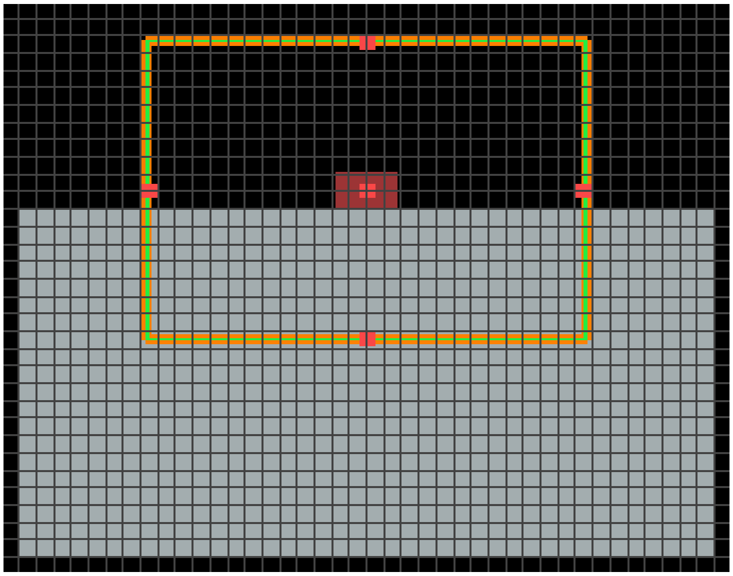
Now I am going to simulate different sized waveguides in lumerical mode to get a variation in group indexes, and then try to make a variety of designs with those size variations.

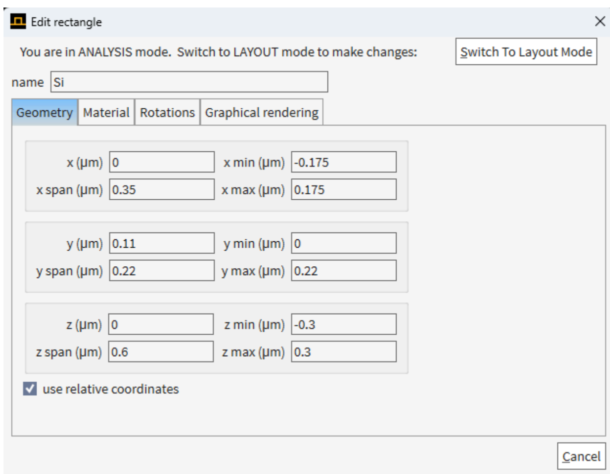
```python
ıgth Difference for ng = 4.507478: " + "{:.2f}".format(calc_necessary_path_diff(4.507478) * 1e6), "um")
ıgth Difference for ng = 4.469343: " + "{:.2f}".format(calc_necessary_path_diff(4.469343) * 1e6), "um")
ıgth Difference for ng = 4.466558: " + "{:.2f}".format(calc_necessary_path_diff(4.466558) * 1e6), "um")
ıgth Difference for ng = 4.525866: " + "{:.2f}".format(calc_necessary_path_diff(4.525866) * 1e6), "um")
ıgth Difference for ng = 4.518220: " + "{:.2f}".format(calc_necessary_path_diff(4.518220) * 1e6), "um")
```

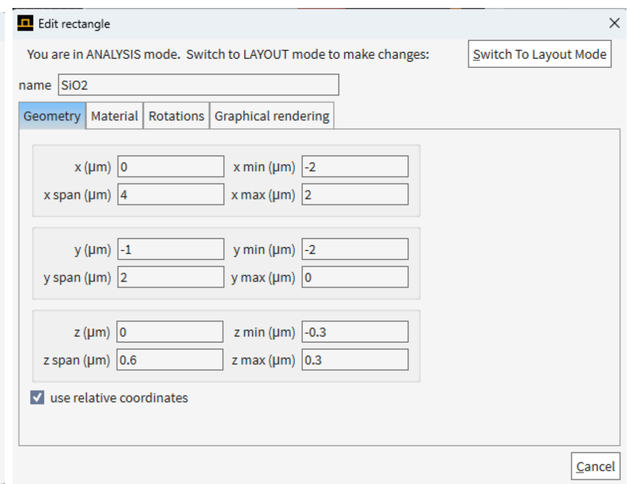
✓ 0.0s Python

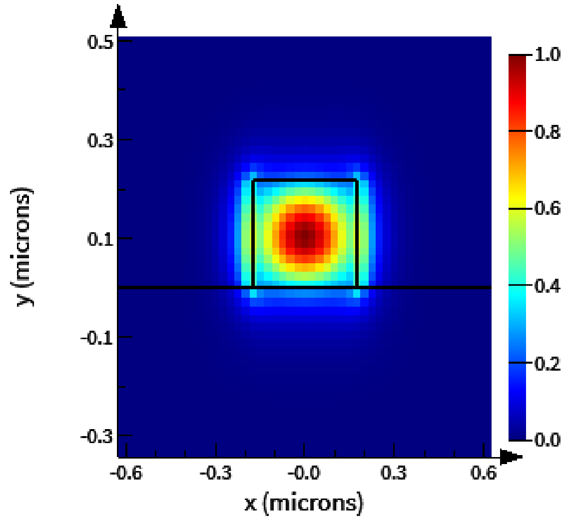
```
Path Length Difference for ng = 4.507478: 2660.40 um
Path Length Difference for ng = 4.469343: 2683.10 um
Path Length Difference for ng = 4.466558: 2684.77 um
Path Length Difference for ng = 4.525866: 2649.59 um
Path Length Difference for ng = 4.518220: 2654.08 um
```

For Chip 2 I began by simulating the waveguide.







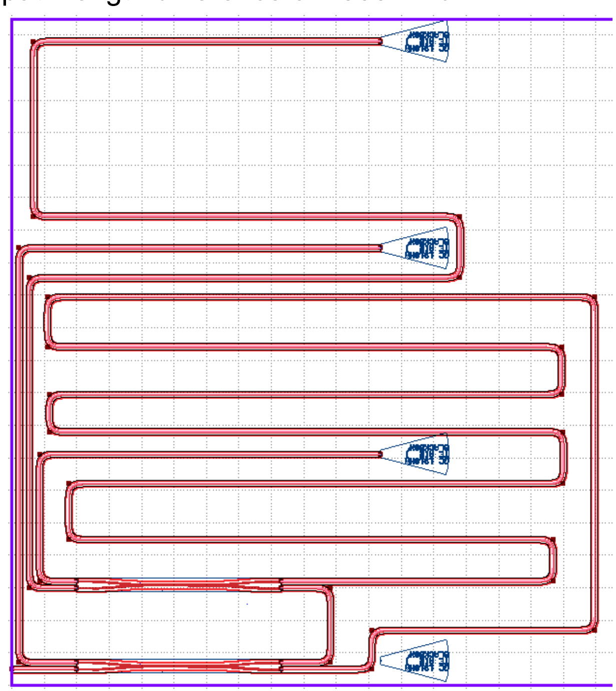


Eigensolver Analysis

Mode list

mode #	effective index	wavelength (µm)	loss (dB/cm)	group index	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)	effective area (µm^2)
1	2.355116+1.723409e-09i	1.31	0.00071798	4.786668+3.484210e-09i	97	65.47 / 84.16	0.140897
2	1.845431+1.543339e-09i	1.31	0.00064296	5.028435+7.395737e-09i	6	59.66 / 87.37	0.200235

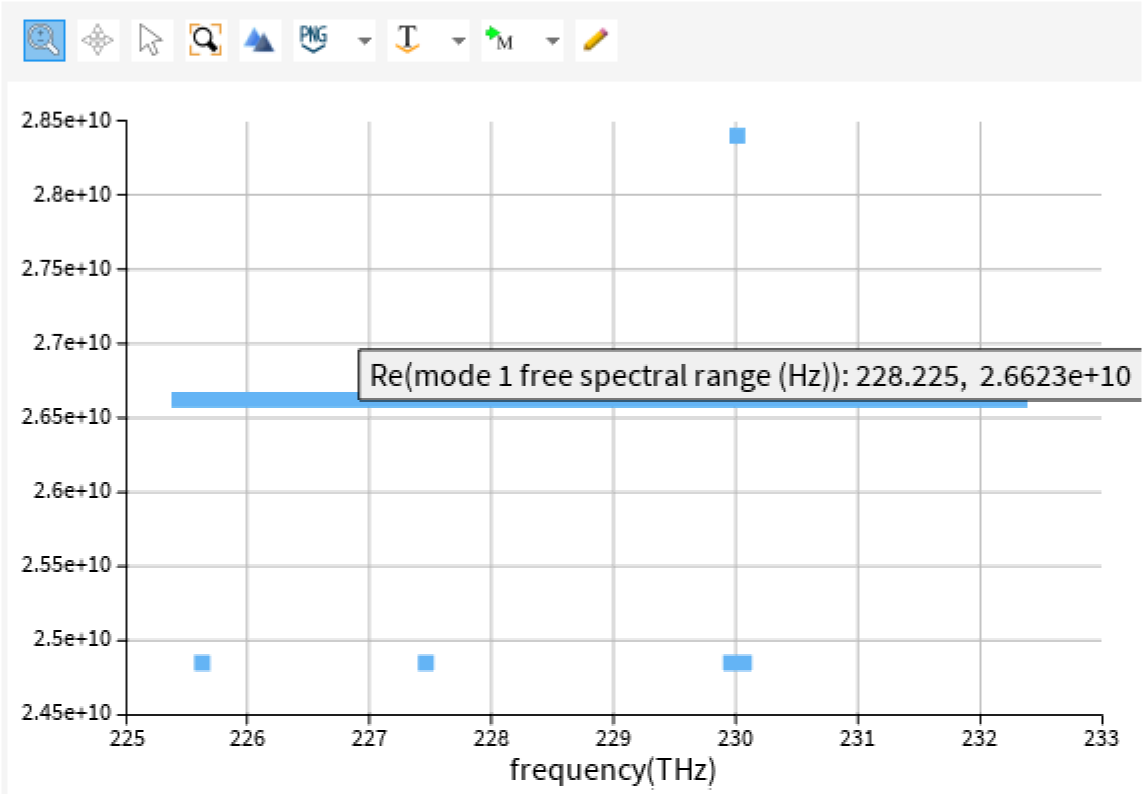
The group index is 4.786668, and from my python calculations, this means there is a required path length difference of 2505.22 um.



Waveguide Length Difference

Difference in waveguide lengths (um): 2505.025
RMS phase error: nan pi radians

OK



Based on my simulation of chip 2, the FSR was about 26 GHz. This is slightly larger than I wanted, however I am confident in my path length difference calculation and so will keep the same pathlength.

Having the correct path difference is resulting in the wrong FSR.

Chip 2 Design

```
print("Path Length Difference for ng = 4.78668: ", calc_necessary_path_diff(4.78668) * 1e6, "um")
ng = 4.78668
L2 = 100.219e-6
L1 = 2605.244e-6

LTotal = L1
R_Total = L2
print("Path 1", LTotal * 1e6, "um")
print("Path 2", R_Total * 1e6, "um")

L_Diff = LTotal - R_Total
print("Path Length Difference = {:.2f}".format(L_Diff*1e6), "um")
FSR = calc_FSR_from_path_diff(L_Diff, ng)
print("FSR_GHz = ", FSR * 1e-9, "GHz")
print("FSR_nm = ", FSR * wavelength**2 / c * 1e9, "nm")
```

```
Path Length Difference for ng = 4.78668:  2505.222475703411 um
Path 1 2605.244 um
Path 2 100.219 um
Path Length Difference = 2505.03 um
FSR_GHz =  25.001970795734678 GHz
FSR_nm =  0.14311861735547823 nm
```