Silicon electro-optic switches using microring resonators with phase-tunable feedback

Linjie Zhou and Andrew W. Poon

Department of Electrical and Electronic Engineering, The Hong Kong University of Science and Technology,
Clear Water Bay, Hong Kong SAR, China
Tel: (852)-2358-7905; Fax:(852)-2358-1485; Email: eeawpoon@ust.hk

Abstract: We report a silicon electro-optic switch using a microring resonator with phase-tunable feedback. We show a wide mode spacing of four-times the ring free-spectral range. The carrier-induced blue-shifted resonance maintains a high extinction ratio.

OCIS codes: (230.5750) Resonators; (230.2090) Electro-optical devices

Silicon electro-optic switches and modulators [1, 2] using free-carrier plasma effect [3] have been attracting considerable recent interest. In order to enhance the device sensitivity to the small carrier-induced refractive index changes, Xu et al. [2] demonstrated a promising approach using high-Q microring resonators that are laterally integrated with p-i-n diodes and thereby causing resonance shifts upon biasing the diode. However, one shortcoming is that the blue-shifted resonance exhibits a significantly reduced extinction ratio due to the phase mismatch between the carrier-injected ring microresonator and the coupled passive waveguide.

In this summary, we report our initial experimental demonstration of an alternative way to electro-optically tune the silicon microresonator resonances by means of a phase-tunable feedback. The key merits are that the phase-control is enabled in a feedback-waveguide external to the microresonator, and thus the resonance wavelengths and extinction ratios can be tuned while preserving the waveguide-microresonator phase matching.

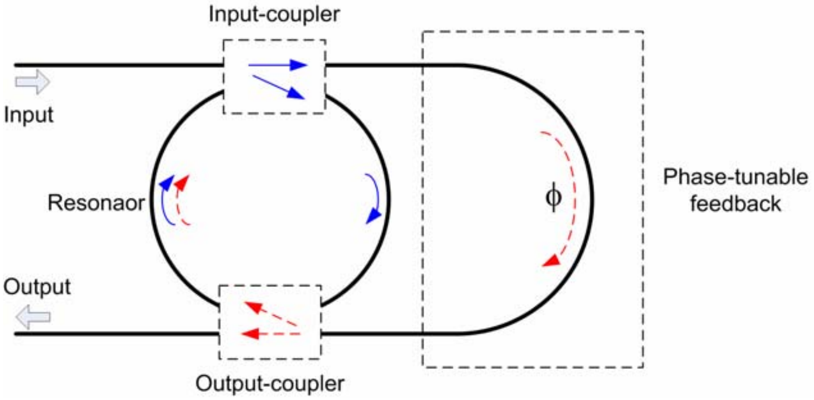

Fig.1. Schematic of the electro-optic switch comprising a microring resonator that is input- and output-coupled to a bended waveguide providing phase-tunable feedback. ϕ: electro-optically tunable feedback phase.

Figure 1 shows the schematic illustration of the optical switch using a microring resonator input- and output-coupled to a bended waveguide. The waveguide provides a phase-tunable external feedback to the microring resonator. Here we outline the device principle. The input light wave is first split by the input-coupler, coupling part of the light wave to the resonator, and part of the light wave to the feedback-waveguide, as depicted by the solid arrows. The feedback-waveguide light wave accumulates a phase shift of ϕ upon reaching the output-coupler and partially couples back to the microring resonator, as depicted by the dashed arrows. The microring lightwave and the external feedback lightwave can then interfere. Thus, by electro-optically tuning ϕ using a forward-biased p-i-n diode, we can obtain controlled resonance tuning without directly tuning the resonator.

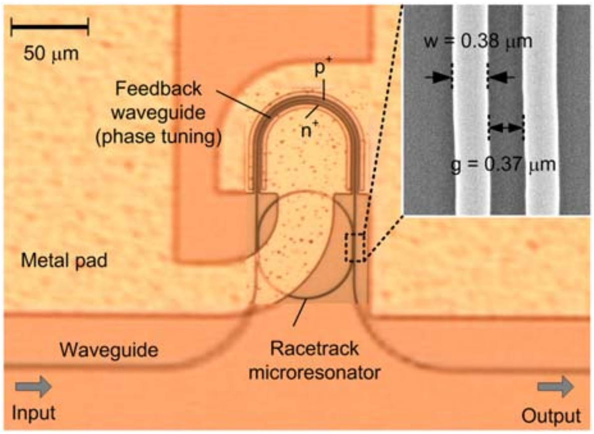

Fig.2. (a) Optical micrograph of our fabricated silicon electro-optic switch using a racetrack ring microresonator input- and output-coupled to a Ω-shaped single-mode waveguide. A lateral p-i-n diode is integrated along the U-bend of the feedback waveguide for phase tuning. Inset: scanning electron micrograph of the microresonator-waveguide coupling region before the oxide cladding deposition.

We fabricated our devices on a silicon-on-insulator wafer with a 0.21 μm device layer and a 2-μm buried oxide layer. We employed i-line (365 nm) photolithography and RIE dry etching. We implanted 1×10^{20} cm^{-3} phosphorous dopants for the n^{+} region and 2×10^{19} boron dopants for the p^{+} region. The entire device is clad with a 0.6-μm-thick low temperature oxide layer for electrical isolation and a 0.7-μm-thick patterned aluminum layer for electrical connections. Figure 2 shows the top-view optical micrograph of our fabricated device. The device comprises a racetrack ring microresonator that is input- and output-coupled to a single-mode Ω-shaped waveguide. The racetrack ring comprises 25-μm-radius curved waveguides joined with 10-μm-long straight waveguides. A 130-μm-long p-i-n diode is laterally integrated with the feedback waveguide. The diode comprises heavily-doped 4-μm-wide n^{+} and p^{+} regions located in the slab layer outside the ridge waveguide, with a separation of ~0.5 μm from the waveguide sidewalls in order to minimize the mode-field overlap with the absorptive doped regions. The inset shows the scanning electron micrograph of the coupling region (before the oxide cladding deposition). The measured waveguide width is ~0.38 μm and the gap size is ~0.37 μm.

Figures 3(a) and 3(b) show the measured TE-polarized (electric field // device plane) transmission spectra of our device and a control notch filter (a straight waveguide coupled with a racetrack ring microresonator) in order to contrast our device performance with that of a conventional notch filter. We discern only 3 pronounced resonances (donated as A, B and C) in the wavelength range of 1540 nm – 1560 nm for our device. Resonance B (~1544.4 nm) has the highest Q of ~10^{4} and the largest extinction ratio of ~18 dB. The absence of pronounced resonances between resonances B and C indicates a mode spacing of ~13 nm. In comparison, the conventional notch filter exhibits single-mode resonances with a Q-factor of ~5,600, an extinction ratio of < 8 dB, and a free-spectral range (FSR) of 3.36 nm (nearly 4 times less than the mode spacing of our device). We attribute the wide mode spacing and the large extinction ratio observed from our device to the wavelength-dependent ϕ that determines the resonance coupling strength between the feedback-waveguide and microresonator.

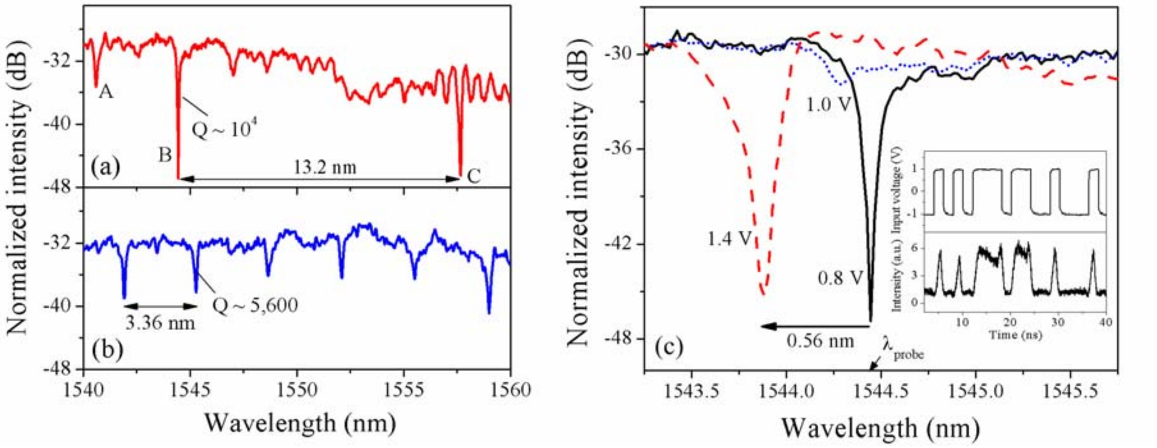

Fig.3. Measured TE-polarized transmission spectra for (a) our device without biasing the p-i-n diode, and (b) a conventional notch filter. (c) Electro-optical tuning of the resonance around 1544 nm under various DC bias voltages of V_d = 0.8 V (solid line), 1.0 V (dotted line), and 1.4 V (dashed line). Inset: modulated 0.5 Gbit/s NRZ optical waveform under ±1V electrical signal at probe wavelength of ~1544.4 nm.

Figure 3(c) shows the measured resonance B transmission spectra under various DC forward biases from 0.8 V to 1.4 V across the p-i-n diode. The spectrum upon 0.8-V forward bias (current 0.016 mA) is nearly identical to the spectrum upon zero bias. Upon a 1-V forward bias (current ~ 0.86 mA), the resonance is blueshifted (due to the free-carrier plasma dispersion [3]) and substantially suppressed. We attribute this resonance suppression upon a small increment in driving voltage to a nearly total destructive interference between the feedback and microresonator lightwaves. As the bias voltage exceeds 1.0 V, the resonance reappears and further blueshifts. Under 1.4 V forward bias (current 5.97 mA), the resonance extinction ratio (~15 dB) nearly recovers to the maximum level (zero bias) with a total resonance wavelength blueshift of ~0.56 nm. The Q-factor is reduced to ~4,000, mainly due to the free-carrier absorption loss.

We also modulate our device (at resonance B) using a non-return-to-zero (NRZ) electrical signal (±1 V amplitude and 0.5 Gbit/s). The inset of Fig. 3(c) shows the modulated optical waveform and the driving signal, revealing that our device modulation speed can be up to 0.5 Gbit/s with the waveform suffering only slight distortions. The device bandwidth can be optimized by, say, reducing the free-carrier transition times in the p-i-n diode.

In summary, we experimentally demonstrated a silicon electro-optic switch using a racetrack microring resonator with phase-tunable feedback enabled by an integrated lateral p-i-n diode. We measured a resonance mode spacing of about 4 times wider than the ring microresonator free-spectral range. By applying forward-bias voltages on the order of 1 V across the p-i-n diode, we demonstrated resonance tuning with controlled extinction ratio, with up to about ~15 dB extinction ratio at a ~0.5 nm blueshifted resonance.

References

[1] Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, “A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor,” *Nature* **427**, 615-618 (2004).

[2] Q. Xu, B. Schmidt, S. Pradhan and M. Lipson, “Micrometre-scale silicon electro-optic modulator,” *Nature*, **435**, 325-327 (2005).

[3] R. A. Soref and B. R. Bennett, “Electrooptical effects in silicon”, *IEEE J. Quant. Electron* **23**, 123-129 (1987).