Loss, Reflection and Transmission Measurement and Analysis of Silicon-on-Insulator Ring Resonators

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Abstract:

This project aims to characterize the wavelength dependent transmission characteristics of a straight silicon-on-insulator waveguide coupled to a silicon-on-insulator ring resonator. The transmission loss of straight silicon waveguides was determined through Fabry-Perot loss measurements. Loss coefficients of 0.194 ± 0.037 cm^{-1} and 0.105 ± 0.08 cm^{-1} were obtained for waveguides of 1 μm and 1.5 μm widths, respectively. The ring resonator parameters, such as ring loss, ring-waveguide-coupling efficiency, quality factor, and finesse are determined by taking wavelength dependent transmission measurements for various ring radii, ring-waveguide-gap distances, and waveguide widths. For rings with a radius of 400 μm, a quality factor of up to 4.05×10^4 and finesse of 7.35 have been measured for a width of 1 μm and a Q of 2.59×10^5 with a finesse of 46.94 have been measured for a width of 1.5 μm.

Introduction:

Silicon ring resonators are becoming an increasingly interesting area of focus in silicon photonics. When light of specific wavelengths is coupled into the ring resonator, there can be a build up or cancellation of optical power due to interference between the light from multiple round trips within the resonator. This, in conjunction with silicon's low loss coefficient, makes silicon ring resonators excellent passive low-loss filters with high quality factors.

Experimental Procedure and Device Fabrication:

The Fabry-Perot loss and ring resonator transmission measurements were made by launching light into the device under test from a tunable laser source, sweeping at wavelengths starting from 1550 nm, through a lensed optical fiber. The span and step of each sweep is determined by the calculated free spectral range so that each scan yields 6 periods and each period has a resolution of at least 250 points. At the opposite waveguide facet, the light is first collimated through an 80x microscope objective and the TM light is filtered out through a polarizing beam splitter. The TE light is then collected by the photodetector.

The waveguides used to form the devices were all rib waveguides with a height of 0.9 μm and a rib etch depth of 0.2 μm. The waveguides were fabricated on SOI in a standard CMOS fabrication facility. The rib waveguides were etched using Cl_2/HBr/Ar to perform inductively coupled plasma etching. A thin layer of SiO_2 was used as a hard mask.

$$\alpha = \frac{1}{L}\ln\left(R\frac{1+\sqrt{\zeta}}{1-\sqrt{\zeta}}\right)$$

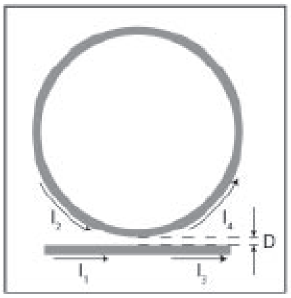
α = loss coefficient
$\zeta = P_{min}/P_{max}$
L = Length of waveguide
R = Reflectivity of waveguide facet

Figure 1: Equation for Fabry-Perot Loss Measurement [1].

Results and Conclusion:

Figure 1 shows the equation relating the loss coefficient to the waveguide length, reflectivity, and the ratio of the minimum to maximum intensity (ζ). Therefore if ζ is measured for two different waveguide lengths, then a system of equations will allow for the reflectivity and loss coefficient to be determined. For waveguides with a width of 1 μm, the average ζ ± SD is 0.277 ± 0.033 and 0.313 ± 0.026 for a length of 3.2 mm and 8 mm, respectively. This results in R = 0.330 ± 0.014 and an α = 0.194 ± 0.037 cm^{-1}. A waveguide 1.5 μm wide has an average ζ = 0.298 ± 0.029 and ζ = 0.317 ± 0.027 for a length of 3.2 mm and 8 mm, respectively. This yields an R = 0.304 ± 0.02 and α = 0.105 ± 0.08 cm^{-1}.

Figure 2 shows the schematic of the ring resonator with the corresponding theoretical equation relating the input and output power that is used to fit the data. The waveguide facets were AR coated to minimize the Fabry-



$$\frac{Iout}{Iin} = \frac{I_3}{I_1} = \frac{a^2 - 2ra\cos(\phi) + r^2}{1 - 2ra\cos(\phi) + r^2a^2}$$

$$a = e^{-\alpha\pi R}$$

$$\phi = \frac{(2\pi)^2 n_{eff} R}{\lambda} \qquad \boxed{Q = \frac{2\pi^2 R n_{eff}\sqrt{ra}}{(1-ra)\lambda_0}}$$

$$r = \sqrt{\eta_{feedback}}$$

$$R = Radius \qquad \boxed{F = \frac{\pi\sqrt{ra}}{1-ra}}$$

Figure 2: Ring schematic and equations for theoretical fit, Q and F [2].

Perot response of the straight coupling waveguide. The data was normalized by dividing out the response of an AR coated straight waveguide. A fit of the normalized data was made using the equation given in Figure 2 by varying and thereby extracting the propagation loss of the ring and the coupling efficiency of the waveguide. These variables allow for the calculation of the quality factor and finesse—both of which are descriptions of peak sharpness and the strength of the resonance of the cavity. Figure 3 shows the wavelength dependent transmission data and theoretical fit for a ring resonator with a 400 μm radius, 0.9 μm gap, and a width of 1.5 μm. This fit results in a quality factor of 2.59 x 10^5 with a finesse of 46.94, a group index of 3.6766 and a loss coefficient of 0.38 cm^{-1}. Figure 4 provides a table summarizing the previously mentioned parameters for rings with a radius of 400 μm but varying waveguide width and gap distance. As expected, α for the rings was higher than that of the straight waveguide due to bend loss and the additional scattering. Furthermore, the 1.5 μm wide waveguides had a smaller loss coefficient than the 1 μm wide rings.

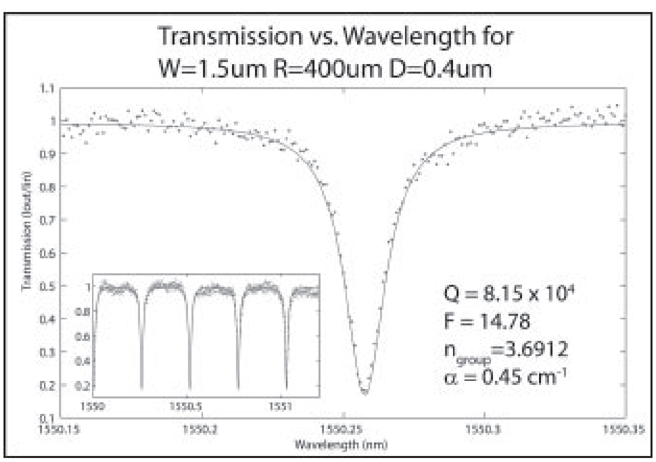


Figure 3: Ring measurements with theoretical fit showing wavelength dependent transmission.

Finally, as the gap distance increased, the quality factor and finesse increased, showing stronger resonance and greater wavelength selectivity. This is expected, as a greater gap distance lowers the coupling coefficient between the ring and waveguide. This leads to a higher feedback coefficient and allows for stronger interactions between the light from multiple roundtrips in the ring.

Rings of smaller radii were tested but due to the high bend loss at these smaller radii (caused by shallow rib etch) the fit was unable to be made due to high noise even after normalizing the data. From the data, the ring response for the wavelength sweep was on the order of the AR coated Fabry-Perot response and noise of the experimental setup.

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References:

[1] Tittelbach et. al. "Comparison of Three Transmission Methods for Integrated Optical Waveguide Propagation Loss Measurement." Pure Appl. Opt. 2 (1993) 683-706.

[2] Rabiei et. al. "Polymer Microring Resonators." Optical Microcavities, 319-366.

Critical Parameters for Rings of Radius=400 µm				
W=1µm				
D(µm)	ngroup	alpha	Q	F
0.4	3.7487	2.4	21000	3.87
0.5	3.7487	2.375	21000	3.89
0.6	3.6766	1.9	25500	4.63
0.7	3.6766	1.4	30000	5.43
0.8	3.6766	1	31800	5.76
0.9	3.6766	0.7	40500	7.35
W=1.5µm				
D (um)	ngroup	alpha	Q	F
0.4	3.6912	0.45	81500	14.78
0.5	3.6822	0.44	102000	18.47
0.6	1.8383	0.145	70000	12.70
0.7	3.6983	0.3	146000	26.39
0.8	3.6325	0.235	198000	35.82
0.9	3.6766	0.375	259000	46.94

Figure 4: Table summarizing ring resonator parameters.