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A study on the effect of varying Bragg Grating Design for a standard Fabry-Perot Cavity

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Abstract This paper indents to investigate the behavior of a specially designed Waveguide in Silicon Photonics: the Bragg Gratings. In particular, the paper examines two different key aspect of the design: I. The effect of change of Bragg corrugation width, II. The effect of Triangular Bragg Gratings compared to Sinusodial Bragg Gratings. By comparing designs with only one varying parameters, a better Bragg Grating Design can be proposed for better Farby-Perot Cavity implementation.

Keywords - Fabrication, Bragg Grating, Pabry-Perot Cavity, Waveguide

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1 Introduction

The idea of Silicon Photonics has gained significant attention with the science and engineering society in the past decade. It seems to most professionals working in this field that the potential of such technology is still an enormous area that is under extensive research.

Currently, there are yet plenty of literature produced in this field with one of them to be *Silicon Photonics Design: From devices to systems* [1], though taking a top-down approach, and diving into the fundamentals of Silicon Photonics design only a very small portion of it was dedicated to the design of Lasers, specifically via a Fabry-Perot Cavity utilizing a device called the Bragg Gratings. Hence the motivation of this project.

This paper intends to discuss and explore the specifics of the Bragg Grating, focusing on changing the design of the grating teeth in two different parameters: 1. The corrugation width, which leads to a more “wavey” and more distinct design, 2. The sharpness of the teeth, mainly, triangular and sinusoidal shapes are explored. By designing same Fabry-Perot Cavities with slightly different Bragg Grating parameters, the devices on the same chip can be measured, analyzed and the best Bragg Grating design can be identified and served as the new baseline moving into the next fabrication run.

2 Theory

2.1

2.2 Fabry-Perot Cavity

A Fabry-Perot cavity is a simple optical resonator. It consists of two plane-parallel panels (light a partial mirror) that can both transmit and reflect light according to Fresnel equations. In silicon photonics, such plane-parallel panels are achieved by designing two materials with slightly different effective index (n) and couple light through it. Due to the change of n, the light is partially transmitted and reflected. By placing two of these kinds of design on both ends of a waveguide, a Fabry-Perot Cavity is created, with light bouncing inside with an exponential decay. With the appropriate design of cavity length, a certain frequencies of reflected light forms a standing wave and and thus produces distinctive peaks in the reflection and transmission spectrum.

2.3 Bragg-Grating

A design of Bragg-Grating effectively achieves the idea of partial transmission and reflection required by the Fabry-Perot Cavity above. Due to the nature of SOI fabrication, only a single material (Silicon) is permitted in the scope of this project. Hence the change of effective index (n) cannot be achieved by a change of material property (such as doping), but was achieved with a change in physical dimension of the waveguide, speficially a change of waveguide width, shown below.

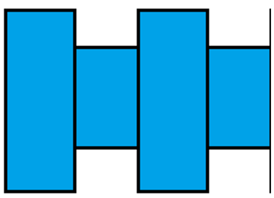

Fig. 1 Bragg Grating Design, Brid view

Since different dimensions of a common strip waveguide will change its effective index of propagation, having two piece of waveguide with different width connected to each other will effectively produce a partial mirror required to construct a Fabry-Perot Cavity. This design is named to be a Bragg Grating and is open used when designing features that requires partial reflection and transmission of light through a normal waveguide.

3 Modelling and Simulation

3.1 Standard Waveguide

Strip waveguide model of 350 $\times$ 220 nano-meters was modelled via the Palik data set of materials in Lumerical MODE Solutions to provide the baseline model of the design. Specifically, the first TE mode profile at $\lambda = 1310$ nm of the proposed design, shown in Fig. 2. By performing a wavelength sweep from $1260 \leq \lambda \leq 1340$ nm, and exporting the data points of effective index versus lambda into MATLAB, curve fitting via initial guess method via a third order Taylor series expansion, a compact model for the effective index for the strip waveguide was obtained as follows and plotted in Fig. 2.

$$n(\lambda) = 2.4344 - 1.5798 \cdot (\lambda - 1.31) - 0.0855 \cdot (\lambda - 1.31)^2 + 0.1575 \cdot (\lambda - 1.$$

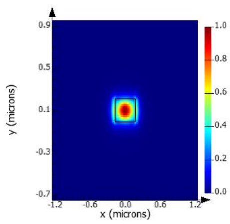

Fig. 2 Simulated cross section and 1st mode profile (98% TE polarization) for a 350 $\times$ 220 nm strip waveguide at $\lambda = 1310$ nm . The mode profile is calculated via Lumerical MODE Solutions.

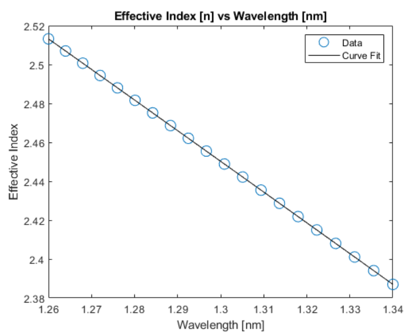

Fig. 3 Plot of Equ. 1, a curve fit of data points simulated from Lumerical MODE Solutions via a third order Taylor series expansion.

3.2 Infinite Bragg Grating - FDTD

To understand the key parameter of a Bragg Grating design, 2.5D flow simulation was conduced via Lumerical FDTD simulations, where one cycle of Bragg Grating (consist of two piece of waveguide with same material property, height, but different width) was simulated, see Fig. 4 below.

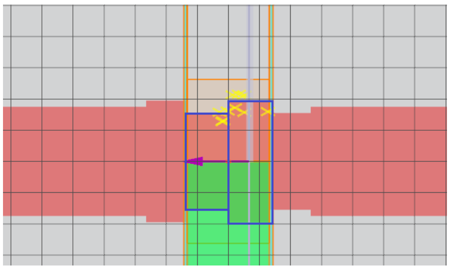

Fig. 4 XY View of one cycle of Bragg Grating under simulation via Lumerical FDTD

The mesh of FDTD effectively takes the cell above and simulate as if there are infinite cells of the same Bragg Grating present, providing a case of a mirror with 100% in reflection and 0% in transmission, the results of central wavelength λ_B, and κ can be extracted. Table 1 below summarized the simulation findings for a Bragg Grating with:

- Waveguide Width: 350nm
- Group Index: 4.5013 (derived from section 3.1)

dwidth	Lambda_B	kappa	d_neff
10	1.3	49066.5	0.03
15	1.3	67937.9	0.04
20	1.3	88696.1	0.06
25	1.3	100962	0.07
30	1.3	114171	0.07
35	1.29	120776	0.08
40	1.31	126268	0.08
45	1.31	126272	0.08
50	1.3	128976	0.08
55	1.29	127381	0.08
60	1.28	126437	0.08
65	1.28	116059	0.08
70	1.28	109454	0.07

Table 1 2.5D TDTD Simulation results for one cycle of Bragg Grating in Lumerical FDTD

Where the value of d_neff indicate the change of effective index of the piece of material when the light travels from one cell to another which has a different width, namely, corrugation width.

3.3 Fabry-Perot Cavity via Bragg Grating - MATLAB

A Transfer Matrix Method (TMM) performed via MATLAB was used to understand the behaviour of a Bragg Grating and can be used to simulate any design of Fabry-Perot Cavity using Bragg Gratings. The TMM method contains four different terms, each maps to it's unique matrix:

- $\mathrm{T_{HW1}}$: A propagation matrix that describes the Reflection (R) and Transmission (T) in an infinite uniform waveguide material #1.
- $\mathrm{T_{HW2}}$: A propagation matrix that describes the R and T in an infinite uniform waveguide material #2.
- $\mathrm{T_{IS12}}$: An index step matrix that describes the R and T when light travels from material #1 to material #2.
- $\mathrm{T_{IS21}}$: An index step matrix that describes the R and T when light travels from material #2 to material #1.

The system treats the above matrices like a 2 port network and with proper chaining of these matrices, a proper Fabry-Perot Cavity's matrix can be constructed.

$$T_{sys} = T_P^{NG} * T_{HW2}^2 * T_{Pinv}^{NG}$$

Here, a Fabry-Perot with 150 grating period on each side was considered,

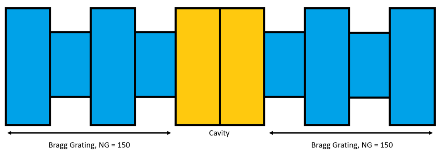

Fig. 5 Visual illustration of the chosen Fabry-Perot Cavity design, with 150 Bragg Grating periods on each side

Sweeping a range of frequencies, the follow was plotted by MATLAB,

where the bandwidth of the above design roughly equals to 20 nm, with a distinct peak (which the frequency of light captured) around 1310 nm.

By changing the corrugation width of the Bragg Gratings, a shift in central frequency will occur, meaning that the plot in Fig. 5 will effectively move left and

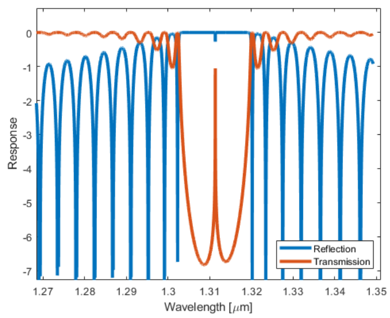

Fig. 6 Frequency sweep of a Fabry-Perot Cavity capturing one mode of light around 1310nm

right slightly. This shift in wavelength would be captured by the measurement equipment and be used to propose better Bragg Grating designs.

4 Fabrication - YET TO BE DONE, DO LATER

Two chips were fabricated in this course. Either report on one dataset, or on both. Choose the text as appropriate.

4.1 Washington Nanofabrication Facility (WNF) silicon photonics process:

The devices were fabricated using 100 keV Electron Beam Lithography [[2]]. 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 185 V. During etching, chips were mounted on a 100 mm silicon carrier wafer using perfluoropolyether vacuum oil.

4.2 Applied Nanotools, Inc. NanoSOI process:

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 H2SO4:H2O2) 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. Reflectometry measurements were performed throughout the process to verify the device layer, buffer oxide and cladding thicknesses before delivery.

5 Experimental Data

To characterize the devices, a custom-built automated test setup [[3]] with automated control software written in Python was used (`http://siepic.ubc.ca/probestation`). 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. A polarization maintaining (PM) fibre was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers [[4]]. A 90º rotation was used to inject light into the TM grating couplers [4]. A polarization maintaining fibre array was used to couple light in/out of the chip [www.plcconnections.com].

Plots of experimental data. The following figure was generated using a built-in Python interpreter!

6 Analysis

Data analysis to extract waveguide group index, etc.

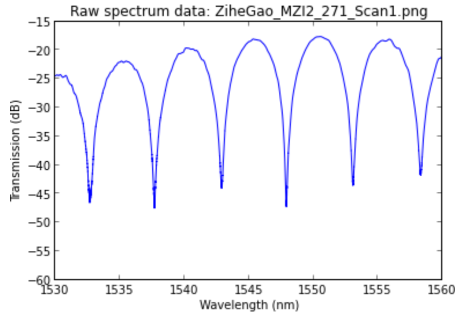

Fig. 7 Measured transmission spectrum on a Mach-Zehnder Interferometer with a path length difference of x microns.

Comparison of experimental results with simulations.

7 Conclusion

The conclusion goes here.

8 Acknowledgements

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