Loss Dependency of Quality Factor for Phase-Shifted Cavities using Bragg Gratings

Davin Birdi

Department of Electrical and Computer Engineering
University of British Columbia, Vancouver, BC V6T 1Z4, Canada

Abstract -- Focusing on a Phase-Shifted Fabry-Perot Cavity consisting of two back-to-back Bragg Gratings, we can fabricate with 3-month turn-around a laser resonator cavity to optimize quality factor. Doing this without an estimation of loss, we characterize our measured device to extract our manufactured parameters such as loss and kappa to update our simulation models to improve further designs. Discussion on developing compact models and their benefits.

I. Introduction:

Lasers consist of two major components, an active gain region and a resonating cavity. The resonating cavity has not only an impact the average power output of the resulting lasing beam of photons from its loss, but also the wavelength at which it focuses at and the quality of the beam.

In this report, we study the effects of varying parameters of the cavity and how it affects our beam, namely the Quality Factor. This is the sharpness of the resonant frequency which is of great importance to applications in communication networks such as the spacing of channels in Wavelength Division Multiplexing (WDM). The Quality Factor also is important for general laser design as it defines how focused the beam is about its frequency. Low Quality factor devices can cause wasted power in spectroscopy applications as power is spent exciting modes away from the intended frequency.

We can apply our theoretical design to an experimental fabrication to validate our knowledge and see real world results.

II. Modelling:

A. Bragg Gratings:

A Bragg Grating is essentially a periodic structure of varying effective indices that both transmits and reflects the input signal.

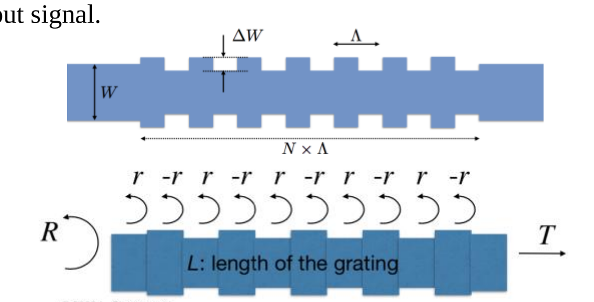

Figure 1: Parameters we can vary in a Bragg grating to affect reflectivity and transmission.

There are reflections at every interface of the grating's changing widths. Each grating has a section with different width with its own effective index. From Snell's Law, every beam of light that enters the cavity gets reflected and transmitted through each interface repeatedly as it propagates through the device.

As designers we can modulate these parameters of the grating:

W	Width of Waveguide	Influences Effective Index of waveguide
ΔW	Corrugation Width	Influences Kappa, the Reflection Coefficient
Λ	Period of Corrugation	Influences λ_B, the resonant wavelength
N	Number of Gratings	Influences Reflectivity of Gratings

Table 1: Above are the Bragg Grating Parameters that we can vary and how they affect our input signal.

1) *Effective Index Compact Models of a Straight Waveguide:*

An essential part of waveguide analysis is the effective index of a certain mode of light within a specific geometry of the waveguide. We use Lumerical MODE to computationally aid us in finding an approximate polynomial fit to our wavelength area of interest from the material response.

Using curve fit material data done by Palik, we can simplify our effective index vs. wavelength relationships using a curve fit on data obtained during a wavelength sweep of a 2D model of our waveguide cross-section. We curve fit to a second order Taylor expansion about our central wavelength.

For a 350nm wide waveguide centered about 1.310μm, we find the effective index and group index Compact Models below using Lumerical MODE:

$$n_{eff}(\lambda) = 2.3542 - 1.85928(\lambda - 1.31)^1 - 0.52956(\lambda - 1.31)^2$$

$$n_g(\lambda) = 4.77027 + 1.3532(\lambda - 1.31) + 1.24954(\lambda - 1.31)^2$$

We note that this can vary depending on the material data we use to fit. When we use a Lorentzian model, we can notice the small differences in coefficients, for example in our effective index:

$$n_{eff-Lorentz}(\lambda) = 2.35391 - 1.8055(\lambda - 1.31)^1 - 0.6413(\lambda - 1.31)^2$$

In further studies we will determine how much the difference in fit source of a waveguide effects the output of our simulated device and will not cover this further.

2) *Simulating the Bragg Grating using FDTD:*

We can easily model straight waveguides using Lumerical MODE's 2D Eigenmode Solver but require other methods for structures such as the Bragg Grating. We are unable to use two MODE simulations for different sized waveguides as that does not accurately model the interaction of light with the geometry of the waveguide. Here we take advantage of the periodicity to speed up our simulation time from orders of hours to minutes:

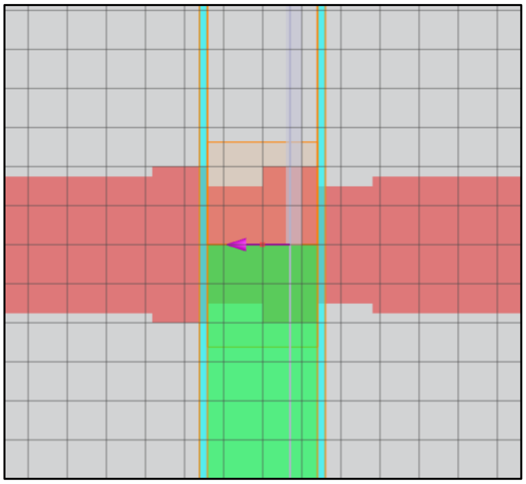

Table 2: Lumerical Mode FDTD Bloch Simulation of an infinite length Bragg Grating.

From a single simulation of 278µm corrugation width we can obtain:

Kappa: κ	164,978	-
Bandwidth: $\Delta\lambda$	19.6	nm
Center Wavelength: λ_B	1.33589	µm

Table 3: Simulation Results using FDTD Method

We can run this same simulation over a parameter sweep of corrugation width to obtain a maximum Kappa. This maximum Kappa gives us the largest delta effective index, which results the most amount of reflectivity per length.

$$\Delta n_{eff} = \kappa \cdot \frac{\lambda_B}{2} \qquad (n)$$

The higher the reflectivity (kappa) of each period of grating, the less gratings we require to achieve a certain reflectivity. The less gratings we have indicated less distance for a photon to travel over, meaning less distance for it to be affected by loss. With less loss we can get a higher quality factor, which is related by:

$$Q = 2\pi \frac{n_g}{\lambda \cdot \alpha} \qquad (n)$$

Now that we have Delta N, we can simulate a Bragg Grating using the transfer matrix method to obtain the reflection and transmission spectrum of a finite length Distributed Bragg Reflector.

B. *Fabry-Perot Cavity and Phase Shifted Cavity:*

As example, we designed a 1-D Fabry-Perot Cavity using the Transfer Matrix Method considering the effective index of our waveguide.

1) *Transfer Matrix Model:*

As these are periodic structures, we can take advantage of their repeatability during modelling. We use the Transfer Matrix Method (TMM) to build up a finite length Bragg Grating.

We use the kappa value from our simulation in Equation (n) to determine our change in effective index per tooth of a single grading period, which we can now use iteratively to build our Bragg Grating. We can run extremely quick simulations with varying parameters such as the number of gratings to get an estimate of our response.

From our simulations, we can also find our quality factor by taking the Full Width Half Maximum of our resonant peak:

$$Q = \frac{\omega}{\Delta\omega_{1/2}} \qquad (n)$$

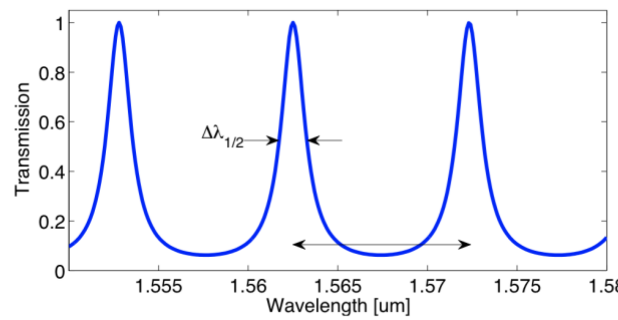

Table 4: Full-Width Half-Maximum, $\delta\lambda_{1/2}$ in units of wavelength. Note this is in the Linear Scale where we can take the width from the location of half of the peak. This also can be represented in the logarithmic domain by the 3dB width, but is much simpler to calculate in the Linear domain using MATLAB's `findpeaks.m` function. Figure from ELEC413 Bragg Grating Slideset.

III. Design:

Figure of Merit: Our goal is to maximize the Quality Factor of our Fabry Perot Resonator. The higher the quality factor, the signal has a narrower the bandwidth and stronger signal, hence this is of importance. We aim to achieve a Quality Factor of 100,000 for our devices.

A. *Design Methodology:*

To get an idea of what to design, we run a parameter sweep of our FDTD Bragg Grating simulation to obtain the highest Kappa values. We find correlation of largest Kappa values at 50nm corrugation widths; hence we will keep this constant for all designs to optimize for Quality Factor.

We do not have an accurate estimation for loss, hence we will assume 3dB/cm. Because this may not be accurate for our measured devices, we will vary the number of gratings about our estimated highest quality factor number of gratings to account for any differences in loss. With measurement data we can verify our loss per grating period to then find an optimal number.

B. *Design of Experiment:*

We will submit designs for the following Fabry-Perot Cavities:

	Single Mode Phase-Shifted Cavities
1.	SM-278P-50DW-070N
2.	SM-278P-50DW-075N
3.	SM-278P-50DW-080N
4.	SM-278P-50DW-085N
5.	SM-278P-50DW-090N
6.	SM-278P-50DW-095N
7.	SM-278P-50DW-100N
8.	SM-278P-50DW-105N

Table 5:List of Single-Mode Devices to be manufactured. Definitions are: (SM) Single Mode, (P) Period length, (DW) Delta Width, and (N) Number of Gratings.

	Multi-Mode Cavities
1.	350FP-1127CAV-110N
2.	350FP-1240CAV-130N
3.	350FP-1400CAV-100N

Table 6: List of Multi-Mode Cavities to be Manufactured with 350nm width. Definitions are: (FP) Fabry Perot, (CAV) Non-Grated Cavity length, (N) Number of Gratings.

We will also manufacture some test devices to calibrate our measurement tools' response and effect on our signal including Loopback for obtaining the Grating Coupler response, as well as a single Bragg Grating to obtain Transmission and Reflection Data.

C. *Manufacturing variability*

A key aspect of the design and measurement is fabrication effects such as insertion loss and noise floor of our measurement devices. We aim in our designs to have a minimum of -30dB power reading to be able to discern our resonance peaks from the noise floor of -70dB.

D. *Mask Layout*

Include images of your Mask Layout. Show the overall layout, plus zoomed in as necessary to describe what you are doing.

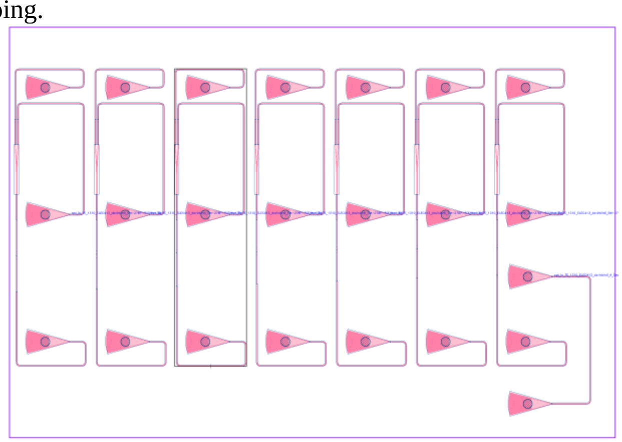

Figure 7: Single Mode Phase Shifted Cavity Layout with varying number of gratings (N) influencing increase in reflectivity and loss per length. The goal is to find the optimal number of gratings to achieve the maximum quality factor.

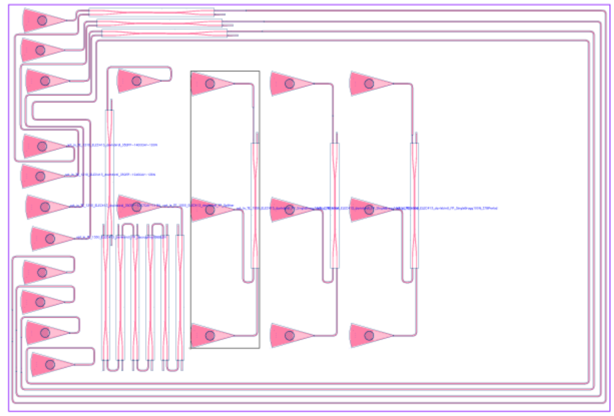

Figure 8: Multi-Mode Fabry-Perot Cavity Layout with variations in Fabry-Perot Cavity length and number of gratings. Loss of waveguides was not explicitly known; therefore high-performance Cavities were designed with expectation that loss of 3dB/cm was over-estimated.

With the assumption of loss being 3dB/cm, we get the following estimation on the quality factor of potential devices:

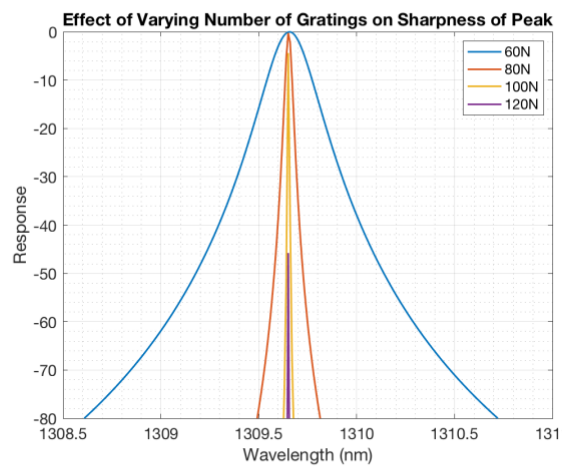

Figure 2: Single Mode Cavity sharpness of peak is affected by number of grating periods, N. See Table 9 for Quality Factors of given peaks. Response in decibels (dB).

Simulation: Single-Mode Phase-Shifted Cavities of 278nm Period and 50% Duty Cycle using loss of 3dB/cm	
Number of Gratings (N)	Quality Factor (Q)
60	4564
80	29071
100	112895
120	127194

Table 9: Estimated Quality Factors of Single-Mode Phase-Shifted Cavity devices using assumption of 3dB/cm loss. We cannot arbitrarily select the highest number of gratings to achieve the highest quality factor, as each grating introduces loss

Our Quality Factor was calculated by taking the Full-Width Half Maximum of our linear transfer function response using MATLAB "`findpeaks.m`" function.

IV. Experiments

A. Fabrication

The photonic devices were fabricated using the NanoSOI MPW fabrication process by Applied Nanotools Inc. More information can be found in Appendix B.

B. Test methodology:

Using the custom-built and programmed probe station that automated the measurement of all the devices on the chip under test, an Agilent 81600B tunable laser was used as the input source and Agilent 81635A optical power sensors as the output detectors.

C. Results:

Unfortunately, measurement is an ongoing technology and not always are devices characterized exactly. Our devices underwent considerable noise resulting in only being able to use some of our lower-Q devices that were designed.

We were able to find these three devices with the following quality factors:

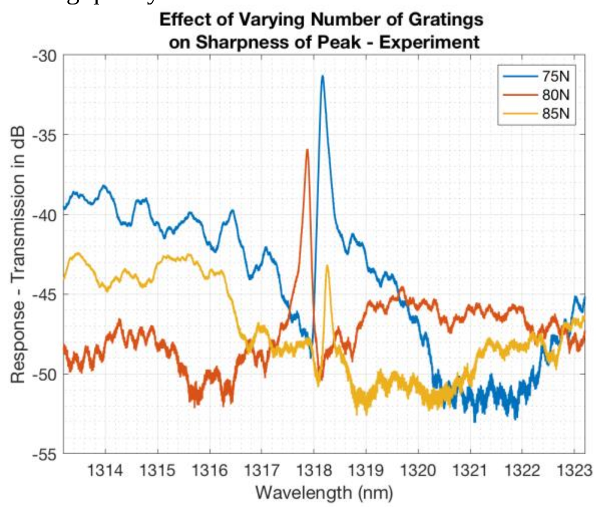

Figure 3: Response of Fabricated Single-Mode Phase-Shifted Cavity devices. Each curve is a varied number of gratings measured in decibels. We can see the insertion loss up to 50dB.

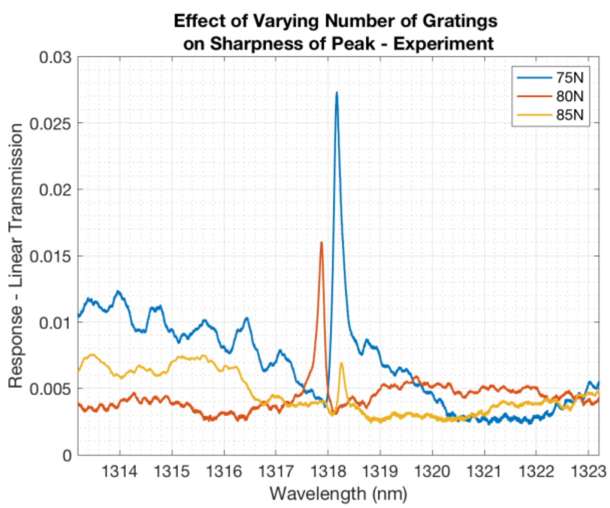

Figure 4: Linear Plot of Power Transmitted of Single-Mode Phase-Shifted Cavity devices. We can more easily see the resonant mode peaks compared to the dB plot, where it is difficult to see the signal from the noise and can easily determine the quality factor.

We can measure the quality factor of each of these devices using the same method we used for our simulations, namely, the full-width half-maximum of our response.

V. Analysis

We can clearly notice the difference between simulation and measurement. We can vary our loss coefficient in simulation to see if our assumption of 3dB/cm does not accurately map to our sample.

Our first thing to do is remove the insertion loss from the grating coupler. There are various ways to do this including fitting a polynomial to the grating coupler's response and subtracting it from our data. Because our data is concentrated around the 1317-1323nm range where the response is approximately flat, we will just shift our data up by the 11dB loss introduced by the grating coupler.

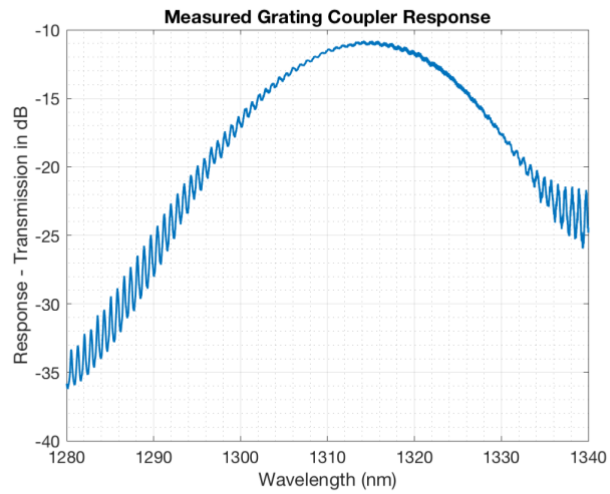

Figure 5: Response of grating coupling depicted in Figure 7. This introduces a wavelength dependent loss which we will be approximating as a constant 11dB loss for the range of 1317-1323nm wavelengths.

We note that a constant shift upwards does not affect the quality factor of the devices, as all wavelengths are equally shifted.

To develop a good model, we must build our simulation such that it accurately represents what we build and test. To do this we can vary our parameters that we used in our simulation to match to our measured experiment. These are the characteristics we can focus on and adjust that all are influenced by manufacturing processes:

- Loss of Waveguide via material dispersion
- Kappa and the delta effective index
- Bragg Period Width

A. Updating Simulation by only Adjusting Loss

We can try to update our simulation by using our measurement to calibrate the loss in the waveguides. We can estimate the loss is rather 1000m^{-1} (30dB/cm) than the 0.5m^{-1} from our initial estimate of 3dB

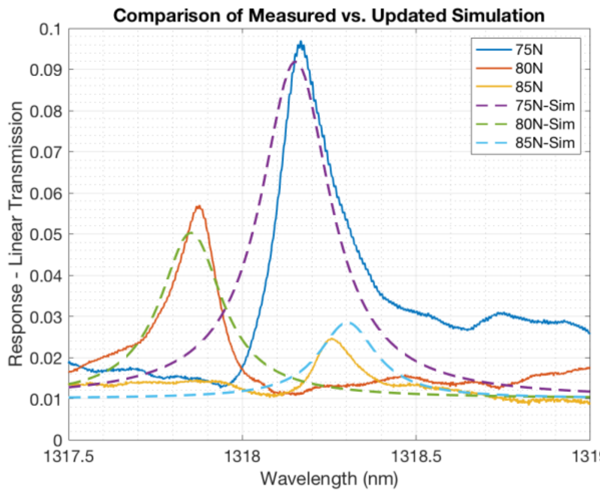

Figure 6: Comparison of Measured Responses (solid lines) versus our Loss Adjusted Simulation (dashed lines) where we adjust our simulation parameters to better fit our measured data.

We can compare the quality factors once we adjust our simulation to a loss value that better represents our measured data, giving us simulations that much better predict what we will manufacture.

Measured Vs. Simulation: Loss Only Single-Mode Phase-Shifted Cavities of 278nm Period and 50% Duty Cycle			
Number of Gratings (N)	**Measured Quality Factor**	**Loss Adjusted Simulation Q**	**Original Unadjusted Simulation Q**
75	6267	5398	~29,000
80	7814	6048	~29,000
85	9922	6540	~29,000

Table 10: Measured Quality Factor from measured single mode devices. Note the difference from our original simulations where loss was considered at 20m^{-1}, versus our loss adjusted simulations at 1500m^{-1}.

B. *Considering Loss and Reflectivity:*

When we consider both the loss and reflectivity, we can approach our measurements with more accuracy:

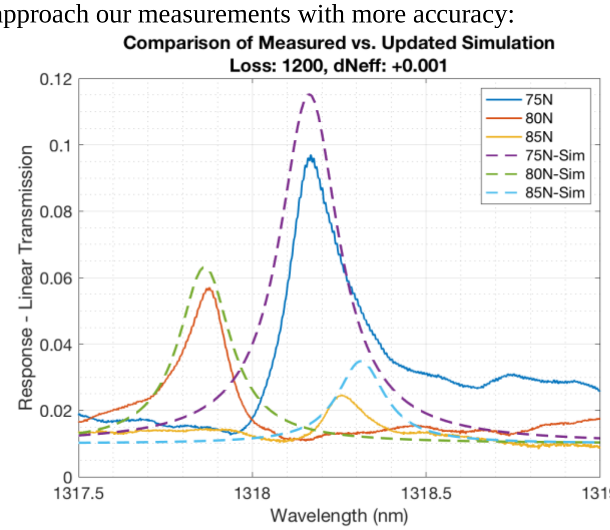

Figure 7: Adjusted Simulation Vs. Measurement when incorporating Loss and changes in delta effective index

Measured Vs. Simulation: Loss and Kappa Single-Mode Phase-Shifted Cavities of 278nm Period and 50% Duty Cycle			
Number of Gratings (N)	**Measured Quality Factor**	**Loss and Kappa Adjusted Simulation Q**	**Difference (%)**
75	6267	6383	+1.81%
80	7814	7269	-7.49%
85	9922	7965	+19.72%

Table 11: Increased Accuracy of simulation containing both changes in loss and delta effective index (influenced by Kappa)

Our new simulation parameters are shown in Table 12

	Updated Simulation Parameters	**Original Simulation Parameters**
Loss	1200m^{-1}	20m^{-1}
Kappa	169,470	164,978

Table 12: After mapping our simulation to our measured results, we can discover what the manufactured values of our simulation parameters are. For future simulations, we can use these values to better predict our manufactured devices.

C. *Further Adjustments not covered at this time: Horizontal-Shift of Bragg Wavelength*

A key aspect is understanding the shift in Bragg Wavelength through manufacturing variations. We know that the Bragg wavelength can shift significantly through different processes. We can use already existing models for the 1550nm TE Bragg Gratings to simulate a Phase Shifted Cavity and apply a Monte-Carlo simulation about typical manufacturing variations, as seen in Figure 8. In Figure 6 we apply post-processing shifts to our data by 10nm. An ideal holistic model would better predict the location of the peaks after manufacturing

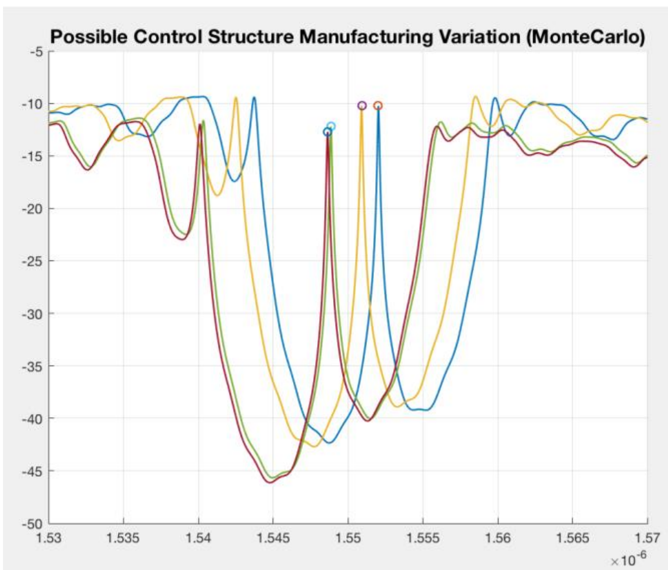

Figure 8: This is an example using a 1550nm wavelength model where we can apply manufacturing variations to a device. Differing location of FP Resonant Peak given variation in wafer and die dimensions.

VI. Discussion:

It was unfortunate that many of our devices were not measured properly, but from analysis of our three working experimental devices we can gain some insight in how the single-mode phase-shifted cavity is characterized.

VII. Conclusion:

As we saw our measurements did not line with our experiments without doing post-processing. After doing this, the ideal case would be to develop a simulation model and parameters that can, with very little error, line up with our experimental data.

Once we have that accurate simulation model, we do what we do for the effective index of a waveguide where we generate a compact model using a Taylor Series Expansion about a region of design. This way we can change and develop our new designs around these operating points that allow us to open the doors to new applications. Given some time constraints, we did not generate these models to give us an accurate prediction of what we will manufacture, but we have learned and understood the importance of being able to work backwards from our measured data to develop a stronger simulation model.

Acknowledgement

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VIII. Appendix

A. Lumerical Mode:

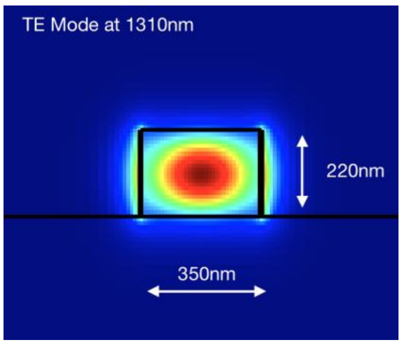

Figure 9: TE Polarized light mode profile simulated in Lumerical MODE

1) Material Properties

There are two ways to set our material properties in Lumerical MODE:

1. Script Lorentzian Fit Parameters:
2. MODE GUI Palik Data Fit: tolerance 0.001 from 1.2 to 1.8 µm wavelengths.

Lukas mentions that the difference is negligible especially compared to manufacturing variations. We can model our devices each way, once using the Lorentz Curve Fit Parameters and the other by using the Fitted Palik Data to quantify how much they affect our simulation.

Notable difference in Group Index:
3.747 using Lorentzian Fit
3.819 using Palik Fitted

The scripts are setup to use the Lorentzian fit, but we would like to note the differences in models that they create.

Test plan:

Create the waveguide geometry

1. Run the Materials.lsf script
2. Follow the EdX tutorial

Then run the simulations without rerunning the Materials.lsf script.

Currently I have scripted in such a way that I can get the wavelength sweeps for a range of waveguide widths. With this data, I can generate the compact models from waveguides of different width.

B. Transfer Matrix Method:

Regarding the Transfer Matrix Method:

1. We can change reflectivity only by changing the number of periods (length of grating)
2. We can shift the Bragg Wavelength by manipulating the effective index. In this question I noticed the Bragg Wavelength (~1.51µm) was far off from our Compact Model central wavelength (1.55µm), I assume that for more accurate models we recalculate our compact model around the Bragg Wavelength to get amore accuracy using the TMM.
3. We can also shift the Bragg Wavelength by manipulating the Grating Period. Larger grating Periods move the Bragg Wavelength upwards.
4. Given a compact model of n_eff, about a desired wavelength, we can solve for the number of periods using the relationship in the slides.
5. I can now design a Bragg Grating about the wavelength I want by selecting the appropriate Bragg Period.