Report: Designing A Resonator Operating Within The O-band With The Highest Quality Factor

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Abstract: Transmission spectrum of a silicon-based resonator cavity is simulated. The effect of varying grating length and cavity length is further investigated in this report.

1. Introduction

Laser integration with silicon manufacturing (e.g, CMOS electronics, silicon photonics) is important for future integrated photonics applications (e.g. Apple Watch with TLDS for temperature and glucose monitoring). Resonators are one of three main components of a laser (other two being an optically amplifying material, and a power source) [1]. In this report, a resonator is simulated with two Bragg gratings with a 350nm by 220nm silicon waveguide in between. The operating mode is a fundamental quasi-TE polarised mode operating within the O-band range at 1310nm. By varying parameters such as grating length and waveguide length, we can examine the effects of these parameters on quality factor and optimise the parameters to produce a resonator with the best quality factor.

2. Background Information and Theory

The resonator built in this report consists of 2 fundamental key components, Bragg gratings and optical rectangular strip waveguides. Bragg gratings function as mirrors to constrain the light within the cavity to promote stimulated emissions. This results in optical amplification to allow laser light to form, assuming the gain is equal to the loss in the semiconductor laser.

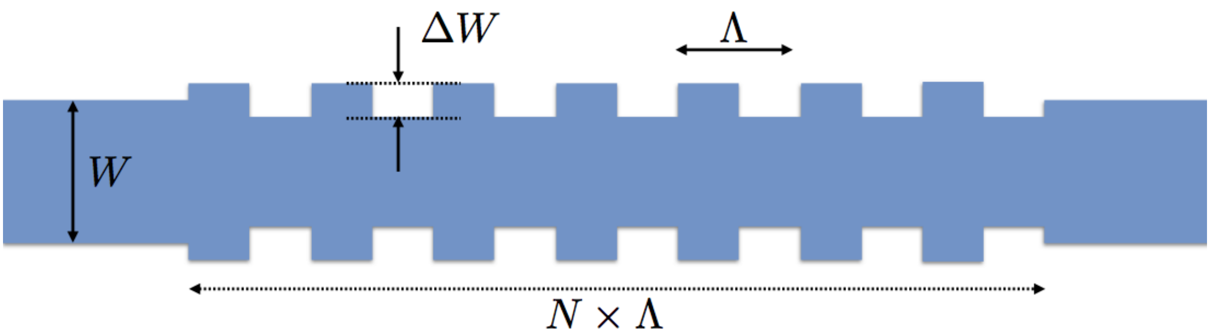

Figure 1: Sample Bragg Waveguide [2]

Bragg gratings consists of various parameters as shown in the above diagram, namely, grating period, corrugation width, mean width and length. In this report, the parameters will be configured to ensure that the cavity is able to operate within the O-band range.

The maximum theoretical quality factor of a cavity is as given by the following formula [2]:

$$Q = 2\pi \frac{n_g}{\lambda \times \alpha}$$

In order to achieve this, the goal is to reduce the losses within the cavity which are limited to propagation losses and mirror losses [2].

3. Simulation Tools

In this report, the main software used are Lumerical MODE and Lumerical Interconnect. Other software include MATLAB to identify the waveguide compact model, Python to calculate the transfer matrix method to simulate an ideal Bragg Grating and resonator cavity.

4. Simulations and Calculations

4.1 Lumerical MODE

Lumerical MODE is initially used to simulate the waveguide and find out the field distributions at the waveguide cross-sections. The waveguide is set to 350nm by 220nm for a fixed width to explore specifically how corrugation width and length of gratings will affect the resonator's performance later on. Shown below is the fundamental mode profile of the quasi-TE mode.

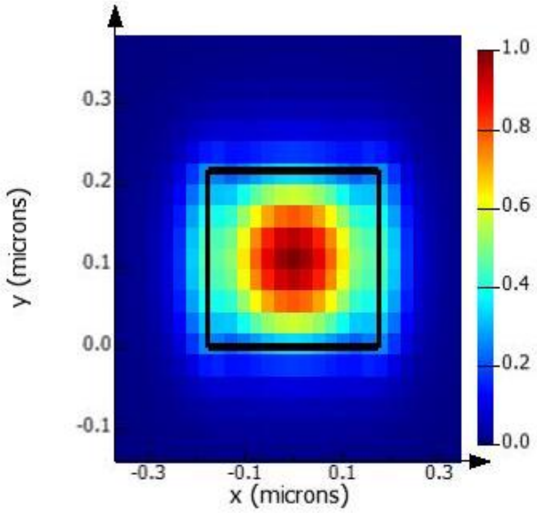

Figure 2: Quasi-TE Fundamental Mode Profile

Frequency sweeps are done at 1260nm to 1360nm to identify the effective index and group index of the quasi-TE mode as shown in Figure 3. This allows us to deduce that the effective index is approximately 2.42 while the group index is 4.483. This data is then exported into MATLAB to create a compact model of the waveguide.

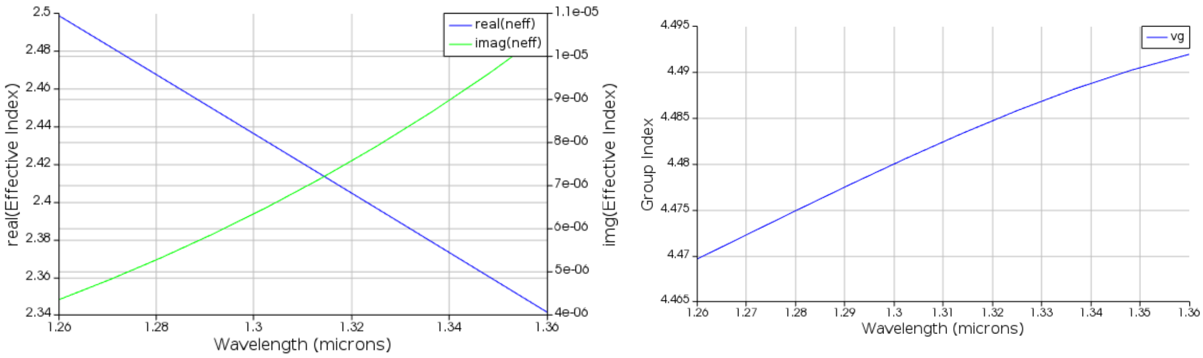

Figure 3: Effective Index and Group Index against Wavelength

Upon obtaining the effective index of the waveguide, we can then proceed to utilise the equation [2]:

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

This allows us to identify that the ideal Bragg period is approximately 270nm for this simulated waveguide.

4.2 MATLAB Simulations

The data exported from the frequency sweep of Lumerical MODE was then imported into MATLAB. Using the data, the coefficients for the compact waveguide model, which utilises the Taylor series expansion, is obtained.

The Taylor expansion around the centre wavelength (1310nm) is as follows [2]:

$$n_{eff(\lambda)} = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0)^2$$

The resultant values are as follows:

$$n_1 = 2.420268169931314$$
$$n_2 = -1.573833473545099$$
$$n_3 = -0.087953720501996$$

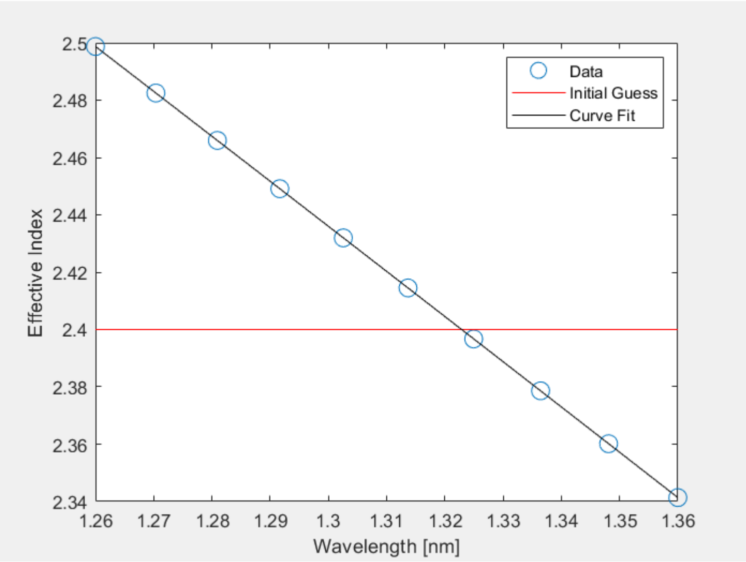

Figure 4: Curve Fitted Model for Waveguide Compact Model

4.3 Lumerical MODE (FDTD) Simulations

A unit cell of rectangular strip waveguide Bragg grating was simulated using Lumerical FDTD with the Bloch mode approach. The modelling allows us to obtain the size and location of the band gap [3], which corresponds to the bandwidth and central wavelength.

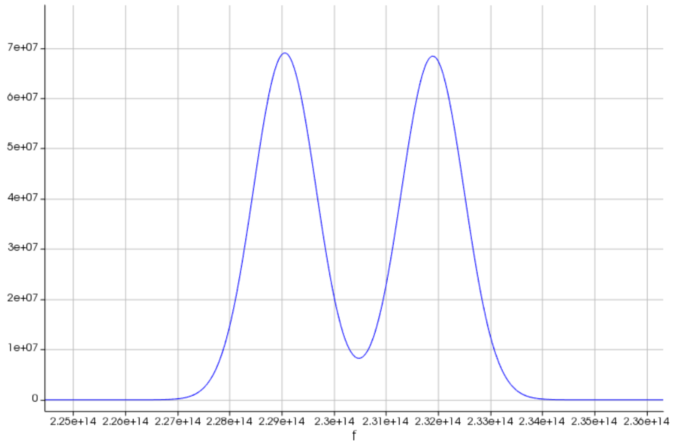

Figure 5: Spectrum results from Lumerical FDTD

The simulations also provided the grating coupling coefficient for the specific parameters of the Bragg gratings. The simulation was then repeated at varying corrugation widths, from 20nm to 80nm, increasing in 15nm intervals. The data was then brought into MATLAB and a curve was fitted to simulate the relationship between Δw and κ. Figure 6 shows the resultant plot and indicates that the optimal values of κ lie within the range of 40nm to 60nm.

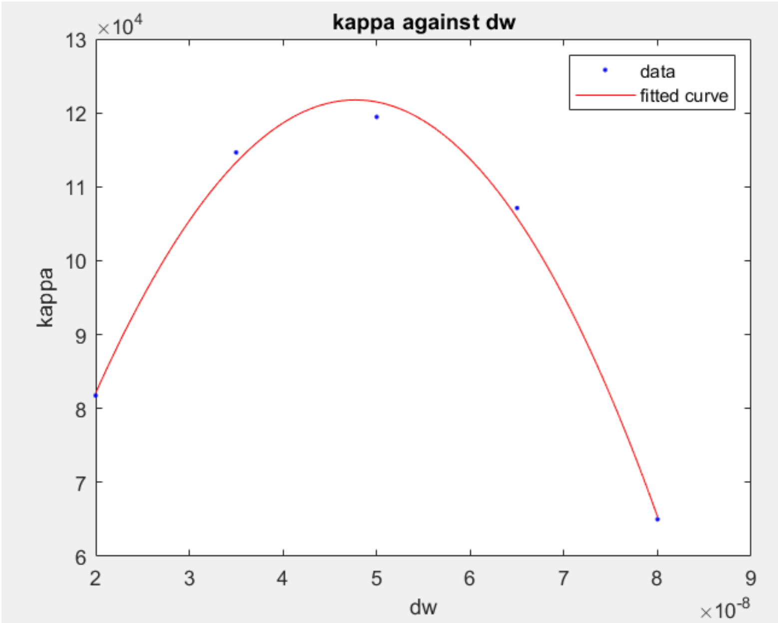

Figure 6: Relationship between corrugation width and coupling coefficient.

4.4 Transfer Matrix Method using Python

The Bragg grating and cavity is modelled using Python via the Transfer Matrix Method. This allows for an easy construct of the simulated transmission and reflection spectrum via matrix representation. For the Bragg gratings, a uniform periodic structure is assumed, where a single period is modelled by a homogeneous waveguide transfer matrix for transmission and an index step matrix for reflection. The equation for modelling is as follows:

$$T_p = T_{hw-1} T_{is-12} T_{hw-2} T_{is-21}$$
$$T_{Bragg} = (T_p)^{NG}$$

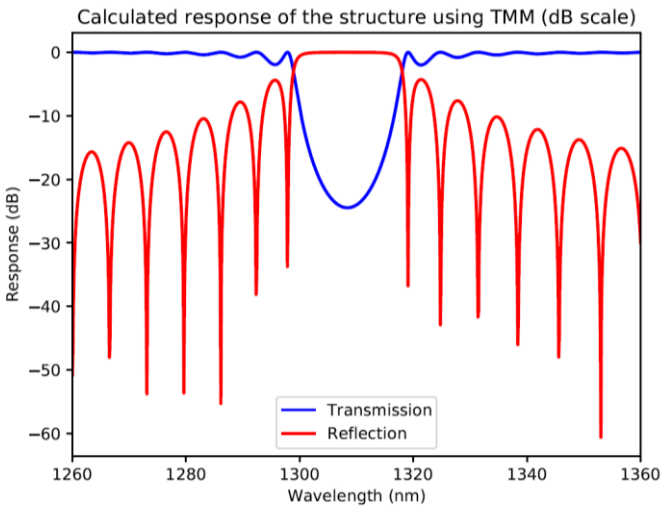

Figure 7: TMM for Single Bragg Grating

These equations allow for the simulation of a single Bragg grating within Python as seen in Fig 7. For a cavity, a waveguide is placed between the Bragg gratings.

The equation for modelling will result in the following instead:

$$T_{Cavity} = (T_p)^{NG}(T_{hw-1})(T_p)^{NG}$$

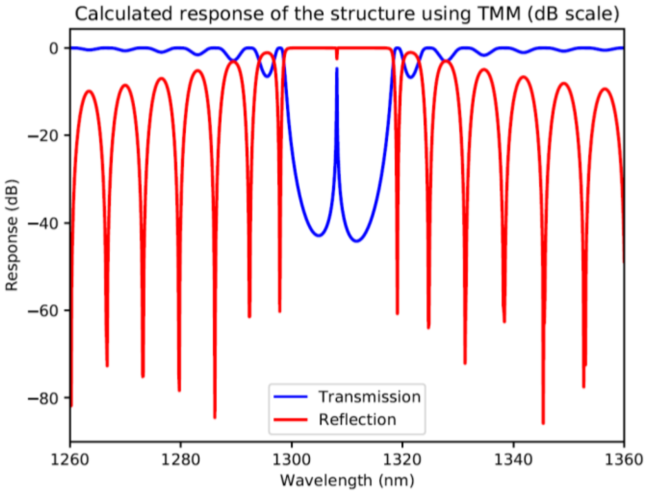

Figure 8: TMM for Cavity

4.5 Lumerical Circuit

The Bragg grating resonator is replicated in Lumerical in the form of a Fabry-Perot Cavity. The circuit comprises of a single optical network analyser with 2 inputs to measure both the reflection and transmission spectrum, two Bragg waveguides and a single rectangular optical waveguide between them. The circuit can be seen in Fig 9. The length of the Bragg waveguides and the length of the optical waveguides are then varied to obtain our results.

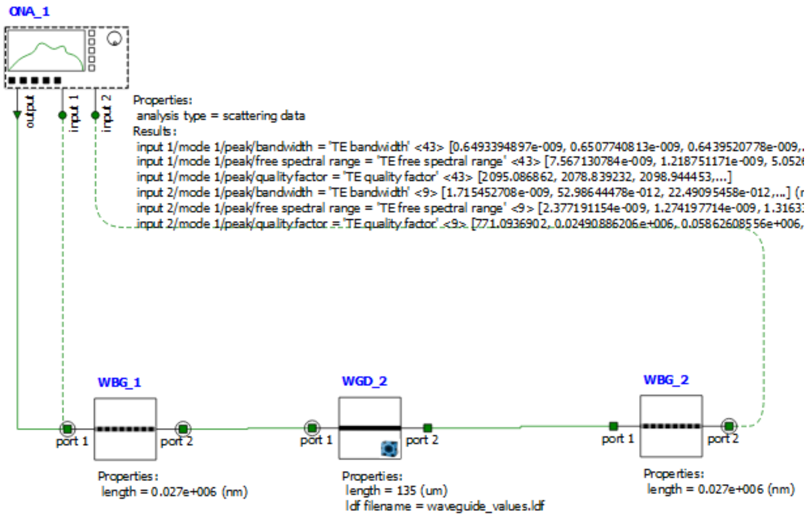

Figure 9: Lumerical Simulation Circuit

5. Results and Analysis

5.1 Results from Lumerical Interconnect

The results of the simulation can be seen as shown in Fig 10 for a Bragg grating for length 27 microns and an optical waveguide length of 135 microns.

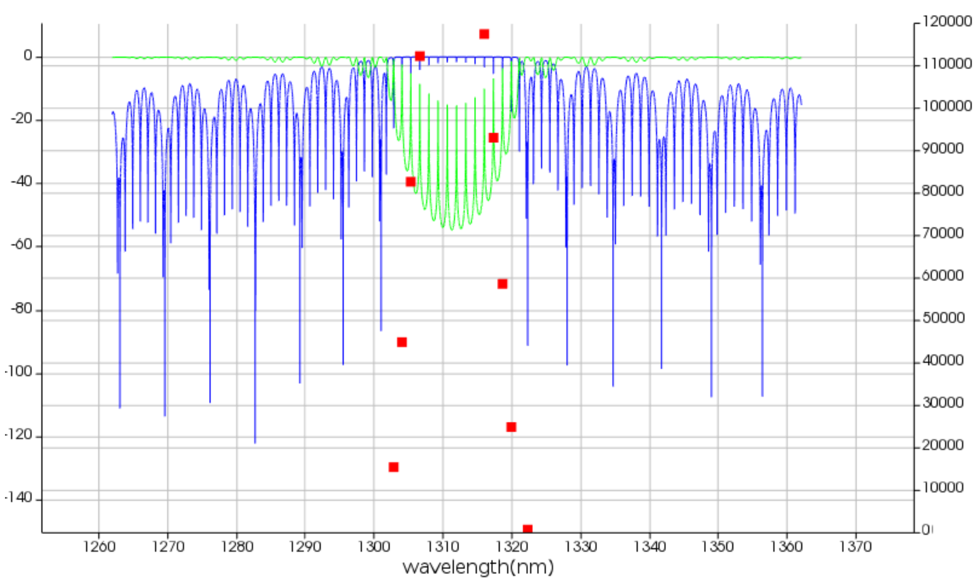

Figure 10: Lumerical Interconnect Results

From Fig 10, the blue curve represents the reflection spectrum and the green curve represents the transmission spectrum. The red squares represent the quality factor obtained from the transmission curve. The results show that this combination of factors result in a rather high-quality factor of approximately 120000.

5.2 Analysis for Proposed Designs

To simplify the design, we fix the waveguide width to be 350nm. From our previous simulations, we identified the ideal value for corrugation width to be 50nm. The Bragg period is also fixed for our waveguide at 270nm. By varying the Bragg waveguide length and the cavity length in Lumerical, the results of our simulations are shown in the graph in Fig 11 and Fig 12.

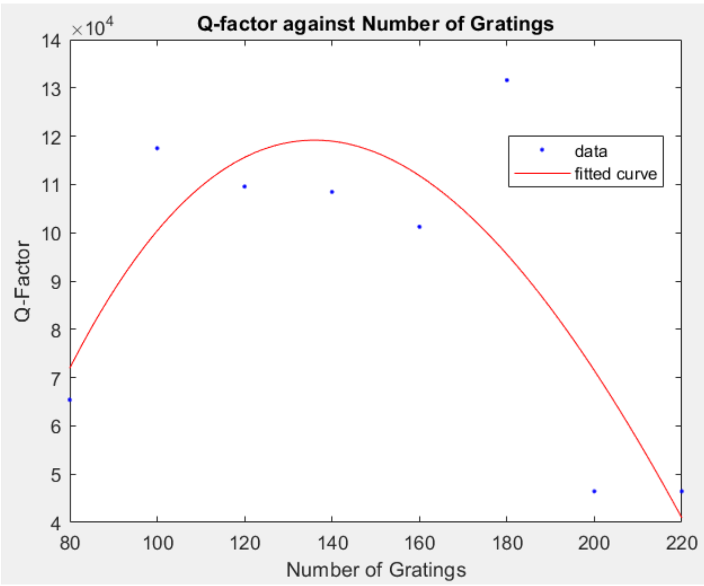

Figure 11: Relationship between Quality Factor and Length of Bragg Waveguides

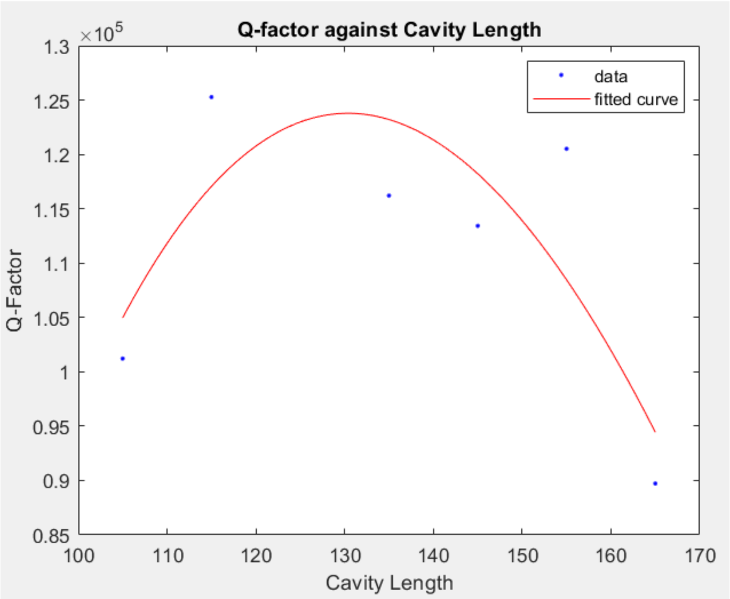

Figure 12: Relationship between Quality Factor and Cavity Length

From the simulations, the quality factor peaks within the range of 32.4 to 43.2 microns for the Bragg waveguide length and 125 to 140 microns for the cavity length.

However, in Lumerical MODE, a picket-fence effect on results is present, where it is impossible to express a continuous result into a discrete graph with finite points. This results in a fluctuation in values of quality factor as some transmission peaks may not be well-represented and thus not picked up by the software. While this can be improved by running a higher number of points, our knowledge of quality factor against grating periods is known to come to a saturation zone beyond a certain number of gratings [2], which differs from Fig 13 above. Thus, it is likely that beyond 160 gratings, the results are likely to plateau. I have incorporated this idea into some riskier designs in order to ensure for myself.

5.3 Proposed Designs

From the information gathered, I propose the following table of parameters to be varied to identify the best performing resonator. From the table, we can see that the insertion losses tend to increase as the length of Bragg gratings are increased. Thus, I have also created another table to include some safer and riskier designs, as seen in Fig 14.

Design	Number of Gratings	Length of Bragg Gratings (nanometres)	Length of Cavity (micrometres)	Insertion Loss (dB)	Quality Factor	Loss (1/m)	Group Index
1	120	32400	135	66	12170	0.612	4.483
2	130	35100	135	73	103294	0.612	4.483
3	140	37800	135	77	116206	0.612	4.483
4	150	40500	135	85	101235	0.612	4.483
5	160	43200	135	91	112484	0.612	4.483
6	140	37800	125	77	72637	0.612	4.483

7	140	37800	130	78	119599	0.612	4.483
8	140	37800	135	77	116206	0.612	4.483
9	140	37800	140	78	100092	0.612	4.483
10	140	37800	145	78	113427	0.612	4.483

Figure 13: Table of Proposed Designs

**Note: Design 3 and 8 are identical so a total of 9 designs are fabricated due to space constraints

Design	Number of Gratings	Length of Bragg Gratings (nanometres)	Length of Cavity (micrometres)	Insertion Loss (dB)	Quality Factor	Loss (1/m)	Group Index
1	80	21600	135	42	94206	0.612	4.483
2	100	27000	135	55	117488	0.612	4.483
3	180	48600	135	100	134291	0.612	4.483
4	200	54000	135	115	46607	0.612	4.483

Figure 14: Extra designs

5.4 Proposed Layout

Utilising KLayout, the Fig 15 is sample of the fabrication layout. It consists of three fibre grating couplers with the resonator. It has been made with fabrication biases for Applied Nanotools, where the waveguides and Bragg gratings are increased by 15nm to offset the bias. The Ebeam_ANT_TE_splitter has been used to ensure accurate recreation during fabrication.

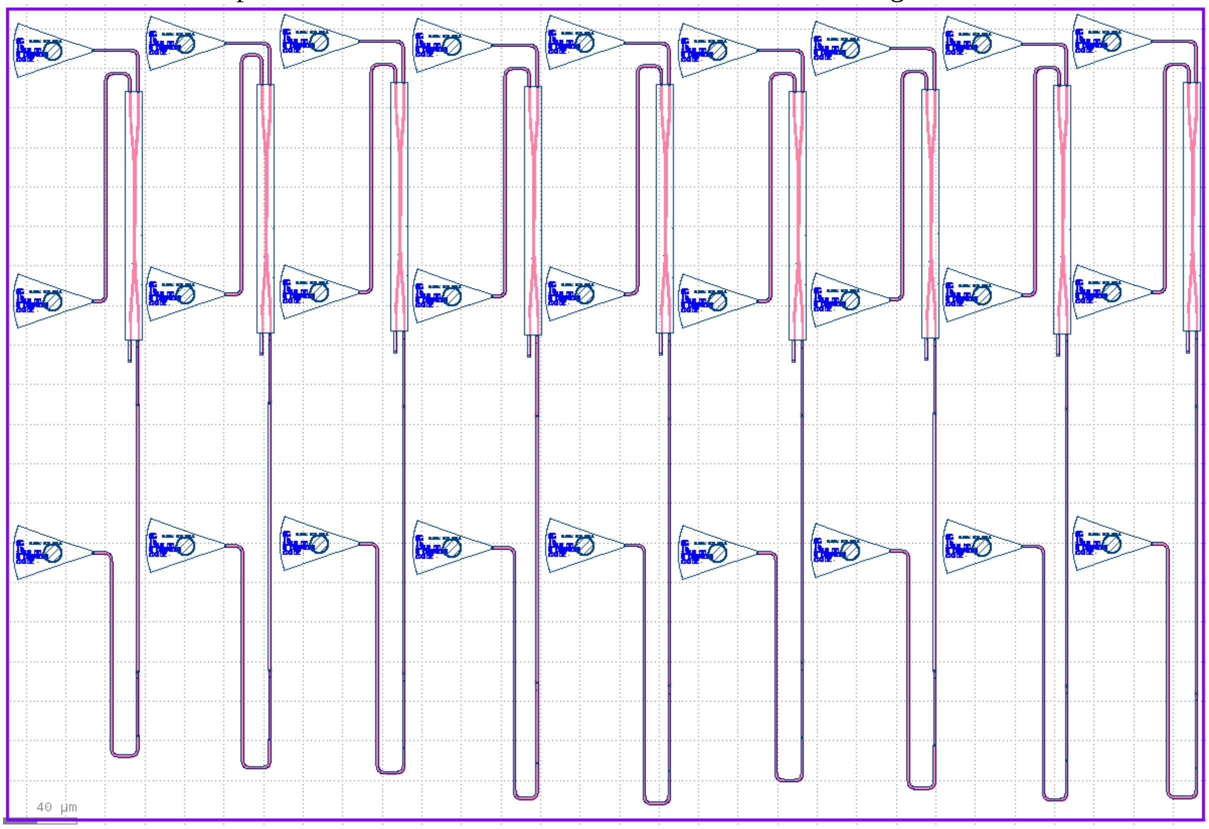

Figure 15: Sample KLayout Fabrication

6. Summary

This report has described the procedure to design a cavity resonator for use in silicon photonics. The layout will be fabricated by Applied Nanotools and future verification and further analysis will be done with the fabricated chip.

References:

[1] L. Chrostowski, “Project Overview,” *edX*, 2023. [Online]. Available: https://learning.edge.edx.org/course/course-v1:UBC+ELEC413-201+2022_W1/block-v1:UBC+ELEC413-201+2022_W1+type@sequential+block@7803892038f042278e89612e74714dbd/block-v1:UBC+ELEC413-201+2022_W1+type@vertical+block@a6469ec73a884e1e86de36d345f5de6e. [Accessed: 13-Feb-2023].

[2] L. Chrostowski and M. Hochberg, *Silicon Photonics Design*. Cambridge University Press, 2019.

[3] X. Wang, “Bragg grating initial design with FDTD – Ansys Optics,” *Ansys Optics*, 2023. [Online]. Available: https://optics.ansys.com/hc/en-us/articles/360042304394-Bragg-grating-initial-design-with-FDTD. [Accessed: 13-Feb-2023].