Impact of Backscattering on Microring-based Silicon Photonic Links

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***Abstract*— The first quantitative analysis of optical power penalty due to the backscattering of silicon add-drop ring resonators is presented. Simulated results based on experimentally retrieved data show the attributing power penalty from fabricated microring is as high as 4.5 dB for 10 Gbps OOK links.**

I. Introduction

SILICON PHOTONICS (SiP) technology promotes the application of silicon microring resonators (MRRs) as the fundamental elements for optical modulation and optical demultiplexing in a wavelength division multiplexed (WDM) scheme, as well as optical switching. Narrow-band spectral response of MRRs (e.g. 10 GHz) in conjunction with high-speed signaling (10 Gbps or higher) puts stringent requirements on the design of MRRs for high-performance links. Previous works [1-3] have studied power penalties due to the Lorentzian spectral lineshape of MRRs both theoretically and experimentally. However, it has been shown that in applications where very narrow linewidths (i.e. high-*Q*) are required, even a slight roughness on the sidewalls of the ring will cause backscattering inside the ring [4, 5]. The effect of backscattering in microring resonators is typically observed in the form of a splitting of the resonance in the spectral response of the ring [5]. Such spectral distortion adds extra complexity that further narrows down the design space of MRRs for minimizing power penalties. An increase of optical bandwidth (thus a decrease of the *Q*-factor) limits the attenuation of the high-frequency components of the dropped signals, but may lead to a truncated filtering shape inflicting higher losses and spectral distortions on the central frequency components of the dropped signals.

In this work, we analyze the impact of backscattering on silicon add-drop ring resonators for high-speed OOK links by quantifying the induced power penalty. Our results show that the observed backscattering from our fabricated silicon add-drop ring component can have a penalty impact of up to 4.5 dB on a 10 Gbps OOK link.

II. Backscattering Power Penalty

A. Modeling of Backscattering

The backscattering of the optical power inside the ring can be correlated to the surface roughness of the sidewalls of the ring resonator (Fig. 1a). Based on the analysis presented by Little *et al.* [4], we assume that the randomness of the scattering from the sidewalls of the ring resonator has no spatial preference. Therefore, the cumulative impact of the back-reflections inside the ring can be lumped at one location along

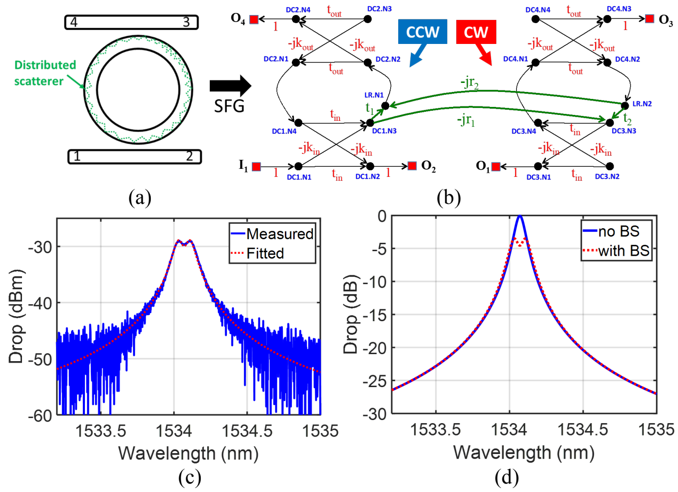

Fig. 1. (a) Schematic of an add-drop ring resonator with distributed backscattering (BS) inside the ring. (b) The proposed signal flow graph (SFG). (c) Measured symmetric backscattering from our fabricated device and the fitted model. (d) Simulated drop response without (solid) and with (dotted) backscattering for the fabricated device.

the ring. We then built a signal flow graph (Fig. 1b) that mutually couples the original counter clockwise (CCW) wave inside the ring to the back scattered clockwise (CW) wave. Based on this model, the drop transfer function (I1 → O4) is calculated as

$$H(\omega) = -\kappa_{in}\kappa_{out}L^{0.25}\exp\left(-\frac{j\phi_{ring}}{2}\right)\times \left[\frac{t_1-(r_1r_2+t_1t_2)G}{1-(t_1+t_2)G+(r_1r_2+t_1t_2)G^2}\right] \quad (1)$$

where κ_{in}, κ_{out}, and L are the input and output coupling of electric field and the round trip power attenuation inside the ring, respectively. G is the round-trip gain inside the ring given by $G=\xi\exp(-j\phi_{ring})$ and $\xi=t_{in}t_{out}L^{0.5}$. Here, t_1 and r_1 are the scattering transmittance and reflectance in the CCW direction while t_2 and r_2 are for the CW direction. If no backscattering is present inside the ring, then $t_1=t_2=1$ and $r_1=r_2=0$ and the transfer function is reduced to the ideal add-drop ring. By assuming that the scattering inside the ring does not cause any radiation outwards (i.e. $|t_1|^2+|r_1|^2\approx 1$ and $|t_2|^2+|r_2|^2\approx 1$), and the round-trip symmetry of the scattering (i.e. $|t_1|\approx|t_2|=t$ and $|r_1|\approx|r_2|=r$), it can be shown that $H(\omega)$ can be expressed around the resonance frequency, ω_0, as

$$H(\omega)=H_0\left[\frac{\frac{1}{2}\left(1-r\sin\frac{\phi_s}{2}\right)^2}{j(\omega-\omega_+)+\frac{\Delta\omega_+}{2}}+\frac{\frac{1}{2}\left(1+r\sin\frac{\phi_s}{2}\right)^2}{j(\omega-\omega_-)+\frac{\Delta\omega_-}{2}}\right] \quad (2)$$

where $\omega_\pm=\omega_0\pm FSR/\xi\times r\cos(\phi_s/2)$ and $\Delta\omega_\pm\approx\Delta\omega_0\pm 2FSR/\xi\times r\sin(\phi_s/2)$. $\Delta\omega_0$ is the original 3dB optical

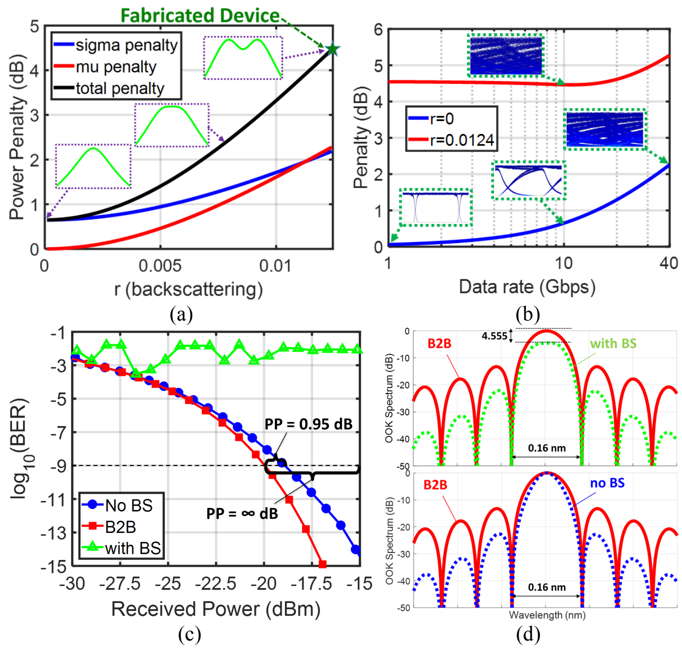

Fig. 2. (a) Calculated power penalty of an add-drop ring resonator with backscattering. Insets show how the drop spectrum changes as backscattering strength increases. (b) Comparison of the power penalty of ideal add-drop ring ($r = 0$) with the fabricated ring with backscattering ($r = 0.0124$) for high-speed OOK signals. Insets show the simulated eye diagrams in Lumerical Interconnect. (c) Simulated BER penalty in Lumerical Interconnect for an ideal and backscatter add-drop ring and 10 Gbps signal. (d) OOK spectrum for 10 Gbps in both cases.

bandwidth of the resonance given by $\Delta\omega_0 = 2(1-\xi)FSR/\xi$ and ϕ_s accounts for scattering phase accumulation in both the CW and CCW directions (i.e. $\angle r_1 + \angle r_2 = \phi_s$). This equation shows that the spectrum of the drop path now consists of two peaks with equal distances from the original resonance of the ring. If $\phi_s = 0$, the two peaks have the same heights and the spectrum is perfectly symmetric. If $\phi_s \neq 0$ then one peak is higher than the other depending on the sign of ϕ_s.

B. *Fabricated Device*

A batch of five add-drop ring resonators were fabricated through the AIM Photonics' MPW run [6]. Each ring is made of 400nm×220nm silicon strip waveguide with 5μm radius and equal input and drop gaps between the ring and the bus waveguides. The gaps are set to 100 nm, 150 nm, 200 nm, 250 nm, and 300 nm, respectively. When measured the spectra of the drop paths, the last structure with 300 nm gaps exhibited a noticeable symmetric splitting of the resonance as shown in Fig. 1c. Our FDTD simulations showed that for this structure the FSR should be about 17.1235 nm and the input and output couplings (κ) should be about 0.11. For this device, the measured FSR is about 17.2 nm, and the input kappa, output kappa, round-trip loss, and the backscattering coefficient were extracted to be $\kappa_{in} = \kappa_{out} = 0.1222$, $L = 0.9998$, and $r = 0.0124$. Since the splitting of resonance is symmetric $\phi_s = 0$. We then used these extracted parameters to build the model of this device. A comparison of the simulated spectrum of this device compared to an ideal add-drop ring is shown in Fig. 1d indicating 4.555 dB loss at the center of the spectrum. The 3dB bandwidth of the ideal add-drop ring ($r = 0$) is estimated to be 0.0964 nm or 12 GHz, corresponding to $Q \approx 16000$.

C. *Power Penalty Analysis*

The signal impairment of the backscattering on NRZ OOK signal was assessed analytically in the spectral domain based on the ideal modulation spectrum $S_{OOK}(f) = \mu^2\delta(f-f_0) + \sigma^2/r_b \times sinc^2((f-f_0)/r_b)$ where r_b is the modulation data rate of the signal (set at 10 Gbps). The total power penalty of the add-drop ring consists of μ-penalty (corresponding to insertion loss) and σ-penalty (corresponding to spectral filtering) [2]. Figure 2a shows the two individual power penalties and the sum of them as a function of the backscattering strength. Insets show how the drop spectrum is affected as the strength of backscattering increases. The 4.555 dB of insertion loss at the original resonance of the ring (Fig. 1d) translates into 2.277 dB of μ-penalty. The σ-penalty is estimated to be 2.185 dB based on the integration of Eq. (2) with the $sinc^2(\ldots)$ part of the OOK spectrum. Therefore, the total penalty is 4.462 dB and by comparing to the ideal case, i.e. without backscattering which exhibits only 0.7 dB power penalty based on our analytical model, it indicates that the backscattering can have a severe impact on the performance of a photonic link [2]. Figure 2b plots the comparison between the estimated power penalty of the observed backscattering and an ideal add-drop ring (presented in Fig. 1d) for high-speed NRZ OOK signals. To further validate our analytical approach, we built the model of the ring with backscattering in Lumerical Interconnect. Insets of Fig. 2b show the eye diagrams for different power penalties. Figure 2c shows the numerically calculated BER curves (2^{11}-1 PRBS) for ideal and backscatter rings at 10 Gbps. The estimated power penalties in this way are 0.95 dB and infinite (no convergence of BER), respectively. Figure 2d presents the frequency spectrum of the OOK signal for the back-to-back case and the drop port of an ideal and backscatter ring. The main difference is in the main lobe while the side lobes are affected in the same way.

III. Conclusions

In conclusion, we presented a quantitative analysis of the backscattering impairment for silicon ring resonators. Our model showed that the power penalty of an add-drop ring resonator due to the observed backscattering can be as high as 4.5 dB for 10 Gbps signaling which can have a severe impact on the power budget of a photonic link.

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