Silicon optical switch elements based on coupled-ring resonators

Liangjun Lu*, Lin Shen, Linije Zhou, and Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks
Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
Author e-mail address: luliangjun@sjtu.edu.cn

Abstract: We experimentally demonstrate two silicon optical switch elements based on coupled-ring resonators (CRR). The third-order CRR is switched by shifting the middle ring resonance, and the second-order CRR is switched by tuning the waveguide coupling.

OCIS codes: (130.4815) Optical switching devices; (230.3120) Integrated optics devices; (230.4555) Coupled resonators

1. Introduction

With the rapid increment of data rates in telecommunications and optical interconnects, integrated optical switches are becoming the essential components in the next generation optical networks. As basic building blocks, high-performance 1×2 and 2×2 optical switch elements (SEs) with low insertion loss, low crosstalk and low power consumption are highly required in order to build large-scale switch matrices. Silicon SEs based on ring resonators are one of the feasible solutions due to their compact size and low power consumption. Several single-ring based optical switches have been demonstrated [1, 2]. Usually, the switching is realized by shifting the resonance wavelength. However, due to the Lorentzian resonance line-shape of the ring resonators, it is unable to obtain "box"-like passbands in single-ring switches. The crosstalk is worsened by the long tail of the Lorentzian resonance peak. Besides, the compromise between the passband width and the switching power limits the extendibility of single-ring based switch fabrics.

Previously, we have proposed and demonstrated a 2×2 switch combining ring resonators with a Mach-Zehnder interferometer (MZI) to obtain broadband and low power optical switching, which we name as a dual-ring assisted MZI (DR-MZI) [3]. We subsequently realized large port-count (4×4 and 16×16) switches based on the DR-MZIs [4]. Coupled-ring resonators (CRR)-based switches composed of two bus waveguides coupled with several cascaded microrings can enlarge the optical bandwidth and make the passband roll off faster [5, 6]. In a conventional switching operation, the resonances of all the rings in the CRR are spectrally shifted away from the operation wavelength to flip the switching state. Here, we present two CRR-based silicon optical switch elements with different switching operation approaches. The first one is a third-order CRR with tuning applied to the middle ring resonator, and the second one is a second-order CRR with tuning applied to the coupling with the bus waveguides. Both of these two structures are promising to build a large-scale optical switch fabric.

2. Third-order CRR switch with middle ring tuning

Figure 1(a) shows the schematic of the 3rd-order CRR optical switch, consisting of three identical racetrack-type ring resonators. By setting the operation wavelength at the resonant wavelength, light from the input port is initially routed to the cross port. To change the state, we shift the resonance of the middle ring while the other two rings are kept untouched. In this case, light coupled from the top ring no longer resonates in the middle ring, and thus cannot couple to the bottom ring. As a consequence, the top ring is over-coupled and light travels to the bar port with low loss, as illustrated in Fig. 1(b).

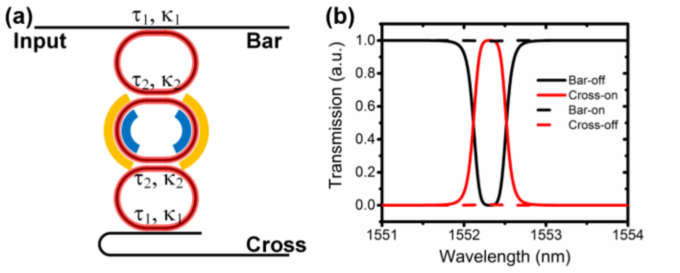

Fig. 1 (a) Schematic of the 3rd-order CRR optical switch. (b) Calculated transmission spectra of the switch.

The device was fabricated on the silicon-on-insulate (SOI) platform with a top silicon layer of 220 nm. The switch was designed for transverse-electric (TE) polarization. The radius of the racetrack-type ring resonators is 10 μm and the coupling length is 5 μm. The gap size between the bus waveguides and the outer rings is 200 nm, and the gap size between the ring resonators is 410 nm. Figure 2(a) shows the microscope image of the fabricated SE. Grating couplers with coupling loss of ~5.5 dB/facet are used for light coupling in and out of the chip. All the rings are integrated with TiN-based thermo-optic (TO) phase shifters for resonance alignment for the initial cross state. A PIN diode is also embedded in the middle ring for electro-optic (EO) tuning of the switching state, as illustrated by the zoom-in view of the CRR in Fig. 2(b).

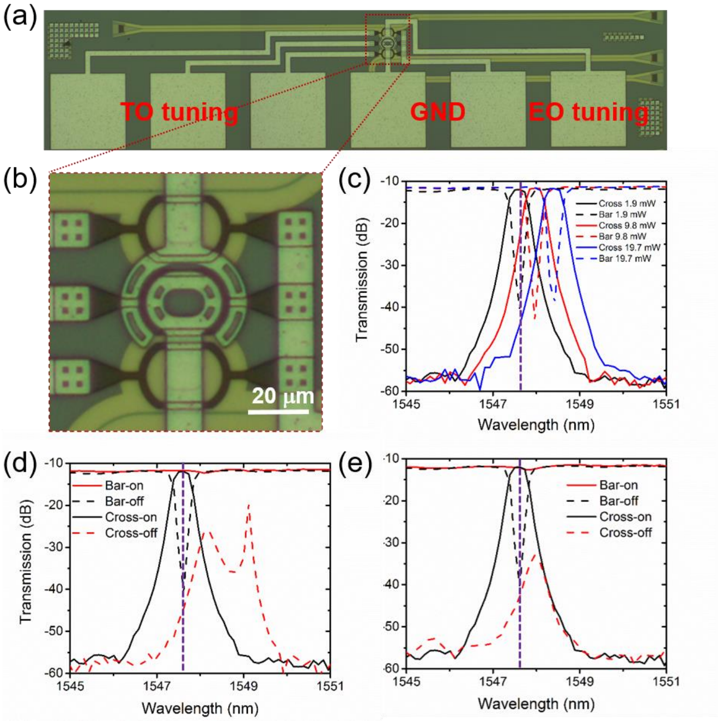

Fig. 2 (a) Microscope image of the fabricated 3rd-order CRR optical switch. (b) Magnified view of the CRR. (c)-(e) Measured transmission spectra of the device under (c) TO tuning of all three rings, (d) TO and (e) EO tuning of the middle ring.

We first used the conventional way to thermally tune all three rings simultaneously to change the switch state. Figure 2(c) shows the measured transmission spectra at the cross and bar ports under various TO power consumptions. The operation wavelength can be set to 1547.6 nm, indicated by the dashed line. The 3-dB optical bandwidth is 54 GHz. With a TO power consumption of 9.8 mW, the resonance is shifted by 0.34 nm, resulting in a large crosstalk of -13 dB. To further reduce the crosstalk below -30 dB, the TO power consumption should be increased to 19.7 mW. Figures 2(d) and 2(e) show the measured transmission spectra of the device upon TO and EO tuning of the middle ring. The bar port shows almost a flat spectrum after switching. The crosstalk at both states reaches -30 dB. As EO tuning is only performed to the middle ring, free-carrier absorption almost has no influence on the bar-port transmission. The on-chip insertion loss is around 0.4 dB. The TO and EO switching power consumptions are 17.8 and 8.7 mW, respectively.

3. Second-order CRR switch with waveguide coupling tuning

Besides shifting the resonant away from the operation wavelength, tuning the coupling coefficients of CRRs is another approach to flip the switching state. Figure 3(a) shows the schematic of the 2nd-order CRR optical switch. Tunable couplers based on MZIs are used to tune the external coupling between the bus waveguides and the ring resonators. Here we define the amplitude transmission coefficient between the top (bottom) bus waveguide and the top (bottom) ring as τ_1(τ_3). When τ_1=τ_3=1 (zero coupling), light from the input port passes though the MZI coupler and directly comes out of the bar port without coupling to the rings. Thus, the switch is at the bar state. The switch works as a single waveguide, producing a flat spectral response as illustrated in Fig. 3(b). When τ_1, τ_3<1, a portion of the light will couple to the rings on resonance. By properly choosing τ_1 and τ_3, the switch can be configured as a second-order optical add-drop filter with a high extinction ratio. As we set the operation wavelength at the resonant wavelength, light from the input port is switched to the cross port and hence the switch is flipped to the cross state.

The switch was also realized based on the silicon ridge waveguides with a height of 220 nm. TiN microheaters and PIN diodes were integrated in the phase shifters of both MZIs. Therefore, the switch can be actuated by both TO and EO tuners. Figure 3(c) shows the microscope image of the fabricated device. Air trenches surround the phase shifters to reduce thermal crosstalk.

Figure 3(d) shows the measured TE-polarized transmission spectra of the device under TO tuning. Although we design the two MZI arms with a slight length difference to ensure π phase difference at the initial state, both of the MZIs are not exactly at the bar state due to the fabrication errors. The TO power for phase error correction is 5.96 mW and 7.15 mW for the top and bottom MZIs, respectively. It can be seen that the bar port has a flat spectral response and the crosstalk is lower than -45 dB. To flip the switch state to the cross state, the TO tuning power for the top and bottom MZIs is increased to 26.4 mW and 20.2 mW, respectively. At the cross state, light is routed to the cross port with on-chip insertion loss of 2.5 dB. The free spectral range (FSR) of the device is 0.45 nm and the crosstalk is -28 dB. The 3-dB optical bandwidth is 8.3 GHz, which can be increased with a larger coupling coefficient κ_2. We can also perform the switching operation by using the EO tuners, as shown in Fig. 3(d). The EO switching power is 1.96 mW and 1.4 mW. It shows a similar response with the TO tuning, except for higher insertion loss of 4.5 dB, caused by the free carrier absorption. The measured crosstalk is -26 dB.

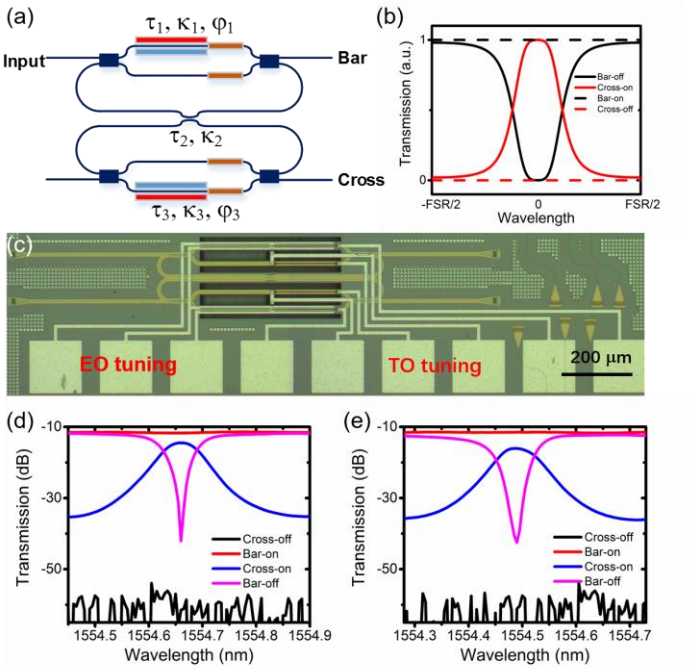

Fig. 3 (a) Schematic view of the second-order CRR optical switch. (b) Calculated transmission spectra of the switch. (c) Microscope image of the fabricated device. (d) and (e) Measured transmission spectra of the device under (d) TO and (e) EO switching, respectively.

4. Conclusions

We have demonstrated two CRR-based optical SEs on the SOI platform. Both of the SEs can be actuated by TO or EO tuners. The 3rd-order CRR SE is switched by only tuning the middle ring, leading to low on-chip insertion loss of 0.4 dB and low crosstalk of -30 dB. The 3-dB optical bandwidth reaches 54 GHz. The 2nd-order CRR SE is switched by tuning the waveguide-ring coupling strength. The insertion loss upon EO tuning is 4.5 dB, and the crosstalk is -26 dB. Both of the two structures can work as basic building blocks for large-scale integrated optical switch fabrics.

References

[1] N. Sherwood-Droz, H. Wang, L. Chen, B. G. Lee, A. Biberman, K. Bergman, and M. Lipson, "Optical 4x4 hitless slicon router for optical networks-on-chip (NoC)," Opt. Express **16**, 15915 (2008).

[2] R. Q. Ji, J. Xu, and L. Yang, "Five-port optical router based on microring switches for photonic networks-on-chip," IEEE Photon. Technol. Lett. **25**, 492-495 (2013).

[3] L. Lu, L. Zhou, X. Li, and J. Chen, "Low-power 2×2 silicon electro-optic switches based on double-ring assisted Mach–Zehnder interferometers," Opt. Lett. **39**, 1633 (2014).

[4] L. Lu, L. Zhou, Z. Li, D. Li, S. Zhao, X. Li, and J. Chen, "4×4 silicon optical switches based on double-ring-assisted Mach-Zehnder interferometers," IEEE Photon. Technol. Lett. **27**, 2457-2460 (2015).

[5] H. L. R. Lira, S. Manipatruni, and M. Lipson, "Broadband hitless silicon electro-optic switch for on-chip optical networks," Opt. Express **17**, 22271 (2009).

[6] P. DasMahapatra, A. Rohit, R. Stabile, and K. Williams, "Optical routing in a4×4 Matrix of Fifth-order Ring Resonator Switches," in *OptoElectronics and Communications Conference and Photonics in Switching*, (Optical Society of America, 2014), ThM1.4.