

A Minimal-Structured Ring Assisted Mach-Zehnder Modulator

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Abstract—We propose a new microring modulator circuit that utilizes both intensity and phase modulations of the ring. It can be considered a ring-assisted Mach-Zehnder modulator with a minimal number of components that improves the ring modulator's performance. Theoretical analyses and a prototype design are presented.

Index Terms—Microring Modulator, Integrated Photonics

I. INTRODUCTION

Integrated electro-optical (EO) modulators are one of the critical building blocks in optical communication systems. Microring resonator based EO modulators are more suitable than conventional Mach-Zehnder modulators (MZM) for large-scale, high-density integration due to their ultra-compact size and low power consumption, and can still achieve high modulation speed [1]. Most conventional ring modulators are designed for intensity modulation at its through port [2]. In this paper, we propose a new circuit design that utilizes both intensity and phase modulation of a ring modulator.

II. OPERATION PRINCIPLE AND ANALYSIS

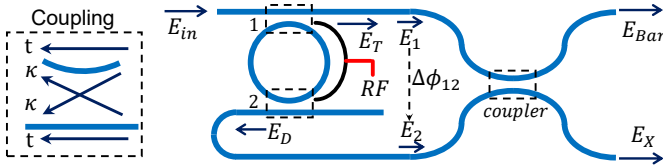


Fig. 1. Schematic of the proposed minimal-structured ring-assisted MZM (MS-RAMZM).

As shown in Fig. 1, this new design is based on an add-drop dual-bus ring modulator. A 2x2 directional coupler then recombines the two output signals of the ring modulator (E_T and E_D). The coupler's inputs are expressed as E_1 and $E_2 = E_1 * e^{-j\Delta\phi_{12}}$, where $\Delta\phi_{12}$ is the phase difference due to the phase modulation of the ring, with potential contributions due to length difference of interconnect waveguides and other systematic errors. The two outputs (E_{Bar} and E_X) from the coupler have phases that are 90° apart. When the amplitudes and phases of E_T and E_D are modulated by the ring modulator, so are the amplitudes of E_{Bar} and E_X , which can be utilized for single-ended or quadrature outputs. As shown below, this new design offers significant improvements in modulation efficiency, insertion loss, and extinction ratio

(ER) as compared to a conventional ring modulator. It can be considered an evolution from the differential ring-assisted Mach-Zehnder modulator (RAMZM) design we previously demonstrated [3], in a more compact footprint and suffering less from device variabilities. We call this new circuit *minimal structured RAMZM* (MS-RAMZM).

Assuming balanced arms, the two output transfer functions of the proposed modulator can be written as Eq. 1.

$$\begin{aligned} \frac{E_{Bar}}{E_{in}} &= \frac{(t_1 - t_2 p^2) t_{cp} + \kappa_1 \kappa_2 \kappa_{cp} p}{1 - t_1 t_2 p^2} \\ \frac{E_X}{E_{in}} &= \frac{(t_1 - t_2 p^2) \kappa_{cp} + \kappa_1 \kappa_2 t_{cp} p}{1 - t_1 t_2 p^2} \end{aligned} \quad (1)$$

$$p = \exp(-\alpha L/2) \exp(j\beta L/2)$$

where t_x and κ_x ($x=1,2,cp$) are the s-parameters of three coupling regions in Fig. 1. α and β are the attenuation and propagation constants of the ring.

Fig. 2-a shows the intensity and phase modulation of the ring resonator at its through and drop ports. The latter is shown as a differential signal in this circuit, i.e., the phase difference $\Delta\phi_{12}$ between the two ports. Fig. 2-b shows that the phase

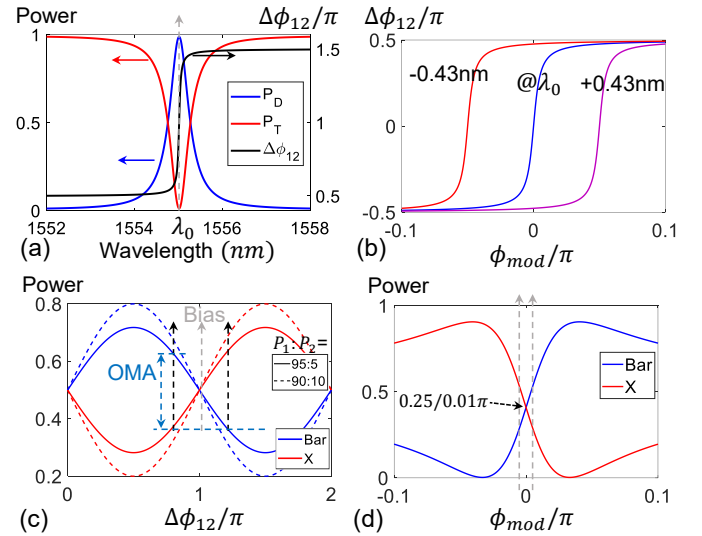


Fig. 2. (a) Power transfer functions at the through and drop ports of a ring, and their phase difference $\Delta\phi_{12}$; (b) $\Delta\phi_{12}$ changes with the phase shift in the ring ϕ_{mod} ; (c) Outputs of a 50:50 directional coupler with several input power ratios changes with $\Delta\phi_{12}$; (d) MS-RAMZM overall modulation transfer function.

modulation transfer function is insensitive to the resonance

wavelength shift, which means that it is more robust against process and temperature variabilities than the ring's intensity modulation. Fig. 2-c shows that outputs of the directional coupler depend on both amplitude and phase differences of its two inputs, which are generated by the ring. By utilizing the relatively large phase modulation generated by the ring, the modulation efficiency of this new circuit can be much higher than that by the ring modulator itself.

For a dual-bus 1st order ring, the through port phase depends on the coupling condition [5]. Unlike the over-coupled rings used in our previously demonstrated highly-overcoupled RAMZM [3], the ring is designed to be slightly under-coupled in this design to achieve a wider range of $\Delta\phi_{12}$. Fig. 2-d shows the overall modulation transfer function. When the coupler's coupling ratio is designed as 50:50 ($|t_{cp}|^2 = 0.5$), the bar and cross ports generate differential outputs (in power) with good linearity. This new modulator, therefore, is well suited for differential signaling (in power).

III. MODULATOR PROTOTYPE DESIGN

To demonstrate the proposed MS-RAMZM, a prototype circuit is designed using AIM Photonics silicon photonic technology based on silicon-on-insulator (SOI) [4] with a top silicon layer about 200 nm. Due to the relatively thick slab in their rib waveguides, we chose a 12 μm ring radius to minimize the round-trip loss while maintaining a neglectable bending loss. The ring-waveguide coupling ratio is designed to be 9% to achieve a Q of 5000. A 36:64 directional coupler is adopted to optimize ER at the Bar port.

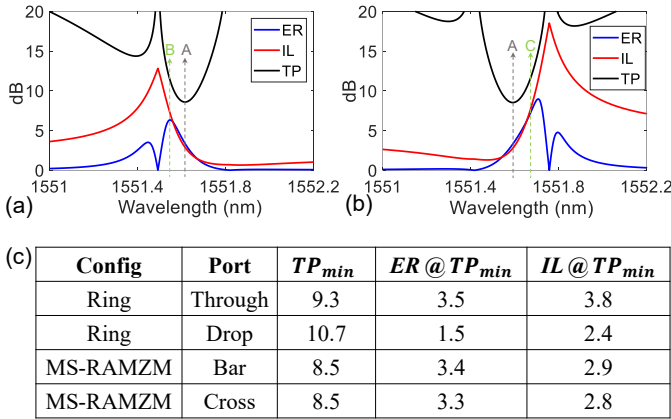


Fig. 3. Simulated performance from the prototype MS-RAMZM. (a) Bar port; (b) Cross port; (c) Table to compare performance of the baseline ring modulator and prototype MS-RAMZM.

We use three main figures of merits (FOMs) to evaluate the modulator performance: ER, insertion loss (IL), and transmission penalty $TP = OMA/2P_{In}$. Fig. 3-ab show FOMs of the prototype design at the Bar and Cross ports, respectively. In min TP operation, the table in Fig. 3-c summarizes the FOMs to compare the MS-RAMZM and the standalone add-drop ring modulator. The new modulator exhibits significantly lower TP and IL, and similar ER compared to the ring modulator's through output, and higher ER compared to the

ring's drop output. Note that the ring exhibits asymmetric characteristics at its through and drop outputs. In comparison, MS-RAMZM exhibit symmetric and balanced performance at its two outputs, even with a non-50:50 coupler. At the minimum TP wavelength, the Bar output has a slightly higher ER than the Cross port due to the 36:64 coupler design. Furthermore, at other wavelengths, an even higher ER can be achieved at the Bar port by sacrificing the TP and IL compared to the Cross port as shown in Fig. 3-ab. An example wavelength is marked with the green arrows, where Bar and Cross have a same 11.3 dB TP, while the Bar ER is 7.4 dB and the Cross ER is 6.3dB.

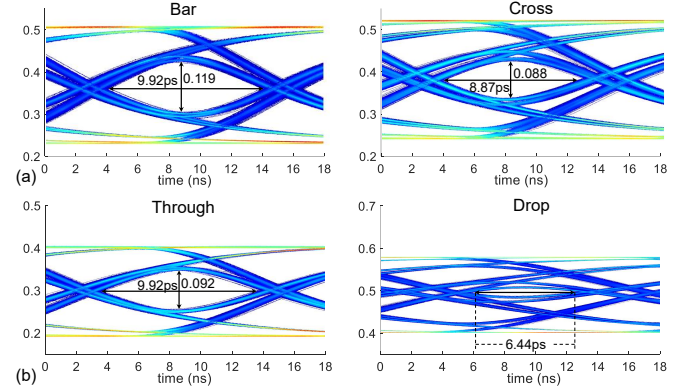


Fig. 4. 80 Gbps NRZ Optical output eye-diagrams at (a) MS-RAMZM's Bar and Cross port; (b) Ring modulator Through and Drop port.

In the digital modulation scenario, Fig. 4 shows an example of the outputs of an 80 Gbps non-return to zero (NRZ) modulation. The Bar eye-diagram shows the largest eye height, which has a 29% improvement compared to that at the microring modulator through port. The Cross eye is slightly narrower due to the 36% waveguide coupler but still comparable to ring through output. The drop eye-opening is very small because of its limited modulation bandwidth. Again, the performance of Bar and Cross outputs is similar based on the eye-diagrams.

IV. CONCLUSION

We present a new minimal structured ring-assisted MZM, which employs a single ring and saves footprint. It generates two outputs and enhances the performance in many aspects with minimal extra cost compared to ring modulator. Moreover, it is suitable for differential signaling, which is challenging in conventional ring modulators.

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