Experimental confirmation of universal relations for microring resonators in SOI technology

Wouter J. Westerveld, Suzanne M. Leinders,
Koen W.A. van Dongen, H. Paul Urbach
Department of Imaging Science and Technology
Delft University of Technology, Fac. of Applied Sciences
Lorentzweg 1, 2628 CJ Delft, The Netherlands

Jose Pozo, Remco A. Nieuwland
Technical Sciences Expertise Centre, TNO
PO Box 155, 2600AD, Delft, The Netherlands

Mirvais Yousefi
Photonic Sensing Solutions
P.O. Box 146003, 1001LC, Amsterdam, The Netherlands

***Abstract*— We present a detailed characterization of a set of microring resonators with bent radii of 1.5 µm, fabricated in silicon-on-insulator technology. Results are in good agreement with the universal relations for coupling between microresonators and dielectric waveguides.**

Optical ring resonators, silicon on insulator (SOI)

I. INTRODUCTION

Photonic microring resonators in silicon-on-insulator (SOI) technology have gained substantial academic as well as industrial interest over the last decade, for example in the fields of sensing and telecommunications [1]. The high index contrast allows for a small device footprint, and industrial CMOS lines offer the possibility of cost-effective mass-production. In 2000, Amnon Yariv published [2] elegant universal relations for coupling between microresonators and dielectric waveguides, and we demonstrate the validity of this model for extremely small resonators in this work.

We designed a set of racetrack-shaped ring resonators (Fig. 1) with a straight section of 10 µm and a very small bend radius of 1.5 µm (circumference l = 30 µm). Such a shape is required for specific applications such as local and directional sensing of mechanical strain [3], but also comes with severe losses. The track consists of Si-in-SiO_2 waveguides with a cross-section of 450 nm by 220 nm, which are fabricated at IMEC via ePIXfab. Light is evanescently coupled from a connecting waveguide to the racetrack by separating the two guides only 200 nm apart over a length L. The transmission spectrum of the connecting waveguide shows dips at the resonance wavelengths of the track, and the shape of these dips strongly depends on the amount of light coupled to the track with respect to the loss of light in the resonator round-trip.

II. THEORY

The resonator is depicted in Fig. 1, to which light is evanescently coupled from the single-mode input waveguide. We describe this coupling with the matrix notation for a lossless coupler [2]

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} te^{i\phi_t} & \kappa e^{i\phi_\kappa} \\ -\kappa e^{-i\phi_\kappa} & te^{-i\phi_t} \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \tag{1}$$

where (a_1,a_2), and (b_1,b_2) represent the modal amplitudes in the waveguides as depicted in Fig. 1. The coupling amplitudes of

This work was supported by TNO and by the IOP Photonic Devices programme of NL Agency of the ministry of EconomicAffairs. We also gratefully acknowledge the EU-funded ePIXfab for wafer-scale fabrication of the devices.

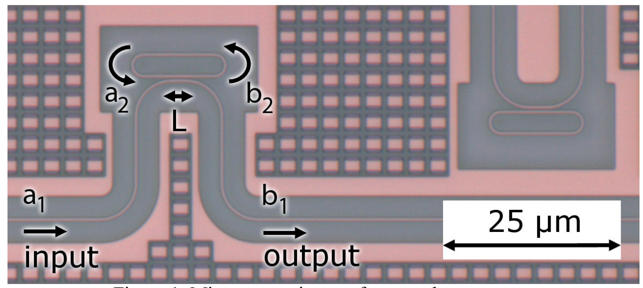

Figure 1. Microscope picture of racetrack resonators.

the light that goes straight through the coupler, t, and the light that is coupled to the racetrack, κ, obey the relation for power conservation: $\kappa^2 + t^2 = 1$. The light that is coupled to the racetrack makes a round-trip described by $a_2 = \alpha\, e^{-i\theta}\, b_2$, where α is the amplitude transmission, and θ is the phase delay. We express the total phase delay of the monochromatic light (vacuum wavelength λ) traveling a round-trip through the racetrack waveguide in terms of its effective index n_{eff}

$$\theta + \phi_t = n_{\text{eff}}(\lambda)\ 2\pi/\lambda \cdot l \tag{2}$$

where it is assumed that the effective index in the coupler region is equal to the effective index of the waveguide. The strong modal dispersion of silicon waveguides is assumed linear around λ_c = 1550 nm, so that we can write the wavelength dependent effective index as

$$n_{\text{eff}} = n_{\text{eff}}(\lambda_c) + \tfrac{\partial n_{\text{eff}}}{\partial \lambda}(\lambda - \lambda_c). \tag{3}$$

The effective group index, $n_g \equiv n_{\text{eff}} - \lambda \cdot \partial n_{\text{eff}}/\partial\lambda$, is introduced to describe this relation. The power in the output waveguide, $|b_1|^2$ is calculated from Eq. (1)

$$|b_1|^2 = \tfrac{\alpha^2 + |t|^2 - 2\alpha|t|\cos(\theta+\phi_t)}{1 + \alpha^2|t|^2\cos(\theta+\phi_t)} |a_1|^2 \tag{4}$$

Light at the output waveguide b_1 is minimal at the resonance

$$n_{\text{eff}}/\lambda_m \cdot l = m \tag{5}$$

Where Eq. (4) reads

$$|b_1|^2 = \tfrac{(\alpha - t)^2}{(1 - \alpha t)^2} |a_1|^2 \tag{6}$$

Transmission dips to zero, or critical coupling, occurs when the straight-through power t^2 in the coupler is equal to the round-trip power transmission α^2 in the resonator.

The light is coupled to the racetrack by means of a directional evanescent field coupler, as depicted in Fig. 2. The coupling between the incoming wave a_1 and the outgoing wave $b_1 = t\, a_1$, is given by [5]

$$|b_1|^2 = \cos^2(K(L + L_0))|a_1|^2 \tag{7}$$

where K is the coupling coefficient that depends on the overlap between the fields of the two modes, i.e. the waveguide dimensions and separation. The coupling that already occurs in the bends of the directional coupler waveguide is accounted by introducing the effective coupler length L+L_0.

III. Results and Conclusions

Separate devices are fabricated to characterize the directional couplers, see Fig. 2 (right). The straight-through transmission t of the directional couplers is characterized by measuring the power from a_1 to b_1 and from a_3 to b_3 for couplers with various lengths L. Light is coupled from optical fibers to the waveguides via an out-of-plane grating coupler [4], and the alignment is automated to provide high repeatability of the power coupled in-and-out of the circuit. The parameters of the coupler K and L_0, as well as in-coupling $|a_1|^2$, as described in Eq. (7), are fitted to the measured spectra. The characterization of the coupler is presented in Fig. 2 (left).

For the characterization of the microracetrack resonators, the parameters in Eq. (4) are fitted to the measured spectra. The track length l and coupling κ (from Fig. 2) are fixed and all other parameters are fitted. The resolution bandwidth of the optical spectrum analyzer is incorporated in this fitting by convoluting the spectrum as calculated with Eq. (4) with a Gaussian curve with a full-width-half-max of 20 pm. An accurate initial guess of n_{eff} and n_{g} (the positions of the dips) in Eq. (4) is necessary for the Levenberg-Marquardt fitting algorithm. The mode number m is estimated from Eq. (5) where the effective index n_{eff} was calculated using a mode solver (film mode matching method in FimmWave, PhotonDesign). The resonance dips where found using *findpeaks* [6] and from this n_{eff} and n_{g} are estimated via Eq. (5).

The resonance dip closest to a vacuum wavelength of 1550 nm is presented in Fig. 3, for a set of racetracks with a varying length of the directional coupler. It is clearly seen that under-coupling (small lengths) or over-coupling (long lengths) lead to shallow resonance dips, while the close-to critical coupled racetracks shows an extinction of -25 dB.

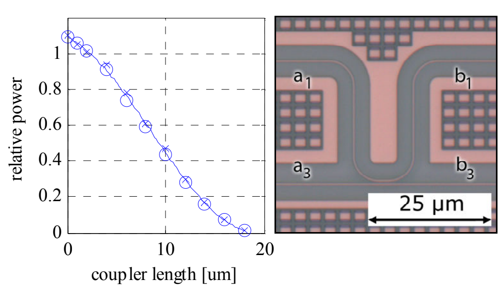

Figure 2.(right) Microscope picture of an individual directional coupler. (left) Transmitted power as function of the coupler length. o is $a_1 \rightarrow b_1$, x is $a_3 \rightarrow b_3$, and the solid line is fitted.

In conclusion, the measured transmission spectra of our microracetrack resonators are in good agreement with the universal relations for coupling between microresonators and dielectric waveguides as presented by Yariv.

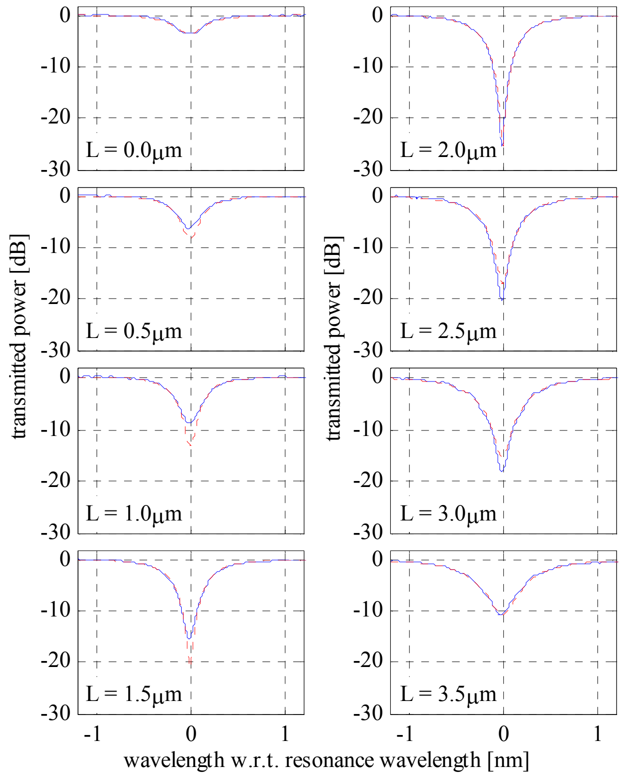

Figure 3. Measured spectra of the racetrack resonators with incrasing length L of the evanescent coupler section. Dashed lines indicate the fitted spectra.

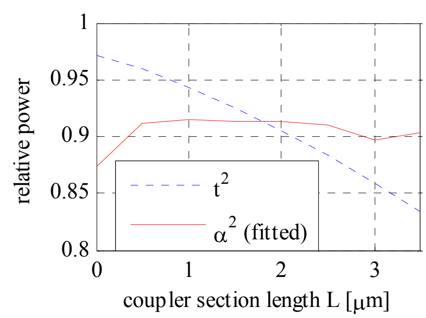

Figure 4. Fitted ring transmission (-0.4 dB) versus coupler length (solid), also coupling through power (dashed). Critical coupling occurs at the crossing.

References

[1] W. Bogaerts *et al*, Laser and Photonic Reviews **6**, 47 (2012)
[2] A. Yariv, Electronic Letters **36**, 321 (2000).
[3] W.J. Westerveld *et al*, Optics Letters **37**, 479 (2012).
[4] W.J. Westerveld *et al*, IEEE J. of Quantum Electronics **47**, 561 (2011).
[5] C. Pollock and M.Lipson, Integrated Photonics (Kluwer, 2003).
[6] *findpeaks* by Tom O'Haver (www.wam.umd.edu/~toh/, 2012)