Demonstration of a Push-Pull Silicon Dual-Ring Modulator With Enhanced Optical Modulation Amplitude

Dongsheng Zheng, Ciyuan Qiu, Member, IEEE, Hongxia Zhang, Xinhong Jiang, and Yikai Su, Senior Member, IEEE, Member, OSA

Abstract—In this article, we demonstrate a push-pull silicon dual-ring modulator based on two cascaded rings which are coupled with each other through two parallel bus waveguides. In the transmission spectrum of the modulator, a narrow transparency peak exists in the center of the broad dip based on the electromagnetically induced transparency (EIT)-like effect. Benefiting from both the EIT-like effect and push-pull drive configuration, a low insertion loss (IL) of 1.4 dB and an extinction ratio (ER) over 6.4 dB are obtained at a bit rate of 10 Gb/s with a peak-to-peak driving voltage (Vpp) of 5 V. The corresponding maximum optical modulation amplitude (OMA) is 0.56, which is almost twice that of a single micro-ring modulator with the same driving voltage. Moreover, the maximum OMA is 0.47 at 20 Gb/s, which is 81% larger than that of a single micro-ring modulator.

Index Terms—Optical modulation amplitude, push-pull, ring modulator, silicon photonics.

I. INTRODUCTION

SILICON electro-optical (EO) modulators are crucial components for optoelectronic integrated circuits, enabling high-speed and low-cost optical interconnect and optical computing systems [1]–[4]. Recently, several types of silicon EO modulators have been demonstrated, including silicon micro-ring modulators (MRMs) [5]–[8], Mach–Zehnder modulators (MZMs) [9]–[12], etc. Among them, MRMs have attracted a great deal of attentions due to their desirable features, such as small footprint [13], [14], low power consumption [8], [15], and CMOS compatibility [2].

To be employed in optical interconnect systems, MRMs are desired to be operated with a large optical modulation amplitude (OMA) [7], [16], expressed as the difference between the maximum output optical power $P_{\text{max}}$ and minimum output optical power $P_{\text{min}}$ divided by the input optical power $P_{\text{in}}$, i.e., $\text{OMA} = (P_{\text{max}} - P_{\text{min}})/P_{\text{in}} = (P_{\text{max}} - P_{\text{min}})/(P_{\text{max}}/P_{\text{in}})$ [8], [17]. Here, $(P_{\text{max}} - P_{\text{min}})/P_{\text{in}}$ corresponds to the modulation depth while $P_{\text{max}}/P_{\text{in}}$ is related to the insertion loss (IL). Thus, a large OMA means a large modulation depth and a low IL, leading to a high receiver sensitivity as well as a low power penalty [7]. To achieve this goal, considering a small resonance shift in the EO modulation [17], [18], a MRM with a sharp resonance (high quality factor Q) is preferred. However, a high-Q resonator has a long photon lifetime which limits the available modulation bandwidth and also makes the device sensitive to temperature fluctuations as well as fabrication variations [2], [19]. Consequently, a MRM based on a low-Q resonator is designed to obtain a wide modulation bandwidth. However, this scheme sacrifices the modulation efficiency [6], [20] and therefore leads to a low OMA since the side wall of the resonance for a low-Q resonator is not steep. Obviously, there is a trade-off between the modulation bandwidth and OMA [17], [21] for MRMs. To solve this issue, Xiao et al. proposed and demonstrated a scheme by increasing the resonance shift efficiency to 40 pm/V with interleaved PN junctions [22]. Moreover, Hu et al. [6] and Gu et al. [7] showed that a steep side wall of the resonance could be created by cascading low-Q resonators with a small inter-ring detuning, which thus can be used to increase the OMA of low-Q resonator-based MRMs. Note that, in these two cascaded ring-based modulators, the two low-Q rings are simultaneously driven by the one electrical signal and shift in the same wavelength direction within the modulation process.

To relieve the above Q-limited problem, Xu has proposed a silicon dual-ring modulator with a high ER and a low IL to increase the OMA [23]. In the dual-ring modulator, an appropriate wavelength detuning between the two coupled low-Q micro-ring resonators (MRRs) is chosen and a narrow central peak can be formed in the spectrum, similar to an EIT system [24], [25]. In that modulator, each MRR has an embedded $p-i-n$ junction. To enhance the modulation efficiency, the modulator is driven by a single-end signal in a push-pull manner [26], [27] and thus the two rings shift in opposite wavelength direction within the modulation process. According to the simulation results, the modulator can achieve a large OMA with a wide optical modulation bandwidth. Note that, in order to obtain a fast modulation speed and a wide modulation bandwidth, the $p-i-n$ junction for each ring modulator needs to operate...
Fig. 1. Spectral schematics of a single-ring modulator and a dual-ring modulator. (a) Simulated transmission spectra of a single MRM. The initial transmission spectrum at zero reverse bias (blue solid line) is shifted ∼60 pm to the right (red dashed line). Inset: Schematic of the single MRM. (b) OMA and ER as a function of wavelength for the single MRM. (c) Zoom-in spectra over a 100 pm wavelength range shown as the green dashed rectangle in (b). (d) Simulated transmission spectra of the dual-ring modulator. The resonant wavelength detuning between the two MRMs has been reduced from 160 pm (blue solid line) to 40 pm (red dashed line) in a push-pull drive manner. Inset: Schematic of the dual-ring modulator. (e) OMA and ER as a function of wavelength for the dual-ring modulator. (f) Zoom-in spectra over a 100 pm wavelength range shown as the green dashed rectangle in (e). BW: Bandwidth.

II. DEVICE PRINCIPLE

To illustrate the principle of the device and the OMA enhancement, the optical characteristic of a single MRM with a diameter of 25 μm is firstly simulated. The intrinsic Q of the ring resonator is 80,000 and the coupling coefficients between two bus waveguides and the ring resonator are set to 0.28. The initial optical transmission spectrum at zero reverse bias is shown as the blue solid line in Fig. 1(a). The loaded Q is ∼8,000. In the EO modulation, the resonant wavelength is red-shifted by ∼60 pm and the transmission spectrum is then shown as the red dashed line in Fig. 1(a). Based on the two transmission spectra, the OMA and ER are calculated. From Fig. 1(b), one can find that the ER peaks at 1550 nm and 1550.06 nm with a maximum value of ∼15 dB, which arise from the two resonant wavelengths in the two states, respectively. However, due to the relatively large ILs at the two resonances, the corresponding OMAs are lower than the maximum values of ∼0.36, which locate at 1549.97 nm and 1550.09 nm with ERs of ∼6 dB. Furthermore, the OMA of the MRM is sensitive to the input wavelength as shown in Fig. 1(b). Since the wavelength jitter of laser source is about ±3 pm, the OMA will decrease from 0.36 to 0.32 if the input wavelength deviates ∼3 pm with respect to the resonant wavelength as shown in Fig. 1(c).

The dual-ring modulator is built by cascading two same ring resonators as shown in the inset of Fig. 1(d). The distance between the centers of the two MRRs is set to be half the circumference of a single MRR, which plays a pivotal role in EIT-like effect [24]. The blue solid line in Fig. 1(d) presents the optical transmission in the ‘ON’ state in which the resonant wavelength detuning between the two MRRs is 160 pm. In this state, each resonator acts as a mirror reflecting the light to the other and the whole device forms a Fabry-Perot (FP)-like cavity. Simultaneously, a narrow transmission peak appears in the center of the broad dip [24]. Here, we denote the wavelength with transmission peak as the central wavelength. Note that, the optical transmission at the central wavelength is enhanced and the transmission close to the peak becomes steep, benefiting from at a low carrier injection level, which requires a complicated electrical design. With a single-end drive signal, one then needs to cautiously control the voltages applied on the p-i-n junctions of the two ring modulators by properly designing the parameters of the p-i-n junctions and integrated resistors in the circuit. Therefore, to the best of our knowledge, this work still remains at a simulation stage [23], [28]. In this paper, we experimentally demonstrated a modified dual-ring modulator by changing both the doping structure and the drive scheme. In order to simplify the electrical circuit, each ring modulator has an embedded p-n junction instead. The modulator is driven by a differential signal pair and the p-n junctions operate in a carrier-depletion mode. Benefiting from the EIT-like effect and push-pull configuration, a low IL of 1.4 dB and an ER over 6.4 dB are obtained at a modulation rate of 10 Gb/s for the dual-ring modulator. The corresponding OMA is 0.56, which is almost twice that of a single MRM with the same driving voltage. Moreover, the maximum OMA is 0.47 at 20 Gb/s, which is 81% larger than that of a single MRM. The device also shows merit regarding insensitivity to fluctuations of temperature and wavelength jitters of laser source.
the EIT-like effect. Furthermore, with a push-pull modulation manner, the two rings shift in opposite wavelength directions. Thus, the central transmission peak would decrease rapidly as the resonance detuning between the two rings decreases. The red dashed line in Fig. 1(d) shows the optical transmission in the ‘OFF’ state, where the resonant wavelength detuning is reduced to 40 pm. Thus, the amplitude variety of the central transmission peak can be used for optical amplitude modulation purpose [23].

The ER and OMA for the dual-ring modulator are then calculated as shown in Fig. 1(e). It is worth noting that a maximum OMA of 0.58 is obtained at the central wavelength for the dual-ring modulator, which is larger than that of the single-ring modulator. The ER at the central wavelength is also enhanced to 10 dB, due to the small detuning between the two resonances of two MRRs. However, due to the slight raise of the optical transmission in the ‘OFF’ state, a local minimum at the central wavelength is observed in the ER curve. Furthermore, the OMA for the dual ring modulator stays at 0.58 within a bandwidth (BW) of 20 pm as shown in Fig. 1(f). Compared with the single ring modulator, this large BW makes the dual-ring modulator insensitive to wavelength jitters of laser source and temperature fluctuations.

Moreover, to get a better understanding on the modulation performance of the device, the OMA, ER and IL as a function of the resonance detuning in the ‘OFF’ state are calculated. As shown in Fig. 2(a), one can find that the ER decreases from 24 dB to 3 dB and the IL decreases from 3.2 dB to 1.1 dB if the detuning increases from 0 pm to 100 pm. A maximum OMA of 0.58 is thus obtained with an optimal detuning of 40 pm.

Meanwhile, the OMA, ER and IL with the optimal detuning are also simulated with respect to the length variation (ΔL) of the bus waveguide between the two MRRs. As shown in Fig. 2(b), it can be found that a large OMA (>0.5) as well as a good extinction ratio (>10 dB) can still be obtained even when ΔL varies about ±50 nm. Thus, for each bus waveguide segment, an embedded heater might not be required unless larger ΔL happens due to high fabrication errors. Note that, the OMAs, ERs and ILs are extracted at the central wavelength which would slightly change with ΔL [24].

III. DEVICE FABRICATION AND CHARACTERIZATION

The dual-ring modulator is fabricated on a silicon-on-insulator (SOI) wafer with a 220-nm-thick top silicon layer in the Institute of Microelectronics (IME). The device is constructed by rib waveguides which have a width of 500 nm and a height of 220 nm. The slab thickness for the rib waveguide is 90 nm. Note that, only the fundamental quasi-TE mode is supported in rib waveguides. The diameters of two rings are set to 25 μm where a slight difference in perimeter between the two rings (~32 nm) is introduced in order to obtain initial resonant wavelength detuning between the two rings [24]. The gaps between the rings and the straight waveguides are ~220 nm. The center-to-center (CTC) distance between the two rings is set to 39.25 μm. The device is defined by a deep-UV lithography and an inductively coupled plasma etching process. Following the etching, p-n junctions are formed across ring resonators by photolithography and ion implantation processes. Highly p+ and n+ doped regions are then implanted for the anode and cathode, respectively. After the doping, a 2.25-μm-thick silica layer is deposited on the silicon layer by using plasma enhanced chemical vapor deposition (PECVD). A 120-nm-thick titanium nitride (TiN) layer is sputtered and etched to form the micro-heaters and impedance match resistors. By using PECVD, another 500-nm-thick silica layer is deposited. Finally, 2-μm-thick aluminum electric connections are formed by sputtering and etching for the p-n junctions, micro-heaters and impedance match resistors.

Fig. 3(a) and Fig. 3(b) show the micrograph of the fabricated device and device schematic diagram, respectively. All the n+ doped regions are connected together. Differential voltages $V_1$ and $V_2$ are used to drive ring 1 and ring 2, respectively. Furthermore, resonant wavelengths of the two MRRs can be adjusted by embedded micro-heaters through the thermo-optic tuning. Note that, in this dual-drive configuration, we choose p-n junctions instead of p-i-n junctions for the two MRRs because ring modulators with p-i-n junctions need the driving signals with pre-emphasis to obtain a wide bandwidth, which requires complicated electrical driving circuits [5].

The optical transmission spectra of a single-ring modulator (Ring 1) under different voltages were measured. As shown in Fig. 4(a), the resonant wavelength red-shifts if the reversed bias...
Fig. 3. (a) Optical micrograph of the fabricated device. Inset: Cross-sectional diagram for the rib waveguide with an embedded p-n junction. (b) Schematic diagram for the dual-ring modulator.

 increases from 0 V to 5 V. The resonance shift per unit voltage is only 12 pm/V [29]. The loaded Q of the single ring resonator is estimated to be approximately 8,100 at zero reverse bias. And a maximum OMA of 0.44 is obtained with an ER of 6.85 dB. Here, the measurement was carried out after increasing the resonance detuning between the two ring resonators to several nanometers, and thus the optical interference between the two rings could be eliminated.

Fig. 4(b) shows the experimentally measured static transmission spectra of the dual-ring modulator in ‘ON’ and ‘OFF’ states. The initial detuning between the two ring resonators is set to ∼105 pm through the thermo-optic tuning. When the p-n junctions of ring 1 and ring 2 are biased at 0 V and −5 V, respectively, the resonance of the ring 2 red-shifts and the detuning between the two MRRs increases to ∼165 pm. As shown in the blue solid line, a central transmission peak appears (‘ON’ state). Moreover, if p-n junctions of ring 1 and ring 2 are biased at −5 V and 0 V, respectively, the detuning between the two resonances reduces to ∼45 pm. Then the central peak disappears (‘OFF’ state), as shown by the red dashed line. Thus, at the central wavelength of 1552.614 nm, a maximum OMA of 0.58 is obtained with an ER over 10 dB, which are higher than that of the single-ring modulator.

Fig. 4(c) presents the zoom-in spectra over a 250 pm wavelength range shown as the green dashed rectangle in (b). Due to a little difference between the resonance shifts of two ring resonators, there is a 10 pm misalignment between the wavelengths of the central peak in the “ON” state and the “OFF” state. Thus, the OMA of the dual-ring modulator would have a narrow peak instead of a broad operating bandwidth, since the OMA is determined by the difference between the optical transmission in the “ON” state and “OFF” state. However, the dual ring modulator still shows a bandwidth of 20 pm where the OMA is larger than 0.56 as shown in Fig. 4(c).

IV. DYNAMIC MODULATION AND DISCUSSION

The experimental setup for the high-speed measurement is shown in Fig. 5. To drive the dual-ring modulator, a pulse pattern generator (PPG) is used to generate a pair of differential signals. Then, each electrical signal is amplified by an electrical amplifier and biased with a bias tee. The two signals are synchronized by using a phase shifter, which are then used to drive the modulator
in a push-pull manner. Here, the voltages of the two driving signals both range from $-5\,\text{V}$ to $0\,\text{V}$. Meanwhile, the polarization of the light from a tunable laser is adjusted to be TE-polarized by using a polarization controller (PC). Then the light is coupled to the silicon-on-insulator (SOI) chip. To enhance the coupling efficiency, inverse tapers with 200-nm wide tips are integrated on the input and output terminals of the device. The measured coupling loss is $\sim4\,\text{dB/facet}$. The modulated light signals are detected by a photodetector (PD), and the eye diagrams are recorded by a sampling oscilloscope. Note that, a dual-ring modulator with the same parameters in the same wafer is chosen to clearly illustrate the enhancement of OMA, the eye diagrams of the single MRM and the dual-ring modulator at the wavelengths with maximum OMAs are shown in Fig. 6(c) and Fig. 6(f), respectively. It can be clearly seen that, a larger ER and a lower IL are obtained for the dual-ring modulator, which enhance the OMA. Furthermore, for the dual-ring modulator, part of the optical energy is stored when it is in the ‘OFF’ state, and released back into the output waveguide when it is switched to the ‘ON’ state [30]. This causes the instantaneous output power to be higher than the steady state and thus overshoots in the eye diagram are observed as shown in Fig. 6(f). Comparing Fig. 6(c) with Fig. 6(f), the eye diagram of the dual-ring modulator shows larger rising and falling times. It might be attributed to the time delay between a pair of differential driving signals or a higher effective quality factor ($Q_{\text{eff}}$) of the central peak of the dual-ring modulator in the ‘ON’ state which corresponds to a longer photon lifetime [7]. Here, the $Q_{\text{eff}}$ of the central peak in the ‘ON’ state is defined as the central wavelength divided by the FWHM, i.e., $Q_{\text{eff}} = \frac{\lambda}{\Delta \lambda_{\text{FWHM}}}$, as shown in Fig. 4(b) [24].

The high-speed measurement at a bit rate of 20 Gb/s was also performed. Figs. 7(a)–(c) and Figs. 7(d)–(f) present the measured data for the single ring modulator and the dual-ring modulator, respectively. Here, the initial detuning between the two ring resonators for the dual-ring modulator is enlarged to $\sim125\,\text{pm}$, considering the corroborative relations between the OMA, bandwidth and frequency detuning [8], [17] and dynamic self heating [31]. It can be observed that the dual-ring modulator achieves a maximum OMA $\sim0.47$ which is 81% larger than that of the single ring modulator $\sim0.26$.

Moreover, one can find that the maximum OMAs of both the two modulators decrease when the modulation frequency increases from 10 Gb/s to 20 Gb/s, which matches the frequency response model in [17]. Furthermore, the measured maximum OMAs of the dual-ring modulator at both 10 Gb/s and 20 Gb/s are close to the simulation results. However, for the single-ring modulator, the OMA in high-speed modulation degrades significantly, which may be due to wavelength jitters of laser source and temperature fluctuations as discussed in the simulations. Meanwhile, the OMAs of the dual-ring modulator at bit rates of 10 Gb/s and 20 Gb/s show a narrow peak instead of a broad operating bandwidth, which could be attributed to the wavelength misalignment shown in Fig. 4(c).
In addition, when the initial detuning between the two ring resonators for the dual-ring modulator is enlarged to ~125 pm, the FWHM of the central peak is 0.08 nm, corresponding to an effective quality factor in the ‘ON’ state of Q_{eff} = 18,000. Thus, if the modulation bandwidth is limited by photon lifetime, the modulation bandwidth could be calculated to be ~11 GHz from the equation defined as \( f_{opt} = \frac{\omega_0}{2\pi Q_{eff}} [15, 21] \). With such a quality factor of 18,000, a ring modulator can achieve a bit rate of 30 Gb/s [8].

Note that, in all these above dynamic experiments, a relatively large driven voltage of 5 V_{pp} is used to achieve a dynamic modulation with a large OMA. Here, the drive voltage depends on the resonance tuning efficiency ~12 pm/V, which is lower than ~20 pm/V of other reported micro-ring modulators [7], [15]. This difference might come from the doping design since a lateral p-n junction is used in our device and only 60% of the waveguide forming the ring is doped which is constrained by the add-drop ring configuration as shown in Fig. 3(b). To effectively decrease the drive voltage, one can increase the resonance tuning efficiency by using interleaved p-n junctions [22] or vertical p-n junctions [32]. Such junction profile would introduce a little extra doping-induced loss but an intrinsic Q factor (~20,000) for each MRM could still obtained which is acceptable for the dual-ring modulator [16], [22]. Meanwhile, one can also adjust the coupling coefficient to further enhance OMA if the doping induced loss affects the OMA. Moreover, if the modulation efficiency is improved by optimizing doping profile design, the resonance detuning in the ‘ON’ state could be enlarged further by a large resonance shift. Then, the quality factor of the central peak of the dual-ring modulator could be lowered and a higher modulation speed could be expected [23]. For instance, when the resonance tuning efficiency is enlarged to 30 pm/V [22], [32] and the resonance detuning in the ‘OFF’ state is optimized to 14 pm, the FWHM of the dual-ring modulator could be increased to 0.18 nm and the effective Q in the ‘ON’ state could be decreased to 8,000, which is similar to the quality factor of the single-ring modulator. In this case, the maximum OMA of the dual-ring modulator is ~0.89 with an ER of 23 dB and an IL of 0.5 dB, which is still larger than that of the single-ring modulator ~0.69 with an ER of 13 dB and an IL of 2 dB under the same resonance tuning condition.

Finally, to get a better understanding of the performance of our dual-ring modulator, the comparison of different micro-ring modulators is provided in Table I. The values in the first two lines represent the modulation speeds, driving voltages, OMAs, ILs, and ERs of the dual-ring modulator investigated in this paper. Although the resonance tuning efficiency (~12 pm/V) is lower than that of other dual-ring modulators, the dual-ring modulator in this paper exhibits a large OMA with 5V_{pp}.

<table>
<thead>
<tr>
<th>Dual-ring modulator type</th>
<th>Modulation speed</th>
<th>Driving voltage</th>
<th>OMA</th>
<th>IL</th>
<th>ER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This work</strong></td>
<td>10Gb/s</td>
<td>5V</td>
<td>0.56</td>
<td>1.4dB</td>
<td>6.4dB</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td>20Gb/s</td>
<td>5V</td>
<td>0.47</td>
<td>0.92dB</td>
<td>3.8dB</td>
</tr>
<tr>
<td>Dual-ring [7]</td>
<td>20Gb/s</td>
<td>2V</td>
<td>0.3^b</td>
<td>4dB</td>
<td>7.13dB</td>
</tr>
<tr>
<td>Dual-ring [27]</td>
<td>20Gb/s</td>
<td>1V</td>
<td>0.097</td>
<td>8.3dB</td>
<td>4.74dB</td>
</tr>
<tr>
<td>Single-ring [15]</td>
<td>11Gb/s</td>
<td>2V</td>
<td>0.48</td>
<td>2dB</td>
<td>6.5dB</td>
</tr>
<tr>
<td>Single-ring [22]</td>
<td>25Gb/s</td>
<td>2V</td>
<td>0.26</td>
<td>4dB</td>
<td>4.54dB</td>
</tr>
<tr>
<td>Single-ring [33]</td>
<td>112Gb/s^b</td>
<td>2.8V</td>
<td>0.22</td>
<td>3dB</td>
<td>2.44dB</td>
</tr>
</tbody>
</table>

^a(Simulation result).  
^b(PAM4).

V. CONCLUSION

We have experimentally demonstrated a dual-ring modulator which offers a better dynamic performance than a single-ring modulator, benefiting from the EIT-like effect and push-pull drive configuration. At the central wavelength, an IL of 1.4 dB and an ER of 6.4 dB are obtained for the dual-ring modulator at a bit rate of 10 Gb/s. The corresponding maximum OMA is 0.56, which is almost twice that of the single-ring modulator. Furthermore, the maximum OMA of the dual-ring modulator is 0.47 at 20 Gb/s, which is 81% larger than that of the single-ring modulator. Besides, the OMA of the dual-ring modulator can stay unchanged at a relatively large BW which makes the device insensitive to wavelength jitters of laser source as well as fluctuations of temperature. Moreover, the demonstrated scheme may also be effective to enhance OMAs for other low-Q resonator based modulators with wide modulation bandwidths.

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