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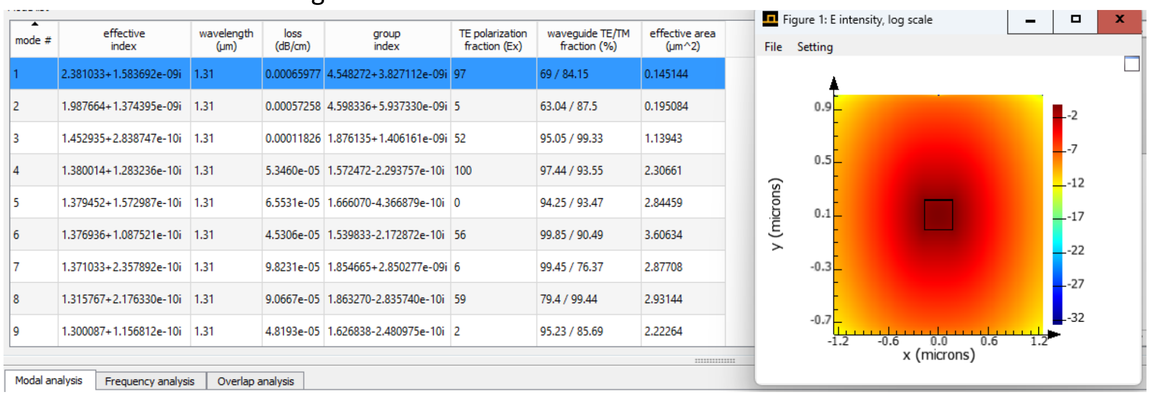
Part 0: Introduction

In this project, a Fabry Perot Cavity is designed with a quality factor above 200,000. Lumerical Mode is used to characterize a waveguide which will be placed in between two resonators. These resonators are Bragg gratings and are simulated using Lumerical FDTD tools. A final python model of the resonator model (waveguide and one Bragg grating on each side) has been developed and is accompanied by a Lumerical FDTD simulation of the entire optical circuit. Models are to be printed and tested using Ebeam lithography techniques.

Part 1: Lumerical Mode and Waveguide Simulation

To obtain a reliable model of the waveguide that is to be used in between the two Bragg gratings, we need to perform a simulation of a small slice of the waveguide and use the obtained values to build our python model (Part3):

1. A waveguide length of 335 nm and thickness of 220nm is chosen. This waveguide shall support light with a 1310 nm wavelength. The cladding of the waveguide is SiO2 and the core material is Si. Simulations and frequency sweeps are done for the lowest TE mode. The results of the simulation are shown in figure 1.



mode #	effective index	wavelength (µm)	loss (dB/cm)	group index	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)	effective area (µm^2)
1	2.381033+1.583692e-09i	1.31	0.00065977	4.548272+3.827112e-09i	97	69 / 84.15	0.145144
2	1.987664+1.374395e-09i	1.31	0.00057258	4.598336+5.937330e-09i	5	63.04 / 87.5	0.195084
3	1.452935+2.838747e-10i	1.31	0.00011826	1.876135+1.406161e-09i	52	95.05 / 99.33	1.13943
4	1.380014+1.283236e-10i	1.31	5.3460e-05	1.572472-2.293757e-10i	100	97.44 / 93.55	2.30661
5	1.379452+1.572987e-10i	1.31	6.5531e-05	1.666070-4.366879e-10i	0	94.25 / 93.47	2.84459
6	1.376936+1.087521e-10i	1.31	4.5306e-05	1.539833-2.172872e-10i	56	99.85 / 90.49	3.60634
7	1.371033+2.357892e-10i	1.31	9.8231e-05	1.854665+2.850277e-09i	6	99.45 / 76.37	2.87708
8	1.315767+2.176330e-10i	1.31	9.0667e-05	1.863270-2.835740e-10i	59	79.4 / 99.44	2.93144
9	1.300087+1.156812e-10i	1.31	4.8193e-05	1.626838-2.480975e-10i	2	95.23 / 85.69	2.22264

Figure 1: Successful Mode simulation for a 335nm wide waveguide

It can be observed in the E field intensity diagram in figure 1 that the field has decayed sufficiently, and our results are reliable. For the lowest TE mode, the effective index is calculated to be 2.381033 and the group index is 4.548272.

2. A frequency sweep must be done on this model to obtain the graph for the changes of the effective index (n_{eff}) vs wavelength. The results are shown in figure2.

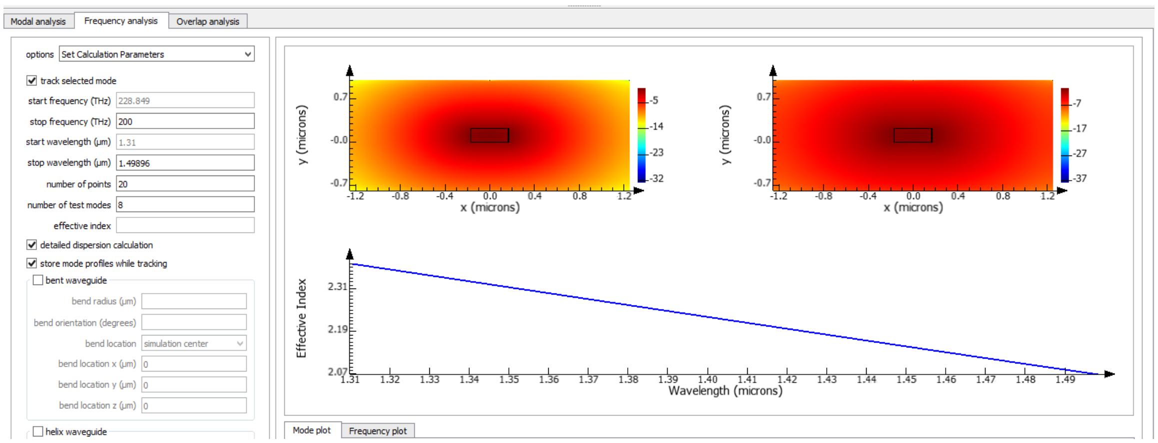


Figure 2: Successful frequency sweep for finding n_{eff} vs wavelength

3. Upon performing a successful sweep, a script (provided by Prof. Lukas Chrostowski for making Compact Models) will fit the sweep data and provide us with the coefficients of a parabolic function that will predict the behaviour of n_{eff} vs wavelength. These coefficients as well as the data which was used for obtaining these coefficients are presented in figure 2 and figure 3. The equation which is used for the waveguide compact model is shown in figure 4.

```
plot (lambda, neff, Y_fit_result);  # plot the result;
result:
1.98693
-1.61663
0.109986
```

Figure 3: Screenshot of the calculated coefficients (a1, a2 and a3 in order) for the waveguide compact model using Lumerical Mode

$$n_{\text{eff}}(\lambda) = a_1 + a_2(\lambda - \lambda_0) + a_3(\lambda - \lambda_0)^2$$

Figure 4: Equation for the waveguide compact model – Taylor series expansion around the central wavelength of 1310 nm

Part 2: Lumerical FDTD and Bragg Grating Simulation

1. A Lumerical FDTD simulation is performed on 2 periods of a Bragg grating. Bragg grating has a width of 335 nm and thickness of 220 nm. The d_w (amount by which we change the width) is set to 30nm. Group index (ng) is found previously from Part 1 – 1. The period of the Bragg grating is calculated to be 269 nm from the formula in figure 5. As a result of this simulation we can obtain a value for kappa – grating strength (113891) and we can also verify that our Bragg grating's central frequency is close to 1310 nm and the bandwidth is sufficiently large. Results of this simulation can be viewed in figure 6. As seen in figure 7, a loss of 0.618 dB/cm is calculated for the following Bragg grating period.

$$\lambda_B = 2n_{\text{eff}}\Lambda$$

Figure 5: Equation for finding the period (Λ) of Bragg (n_{eff} = 2.381033, is calculated in Part 1 – 1, and Λ_B is 1310 nm)

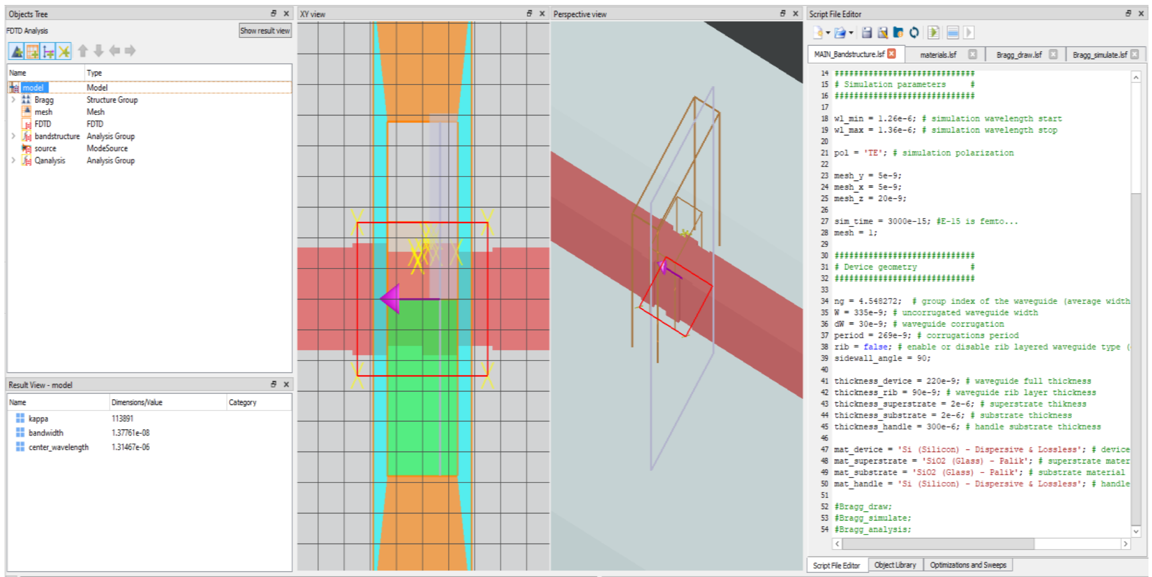


Figure 6: Lumerical FDTD simulation of two period of the Bragg grating

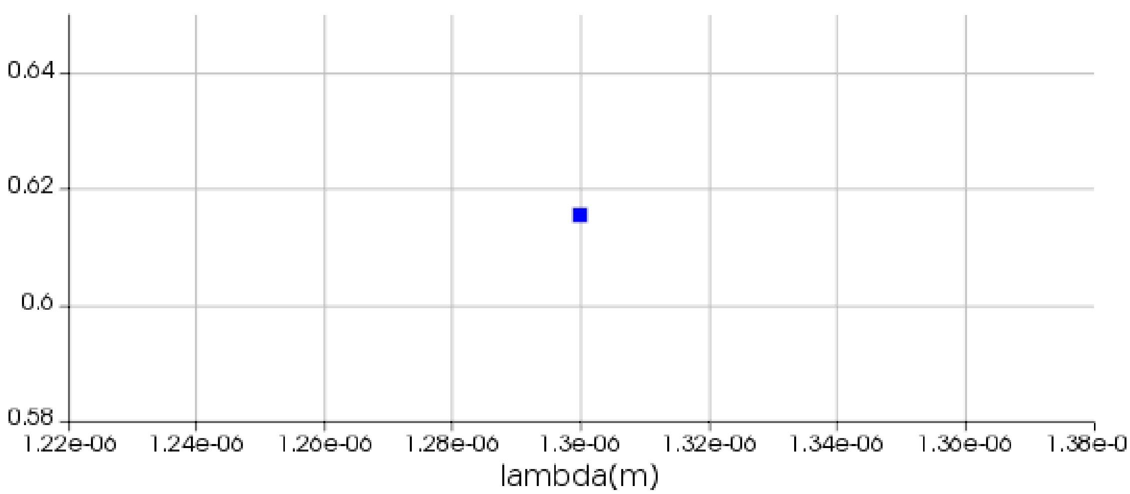


Figure 7: Lumerical FDTD calculated loss for the Bragg grating in dB/cm

Part 3: Lumerical FDTD and Cavity Simulation

After simulating the characteristics of each separate part of the Fabry Perot cavity resonator, we combine the simulations using two different tools to verify our assumptions. First a python model is used for simulating the behaviour of reflectivity and transmissivity of the resonator as whole. Next, a more in depth Lumerical FDTD simulation is performed to check the quality factor of the Fabry Perot cavity resonator alongside the transmissivity and reflectivity of the cavity. To obtain a high quality factor, reflectivity should be at a maximum while the waveguide and mirror loss (in our case Bragg grating loss) have to be at a minimum. The python model can predict the behaviour of the reflection and transmission accurately, however without accurate models for loss and change in the n_{eff}, the central frequency of the Fabry Perot will be modeled inaccurately. Therefore, in addition to the python model, a Lumerical FDTD simulation using simple library models (two simple unidirectional Bragg grating, an analyzer and a simple waveguide) has been created to model the cavity to the best of our abilities.

The python model produces figure 8, which shows that the central wavelength of the cavity has been shifted to 1290nm. The cavity in this model has 200 periods of Bragg grating on each side of a 100um long waveguide. A discussion of the causes is included in Part 4.

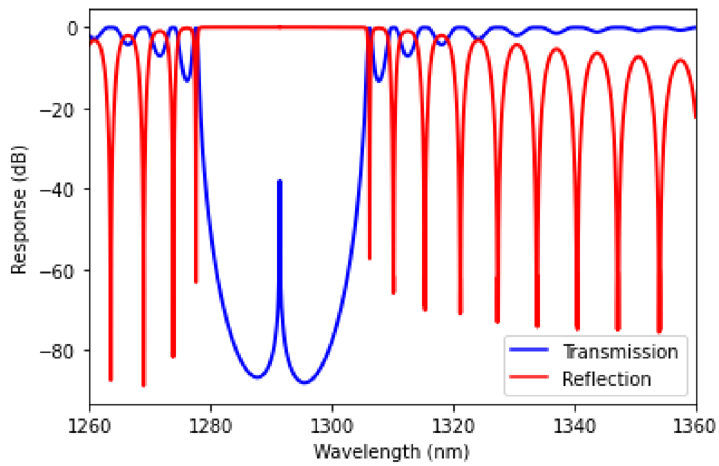


Figure 8: Calculated Response of the Resonator using Bragg TMM (dB scale)

In figure 9, the graph of transmissivity (purple line) and reflectivity (black line) vs wavelength is shown. It is evident that according to our model the central wavelength of the cavity has been shifted to 1293nm. (for more information see Part 4). The value of the free spectral range is shown on the graph using black dots. The free spectral range at the central frequency is calculated to be 7.109nm. From these two simulations we can conclude that our cavity is likely to operate in the range of 1290 – 1310 nm.

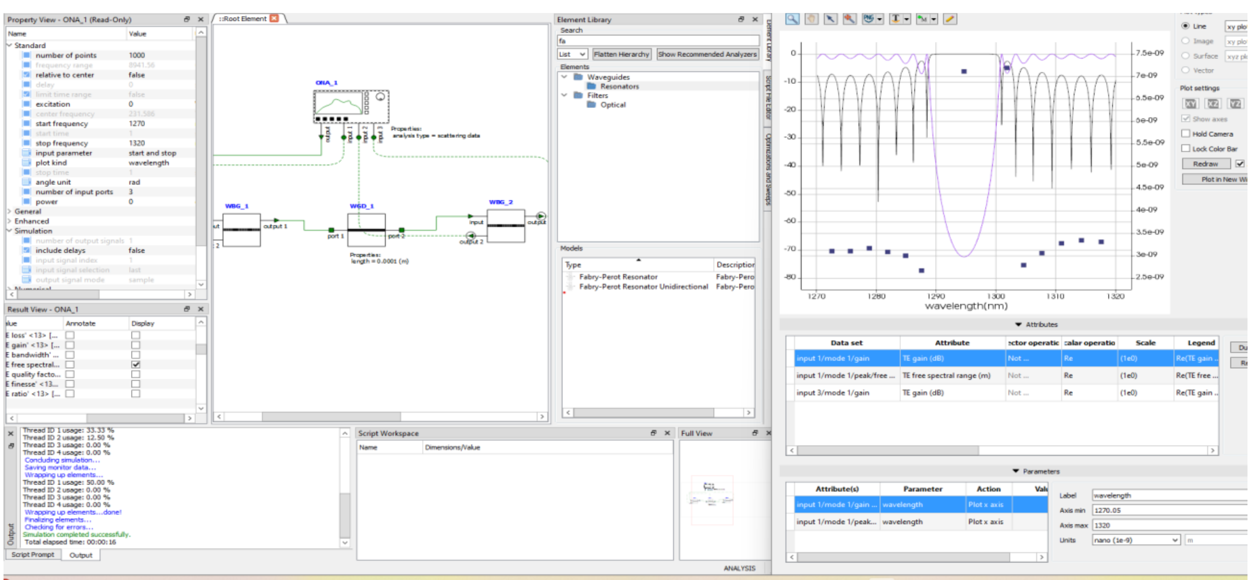


Figure 9: Lumerical FDTD Simulation for the Cavity

Part 4: Discussion and Summary

This cavity design presented here is a 335 nm wide cavity while the KLAYOUT model that is submitted for this project has a width of 350 nm. This is because during fabrication there is a bias where printed silicon shrinks at the top and is not exactly the 350 nm throughout. It is expected that if a 350 nm waveguide is printed the behaviour would be similar to a 335 nm waveguide due to this shrinkage. The period of 269 nm is calculated for a 350 nm Bragg grating and has not been modified to 275 nm for the 335 nm wide Bragg grating. This is because the instructor's previous experience with the lithography process suggests that the periods will be modeled very accurately.

To be able to better understand the effects of this bias and its effects on the central wavelength and the period of Bragg gratings, 3 Klayout models have been submitted for fabrication. In two of these layouts the Bragg grating number (how many times the period is repeated) of a 350 nm wide cavity with d_w of 30 nm and period of 269nm are sweeped (10 periods in difference), overall length of the cavity stays the same, therefore as the number of Bragg grating periods increase the length of the waveguide in between decreases (becomes less than 100um). In the third one, Bragg grating number (how many times the period is repeated) of a 350 nm wide cavity with d_w of 30 nm and period of 275nm are sweeped, same condition applies to the waveguide as with the other two layouts. These sweeps will later help me with understanding the limitations of my software, and the specifics of the aforementioned bias process.

Part 5: Model names and specifications:

1. Ebeam_ELEC413_AryanC (x6 circuits)

Width	350 nm
d_w	30nm
Thickness	220 nm
Period	269 nm
Period number	110 – 120 – 130 – 140 – 150 – 160
Expected quality factor	105,000-155,000

Table 1: Table of specifications for layout number 1

2. Ebeam_ELEC413_AryanC2 (x6 circuits)

3. Width	350 nm
d_w	30nm
Thickness	220 nm
Period	269 nm
Period number	170 – 180 – 190 – 200 – all Bragg (no waveguide) – all waveguide(no Bragg)
Expected quality factor	105,000-155,000

Table 2: Table of specifications for layout number 2

4. Ebeam_ELEC413_AryanC3 (x6 circuits)

5. Width	350 nm
d_w	30nm
Thickness	220 nm
Period	275 nm
Period number	110 – 130 – 150 – 170 – 190 – 100
Expected quality factor	> 200,000

Table 3: Table of specifications for layout number 3