Backscattering Effects In Silicon Ring Resonators

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***Abstract*—Backscattering can dramatically modify the response of ring resonators and be the limiting parameter of the Q-factor. We present evidence of backscattering, a model, and a fitting procedure that provides a complete characterization of the resonance.**

***Keywords*—resonators; backscattering;**

I. Introduction

Microring resonators are simple to fabricate and used for devices such as optical filters, sensors, modulators etc. A high quality factor is usually the key parameter that determines the performance of the device; however, in this technology what limits its highest possible values is in most cases not the propagation loss, but the backscattering effect due to sidewall roughness [1]. Backscattering in a resonator cannot be accounted for as a loss mechanism because in a cavity it can grow coherently much faster than losses. Backscattering is a well known cause of resonance splitting [2]; but even before splitting occurs, it can dramatically modify the shape of the resonance. If this effect is not taken into account and one extracts the parameters of the ring from a fit, it can produce a good curve agreement but with very wrong results. In this work, we propose a characterization technique and a fitting procedure that allows a complete characterization of all the parameters of the ring including backscattering, without the need of a coherent backscattering measuring system as in [1] and [3].

II. Experiment

The waveguides used are fully-etched 220×450nm channels, covered with a 2μm SiO2 layer. Waveguides were patterned with deep-UV lithography (using EPIXfab facilities). Transverse-electric (TE) polarization was used in all the experiments. The rings had a 20μm radius and two coupling points, providing a *through* and a *drop* port. However, in this experiment we also collect the counter-propagating drop port, which we will call *counter-drop* port. Measuring this port is crucial to fully characterize the ring, as it directly provides the information about the backscattering inside the cavity. The gap of the through and drop couplers was 275nm and 300nm respectively.

Figure 1 shows the measured transmission through all three ports of one microring. It is worth noting that the shape of the resonances is very variable, even though one would expect the loss and the coupling coefficients to be approximately the same in all cases. The reason for this behavior is the backscattering parameter, which is intrinsically noisy, thus producing an apparently random response. It is noisy because reflections are produced by sidewall roughness along the ring, so they are randomly distributed along its length, and the overall reflection coefficient results from the interference of all the components, giving rise to sharp spectral variations. In order to extract the parameters of the ring, one must take into account backreflection, otherwise the estimation of the loss and coupling coefficients would depend on which resonance we select, which is unphysical and would produce wrong results. Therefore, a procedure to extract all the parameters including backreflection is needed in order to understand the behavior of our microring resonator.

III. Theory

Following the guidelines in [4], [5] the following expressions for the signal in the different ports shown in Fig. 1 are easily expressed in terms of quality factors as:

$$T = \left\| 1 - \frac{\frac{2}{Q_{e,1}}(2j(\omega'-1)+\frac{1}{Q})}{(2j(\omega'-1)+\frac{1}{Q})^2+\frac{1}{Q_r^2}} \right\|^2 \tag{1}$$

$$D = \left\| \frac{\frac{2}{\sqrt{Q_{e,1}Q_{e,2}}}(2j(\omega'-1)+\frac{1}{Q})}{(2j(\omega'-1)+\frac{1}{Q})^2+\frac{1}{Q_r^2}} \right\|^2 \tag{2}$$

$$C = \left\| \frac{\frac{2}{Q_r\sqrt{Q_{e,1}Q_{e,2}}}}{(2j(\omega'-1)+\frac{1}{Q})^2+\frac{1}{Q_r^2}} \right\|^2 \tag{3}$$

where ω' is the normalized angular frequency of the resonance under study, and the Q-factors are related to the τ constants of a time-domain analysis through $Q_j = \omega_o\tau_j/2$ and can be expressed as a function of the usual energy coupling and losses constants using the expression in [5] by:

$$K_j = \frac{\omega_o L}{Q_{e,j} v_g} \qquad \alpha = \frac{\omega_o}{Q_i v_g} \qquad \sqrt{R} = \frac{\omega_o L}{2 Q_r v_g} \tag{4}$$

In this expression v_g is the group velocity of the waveguide, K_1 and K_2 are the energy coupling of the input and output waveguides to the ring, α is the intrinsic losses and R is the strenght of the coupling in between the two modes. The Q values $Q_{e,1}$, $Q_{e,2}$, Q_i and Q_r correspond respectively to the extrinsic coupling with the bottom and top waveguides, the intrinsic losses and the coupling constant. Q_r has been related to the total reflectivity in a single-pass, R, that is, the fraction of energy coupled into the counter-propagating mode in one

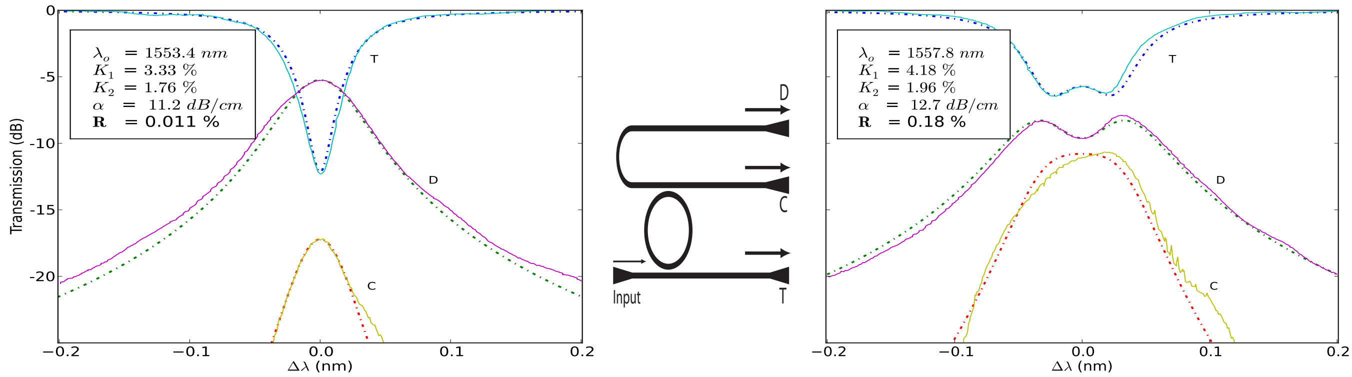

Fig. 1. Detail of 2 consecutive resonances of a ring. Transmission has been normalised. Solid lines are the experimental data and dashed lines are the analytical ones using the parameters extracted from the fitting procedure described in this work. The middle figure shows an schematic of the rings used. The labels in the peaks correspond to: Through (T), Drop (D), Counter-Drop (D).

trip around the ring. It sholud be noted that the total Q-factor is defined as usual, $Q^{-1} = Q_{e,1}^{-1} + Q_{e,2}^{-1} + Q_i^{-1}$. In order to extract the value of the different parameters, a measurement of the through, drop and counter-drop ports is needed. When $\omega' = 1$ (T_o, D_o, C_o) and the full width half maximum $(\Delta\omega')$ of the counter-drop port, the 4 parameters that characterize the ring can be deduced as described in [6]. The expressions that result from particularizing equations 1,2 and 3 for $\omega' = 1$ and measuring the FWHM of the counter-drop port, are given by:

$$Q = \frac{1}{\Delta\omega'}\left(\frac{C_o}{D_o} - 1 + \sqrt{2}\sqrt{\left(\frac{C_o}{D_o}\right)^2 + 1}\right)^{1/2} \tag{5a}$$

$$Q_r = \frac{1}{Q}\sqrt{\frac{D_o}{C_o}} \tag{5b}$$

$$Q_{e,1} = \frac{2}{Q(Q^{-2} + Q_r^{-2})(1 \pm \sqrt{T_o})} \tag{5c}$$

$$Q_{e,2} = \frac{2(1 \pm \sqrt{T_o})}{QD_o(Q^{-2} + Q_r^{-2})} \tag{5d}$$

The sign ambiguity in (5c) and (5d) is a byproduct of the existence of two degenerate operation regimes in the ring with different parameters but the same resonance shape. This ambiguity is well known in cases without any backreflection effect. In our case the ambiguity is not relevant since one of the signs would give rise to a negative loss coefficient, which is unphysical. As the sign has to be the same for all the peaks in a ring, this provides a way to decide the correct sign in the expressions by analyzing more than one peak and looking for non-physical solutions. Although the characteristics of this model imply a uniformly distributed backscattering, reflections really occur at randomly localized points, giving rise to the random nature of the variations of backscattering versus wavelength [7].

IV. Results

From the experimental data we have chosen two consecutive resonances which show quite different behavior in terms of extinction ratio and degree of splitting. The results obtained from the method described in section III for each resonance are shown in the insets of Fig. 1, and the corresponding theoretical curves are superimposed, where a good agreement is observed. It is worth noting that the coupling constants and the loss show small variations among resonances, being R the one showing the strongest variations. This is expected from the nature of backscattering, and demonstrates the validity of our model.

V. Conclusion

We have described an analytical model and a fitting procedure that allows extracting all the key parameters of a ring resonator with two coupling points. We demonstrate that variations of the backscattering parameter are the cause of the strong variations in the shape of different resonances of the same microring. All these parameters can be extracted from simple transmission measurements.

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References

[1] F. Morichetti, A. Canciamilla, M. Martinelli, et al, "Coherent backscattering in optical microring resonators," *Appl. Phys. Lett.,* vol. 96, 2010, p. 081112.

[2] B. E. Little, J. P. Laine, and S. T. Chu, "Surface-roughness-induced contradirectional coupling in ring and disk resonators," *Optics letters,* vol. 22, Jan. 1997, pp. 4-6.

[3] F. Morichetti, A. Canciamilla, C. Ferrari, et al, "Roughness induced backscattering in optical silicon waveguides," *Phys. Rev. Lett.,* vol. 104, 2010, p. 33902.

[4] H. A. Haus, "Waves and fields in optoelectronics," Ch. 7, Prentice-Hall, 1984.

[5] B. E. Little, S. Chu, H. Haus, et al, "Microring resonator channel dropping filters", *J. Lightwave Technol.*, vol. 15, no. 16, 1997, p.998-1005.

[6] G. C. Ballesteros, J. Matres, J. Martí and C. J. Oton, "Characterizing and modelling backscattering in silicon microring resonators," *Opt. Express,* vol. 19, no. 25, 2011, p.24980-24985.

[7] F. Morichetti, A. Canciamilla and, A. Melloni, "Statistics of backscattering in optical waveguides", *Opt. Lett*, vol. 35, no. 11, 2010, p.1777-1779