# Aryan Chahardovalee – ELEC 413 – Semiconductor Lasers _ Project 1 Design document

## Part 0: Introduction

In this project, an optical resonator is designed with a quality-factor above 100,000 using the SiEPIC - EBeam Process Design Kit (PDK). Resonators are a one of the three main components of a laser (resonator, source and gain medium) and having a high quality-factor resonator can improve lasing significantly.

The approach taken in this project is to design a Fabry Perot Cavity resonator by sandwiching a waveguide between two equally-lengthed Bragg gratings. Lumerical MODE simulation software is used to characterize the waveguide characteristics of this cavity. Furthermore, the Bragg gratings on either side are simulated using Lumerical FDTD simulation software. A final python model of the resonator model which is based on the waveguide transfer matrix has been developed and is accompanied by a Lumerical INTERCONNECT simulation of the entire optical circuit.

Models are to be printed and tested using Electron Beam (EBeam) Lithography techniques. There is a bias to this fabrication process where waveguides with a specified width of 350nm will be printed 335nm, which is 15nm smaller than the specified width. Because of this biassing effect the Fabry Perot Cavity in this project is designed for a width of 335nm and is drawn for fabrication at 350nm.

**Table 1:** Geometrical parameters summary

| **Name of Parameter** | **Value of Parameter** | **Type of Parameter** |
|---|---|---|
| Width | Actual: 335 nm / fabricated: 350nm | Fixed parameter |
| Corrugation Width | 30 nm | Fixed parameter |
| Thickness | 220 nm | Fixed parameter |
| Bragg Number | Range from 100 to 200 – steps of 10 | Varying parameter |
| Length of the Waveguide in between the Bragg Gratings | Varies from 100 ɥm to 40 ɥm – steps of 5.38 ɥm | Varying parameter |
| Bragg Period * | 269 nm or 275 nm | Varying parameter |

* Bragg period is alternated between 269 and 275 in separate designs to check for possible shift of the central frequency.

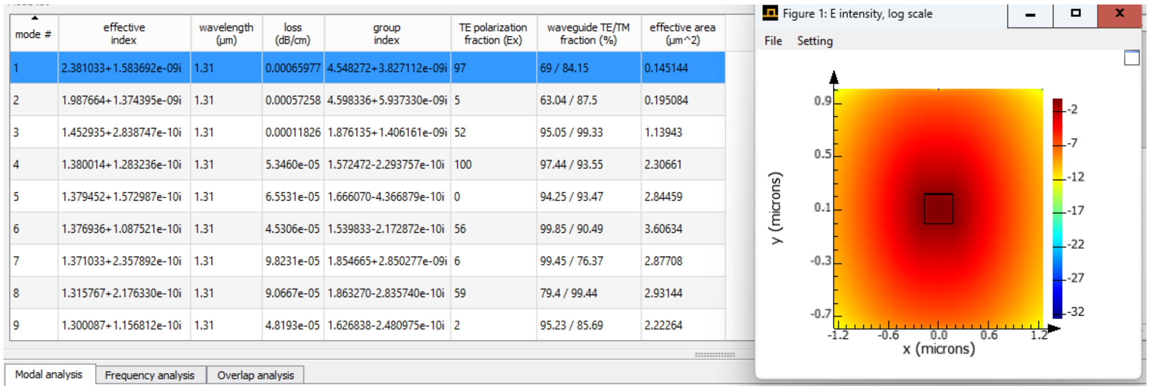
Increasing the strength of the Bragg gratings (e.g., by increasing the grating length) generally leads to a higher Q-factor, as it increases the amount of light that is reflected back from the resonator and reduces the amount of light that is lost. This is because the Bragg gratings act as mirrors that reflect the light back into the waveguide, causing it to bounce back and forth and be stored in the resonator for longer periods of time.

Therefore, increasing the strength of the Bragg gratings typically results in a higher Q-factor, which in turn can lead to narrower free spectral range and a higher output power from the laser. However, there is a limit to how much the Bragg grating strength can be increased before other factors such as scattering losses or nonlinear effects start to dominate and limit the Q-factor. Therefore, in this project the Bragg number (Bragg length) and the waveguide length are varied.

## Part 1: Lumerical Mode and Waveguide Simulation

To obtain a reliable model of the waveguide characteristics 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 Silicon Dioxide ($SiO_2$) and the core material is Silicon (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:* Lumerical 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.

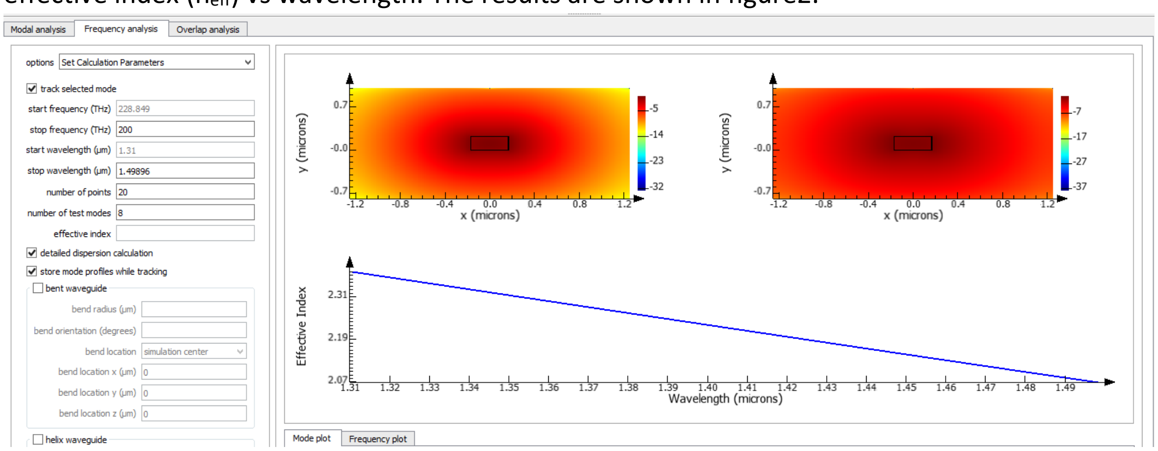



*Figure 2:* Frequency sweep to obtain $n_{eff}$ vs wavelength

3. Upon performing a successful sweep, a script (ref1) 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 come from the graph in figure 2 and are as such:

$a_1$ = 1.98693 $a_2$ = -1.61663 $a_3$ = 0.109986

The equation which uses the above coefficients to predict the behaviour of $n_{eff}$ vs wavelength is as such:

$$n_{eff}\ (\lambda) = a_1 + a_2(\lambda - \lambda_0) + a_3(\lambda - \lambda_0)^2,\ \lambda_0 = 1310\ \text{nm}$$

This behaviour is to be used by the waveguide compact model (Part 3).

**Table 2:** Lumerical Mode simulation results

| **Parameter** | **Simulation Result** |
|---|---|
| Group Index ($n_g$) – lowest TE mode | 4.548272 |
| Effective Index ($n_{eff}$) – lowest TE mode | 2.381033 |
| neff vs λ characteristic equation | neff (λ) = 1.98 - 1.61*(λ - $\lambda_0$) + 0.11(λ - $\lambda_0$)2, $\lambda_0$ = 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 corrugation width is set to 30nm. Group index ($n_g$) is found previously from Part 1 – 1. The period of the Bragg grating is calculated to be 275 nm from the formula below.

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

Due to the biassing effect during fabrication, it is unclear that whether 269nm Bragg period (corresponding to a 350 nm waveguide) is to be used or the 275nm (corresponding to a 335 nm waveguide). Therefore, two different designs have been submitted for fabrication to ensure that the Bragg resonator will operate within the specified range (1290 -1320 nm).

2. 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.

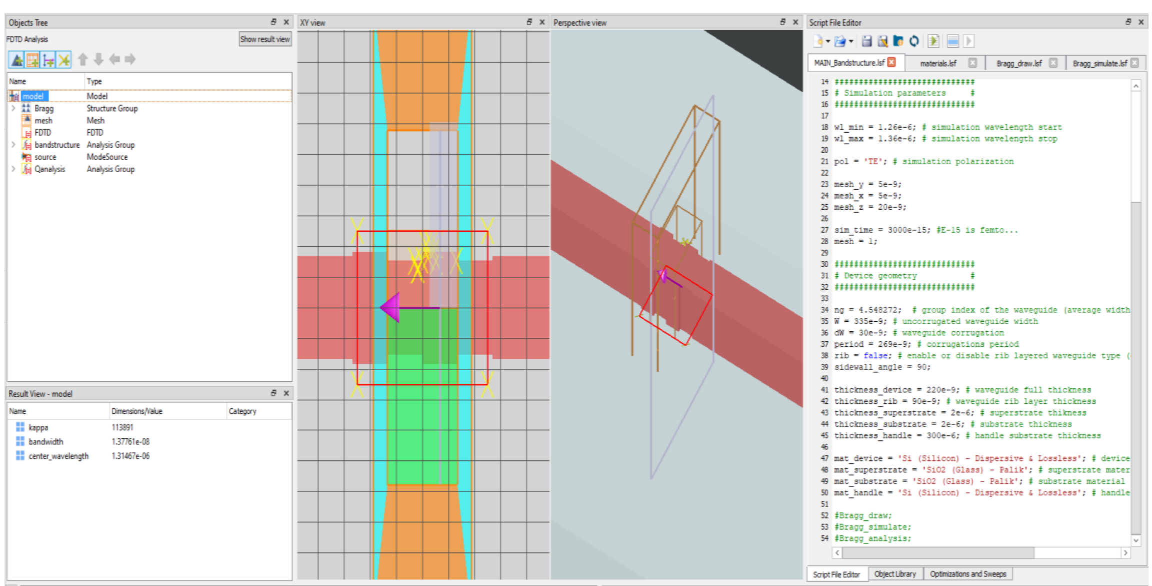



*Figure 6:* Lumerical FDTD simulation of two period of the Bragg grating

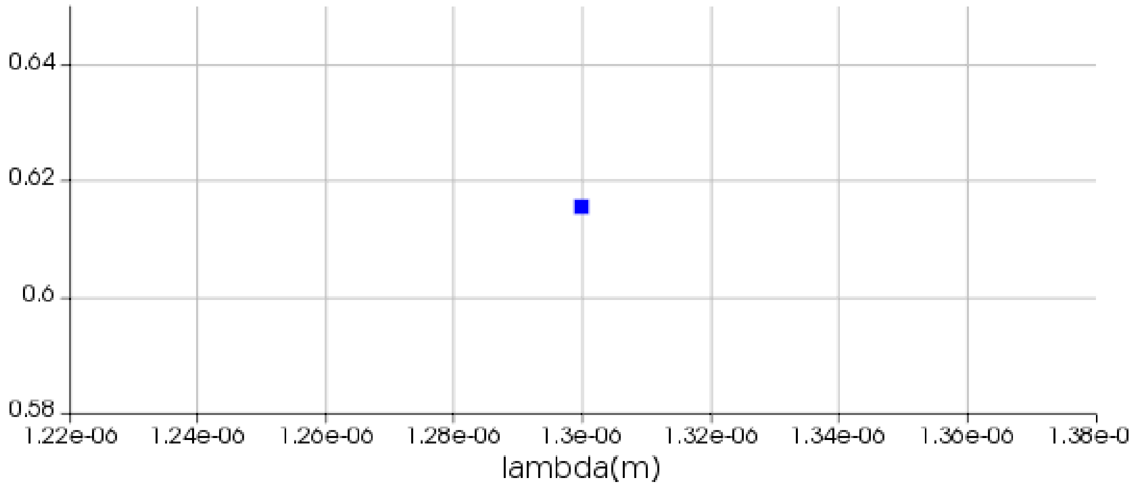



*Figure 7:* Lumerical FDTD calculated loss for the Bragg grating in dB/cm

## 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.

1. 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. 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. 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.

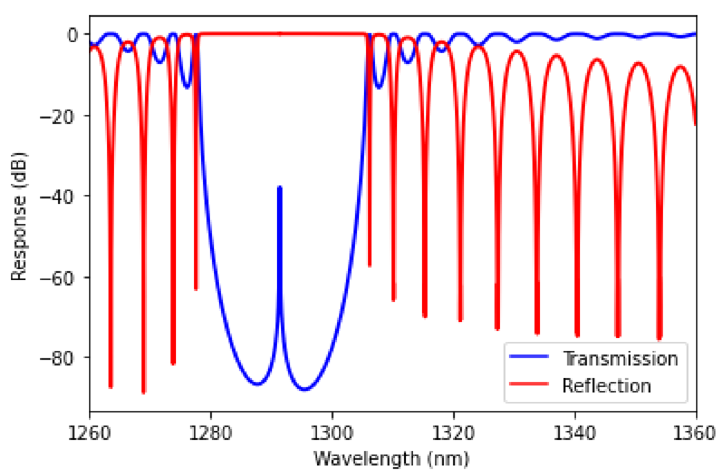



Figure 8: Calculated Response of the Resonator using Bragg TMM (dB scale)

2. 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. In figure 9, the graph of transmissivity (orange line) and reflectivity (purple line) vs wavelength is shown. Wavelength axis is adjusted so that 0 is the central wavelength of 1310nm. From these two simulations we can conclude that our cavity is likely to operate in the range of 1290 – 1310 nm.

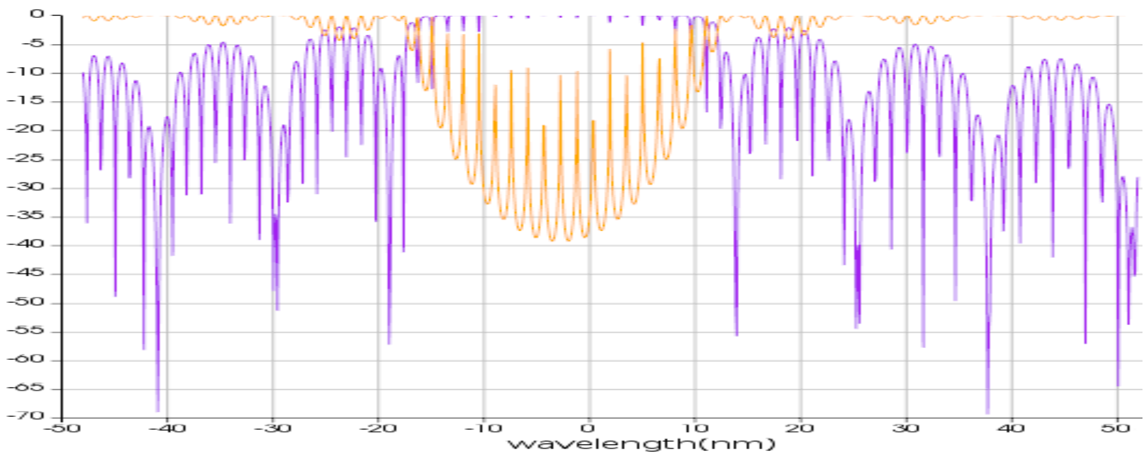



Figure 9: Lumerical FDTD Simulation for the Cavity

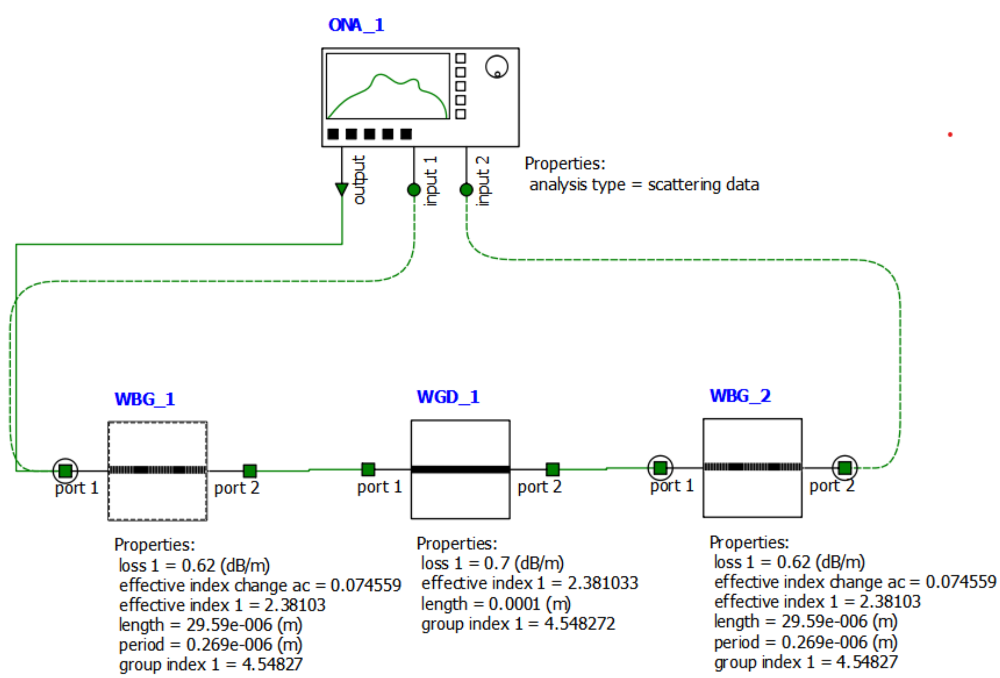



Figure 10: Lumerical FDTD Simulation Setup

## Part 4: Fabrication

1. KLayout software is used to draw the waveguides and to fabricate and physically test the Fabry Perot Cavity resonators. Ebeam lithography technology is used to print the circuits as per specified. Figure 11 shows an example of the Klayout model. Three grading couplers placed 127 ɥm away from each other are required to be able to provide a light input into the circuit and to be able to output both transmission and reflection of the cavity. The circuit in figure 11, also takes advantage of an adiabatic Y splitter for getting the light into the cavity and receiving the reflectivity data. The Bragg gratings are placed on either side of a waveguide and multiple instantiations of the circuit is drawn with different period numbers. A summary of all of the variations and designs in provided in table 3-5.

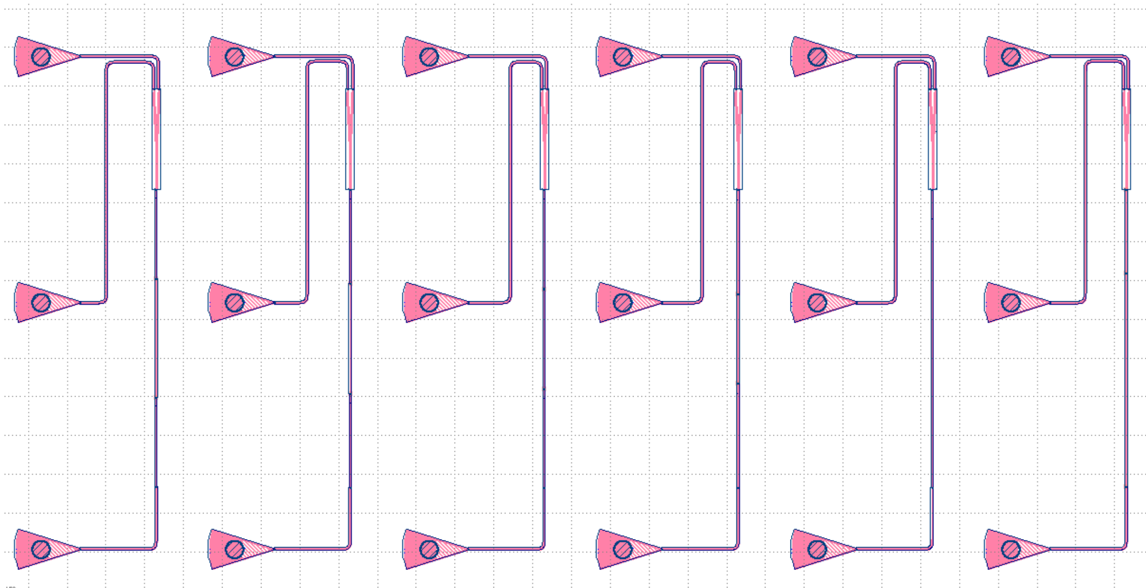


Figure 11: Klayout example: EBeam_ELEC413_AryanC2

2. 3 Klayout models have been submitted for fabrication. In two of these layouts the period number of a 350 nm wide cavity with $d_w$ of 30 nm and period of 269nm are swept (10 periods in difference). Overall length of the cavity stays the same, therefore as the number of Bragg grating periods increases the length of the waveguide in between decreases (becomes less than 100um). In the third one, period number of a 350 nm wide cavity with $d_w$ of 30 nm and period of 275nm are swept, same condition applies to the waveguide as with the other two layouts.

**Table 3:** Table of specifications for layout Ebeam_ELEC413_AryanC

| | |
|---|---|
| **Fabrication Width** | 350 nm |
| **Corrugation width - $d_w$** | 30nm |
| **Thickness** | 220 nm |
| **Period** | 269 nm |
| **Period number** | 110 – 120 – 130 – 140 – 150 – 160 |
| **Expected quality factor** | 100,000-110,000 |

**Table 4:** Table of specifications for layout Ebeam_ELEC413_AryanC2

| | |
|---|---|
| **Fabrication 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** | 100,000-110,000 |

**Table 5:** Table of specifications for layout Ebeam_ELEC413_AryanC3

| | |
|---|---|
| **Fabrication Width** | 350 nm |
| **$d_w$** | 30nm |
| **Thickness** | 220 nm |
| **Period** | 275 nm |
| **Period number** | 110 – 130 – 150 – 170 – 190 – 100 |
| **Expected quality factor** | > 100,000 |

## Part 5: Experimental Data and Analysis

To be performed after the fabrication.

## Part 6: Discussion and Summary

To be performed after the fabrication.

## Part 7: References

To be completed after the fabrication.