A Silicon Photonic Ring-Assisted Mach-Zehnder Modulator with Strongly-Coupled Resonators

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***Abstract*—We propose a new ring-assisted Mach-Zehnder modulator (RAMZM) based on strongly coupled rings. The new design uses moderately doped PN junction phase shifters to increase the modulation bandwidth. Theoretical analysis and experimental demonstration are presented.**

I. Introduction

To meet the ever-increasing bandwidth demands in data center communications, Mach-Zehnder modulators (MZMs), which are the main component in high-density, high-speed integrated optical transceivers, need to have smaller size and higher energy efficiency. To achieve 0 to π phase difference between the two arms, an MZM typically requires either high modulation efficiency for its phase shifters or large RF voltage swing. There are trade-offs between the phase shifter length, optical loss and RF modulation bandwidth in the MZM phase shifter design [1]. For PN-junction phase shifters, which are typically used in high-speed silicon photonic MZMs, the design variables are the cross-section geometries and doping profile [2].

Ring-assisted MZMs (RAMZMs), as illustrated in Fig. 1-a, were proposed [3], [4] to reduce the phase shifter length and hence the MZM size. It potentially combines the advantages of both MZM and ring modulators, e.g., high extinction ratio (ER) [5], good linearity [6], and low RF power consumption [7]. Most previous RAMZM designs chose heavily doped PN junctions in the rings to allow low RF voltage swing. To reduce the ring induced insertion loss, the rings were designed to be weakly coupled to the waveguides to keep their relatively high Q – this in turn results in a long photon lifetime and hence small modulation bandwidth. In this work, we explore new RAMZM designs with strong ring-waveguide coupling and moderately doped PN junctions to achieve a better trade-off between insertion loss and modulation bandwidth.

II. Microring Phase Modulation and RAMZM

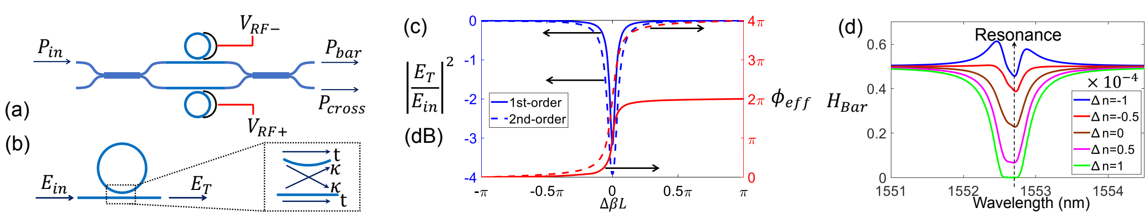

Fig. 1. (a) A push-pull 2x2 RAMZM driven by a differential RF signal. (b) A single-bus ring resonator. (c) Through-port power transfer and phase shift of a 1st- or 2nd-order ring resonator. (d) Power transmission of RAMZM when changing effective index difference in the ring modulators on two arms.

Fig. 1-b shows a first-order ring resonator with a single bus waveguide. The ring-waveguide coupling region is modeled with s-parameters t and κ. Assuming a lossless symmetric coupling region and t is real, $\kappa = j\sqrt{1-t^2}$. The rest of the ring is characterized as $p = e^{(-\alpha+j\beta)L}$, where L is its waveguide length. This resonator's transfer function is calculated as:

$$\frac{E_T}{E_{in}} = \frac{\kappa^2 p}{1-pt} + t = -(1-t^2)\frac{p}{1-pt} + t = \frac{t-p}{1-pt} \tag{1}$$

The effective phase shift due to the ring is $\phi_{eff} \equiv \arg(E_T/E_{in})$. As shown in Fig. 1-c, if the ring-waveguide is over-coupled ($|p| > t$), ϕ_{eff} changes from 0 to 2π within one free spectral range (FSR), i.e., when βL changes by 2π. ϕ_{eff} exhibits a steep slope near the resonance, which means a high phase modulation efficiency when the resonator is biased here. This resonance enhancement comes at the price of insertion loss (IL) at resonance. The latter is affected by the PN junction doping in the phase shifter. There is a design trade-off between the phase modulation efficiency and IL. We propose to use strong ring-waveguide coupling and moderate PN-junction doping in RAMZM applications. Larger $|\kappa|$ and hence smaller t results in a lower Q and hence a larger modulation bandwidth. At the same time, IL at resonance is reduced, considering that at resonance $t - p < 0$ in Eqn. 1. Moderate doping reduces ring-induced loss (smaller α). A higher order ring resonator can further enhance these resonance effects, and potentially present a better design tradeoff. Fig. 1-c shows an over-coupled 2nd-order ring with weak ring-ring coupling which exhibits a higher modulation efficiency and a slightly larger IL.

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III. Prototype Chip Design and Measurement Results

To demonstrate the proposed RAMZM design, a prototype device is designed and fabricated using IMEC SOI silicon photonics technology [9]. The push-pull 2x2 RAMZM employs two second-order ring resonators on each arm (Fig. 1-a). The MZM is biased at half-π phase difference using static arm length difference and thermal phase shifters. The rib waveguide components are modeled and optimized using eigenmode and FDTD simulations, and the PN junction is characterized using semiconductor device simulations. The 2nd-order resonator with two 15-μm rings is strongly-coupled to the waveguide on each arm with $|\kappa_1|^2 = 0.38$ and the ring-ring coupling of $|\kappa_2|^2 = 0.015$. Instead of a high doping level of $\sim 10^{18}/cm^3$ typically used in ring modulators, here we use a lower doping concentration of $\sim 10^{17}/cm^3$ for both P and N regions in the modulator. This ensures low loss inside the rings. To maximize the modulation efficiency, we optimize the offset of PN junction [10] with a 85-nm offset across the 450-nm rib region.

Fig. 1-d shows the calculated power transmission at the Bar output port ($H_{bar} = P_{bar}/P_{in}$). An extinction ratio (ER) of 26 dB is achieved when the effective index difference between the two ring modulators (Δn) is changed in the range of $\pm 1 \times 10^{-4}$ with a 2-V voltage swing on the RF signals. The large ER enables this RAMZM to be used as a 2x2 switch in large-scale photonic switching networks or as a high-speed sampler in photonic signal processing [8].

Fig. 2-a shows the fabricated prototype chip. Fig. 2-b shows the measured output spectra without thermal bias or RF inputs. The MZM has a 22-nm FSR, corresponding to 25-μm static arm length difference in the design. The FSR of rings is 6.3-nm, corresponding to a 15-μm ring radius. Fig. 2-c shows the Bar output spectra when the MZM is biased at half-π and DC bias applied to the ring modulators on both arms. Resonance peak shift is 143.5 pm for $0 \sim -3V$ bias, which implies a 2.7×10^{-4} effective index change. Hence $V_\pi L$ of the modulator is calculated to be 1.73 V-cm.

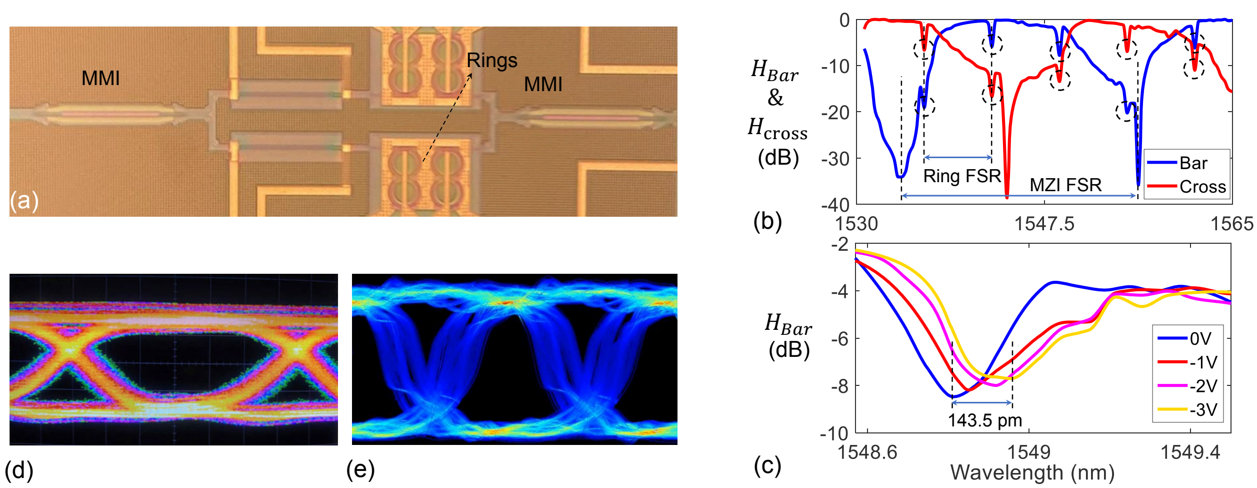

Fig. 2. Measurement results of the prototype RAMZM. (a) Chip photo. (b) Output spectra with $V_{RF\pm} = 0$. (c) Detailed Bar port spectra near the 1549-nm resonance with different $V_{RF\pm}$ DC bias voltages. Eye-diagrams of (d) the RF modulation signal and (e) the optical output.

In the following high speed test, the ring modulators are biased at -1-V. A pair of 12-Gbps 2-V peak-peak differential RF signals are generated by a PRBS generator, amplified, and applied to the ring modulators. The input 12-Gbps RF signal waveform is shown in Fig. 2-d. Fig. 2-e shows the eye diagram of the Bar output with ER=10.5 dB. The calculated 3-dB bandwidth is f_{3dB} =45.3 GHz. The eye diagram deterioration is likely due to the clock jitter and input differential signal phase error in the measurement system.

References

[1] J. Gao, and H. Wu, "An equalized traveling wave electrode design for Mach Zehnder modulator," *IEEE OI Conf.*, 64-65 (2016).

[2] J. Gao, and H. Wu, "Multi-function Mach-Zehnder modulator for pulse shaping and generation," *Optics Express*, **24**(19): 22239-22249 (2016).

[3] Z. Wang, S.-J. Chang, C.-Y. Ni, and Y. J. Chen, "A high-performance ultracompact optical interleaver based on double-ring assisted Mach–Zehnder interferometer," *IEEE PTL*, **19**(14): 1072-1074 (2007).

[4] Z. Guo, L. Lu, L. Zhou, L. Shen, and J. Chen, "16×16 silicon optical switch based on dual-ring-assisted Mach–Zehnder interferometers," *IEEE JLT*, **36**(2): 225-232 (2018).

[5] M. Li, L. Wang, X. Li, X. Xiao, and S. Yu, "Silicon intensity Mach–Zehnder modulator for single lane 100 Gb/s applications," *Photonics Res.*, **6**(2): 109-116 (2019).

[6] J. Cardenas et al, "Linearized silicon modulator based on a ring assisted Mach Zehnder inteferometer," *Optics express*, **21**(19): 22549-22557 (2013).

[7] R. Dubé-Demers, S. LaRochelle, and W. Shi, "Ultrafast pulse-amplitude modulation with a femtojoule silicon photonic modulator," *Optica*, **3**(6): 622-627 (2016).

[8] M. Gong, and H. Wu, " A Microring-based Time-Division Demultiplexer with Differential Signaling," *IEEE OI Conf.*, 21-22 (2018).

[9] M. Pantouvaki et al, "Active components for 50 Gb/s NRZ-OOK optical interconnects in a silicon photonics platform," *IEEE JLT*, **35**(4): 631-638 (2017).

[10] X. Xiao et al, "High-speed, low-loss silicon Mach–Zehnder modulators with doping optimization," *Optics Express*, **21**(4): 4116-4125 (2013).