

Asymmetrically Coupled Silicon-On-Insulator Microring Resonators for Compact Add-Drop Multiplexers

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Abstract—We report on improved filter characteristics of microring resonators (MRs) used as add-drop multiplexer for integrated photonic circuits. By introducing an asymmetrical coupling of the signal waveguides to the resonator, a higher throughput attenuation and drop efficiency is attained. The throughput attenuation is the decisive property for the application of microrings in photonic networks since it determines the crosstalk between drop signal and add signal at the throughput channel of an add-drop multiplexer. Experimental results are compared with analytical relations. MRs with a free-spectral range of 24 nm are fabricated on silicon-on-insulator substrates. A crosstalk reduction by 8.8 dB due to asymmetrical coupling is demonstrated.

Index Terms—Add-drop multiplexer (ADM), channel-drop filter, integrated optics, microring resonator (MR), racetrack resonator, ring resonator, silicon-on-insulator (SOI), 1.3 μm , 1.55 μm .

I. INTRODUCTION

ADD-DROP multiplexers (ADM), which allow the flexible addition and extraction of dense wavelength-division-multiplexing signals, are key components of photonic networks. Current solutions for this task are large and costly, and therefore provide solutions for long-haul fiber backbone network applications only. With increasing complexity and penetration of photonic networks for systems like fiber-to-the-home or fiber-to-the-building, however, new cost-efficient highly integrated solutions are required. Recently, microring resonators (MRs) have attracted considerable attention as ADMs for photonic networks [1], [2]. The small size of MRs and high attainable quality factor (Q factor) make them attractive for highly integrated components. To optimize the filter characteristics, parallel and serial coupling of MRs has been proposed [1], [3], [4]. Here, we experimentally demonstrate the improvement of the throughput attenuation and drop efficiency through an asymmetrical coupling of the signal waveguides to the MR, that leads to a crosstalk reduction between drop signal and add signal at the throughput. Theoretical calculations are

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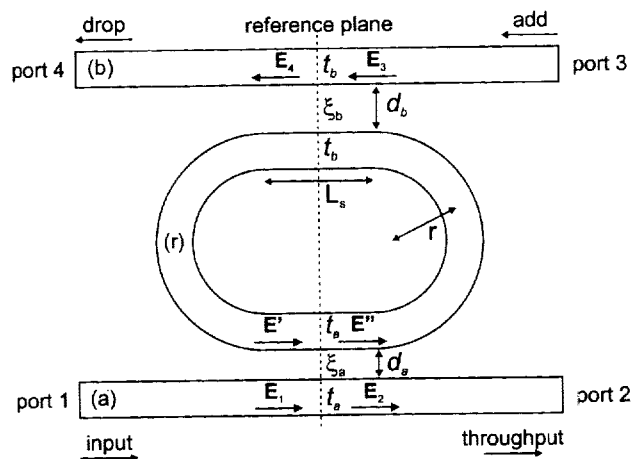


Fig. 1. Sketch of an asymmetrically coupled racetrack resonator.

compared with experimental results of racetrack resonators fabricated on silicon-on-insulator (SOI) substrates. Racetrack resonators are MRs with straight waveguide parts parallel to the signal waveguides to increase the coupling coefficients. SOI substrates are used since this material is a very promising candidate for highly integrated photonic circuits, since the buried oxide (BOX) layer acts as a natural optical confinement layer in vertical direction. Additionally, the high index contrast between silicon and oxide, respectively, silicon and air, allows us to achieve very high integration densities. Furthermore, the devices can be fabricated using the highly elaborated and cost-efficient silicon process technology, promoting the convergence of microelectronics and integrated optics.

II. THEORY

The transfer functions and Q factor of a MR can be described by general parameters that are not bound to the actual shape (e.g., ring or racetrack) of the resonator. For the case of an asymmetrically coupled resonator, shown in Fig. 1, the following relations of the amplitude and phase of the field at the reference plane are used:

$$E_2 = t_a E_1 + i \xi_a E' \quad (1)$$

$$E'' = t_a E' + i \xi_a E_1 \quad (2)$$

$$E' = t_b E'' \tau e^{i\phi} \quad (3)$$

$$E_4 = i \xi_b E'' \sqrt{\tau} e^{i\phi/2} \quad (4)$$

$$E_3 = 0. \quad (5)$$

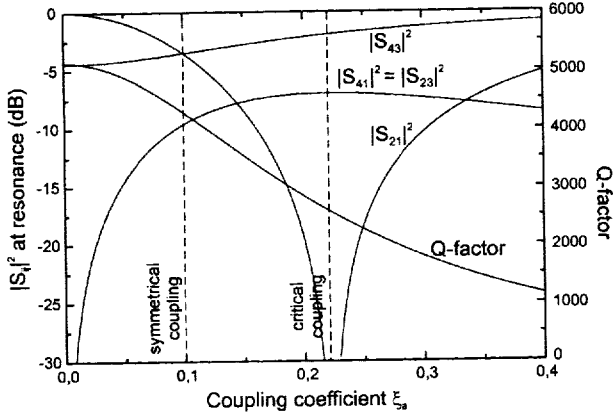


Fig. 2. Transfer functions and Q factor of a lossy ($\tau = 0.98$), asymmetrically coupled MR ($\xi_b = 0.1$, $L_{\text{eff}} = 20 \mu\text{m}$, $n_{\text{eff}} = 3.2$, $\lambda_0 = 1.55 \mu\text{m}$).

Here, ξ_a and ξ_b are the coupling coefficients between the racetrack resonator (τ) and the signal waveguides (a, b), $t_{a,b} = \sqrt{1 - \xi_{a,b}^2}$ the transmission coefficients, τ is the attenuation and $\phi = k_0 n_{\text{eff}} L_{\text{eff}} = k_0 n_{\text{eff}} 2(\pi r + L_s)$ the phase shift for one roundtrip along the resonator. Equations (1)–(5) give the transfer functions between Port 1 and Port 2 (throughput attenuation), respectively, Port 1 and Port 4 (drop efficiency)

$$|S_{21}|^2 = \left| \frac{E_2}{E_1} \right|^2 = \frac{t_a^2 + t_b^2 \tau^2 - 2t_a t_b \tau \cos \phi}{1 + t_a^2 t_b^2 \tau^2 - 2t_a t_b \tau \cos \phi} \quad (6)$$

$$|S_{41}|^2 = \left| \frac{E_4}{E_1} \right|^2 = \frac{\xi_a^2 \xi_b^2 \tau}{1 + t_a^2 t_b^2 \tau^2 - 2t_a t_b \tau \cos \phi}. \quad (7)$$

Using these equations, the Q factor of this device can be approximated by

$$Q \approx \frac{\lambda_0}{\Delta \lambda_{3\text{dB}}} = \frac{\pi L_{\text{eff}} n_{\text{eff}}}{\lambda_0 \arccos \left(\frac{1 + t_a^2 t_b^2 \tau^2 - 4t_a t_b \tau}{-2t_a t_b \tau} \right)}. \quad (8)$$

Here, λ_0 is the resonance wavelength and $\Delta \lambda_{3\text{dB}}$ the 3-dB linewidth. If the MR is used as an ADM, the add signal is introduced at Port 3 and transferred to Port 2, in addition to the channel drop from Port 1 to Port 4. Due to the device symmetry, the corresponding transfer functions can easily be derived from $|S_{41}|^2$ and $|S_{21}|^2$ as $|S_{23}|^2 = |S_{41}|^2$ (add and drop efficiency are always equal) and $|S_{43}|^2$ can be derived from $|S_{21}|^2$ by exchanging t_a and t_b (add and throughput attenuation are different for asymmetrical coupling).

Efficient channel drops require efficient throughput attenuations, since they have to deallocate the channel. A residual drop signal at the throughput leads to crosstalk if the channel is used by a new signal. Therefore, device optimization has to focus on the throughput attenuation at resonance. In Fig. 2, the transfer functions and the Q factor at resonance ($\phi = m2\pi$, $m \in \mathbb{N}$) for a lossy ($\tau = 0.98$) asymmetrically coupled MR ($\xi_b = 0.1$) as a function of ξ_a are shown. Starting from no coupling ($\xi_a = 0$) $|S_{21}|^2$ decreases with increasing coupling coefficient ξ_a , reaches $|S_{21}|^2 = 0$ and increases again. The point $|S_{21}|^2 = 0$ that constitutes the situation of zero crosstalk is called critical coupling [5]. It is given by

$$t_a = t_b \tau. \quad (9)$$

At this point, the loss-induced intensity decrease in the MR, responsible for an incomplete throughput attenuation at resonance for a symmetrically coupled MR, is compensated by an increased coupling into the MR. Although $|S_{41}|^2$ reaches its maximum at this point, the signal transfer is still not complete ($|S_{41}|^2 < 1$). On the other hand, the improved transfer characteristic ($|S_{21}|^2 = 0$, $|S_{41}|^2$ maximal) is attained at the expense of a decreased Q factor. Furthermore, the asymmetrical coupling brakes the symmetry of the device. While the residual drop signal is completely attenuated at the throughput ($|S_{21}|^2 = 0$), there is no complete attenuation of the residual add signal at the drop ($|S_{43}|^2 > 0$) leading to crosstalk, if the device is used for a channel add in addition to the channel drop. This problem can be solved, however, by a second racetrack resonator ($\xi_{a,2}$, $\xi_{b,2}$), having the coupling coefficients exchanged ($\xi_{a,2} = \xi_{b,1}$ and $\xi_{b,2} = \xi_{a,1}$), and exhibiting no coupling with the first MR. The decoupling of the MRs can be achieved by a sufficient gap between the MRs. With two MRs the device symmetry is restored. While the channel drop at resonance is performed by the first MR critically coupled to waveguide (a), the channel add is performed by the second MR critically coupled to waveguide (b). Thus, the crosstalk at resonance between add and drop signal is completely suppressed.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The fabrication of ADMs consisting of two MRs critically coupled to the signal waveguides needs a very precise fabrication technology. However, to experimentally demonstrate the improved filter characteristics due to an asymmetrical coupling, devices with only one MR are sufficient. Therefore, we fabricated and characterized single asymmetrically coupled SOI racetrack resonators. The thickness of the silicon device layer and the BOX of the SOI substrate are $0.4 \mu\text{m}$ each. The racetrack resonators are defined by high-resolution electron beam lithography and etched to the BOX by an HBr inductive coupled plasma reactive ion etching process. The width of the signal waveguides coupled to the racetrack resonator and the waveguide of the racetrack resonator is $0.4 \mu\text{m}$. Outside the coupling region, the signal waveguides are tapered to a $10\text{-}\mu\text{m}$ width to reduce the loss and improve the coupling to optical fibers. The center bending radius of the racetrack resonators is $r = 3 \mu\text{m}$ and the length of the straight waveguide parts $L_s = 1 \mu\text{m}$. Thus, the footprint of the active region of the devices is approximately $7 \times 8 \mu\text{m}^2$. Devices with fixed $d_b = 0.2 \mu\text{m}$ and varying $d_a = 0.1 \mu\text{m}$ to $0.2 \mu\text{m}$, respectively, fixed $d_b = 0.25 \mu\text{m}$ and varying $d_a = 0.125 \mu\text{m}$ to $0.25 \mu\text{m}$, have been fabricated.

The racetrack resonators are characterized using a commercial measurement setup consisting of an external cavity diode laser and a photodetector. Transverse-magnetic polarized light (electric field perpendicular to the device plane) is butt coupled to the input by a polarization-maintaining optical fiber. The light at the throughput and drop is butt coupled to a multimode fiber and detected with the photodetector. The measured intensities are normalized to the intensity of the throughput outside a resonance.

The free-spectral range of the SOI racetrack resonators is approximately 24 nm . Fig. 3 shows transfer functions of SOI race-

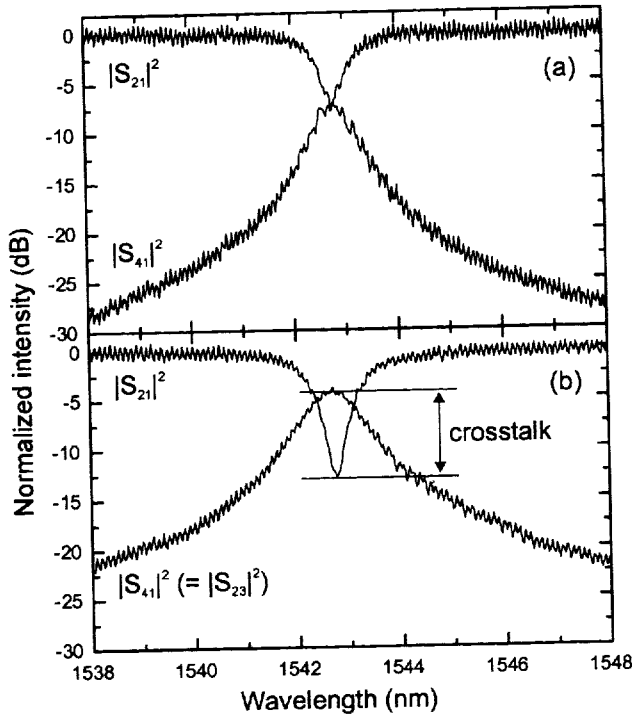


Fig. 3. Transfer functions of (a) a symmetrically coupled ($d_a = d_b = 0.2 \mu\text{m}$) and (b) an asymmetrically coupled ($d_a = 0.16 \mu\text{m}$, $d_b = 0.2 \mu\text{m}$) SOI racetrack resonator. For the determination of the crosstalk between add and drop signal at Port 2, consider $|S_{23}|^2 = |S_{41}|^2$.

track resonators with $d_b = 0.2 \mu\text{m}$. Changing from symmetrical ($d_a = d_b$) to asymmetrical coupling ($d_a = 0.16 \mu\text{m}$), the throughput attenuation increases from -7.2 to -12.8 dB, while the drop efficiency increases from -7.5 to -4.3 dB. Thus, the crosstalk, defined as the relation between drop efficiency (= add efficiency) and throughput attenuation at resonance, decreases from 0.3 dB for the symmetrically coupled racetrack resonator to -8.5 dB for the asymmetrically coupled racetrack resonator, while the Q factor (determined by $\lambda_0/\Delta\lambda_{3\text{dB}}$) decreases from 1800 to 1300 . An exact adjustment of the critical point has not been possible, since the fabrication technology has not been optimized for the reproducibility of loss and coupling coefficients.

Fig. 4 shows the throughput attenuation at resonance and the Q factor of a series of asymmetrically coupled SOI racetrack resonators of different d_a at constant d_b . Due to the limited reproducibility of ξ_b , τ , and n_{eff} for different $\xi_a(d_a)$, a reliable determination of these many parameters by fitting the theoretical transfer functions $|S_{21}|^2$ and $|S_{41}|^2$ to the experimentally determined transfer functions is problematic. Therefore, in Fig. 4, the distance d_a is used as parameter instead of ξ_a . Starting from symmetrical coupling ($d_a = 0.25 \mu\text{m}$), the throughput attenuation increases from -2.1 to -12.5 dB for $d_a = 0.175 \mu\text{m}$ and then decreases again to -4.4 dB for $d_a = 0.125 \mu\text{m}$. The Q factor decreases from 2580 to 1030 in the range investigated. The experimentally determined behavior of the throughput attenuation and Q factor is similar to the theoretical behavior

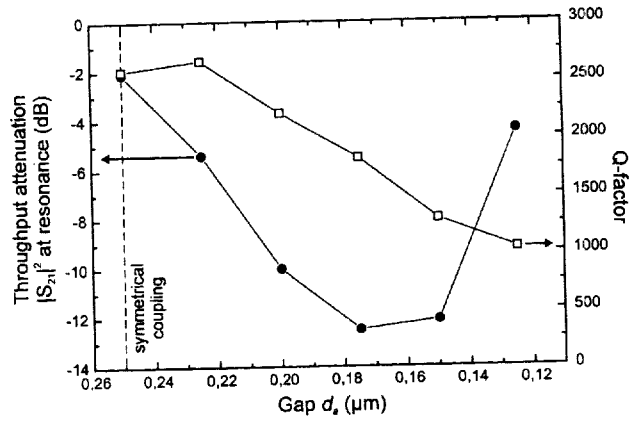


Fig. 4. Throughput attenuation $|S_{21}|^2$ at resonance and Q factor of symmetrically coupled SOI racetrack resonators ($d_b = 0.25 \mu\text{m}$) as a function of decreasing d_a (i.e. increasing coupling coefficient ξ_a).

shown in Fig. 2. Thus, the results experimentally demonstrates the improved throughput attenuation of MRs due to asymmetrical coupling.

IV. SUMMARY

We experimentally demonstrated the improvement of the filter characteristics (throughput attenuation and drop efficiency) of MRs due to asymmetrical coupling the signal waveguides to the resonator. The throughput attenuation is the decisive property that determines the crosstalk between drop signal and add signal at the throughput if MRs are used as ADMs. The experimental results have been compared with analytical relations. Applying asymmetrical coupling, a crosstalk reduction by 8.8 dB has been demonstrated for SOI racetrack resonators having a free-spectral range of approximately 24 nm at $1.55 \mu\text{m}$.

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