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Silicon Microring Resonator-Based Reconfigurable Optical Lattice Filter for On-Chip Optical Signal Processing

Linjie Zhou, Stevan S. Djordjevic, Nicolas K. Fontaine, Zhi Ding, Katsunari Okamoto, and S. J. B. Yoo
Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA
e-mail: yoo@ece.ucdavis.edu

Abstract: We present a silicon microring resonator-based reconfigurable optical lattice filter for on-chip signal processing. The device design employs a novel infinite impulse response (IIR) structure with high flexibility for rapid reconfiguration. Preliminary measurement results show high-quality filter response.

High-performance signal processing is critically important in modern communication and computing systems [1]. It is essential that such signal processing system can handle high-bandwidth signals at low power consumption. While electronics offer flexible and diverse signal processing capabilities, all-optical signal processing independently or in conjunction with electronic signal processing can significantly reduce the power consumption, latency, and complexity related to processing requirements. Signal processing in optical domain can cover orders of magnitude wider bandwidths and avoids energy consumption at the bit rate. The optical signal processing can potentially find applications in laser radar (LADAR), electronic warfare (EW), free space optical (FSO) communications, synthetic aperture radar (SAR), and electro-optic/infrared (EO/IR) sensing, and many others.

Here we present a silicon micoring resonator-based on-chip ultrahigh-performance, reconfigurable optical lattice filter for photonic signal processing. Optical Lattice filter is an essential component for optical signal processing [2-5]. Figure 1(a) shows the schematic of the device unit-cell [6], a basic building block for more complicated high-order filters. The unit-cell comprises of a Mach-Zehnder interferometer (MZI) coupled with a microring resonator with several tuning elements positioned inside for the reconfigurable functionality [7]. It should be noted that the MZI input/output and MZI-ring couplers are all composed by small tunable MZI couplers, such that the corresponding coupling coefficients can be independently controlled. The tuning is realized upon free-carrier plasma dispersion effect in silicon using laterally embedded p-i-n diodes [8]. The unit-cell has an infinite impulse response (IIR) due to the resonance structure [3], when the coupling coefficient between the ring resonator and the waveguide is below 100%. On the other hand, the reconfiguration of the MZI coupler to achieve 100% coupling coefficient will essentially remove the optical resonance in the ring to make the unit-cell operate as a finite impulse response (FIR) filter. The unit-cell transfer function has one pole and one zero, which is determined by the tuning elements in the microring resonator, MZI-ring coupler, MZI reference arm, MZI input and output couplers. Thus, by controlling these elements, we can arbitrarily position the pole and zero within the unit circle, and thus realize arbitrarily reconfigurable FIR and IIR filters.

The unit-cell design incorporates two types of silicon rib waveguides: a 3-μm wide waveguide to maintain low propagation loss with low optical nonlinearity and a 0.5-μm wide waveguide to allow single-mode confinement, strong lateral evanescent coupling, and low-tuning-current operation . Figure 1 (b) and (c) show the simulated mode profiles for these two waveguide structures. Fig. 1(c) also illustrates the p-i-n diode.

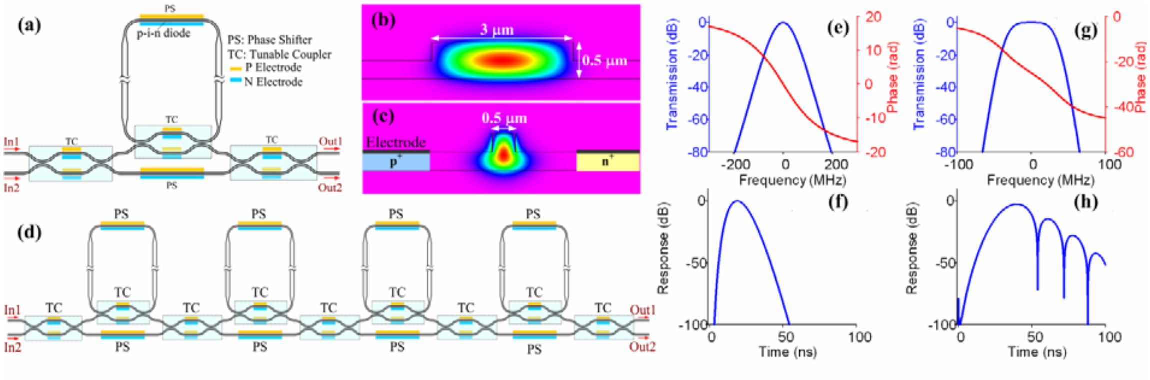

Figure 1. (a) Schematic of a single-unit-cell filter. (b) and (c) Simulated TE polarization electric field (parallel to chip plane) mode profiles of the (b) 3-μm-wide rib waveguide and (c) 0.5-μm-wide waveguide. (d) Schematic of a four-unit-cell filter. (e-h) Calculated IIR filter frequency and time domain responses, (e) and (f) pole-contrained filter design, (g) and (h) cascaded inverse Chebyshev design.

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A high-order filter can be implemented by cascading a number of unit-cells. Figure 1(d) shows an example of four-unit-cell lattice filter. In each unit cell, the phase shifters and tunable couplers can be independently tuned, which implies that the filter transfer function can be closer to ideal filtering performance. Figure 1(e)-(h) show the calculation results for two implementations of high-order IIR filters: (i) constrained pole design (Fig. 1(e) and (f)); (ii) cascaded-inverse Chebyshev design (Fig. 1(g) and (h)). Each filter is designed to have a 3dB bandwidth of 50 MHz within a 10 GHz FSR and is built by cascading 4 identically designed stages each with 4 unit-cells (for a total of 16 poles and 16 zeros). The pole-constrained filter has a compact slower roll-off than the inverse Chebyshev filter. However, the time domain impulse response is tighter and shorter in duration. Such a design is more resistant to losses because the signal spends less time in the filter.

The device fabrication is fully CMOS-compatible, meaning that electronic driver or other circuits can be monolithically integrated on the same silicon chip. Loss-loss optical waveguiding is critically important in realizing high-fidelity optical lattice filters. Waveguide loss mainly comes from sidewall roughness induced scattering loss. To reduce this loss, we employed photoresist reflow and dry oxidation in the waveguide fabrication processes. The measured waveguide propagation losses are estimated at < 0.5 dB/cm.

Figure 2(a) and (b) show the fabricated single-unit-cell and 4-unit-cell lattice filter chips. The microring resonator has a perimeter of ~8 mm, corresponding to a resonance FSR of 10 GHz. Figure 2(c) shows the measured complementary transmission spectra from the two output ports of the single-unit-cell device. The spectra are normalized to a straight waveguide. The resonance has a Q-factor of $\sim 10^5$ and an extinction ratio of ~18 dB. The transmission spectrum is similar to that of a typical microring add-drop filter expect that it has an asymmetric resonance line-shape. This asymmetric Fano-resonance line-shape is caused by interference between resonance channel and background channel [7]. Figure 2(d) shows the transmission spectra of 4-unit-cell lattice filter. We can observe high order filter characteristics. The 'drop' transmission has a broader bandwidth and sharper roll-off, although it has a low crosstalk. The filter performance can be further improved and reconfigured by accurately tuning each phase shifter and tunable coupler in the device. The active device measurements have also indicated successful tuning and reconfiguration of the unit cell.

In summary, we have designed, fabricated, and tested low-loss optical lattice filter unit cell on a CMOS-compatible silicon-on-insulator platform.

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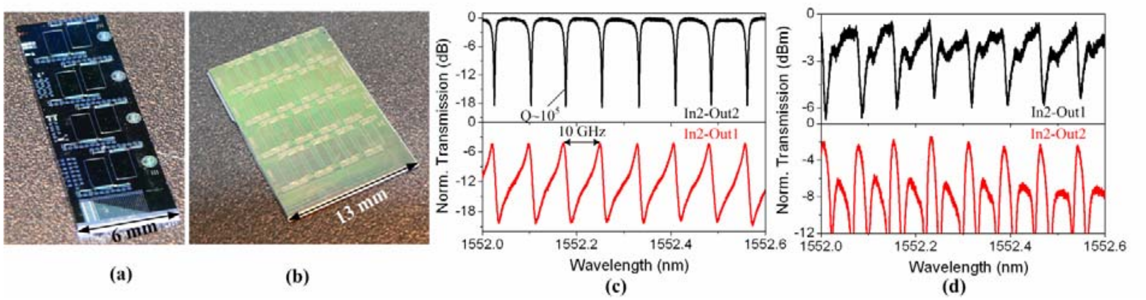

Figure 2. (a) and (b) Microscope images of the fabricated (a) single-unit-cell chip and (b) 4-unit-cell chip. (c) and (d) Measured two output ports transmission spectra of the (c) single-unit-cell device and (d) 4-unit-cell device.

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