Design Proposal of a Waveguide Bragg Grating Resonator

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Introduction

A laser requires three main components: a resonator, an optically amplifying material, and a power source. This report will cover the theory, modelling, and simulation of two Bragg Grating Resonators, to be used as a component in a silicon-integrated-circuit laser. That type of manufacturing is important to the furutre of integrated photonics, because it enables fast data transfer and tiny laser systems for a wide variety of new applications.

Project 1: Multiple Designs

Project 1 aims to use the SiEPIC-EBeam Process Design Kit (PDK) to perform a design-fabrication-test cycle on a bragg grating resonator structure. The ultimate design will include at least ten variations on the test structure, aiming for the highest possible quality factor (likely lying between 20 000 and 150 000). Additionally, the operating wavelength should be between 1270 and 1330 nm, ideally centred at 1310 nm.

For a device such as this, there are two possible designs: Two Bragg Gratings with a length of waveguide between them, or two Bragg Gratings connected directly front-to-back. Both options create a Fabry-Perot cavity between the two gratings where resonance can occur. The main difference is the length in cavity, and therefore the number of resonant frequencies that can exist within it.

For Project 1 the second option will be considered. The direct grating-to-grating connection and lack of extended waveguide means that only a single Bragg Frequency exists between the two gratings, eliminating the need to determine which frequency should be considered.

Project 2: Single Design

Project 2 aims to refine the design from Project 1, simulating and laying out a photonic integrated circuit where a laser is attached to one of the simulated resonator designs. The selected design should be one that has an FSR of less than 0.2, which means an extended Fabry-Perot cavity of at least 1000nm is necessary between the gratings.

Technology

Lumerical MODE, INTERCONNECT, and FDTD [1] and Matlab were all used to simulate various aspects of the design and determine the best value to assign each component of the design. The values found through these simulations apply to both Project 1 and Project 2.

The layout software was KLayout [2]. Project 1 was laid out using the EBeam technology, and Project 2 was laid out using Python and SiEPIC_fab_Ebeam_ZEP in KLayout. All designs were then uploaded into a shared design with the rest of the class through Github and a Qdot-Nexus server.

Theory

The bragg grating acts as a resonator for a laser, both reflecting and transmitting light. Within the Fabry-Perot cavity connecting the two gratings, the light bounces back and forth and eventually reaches a "lasing" state. In designing a bragg grating, there are four main physical attributes that can be changed: Width, change in width, period, and number of periods. In this project, everything but change in width will be set to a reasonable value based on previous simulations done in class [3]. From a physical standpoint, Δw changes how much light is reflected and how much is transmitted, due to its direct relationship with the change in index between the narrow and wide sections of the grating. This impacts the quality factor by changing the bandwidth at the point where the two gratings meet. Six variations on the Δw will be modelled and created in KLayout.

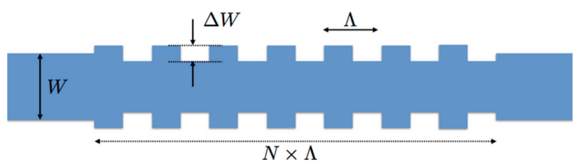

Figure. 1: A Bragg Grating with relevant variables labelled.

There are many other variables that come into play throu[1]ghout this report. They are listed below, along with their values (if known from the beginning) and how they will come to be known by the end.

Variable	**Value**	**How it is Known**
Average Width (w)	335* nm	Selected
Period	290 nm	Selected
Number of Periods (N)	175	Selected
Change in Width (Δw)	Varied	Varied
Target Wavelength	1310 nm	Given
Grating Thickness	220 nm	Given
Polarization	TE	Selected (vs TM)
Losses	-3 dB/cm	Estimated from Class
κ	unknown	Simulated (FDTD)
Effective Index (n_{eff})	unknown	Simulated (MODE, Matlab)
Group Index (n_g)	unknown	Simulated (MODE)
Change in Index (Δn)	unknown	Calculated: $\Delta n = \frac{\kappa \lambda_B}{2}$
Quality Factor (Q)	unknown	Calculated: $Q = \frac{2\pi \lambda_0 T_{rt}}{IL}$

Table 1: Variables at the beginning of the project

[1] The manufacturing bias for Project 1 is 15 nm, so its KLayout average width will be set to 350 nm. For Project 2 the bias is 35 nm, so its KLayout average width will be set to 370 nm. All simulations will be run using an average width of 335 nm.

Modelling and Simulation

Lumerical MODE

The waveguides that will be used are TE polarized and have a 335x220nm silicon core surrounded by a layer of SiO_2. This was modeled in Lumerical MODE for several calculations.

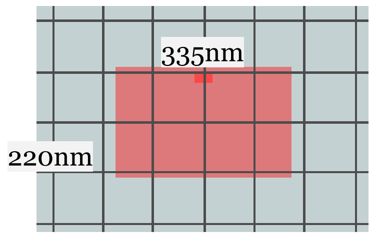

Figure 2: The cross-section of the waveguide.

First, the energy intensity within the waveguide is shown below.

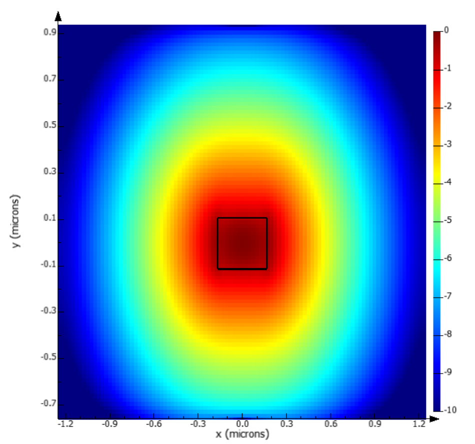

Figure 3: Energy intensity within the waveguide, on a log scale.

Next, a frequency analysis was done to see how the effective and group indexes change with wavelength, centred on the goal wavelength of 1310nm.

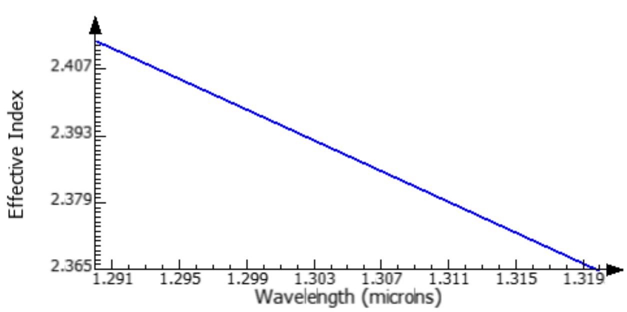

Figure 4: Effective index vs wavelength

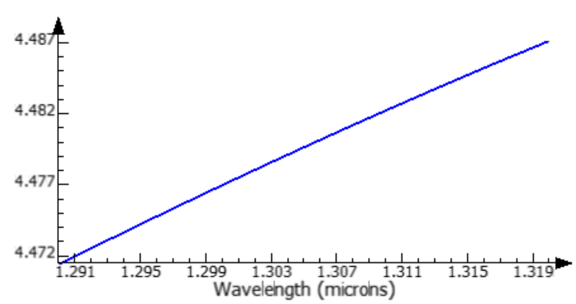

Figure 5: Group index vs wavelength

Together, this shows that the effective index at 1310nm is 2.38097 and the group index at 1310nm is 4.48226.

This data was then exported into Matlab.

Matlab (Compact Equation)

The data imported from Lumerical MODE, as well as the Phot1x_wg_compactmodel.m script provided in the ELEC314 Github [4], was used to find the compact equation of the system. This equation gives the effective index as a function of a "scanned" wavelength, in relation to the base wavelength (here, 1310 nm).

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

The output of the script gives the a1, a2, and a3 values of the compact equation:

```
X =

   2.380967411629838  -1.603991821840072  -0.200245817351706
```

As a result, the compact equation is:

$$n_{eff} = 2.380 - 1.603(\lambda - 1.310) - 0.200(\lambda - 1.310)^2$$

When plotted through the base wavelength, the resulting graph is identical to the one created by Lumerical MODE. This verifies that the script and data were correctly implemented in Matlab.

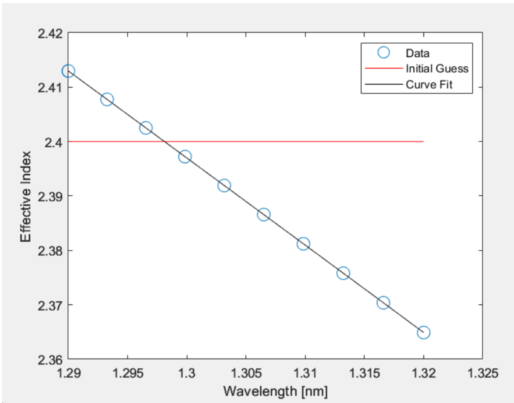

Figure 6: Matlab graph of effective index vs wavelength

Lumerical FDTD

A Lumerical FDTD model was made with an average width of 335n and period of 290nm. The Δw was altered until the resulting plot showed a central wavelength of 1311 nm. This set the $\Delta w = 60nm$.

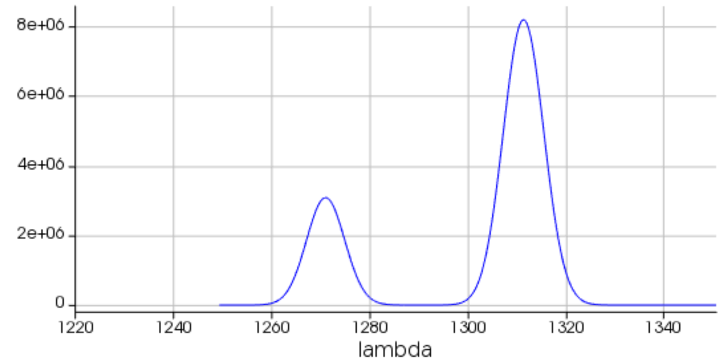

Figure 7: The bragg wavelength and width as shown by FDTD.

Recalculating the effective index from this shows that

$$n_{eff} = frac\lambda_B 2\Lambda = \frac{1311}{2*290} = 2.26$$

This is fairly close to the Matlab model from earlier. Updating the compact equation gives:

$$n_{eff} = 2.261803 - 1.603(\lambda - 1.310) - 0.200(\lambda - 1.310)^2$$

The relationship between coupling index κ and Δw was graphed using an example model provided by Ansys [6]. This parameter sweep keeps the average width and period the same, but plots the Δw between 30 and 90 nm.

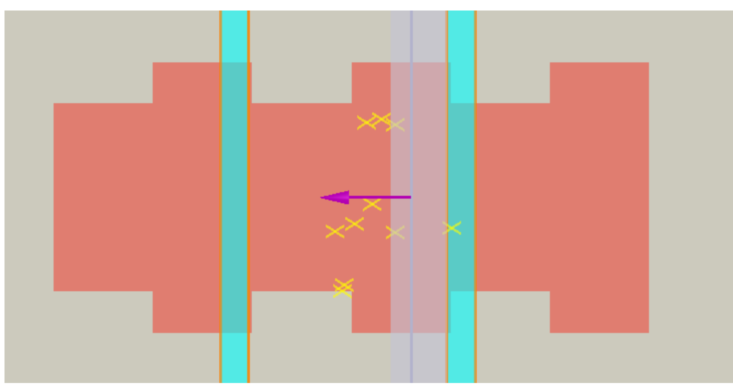

Figure 8: A section of grating as modeled in FDTD.

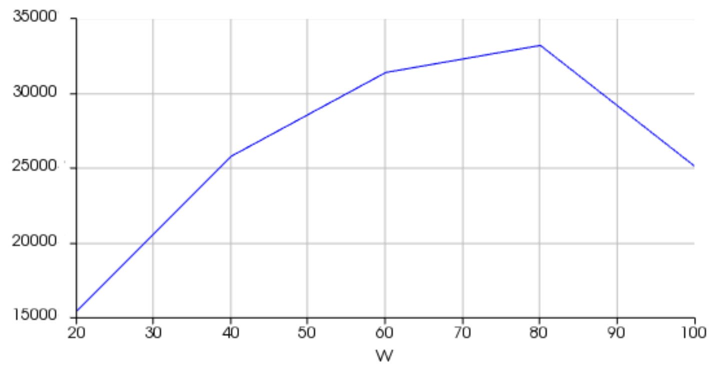

Figure 9: Kappa vs change in width, as modelled in FDTD.

The graph is slightly rough, since only five sweep measurements were made, but it is still enough to determine κ at various Δw's. The selected width changes are centred at 60nm, since that was determined to give a central wavelength of 1311nm. Lumerical INTERCONNECT expressed Δw as Δn, so the one was transformed into the other using the equation

$$\Delta n = \frac{\kappa \lambda_B}{2} .$$

These variables are listed below in table 2.

Lumerical INTERCONNECT

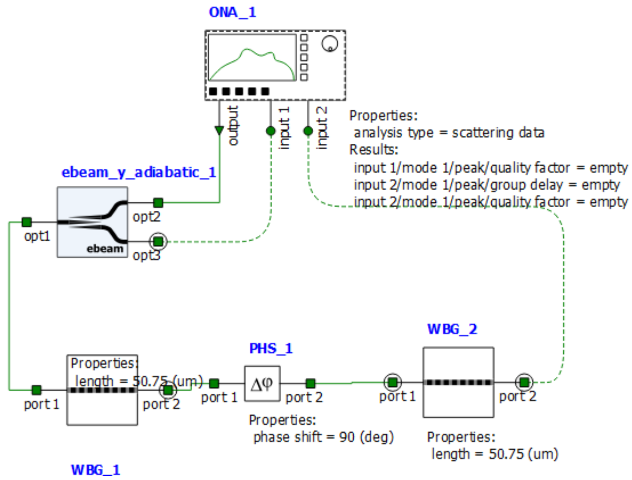

Figure 10: Lumerical INTERCONNECT model

This model was created to test the reflection and transmission of the Bragg Grating system. The phase shift between the two Bragg Grating sections represents the Fabry-Perot cavity created when their two ends are placed together at a 180-degree rotation. The waveguides and gratings all were set to an estimated -3 dB/cm loss.

By varying the Δn as found from the FDTD data, a varying quality factor Q and insertion loss IL were found. The insertion loss was taken directly from the simulation graphs, but Q was calculated as:

$$Q = \frac{2\pi\lambda_0 T_{rt}}{IL}$$

Where Trt is the group delay and IL is expressed as a percentage (calculated using the Matlab db2mag function) [7].

Δw (nm)	52	56	60	64	68	72
κ	28443	29467	30491	30724	30958	31191
Δn	0.0186	0.0193	0.02	0.0201	0.0203	0.02045
Q	51900	60100	69500	70800	73900	76200
IL (dB)	-27.51	-28.77	-30.03	-30.21	-30.57	-30.84

Table 2: Experimental data with varying widths in INTERCONNECT

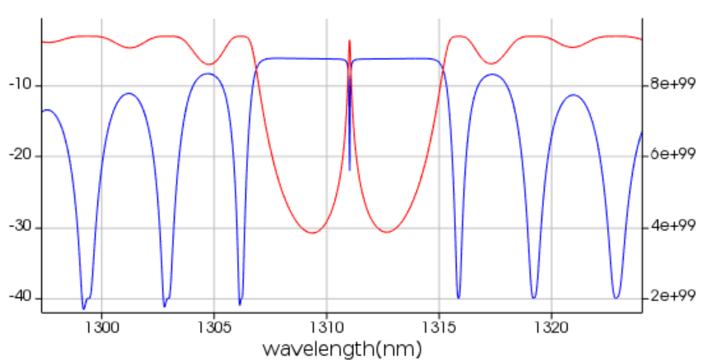

Figure 11: A plotted waveform where the change in width is 72 nm.

As the quality factors increase so does the insertion loss, but the quality increases at a much higher rate. The loss is a bit more than -20dB, but decreasing the loss would sacrifice a lot of the quality so this risk is warranted.

Thanks to these final calculations, all of the necessary variables can now be expressed.

Variable	**Value**	**How it is Known**
Average Width (w)	335 nm	Selected
Period	290 nm	Selected
Number of Periods (N)	175	Selected
Change in Width (Δw)	As listed above	Varied
Actual Wavelength	1311 nm	Simulated
Grating Thickness	220 nm	Given
Polarization	TE	Selected (vs TM)
Losses	-3 dB/cm	Estimated from Class
κ	As listed above	Simulated (FDTD)
Effective Index (n_{eff})	2.261803 at 1311 nm	Simulated (MODE, Matlab)
Group Index (n_g)	4.48226 at 1311 nm	Simulated (MODE)
Change in Index (Δn)	As listed above	Calculated: $\Delta n = \frac{\kappa \lambda_B}{2}$
Quality Factor (Q)	As listed above	Calculated: $Q = \frac{2\pi\lambda_0 T_{rt}}{IL}$

Table 3: Variables as known at the end of the simulations.

KLayout (Project 1)

Finally, the physical model. All variations of the design must fit within a 620x405 nm space, so they were designed to have as small a footprint as possible while still meeting the spacing requirements (all components and spaces at least 60nm wide, waveguide curves at least 5um in diameter, 127um spacing between grating couplers).

Due to manufacturing bias the width of the gratings must be designed as 15nm wider than they were simulated. As stated earlier, the simulations were run at 335nm average width, so the KLayout model was designed with a width of 350nm in the gratings and waveguides.

There is room for twelve circuits on the model, but only six width variations were simulated. Therefore each Δw will be done on a square and a sinusoidal grating, to observe the effects of the sinusoid on the behaviour of the reflector.

Two de-embedding structures were also included in the layout to help correct for noise in the measurements. One corrects reflection, and the other transmission.

The circuits are laid out:

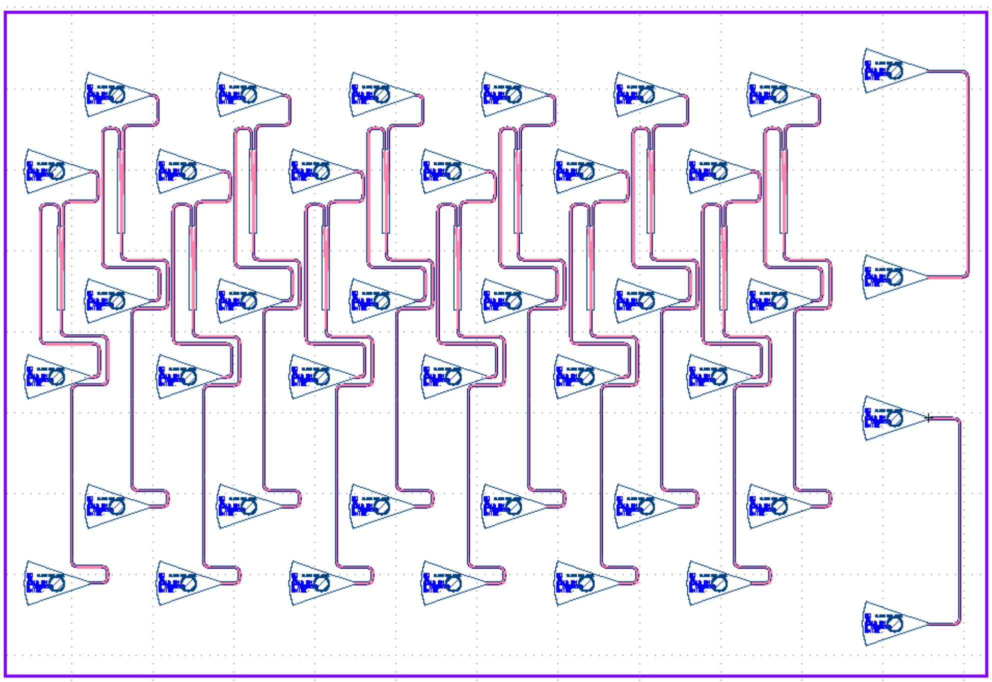

Figure 12: The KLayout for Project 1.

KLayout (Project 2)

For project 2, the goal is to design a single circuit that incorporates the grating design from project 1 with a long waveguide between the two bragg gratings. This will be manufactured on a chip to connect the Fabry-Perot circuit to a laser.

The grating design used here will be the one with $\Delta w = 72nm$, because it had the largest quality factor and not much more loss than the other designs. The square grating will be used, since the inclusion of the sinusoidal guide was more for experimentation and is a less certain design.

In fabricating this circuit the widths will be shaved down by 35 nm, not 15 like in Project 1. Therefore, the widths of the gratings and waveguides were designed as 370 nm. The number of periods was also lowered from 175 to 125 in order to meet the minimum bend requirements of the chip.

The provided design was adjusted to include the correct parameters from Project 1, and uploaded to the class' chip:

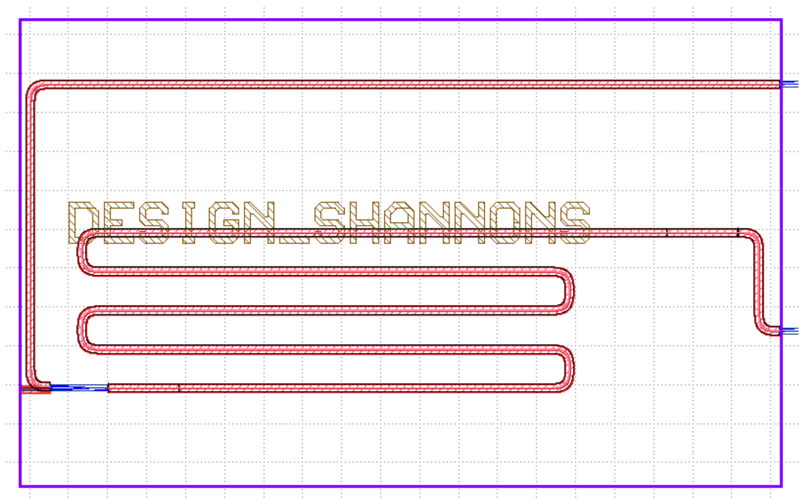

Figure 13: KLayout for Project 2.

References

[1] Lumerical. https://www.lumerical.com/

[2] KLayout. https://klayout.de/

[3] Chrostowski, L. *UBC ELEC 413-201,* EdX.
https://learning.edge.edx.org/course/course-v1:UBC+ELEC413-201+2022_W1/home

[4] Chrostowski, L. *UBC-ELEC-413-2023,* Github. https://github.com/SiEPIC/UBC-ELEC413-2023

[5]*Documentation,* Matlab. https://www.mathworks.com/help/

[6]*Bragg Grating Initial Design with FDTD*. Ansys Optics Support.
https://optics.ansys.com/hc/en-us/articles/360042304394-Bragg-grating-initial-design-with-FDTD

[7]Paschotta, R. *Q Factor,* RP Photonics Encyclopedia. https://www.rp-photonics.com/q_factor.html