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Bragg Grating Cavity Design Using Bragg Gratings

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Abstract

The aim of the experiment is to design Bragg Grating Cavity design (to show Fabry Perot effects) for High Quality Factor. The basic Bragg Grating design used in this project consists of two identical Bragg Gratings and a cavity between the two Gratings. Bragg devices are first simulated using Transfer Matrix Model (TMM) on MATLAB. Parameters like Number of Grating Periods, Cavity Length and Type of Grating are varied to note the effect on Quality Factor. 7 Bragg devices are then designed using KLayout, visualized using Lumerical Interconnect and compared to Matlab TMM model. Simulated results are compared to Measured results using MATLAB and the differences between measurement data and simulated data are discussed. Out of the several implemented designs, the rectangular grating type design with Grating periods of 195, cavity length of 54.6µm and corrugation width 0.045µm resulted in the highest experimental Quality Factor.

Keywords: Lazers, Bragg Cavity

I. INTRODUCTION

In the last few decades, Technological innovations have been increasing exponentially. Innovations ranging from Supercomputers to proliferation of connected devices within Internet of things as well as growth of big data have reshaped the potential of humans in many ways. Almost all modern devices using these technologies rely on electrical wiring to transmit data. As we approach the physical limit of chip miniaturization, shortcomings of copper wires as well as semiconductor devices come into focus. The limited bandwidth, speed limitations, current leakage as well as crosstalk are few limitations of Copper wires. As for semiconductor devices, the limitations on the physical mobility of electrons and effects such as Tunneling and heating cause impediments in extensive usage of such devices in data transfer in the coming years.

This has led to the increasing need for a new method of faster data transfer. Silicon photonics offers numerous benefits in the field of data transfer, Communication, and strain sensing. Silicon Photonics devices have the advantage of having less consumption of power, less heat generation, high bandwidth capabilities and high speed of data transfer. These devices are also insusceptible to any interference from Electromagnetism as well as can be incorporated to use existing nanofabrication technology. The Silicon Photonics Market is projected to grow from USD 1.0 billion in 2020 to USD 3.0 billion by 2025, growing at a rate of 23.4% [1]

Klayout with SiEPIC-EBeam is the software used to design the Bragg Grating Devices. Each device can be imported to Lumerical INTERCONNECT to visualize the Transmission and Reflection spectrum of the device. This Lumerical Spectrum data can then be compared to Matlab predictions and to measurement data.

This report demonstrates the design of a Bragg Grating Cavity device (figure 1a and 1b). Various tasks such as the simulation, curve fitting of data, fabrication, manufacturing variability is discussed.

II. THEORY DESCRIPTION

The devices are measured by sweeping wavelength from 1500- 1600nm and noting the Transmission Spectrum (dB). Peaks will then be identified. In this design, a Multimode system (2-3 peaks) is chosen by increasing the cavity length. The quality factor Q for each peak can be calculated using the formula: $Q = \frac{\omega}{\Delta\omega_{3dB}}$ where $\Delta\omega_{3dB}$is the 3dB bandwidth. The chosen Bragg grating cavity device consists of a testing input for the input Lazer beam and 2 detectors to detect the Reflection and Transmission Spectrums. There are 2 identical Bragg gratings (top and bottom gratings in Figure 1a) with a Fabry Perot Cavity in between. This design is to trap light and transmit only at certain wavelengths.

III. DIAGRAMS AND ILLUSTRATIONS

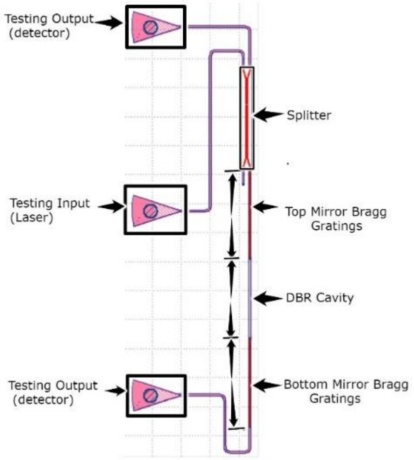


Figure 1a: We can see a simple Bragg grating cavity device. The detectors and lazer inputs are separated by 127µm.

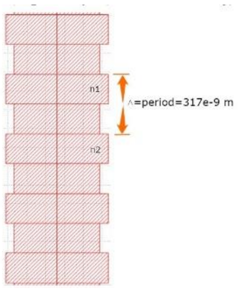


Figure 1b: A basic structure the Bragg grating. It consists of alternating material of n1 and n2 with a period of $317X10^{-9}$m.

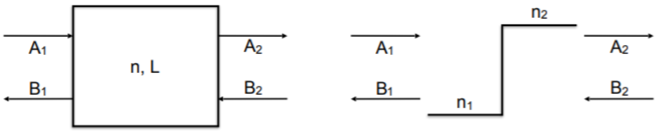
IV. MODEL DESCRIPTION

A. Transfer Matrix Method

The Transfer Matrix Method can be used to obtain a simulated Transmission Spectrum of the Bragg

Grating Design. Shown below are two Transfer Matrix systems, one called the propagation matrix (homogeneous) and the second called index step matrix (going from material with refractive index n1 to index n2). The inputs and outputs are (A1, B2) and (A2, B1).

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}$$



(a) Propagation matrix. (b) Index step matrix.

Figure 2: Propagation Matrix and Index Step Matrix [2]

For the above Figure 2, given below are the equations used from class to Calculate these 2 matrixes. For Figure 2b, L is the thickness of each layer. For Figure 2c, n1 and n2 are the refractive indexes of medium 1 and 2.

$$T_{\text{hw}} = \begin{bmatrix} e^{j\beta L} & 0 \\ 0 & e^{-j\beta L} \end{bmatrix}$$

$$\beta = \frac{2\pi n_{\text{eff}}}{\lambda} - i\frac{\alpha}{2}$$

Figure 2b: Propagation matrix with β defined. [2]

For our design, Loss= 7.1 dB/cm, we get α=163.46m^{-1}. For Figure 2c, $n_{1,2} = n_{eff} \mp \frac{\Delta n}{2}$ [2]. Also, $\Delta n = \frac{\kappa\ X\ \lambda_B}{2}$ [2] , where κ is kappa and λ_B =central wavelength=1550nm. Also, $\lambda_B = 2\Lambda n_{eff}$ [2] where n_{eff}=effective index and Λ=grating period. More Discussion on n_{eff} is found on the next section on Lumerical modes.

$$T_{\text{is-12}} = \begin{bmatrix} 1/t & r/t \\ r/t & 1/t \end{bmatrix} = \begin{bmatrix} \frac{n_1+n_2}{2\sqrt{(n_1 n_2)}} & \frac{n_1-n_2}{2\sqrt{(n_1 n_2)}} \\ \frac{n_1-n_2}{2\sqrt{(n_1 n_2)}} & \frac{n_1+n_2}{2\sqrt{(n_1 n_2)}} \end{bmatrix}$$

Figure 2c: Index step matrix [2]

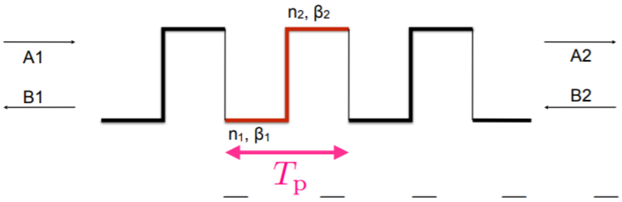


Figure 3: Transformation Matrix Tp for one grating [2]

This matrix Tp (for 1 grating) can be calculated using the formula: $T_p = T_{hw-1}T_{is-1,2}T_{hw-2}T_{is-2,1}$ [2]

For N gratings, $T_{\text{Top}} = (T_p)^N$ and $T_{\text{bottom}} = (T_p)^M$. Transfer matrix of cavity is $T_c = T_{is2c}T_{hwc}T_{isnc}$ [10]

Therefore, the overall stacked Transfer matrix for this system is given by $T = T_p^{(N-1)}T_{hw1}T_{is12}T_{hw2}T_cT_p^M$ [10]

For a symmetric design, the equation above will be modified to $T = T_p^{(N-1)}T_{hw1}T_{is12}T_{hw2}T_cT_p^N$

Shown below is the simulated Matlab Spectrum (using the above derived Transfer Matrix method) for the device with the highest simulated and measured Q. The design is called BraggS4 and has the

following properties:

- Number of periods=195,
- Λ (Grating period) =317X10^{-9}m
- Cavity Length = 54.395X10^{-6} m.
- Corrugation width=0.045 μm
- ➢ Increasing Corrugation width increased kappa which increases Q factor. However, this increase in Corrugation width lowers central wavelength which decreases Q factor. For this reason, a moderate value was chosen.
- Propagation Loss=2.17dB/cm
- Kappa=7.12X10^4 approximated as 7.1X10^4
- As per next section on Lumerical Modes, $n_{\text{eff}}(\lambda) = 2.44689 - 1.16094(\lambda - \lambda_0)$ -0.0761836$(\lambda - \lambda_0)^2$ where $\lambda_0 = 1550nm$

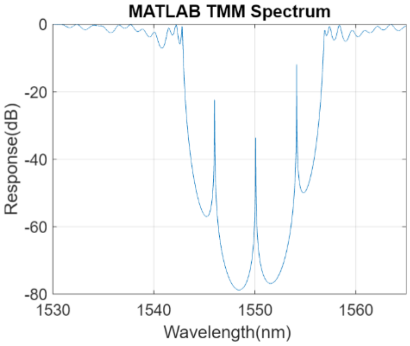


Figure 4: Simulated Transmission spectrum from Matlab simulations using previously described TMM

B. Lumerical Modes

Lumerical MODES can find the guided mode properties of the chosen waveguide. Given below is the TE mode of waveguide. The waveguide has a width of 500nm and height of 220nm

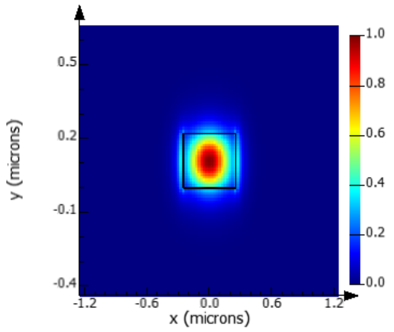


Figure 5: TE mode of waveguide

Using MATLAB, the Waveguide compact model was calculated. A taylor expansion approximation was used. The equation was as follows: $n_{\text{eff}}(\lambda) = a_1 + a_2(\lambda - \lambda_0) + a_3(\lambda - \lambda_0)^2$. The central wavelength $\lambda_0$was chosen as 1550 nm.

In the equation above for n_{eff} = 2.44689, a_2 = -1.16094, a_3= -0.0761836

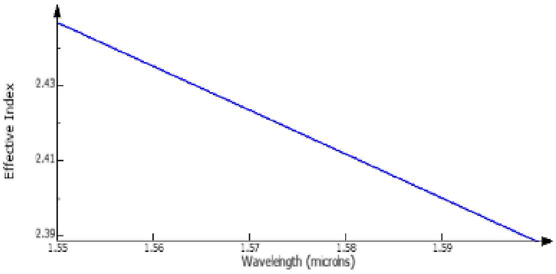


Figure 6a: Effective Index v/s wavelength

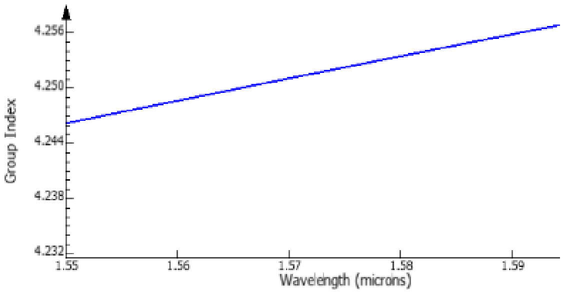


Figure 6a: Group Index v/s wavelength

Properties for the updated TMM to match experimental results can be found in Table 4 on page 7

V. DESIGN METHODOLOGY

To ensure variation in parameters, 7 designs were created and submitted. 2 other designs were included additionally whos Transmission Spectrum and designs can be found in the Appendix, and information on parameters can be found in Table 1b on Page 4 and quality factor information in Table 3b on Page 6.

The following parameters were varied to identify their effect on Quality factor:

- **Number of grating periods**

The grating periods are varied from 140 to 205 and the quality factor was analyzed. An increase in Q was observed by increasing Number of periods until 195 periods after which there was a decrease of quality factor at ~205 periods. Variation was also observed from 100-140 periods and an increase in Q was observed as Grating periods increased. The data is added in the Appendix. Therefore, the number of periods were varied from 140 to 205 directly to show general trend.

- **Length of cavity**

Increasing the number of peaks by increasing the cavity length makes it difficult to calculate Q factor for each of the peaks for each of the designs. Therefore, a cavity length of 54.4 µm was chosen to reduce the number of observed peaks in Transmission Spectrum to 3 peaks to analyze from. Increasing the length increased quality factor for small to moderate cavity lengths. For example, the Q factor for cavity length 54.4 µm is higher than for 22.2 µm

- **Type of Bragg Grating (Rectangular and Sinusoidal)**

There were some designs that were checked with both Sinusoidal and Rectangular gratings. It was observed that a corrugation width of 0.045-0.0051 um (range chosen in this design), Rectangular gratings resulted in higher quality factor than sinusoidal gratings.

VI. SIMULATION RESULTS

i. Increasing the number of Bragg grating periods increases the Quality Factor for a certain wavelength.

- The 4 points in the Figure 7 are the Simulated Quality factor values for the 4 designs submitted: BraggS2, BraggS6, BraggS1/BraggS4, BraggS7, which can be noted as the blue marked points in the Figure 7 in the same order as they are seen from left to right.

❖ The Highest Simulated Q was at **195 gratings** for device **BragsS4** noted as **96740**. BraggsS4 was a design identical to BraggS1 with a slightly lower Corr. Width than BraggS1 (0.045µm instead of 0.051µm).

❖ Number of periods calculated from the best fit curve point for the Figure 7 drawn below, which is **195**

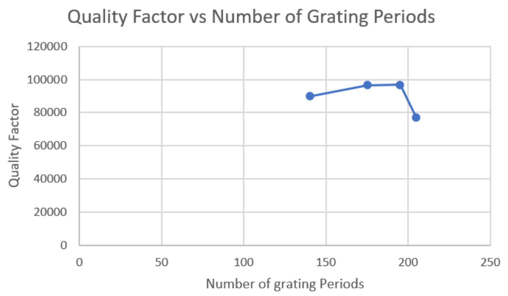


Figure 7: Quality factor as a function of the Number of Grating periods periods.

ii. As cavity length increases, it will allow more wavelengths to resonate. This in turn will increase the number of peaks as length increases.

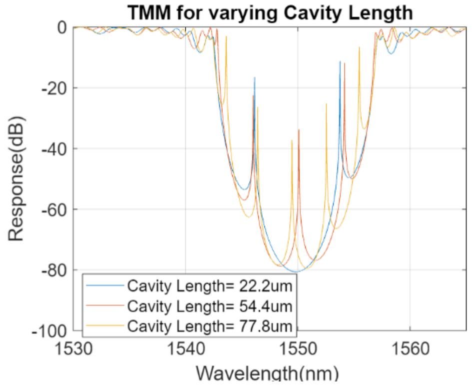


Figure 8: Cavity length effect on number of peaks &Q

iii. At corrugation width ranges of about 45-51 nm as used in this project, Rectangular Bragg Gratings perform better than Sinusoidal gratings (example, comparing BraggS3 and BraggsS5)

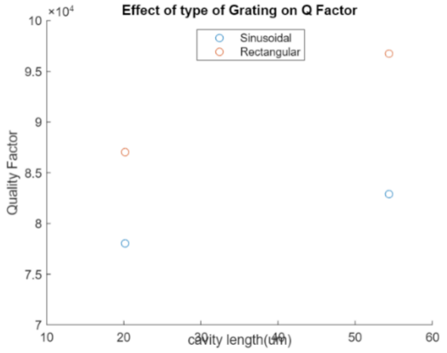


Figure 9: Effect of Sinusoidal and Rectangular Grating

iv. As a general trend, the Quality factor increased with increasing Cavity length. However, it was observed for Rectangular grating that the optimal Q factor was observed at around length= 54.4µm.

v. Shown below in figure 10 is the comparison between simulated Transmission spectrum derived on Matlab (derived using Transfer matrix method) and results from Numerical Interconnect.

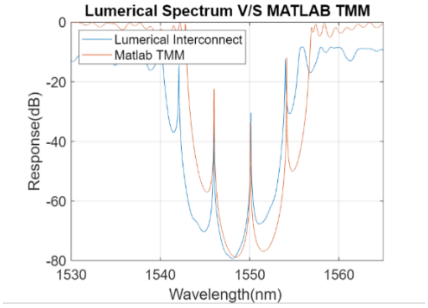


Figure 10: Comparison of simulated Transmission spectrum calculated using Matlab and the results obtained from Lumerical Interconnect.

VII. MASK LAYOUT

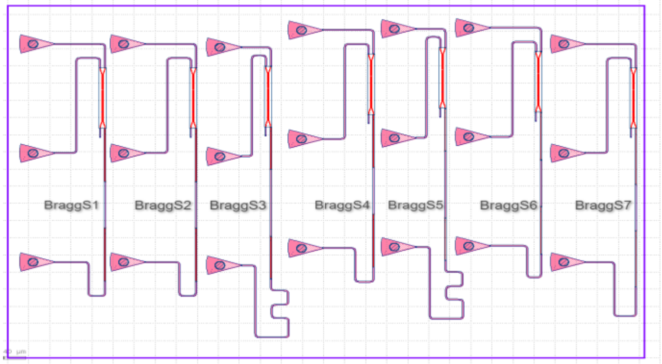


Figure 11: Bragg grating cavity devices sent for fabrication. Labelled in diagram. There is variation in number of periods inBraggS2, BraggS6, BraggS1, BraggS7 and inclusion of sinusoidal gratings in BraggsS3, BragsS5 and BraggS2 to compare with rectangular gratings. Cavity length changes were observed by comparing using BraggS5 with BraggS3

The table below notes all the values and parameters chosen in each layout design: Here CW refers to Corrugation width and PN to number of periods.

Bragg number	Cavity Length (µm)	Sin/rec	CW (µm)	PN
BraggS4	54.4	rec	0.045	195
BraggS3	77.8	rec	0.06	160
BraggS5	77.8	sin	0.06	160
BraggS6	54.4	rec	0.051	175
BraggS7	54.4	rec	0.051	205
BraggS2	54.4	sin	0.051	140
BraggS1	54.4	rec	0.051	195

Table 1: All layouts labelled with shown parameters

Below in Table 1b are parameters of 2 extra devices. The results from 2 extra devices were used in parameter variation (cavity length) were used but has not been added to the final submission due to lack of space on layout. The layout designs as well simulations from these 2 extra devices have been added to the Appendix and Simulated Q factors were calculated for these 2 devices as per Table 3b on Page6.

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Bragg number	Cavity Length (µm)	Sin/rec	CW (µm)	PN
Extrarec*	20.2	rec	0.045	195
Extrasin*	20.2	sin	0.045	195

*not added to final submission

Table 1b: Extra layouts with shown parameters

Bragg number	Cavity Length (µm)	Sin/rec	CW (µm)	PN
BraggS2	54.4	sin	0.051	140
BraggS6	54.4	rec	0.051	175
BraggsS1	54.4	rec	0.051	195
BraggS7	54.4	rec	0.051	205

Table 2a: Layouts Designs for varying Number of periods

Bragg number	Cavity Length (µm)	Sin/rec
Extrarec*	20.2	rec
Extrasin*	20.2	sin
BraggS4	54.4	rec
BraggS2	54.4	sin
BraggS3	77.8	rec
BraggS5	77.8	sin

Table 2b: Layout designs for varying cavity length and Type of gratings

VIII. TEST METHODOLOGY

‘To characterize the devices, a custom-built automated test setup [4, 5] with automated control software written in Python was used [6]. An Agilent 81600B tunable laser was used as the input source and Agilent 81635A optical power sensors as the output detectors. The wavelength was swept from 1500 to 1600 nm in 10 pm steps (or 1 pm steps for those that requested it). A polarization maintaining (PM) fibre was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers [7] (or TM if you designed your circuits for TM, in which case a 90° rotation was used to inject light into the TM grating couplers [7]). A polarization maintaining fibre array was used to couple light in/out of the chip [8].' [3].

IX. FABRICATION

Chips are fabricated at two foundries: Applied Nanotools and Washington Nanofabrication Facility. Description is found below:

Fabrication Process at Washington Nanofabrication foundry:

"The devices were fabricated using 100 keV Electron Beam Lithography [9]. The fabrication used silicon-on-insulator wafer with 220 nm thick silicon on 3 µm thick silicon dioxide. The substrates were 25 mm squares diced from 150 mm wafers. After a solvent rinse and hot-plate dehydration bake, hydrogen silsesquioxane resist (HSQ, Dow-Corning XP-1541-006) was spin-coated at 4000 rpm, then hotplate baked at 80 °C for 4 minutes. Electron beam lithography was performed using a JEOL JBX-6300FS system operated at 100 keV energy, 8 nA beam current, and 500 µm exposure field size. The machine grid used for shape placement was 1 nm, while the beam stepping grid, the spacing between dwell points during the shape writing, was 6 nm. An exposure dose of 2800 µC/cm2 was used. The resist was developed by immersion in 25% tetramethylammonium hydroxide for 4 minutes, followed by a flowing deionized water rinse for 60 s, an isopropanol rinse for 10 s, and then blown dry with nitrogen. The silicon was removed from unexposed areas using inductively coupled plasma etching in an Oxford Plasmalab System 100, with a chlorine gas flow of 20 sccm, pressure of 12 mT, ICP power of 800 W, bias power of 40 W, and a platen temperature of 20 °C, resulting in a bias voltage of 185V. During etching, chips were mounted on a 100 mm silicon carrier wafer using perfluoropolyether vacuum oil. Cladding oxide was deposited using plasma enhanced chemical vapor deposition (PECVD) in an Oxford Plasmalab System 100 with a silane (SiH_4) flow of 13.0 sccm, nitrous oxide (N_2O) flow of 1000.0 sccm, high-purity nitrogen (N_2) flow of 500.0 sccm, pressure at 1400mT, high-frequency RF power of 120W, and a platen temperature of 350C. During deposition, chips rest directly on a silicon carrier wafer and are buffered by silicon pieces on all sides to aid uniformity." [3]

Fabrication process at Applied Nanotools, Inc. NanoSOI:

"The photonic devices were fabricated using the NanoSOI MPW fabrication process by Applied Nanotools Inc. (http://www.appliednt.com/nanosoi; Edmonton, Canada) which is based on direct-write 100 keV electron beam lithography technology. Silicon-on-insulator wafers of 200 mm diameter, 220 nm device thickness and 2 µm buffer oxide thickness are used as the base material for the fabrication. The wafer was pre-diced into square substrates with dimensions of 25x25 mm, and lines were scribed into the substrate backsides to facilitate easy separation into smaller chips once fabrication was complete. After an initial wafer clean using piranha solution (3:1 H_2SO_4:H_2O_2) for 15 minutes and water/IPA rinse, hydrogen silsesquioxane (HSQ) resist was spin-coated onto the substrate and heated to evaporate the solvent. The photonic devices were patterned using a Raith EBPG 5000+ electron beam instrument using a raster step size of 5 nm. The exposure dosage of the design was corrected for proximity effects that result from the backscatter of electrons from exposure of nearby features. Shape writing order was optimized for efficient patterning and minimal beam drift. After the e-beam exposure and subsequent development with a tetramethylammonium sulfate (TMAH) solution, the devices were inspected optically for residues and/or defects. The chips were then mounted on a 4” handle wafer and underwent an anisotropic ICP-RIE etch process using chlorine after qualification of the etch rate. The resist was removed from the surface of the devices using a 10:1 buffer oxide wet etch, and the devices were inspected using a scanning electron microscope (SEM) to verify patterning and etch quality. A 2.2 µm oxide cladding was deposited using a plasma-enhanced chemical vapour deposition (PECVD) process based on tetraethyl orthosilicate (TEOS) at 300ºC. Reflectrometry measurements were performed throughout the process to verify the device layer, buffer oxide and cladding thicknesses before delivery.” [3]

X. EXPERIMENT DATA

Given below is the plot for the experimental results for the device BraggS4 (with the highest Q):

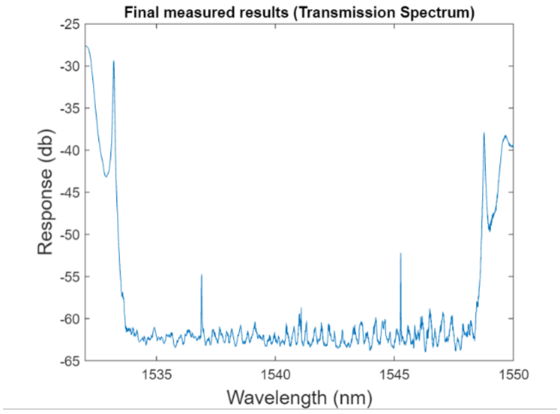


Figure 12: Experimental Transmission spectrum results for BraggS4

Shown below in Figure 13 is the **raw comparison** between the Experimental results and simulation results from Matlab and Lumerical Interconnect. It must be noted that during measurements, the peaks were translated towards the left by around 10 nm as compared to the simulation results. This will be accounted for in the next section using corner analysis by changing the coefficients of the effective index equation. The parameters of the new TMM model (to match experimental results) can be found in Table 4 in Page 7. The number of peaks as well as the nature of peaks obtained in the experimental results are very similar to Simulated peaks and the Q factor of each of the peaks are comparable in both the cases.

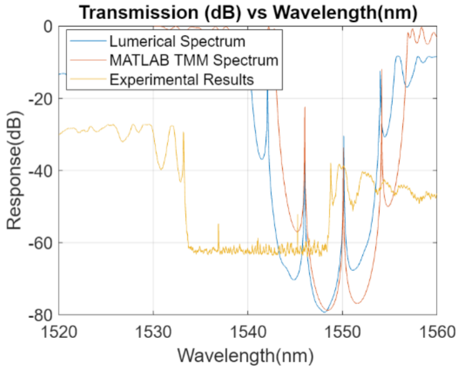


Figure 13: Comparison of Lumerical, Matlab and Measurement Data

XI. ANALYSIS: QUALITY FACTOR & INSERTION LOSS

Quality Factor

Lorentz curve is fitted on Measurement data to help get more accurate measurement of Quality factor. The given equation is used to fit the curve:$F = (P0(1)./((x - P0(2))\text{^}2 + P0(3))) + P0(4)$. P0 = [52

1545.27 0.0114 -500]. In P0, 52 is the magnitude peak, 1545.27nm the central wavelength, 0.0114 the 3dB bandwidth. However, since the high-resolution data could not be measured for my designs, I could not get a smooth Lorentzian curve and approximated the Q values

Note: I had put ELEC 413 in the labels but the system did not catch it. I falsely assumed that the high resolution data would be measured automatically and did not add my name to the google sheets in time. The TA asked me to mention the same in the report.

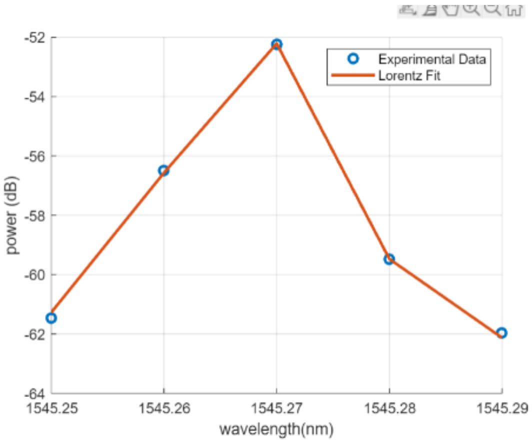


Figure 14: Lorentzian curve fitted to actual data. In the example shown, the resolution is not very high

Shown below in Table 3 is the calculated Q factor (using Lorentzian fit) versus simulated Q factor from Lumerical Interconnect. In Table 3, Qcalc=Calculated Quality factor and
sQlum= Quality Factor observed from Lumerical Interconnect

Device number	**Cavity Length (µm)**	**Sin /Rec**	**Qcalc**	**Qlum**
BraggS4	54.4	rec	135550	96740
BraggS3	77.8	rec	81652.4	95430
BraggS5	77.8	sin	84737	83824
BraggS6	54.4	rec	106608	96504
BraggS7	54.4	rec	77001	67006
BraggS2	54.4	sin	89760	82682.88
BraggS1	54.4	rec	X	96966

Table 3: Quality Factors using Lorentzian curve for different devices. X in BraggS1 could not be calculated because it was below tolerance line for fabrication.

****Extra design values****

Bragg number ______	**Cavity Length (um)**	**Sin/rec**	**Qcalc**	**Qlum**
Extrarec *	20.2	rec	X	87020

Extrasin *	20.2	sin	X	78010

not added on original submission

Table 3b: Quality Factors for extra devices as mentioned in Table 1b.

Insertion loss is calculated as -15.86dB

XII. ANALYSIS: UPDATED TMM MODEL PARAMETERS

To match the TMM to experimental data, design BraggS4 (with highest quality factor) is analyzed. To account for the translation of peaks in the experimental data left by 10 nn when compared to simulated data, corner analysis is done (changing the coefficients of the effective index equation) in order to shift the peak wavelength as well as change the bandwidth of each peak.

The equation for the Updated effective index equation is modified to shift the Simulated peaks wavelength (accounted by change in a_1) and band width of peaks (accounted by change in a_2) to match the Experimental results. The complete equation after corner analysis is as follows:

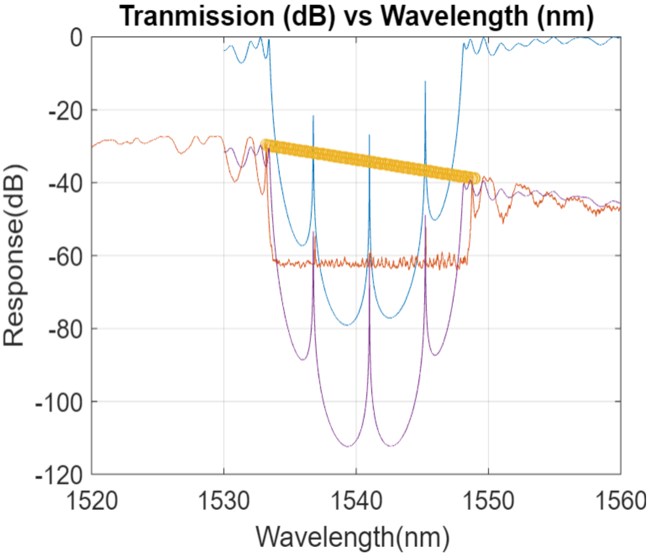
Equation A

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

where a_1 = 2.4202, a_2 = -1.040, a_3=-0.0761836

The group index can $n_g$be related to effective index n_{eff} using the following relation: $n_g = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$ [10]

The magnitude of Transmission spectrum was also shifted downwards in the dB scale in the experimental data as compared to MATLAB TMM model as seen in the following Figure 15a (blue and red curves):



The following exercise was done:

Figure 15a: Matlab TMM model Transmission spectrum dB manipulation

In the above Figure 15a, the MATLAB TMM model is shown in blue and Measured results in Red. A straight line (shown in yellow) is drawn in the measured data to match its background. The TMM Spectrum is then shifted down by the difference in dB between the background of TMM (0dB) and the yellow line to obtain the purple curve. It is important to note noting that after this exercise, the background of both the TMM and experimental data match and the spectrum shift (in dB) is correctly accounted for. Next, another iteration is done to match the bandwidth changes and any slight peak shifts using parameters a1 and a2 in Equation A (n effective equation).

Note: The values mentioned in Equation A are the final values after the reiteration of the n effective equation coefficients.

Given below in Figure 15b on the next page is the updated TMM model to match the experimental results: It can be noted that the central peak matches exactly, and the other peaks match very well. Several iterations were made to find the exact n effective equation before finalizing the model

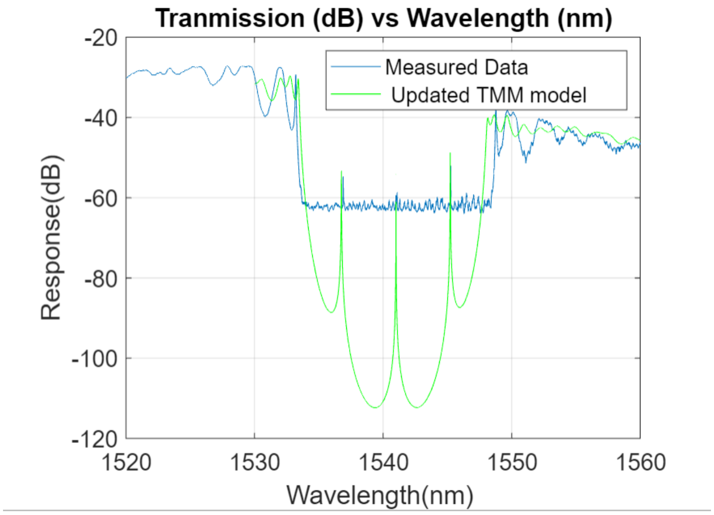


Figure 15b: Matlab TMM model Transmission spectrum with updated Parameters vs Expiremental data. Both match well

For the model above, the following parameters are used. For Insertion loss and Propagation loss, the modulus of provided values can be used.

Parameter	Value
Kappa	**7.1X10^4**
Insertion Loss (dB)	**-15.86**
Propagation Loss(dB/cm)	**-2.17**
∆n	**0.055**

Table 4: Updated TMM matrix parameters used to match the spectrum of Experimental vs Simulated results

XIII. DISCUSSION

The peaks and spectrum from the experimental results match well with the updated transfer matrix model. The simulated quality factor has some variation with the experimental quality facto, which may be attributed to some inaccuracies with calculation of propagation loss. The system tolerances in experimental setup makes it impossible to have a perfectly superimposed Transmission Spectrum for Simulated vs Experimental results. Due to manufacturing errors, it also also possible to have slightly different dimensions for the cavity length as well as waveguide.

XIV. FUTURE WORK

- For more work in the future we could include a wider variation comparing Sinusoidal and Rectangular Gratings.
- There could be more variation in Corrugation width to analyze effect on Q factor
- Include Spiral Designs for better identification of Propagation loss
- Change cavity length (decrease) to change to single peak system at desired center frequency

XV. CONCLUSION FROM RESULTS

1. Number of grating periods:

The number of grating periods were varied from 140 to 205. As a general trend, increasing the grating period increased the quality factor. However, for values higher than 195 grating periods higher grating period, the propagation loss will decrease the quality factor.

2. Cavity length:

As a general trend, increasing cavity length increases number of peaks. Increasing the length also increases the Quality factor. For my designs, an ideal length of 54.4 um yielded the highest Q factor (saturation value).

3. Type of Grating

For corrugation widths of around 0.045-0.051 um (chosen in this project), Sinusoidal Gratings had lower Quality Factor than Rectangular.

XVI. FINAL CONCLUSION

Various parameters like the type of Grating, Number of Grating periods, Corrugation width can be varied to achieve the highest quality factor.

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7. www.plcconnections.com, PLC Connections, Columbus OH, USA.
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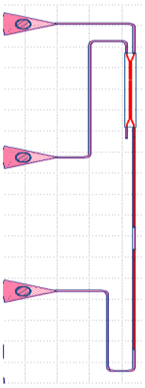
XVII. APPENDIX

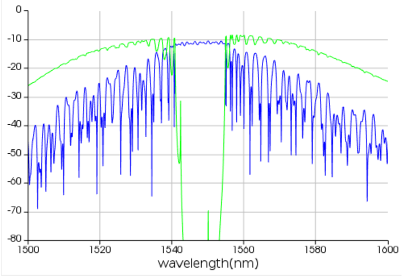
Extra designs:

1. Extrarec:

Mask Layout:

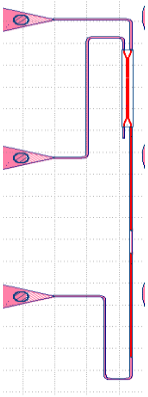


Spectrum:

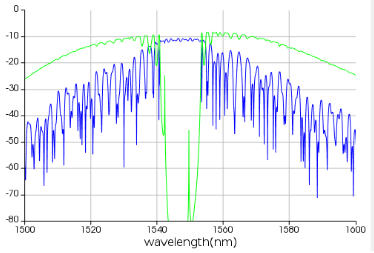


2. Extrasin

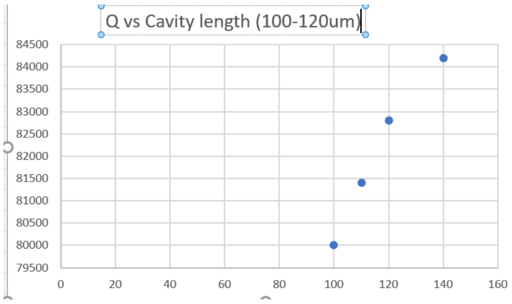
Mask layout:



Spectrum:



Q factor Varying length 100-140um:



Matlab Updated TMM code:

```
% Base Matlab code By Xu Wang, UBC
% plot the spectrum
```

%TMM code:

```
function main
clear;
span = 40e-9; % Set the wavelength spanfor the simultion
resolution = 0.0125e-9; % Set the wavelength resolution
N = span/resolution;
disp([ 'Number of points: ' num2str(N) ])
Lambda = zeros(N+1,1);
R = zeros(N+1,1);
T = zeros(N+1,1);
for i=1:N+1
 wavelength = 1550e-9 +(i-1-N/2)*resolution; % Wavelength sweep
 Grating_Parameters(wavelength*1e6);
 [r,t] = Grating_RT(wavelength); % Calculate the R and T
 Lambda(i) = wavelength*1e9; % in nm
 R(i) = r;
 T(i) = t;
%UBC ELEC 463 Report 10
end
% plot(Lambda,[R T],'LineWidth',2);
T_dB_26 = 10*log10(T);
%save('C:\Users\ni\Documents\ELEC413\Report\TMM\TMM_Bragg26_arm.mat','T_dB_26');

plot(Lambda,T_dB_26-(0-(-0.5812878*Lambda + 861.5259)),'g');
%plot(Lambda,T_dB_26,'LineWidth',2);
xlim([1520 1560])
set(gca,'FontSize',14);
title('Tranmission (dB) vs Wavelength (nm)')
xlabel('Wavelength(nm) ')
ylabel('Response(dB)')
```

```
%xtickformat('%10.4'); ytickformat('%10.4f');
%legend("Matlab updated TMM","Experimental Results",'location',"northwest")
grid on
hold on
%legend("Measured Data", " Updated TMM model")
% legend('Reflection','Transmission');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function Grating_Parameters(lambda)
%Set the parameters
global Period NG L delta_n n1 n2 n_eff loss cavityLength;
Period = 317e-9; % Bragg period
%n_eff = 2.419-1.16094 * (lambda-1.550) -0.0761836 *(lambda-1.550)^2;
%good next line
% n_eff = 2.4202-1.04* (lambda-1.550) -0.0761836 *(lambda-1.550)^2;
n_eff = 2.4202-1.040* (lambda-1.550) -0.0761836 *(lambda-1.550)^2;
cavityLength = 54.39500e-6;
NG = 195;%1500; % Number of gratingperiods
L = NG*Period; % Grating length
%kappa = 7.53*10^4;
%kappa = 7*10^4;
kappa = 7.1*10^4;
delta_n =(kappa*1550e-9)/2; % Index contrast between n1 and n2
n1 = n_eff-delta_n/2;
n2 = n_eff+delta_n/2;
loss = 50; %-2.17dB/cm
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [R,T] = Grating_RT(wavelength)
%Calculate the R and T for a certain wavelength
M=Grating_Matrix(wavelength);
T=abs(1/M(1,1))^2;
R=abs(M(2,1)/M(1,1))^2;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function T = Grating_Matrix(wavelength)
% Calculate the total transfer matrix of the gratings
global Period NG;
%UBC ELEC 463 Report 11
```

```
global n1 n2 n_eff loss cavityLength;
arm_length = 100.5e-6;
l = Period/2;
T_hw1 = HomoWG_Matrix(wavelength,l,n1,loss);
T_is12 = IndexStep_Matrix(n1,n2);
T_hw2 = HomoWG_Matrix(wavelength,l,n2,loss);
T_is21 = IndexStep_Matrix(n2,n1);
Ttop = T_hw1*T_is12*T_hw2*T_is21;
T_is2n = IndexStep_Matrix(n2,n_eff);
T_hwn = HomoWG_Matrix(wavelength,cavityLength,n_eff,loss);
T_isn1 = IndexStep_Matrix(n_eff,n1);
%T_hwarm = HomoWG_Matrix(wavelength,arm_length,n_eff,loss);
NG=195;
T =
T_isn1*Ttop^(NG)*T_hw1*T_is12*T_hw2*T_is2n*T_hwn*T_isn1*Ttop^(NG+50)*T_hw1*T_is12*T
_hw2*T_is2n;
end
%T = Ttop^(NG)*T_hw1*T_is12*T_hw2*T_is2n*T_hwn*T_isn1*Ttop^(NG);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function T_hw = HomoWG_Matrix(wavelength,l,neff,loss)
% Calculate the transfer matrix of a homogeneous waveguide.
Grating_Parameters(wavelength*1e6);
%Complex propagation constant
beta = 2*pi*neff/wavelength-1i*loss/2;
v = [exp(1i*beta*l) exp(-1i*beta*l)];
T_hw = diag(v);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function T_is = IndexStep_Matrix(n1,n2)
% Calculate the transfer matrix for a index step from n1 to n2.
a = (n1+n2)/(2*sqrt(n1*n2));
b = (n1-n2)/(2*sqrt(n1*n2));
T_is = [a b; b a];
end
end
```

[10]