Silicon Electro-Optic Switching Based on Coupled-Microring Resonators

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Abstract: We analyze silicon coupled-microring resonators-based electro-optic switching using injection-type p-i-n diodes. Numerical simulations and modeling suggest electronic-logic lightwave switching by applying two electrical data streams. We observe non-reciprocity between states (0, 1) and (1, 0).

Coupled-microring resonators [1-2] have received considerable attention as promising technologies for realizing photonic integrated circuits. On the silicon electro-optic (EO) active devices front, Xu et al. [3] demonstrated up to 4-Gbps NRZ modulation based on cascaded microring resonators. On the network and subsystem level, realizing the building blocks with different functionality of the optoelectronic integrated circuits is also attracting interest. Among various components, ultrafast, compact, electronic-logic switchable devices can be key elements for the switch nodes in next-generation telecommunication networks.

Here we propose silicon coupled-microring resonators-based electro-optic switches using injection-type p-i-n diodes. Our initial simulations suggest electronic-logic lightwave switching by applying a pair of electrical digital data streams on the embedded p-i-n diodes based on the coupled-microring resonators. Moreover, we observe the non-reciprocity of the coupled double-ring microresonators with free-carrier-induced refractive index and absorption changes in only one of the two microrings.

Figure 1 (a) shows the top-view schematic of our p-i-n diode integrated EO switch based on coupled-microring resonators on a silicon-on-insulator (SOI) substrate. The device comprises two p-i-n diode embedded coupled microring resonators laterally coupled to the straight single-mode bus waveguides. We employ standard silicon microfabrication processes to fabricate our EO switches as in our previous work [4]. Fig. 1(b) shows the top-view scanning electron micrograph of the fabricated coupled-microring resonators-based electro-optic switch in thin SOI.

By controlling the two input electrical digital signals, we can intelligently route an optical wavelength channel by changing the microring refractive index and absorption coefficient according to the free-carriers dispersion effect in silicon. Such resonance modulation will then be employed for the optical signal ON/OFF switching at a probe
wavelength near an optical resonance.

We adopt the two-dimensional finite-difference time-domain (FDTD) simulations to investigate the lightwave switching with the coupled-microring resonators. The dark gray and light blue regions in Fig. 1(a) indicate the intrinsic regions of the embedded p-i-n diodes, where the refractive index change $\Delta n$ and the imaginary part of the refractive index change $\Delta n_I$ are assumed when a forward bias is applied on nodes A or B. We employ effective index method to simulate the refractive index contrast between silicon and oxide and effectively accounting for the vertical dimension.

![Normalized Intensity vs Voltage](image)

**Fig. 2.** (a) FDTD simulated throughput- (solid) and drop-port (dashed) spectra for different electrical signal input states of (0,0), (1,0), (0,1) and (1,1). $\lambda_{probe}$: probe wavelength. (b) Modeled different throughput- (solid) and the identical drop-port (dashed) spectra with (1,0) and (0,1). (c), (d) Electrical input data streams A and B. (e) Calculated optical throughput- (solid) and drop-port (dashed) signal at a probe wavelength near a resonance as a function of time.

Fig. 2(a) shows the FDTD simulated throughput- (solid) and drop-port (dashed) spectra for different electrical signal input states of (0,0), (1,0), (0,1), and (1,1). We observe the mode splitting due to strong coupling between two identical microrings. The resonances spectrally blueshift when nodes A or B or both are switched on. We note that the optical throughput spectra are different between states (1,0) and (0,1), revealing the non-reciprocity in such coupled-microring system while the drop-port spectra remain identical [5]. We attribute the observed non-reciprocity in the throughput transmission spectra to the broken inversion symmetry as the refractive index and absorption changes are asymmetrically introduced into only one of the two microrings.

In order to verify the simulated results on non-reciprocity, we also model the throughput- and drop-port spectra using transfer matrix method [1]. Fig. 2(b) shows the modeled different throughput- (solid) and identical drop-port (dashed) spectra for states (1, 0) and (0, 1), as suggested by the FDTD simulations.

Fig. 2(c)-(e) presents the proposed coupled microring resonator-based electro-optic temporal switching concept, based on numerical modeling. For example, we use input 1-GHz square-wave electrical data streams A and B (Figs. 2(c) and (d)). The calculated optical throughput- (solid) and drop-port (dashed) signal at the probe wavelength, as shown in Fig. 2(c), spans all possible binary combinations. The throughput optical signal exhibits the OR function switching, whereas the drop signal exhibits the NOR function switching. We do not observe non-reciprocity in the time domain as we select the proper probe wavelength near a resonance. We remark that the optical rise time of state (1, 1) is shorter than those of states (0, 1) and (1, 0), which we attribute to the larger resonance blueshift for (1,1) as both microrings are carrier-injected. Device characterization and further device parameters optimization are in progress.