Fully Reconfigurable Compact RF Photonic Filters Using High-Q Silicon Microdisk Resonators

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Abstract: We present a fully reconfigurable fourth-order SOI RF-photonic filter with a tunable bandwidth of 0.9–5 GHz, FSR > 600 GHz, out-of-band rejection > 38 dB, and compact size (0.15 mm^2) using high-Q resonator-based components.

OCIS codes: (130.3120) Integrated optics devices; (130.7408) Wavelength filtering devices.

The increasing demand for wideband wireless communication and ranging applications is pushing the RF signal carriers to higher RF frequencies in order to achieve higher bandwidths. However, the speed and precision of wideband signal processing in the electronic domain is usually limited by the available sampling frequencies (up to a few GHz) and resolution of the analog to digital converters. The tuning range of electronic RF filters is also limited by the RF carrier frequency. Reconfigurable optical systems offer a solution to this challenge by providing low-loss and high-bandwidth filters that can be tuned over a wide frequency range [1]. By modulating an optical carrier with the RF signal and processing the result in the optical domain prior to digitization, RF photonics technology expands our ability to process wideband RF signals [1].

In recent years different optical filter architectures have been proposed and demonstrated for RF photonics applications [1]. Among them, integrated optical filters provide the specific advantages of lower cost and compactness [2]. In this work, we present a new architecture for fully reconfigurable optical filters on a CMOS-compatible silicon-on-insulator (SOI) platform. Our proposed filter architecture is based on compact delay line elements enabled by high-Q microdisk resonators while utilizing the thermo-optic effect in silicon (Si) to reconfigure the filter by thermal tuning. The use of this resonator-based filter architecture enables a dramatic reduction in size with the potential to cascade several (up to 64) filter unit cells in a compact die.

Our filter architecture is based on cascading multiple unit cells, each of which consists of a Mach-Zehnder interferometer (MZI) with a single-pole, single-zero all-pass filter (APF) on each arm. A schematic of the filter unit cell is shown in Fig. 1(a). The APF consists of a tunable coupler which couples the light from the MZI arm to a racetrack resonator that acts as a feedback path. On the feedback path, an additional delay line (with a fixed delay) is implemented by strongly coupling (i.e., over-coupling) a high-Q microdisk resonator (intrinsic Q ~ 1,000,000 corresponding to 0.7 dB/cm loss) to the feedback waveguide. The coupling between the waveguide and the microdisk is adjusted to generate a delay of 100 ps at the 1550 nm wavelength. Strong single-mode waveguide-microdisk coupling is achieved through a using pulley coupling scheme [3]. This design approach is used to implement a compact delay line with a very low loss (0.7 dB/cm compared with 4.9 dB/cm for a 450-nm wide waveguide on the same platform). It also results in a much larger FSR compared with a waveguide-based delay line, which enables a wider filter tuning range and larger filter out-of-band rejection. An optical micrograph of the APF is shown in Fig. 1(b). The thermally tunable phase shifters are implemented by designing metallic heater elements tailored to locally heat a part of a waveguide or a resonator [4]. The APF poles and zeros are located at reciprocal locations with respect to the unit circle in the complex plane, as shown in Fig. 1(b). The phase and the distance of each APF pole from the unit circle can be adjusted by changing the phase shift in the feedback path and the coupling ratio of the tunable coupler, respectively. While the locations of the unit cell poles are determined by the APF poles, the locations of its zeros can be tuned independently by adjusting the input and output couplers and the phase shift between the two arms of the MZI. This gives us full control over the placement of the unit cell poles and zeros and enables us to implement both FIR and IIR filters based on the same unit cell architecture. A fourth-order (i.e., four pole, four zero) filter is designed by cascading two second-order unit cells (Fig. 2(a)).

The designed filters are fabricated on an SOI wafer with a 230nm thick Si device layer. The device layer is patterned using a JBX-9300FS e-beam lithography system with HSQ as negative e-beam resist. Dry etching is then performed in an inductively-coupled plasma etching system with Cl_2 chemistry. Finally, the device is covered with a 1-μm thick SiO_2 layer using spin-on flowable oxide (FOx). The metallic traces and contact pads are fabricated on top of the SiO_2 layer through e-beam lithography, e-beam evaporation, and the subsequent lift-off process.

To characterize the fabricated filter, the sample is placed on a thermally stabilized (0.01°C accuracy) stage. Light is coupled into and out of device using tapered optical fibers, and multi-contact probes are used to apply the tuning currents. The tuning power consumption of the phase shifters is measured to be 20–30 mW per π phase shift. Fig. 2(b) shows the spectral response of the device configured as a fourth-order band-pass (i.e., IIR) filter showing a bandwidth of 4.3 GHz, an FSR > 600 GHz, and an optical out-of-band rejection > 38 dB. Fig. 2(c) depicts a close-up view of the area in the dashed rectangle in Fig. 2(b) showing two flat-top band-pass responses with slightly different bandwidths obtained by fine-tuning the filter coefficients. Fig. 2(d) shows the tuning of bandwidth over a wide range from 4 GHz to 900 MHz. The 5dB increase in the insertion loss at lower bandwidths is a result of the increase in the number of roundtrips in the racetrack, as the APF coupling ratio approaches the critical coupling condition for the racetrack.

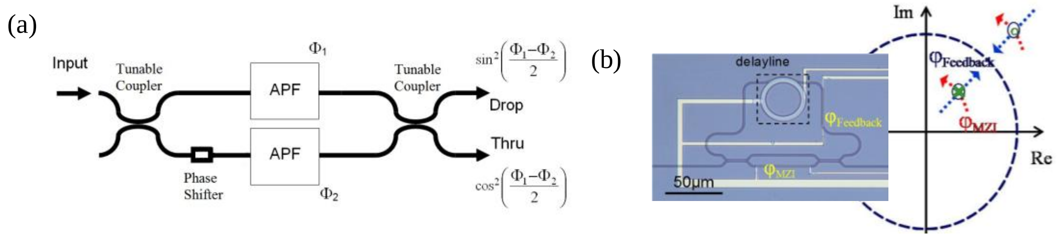

Fig. 1. (a) Simplified schematic of the two-pole two-zero unit cell composed of a Mach-Zehnder interferometer (MZI) with an all-pass filter (APF) in each arm. (b) Optical micrograph of the designed APF composed of a microdisk resonator-based delay line in the feedback path and an MZI-based tunable coupler. The right figure shows the corresponding pole-zero diagram and the movement directions of the pole and zero as a function of the changes in the tunable elements.

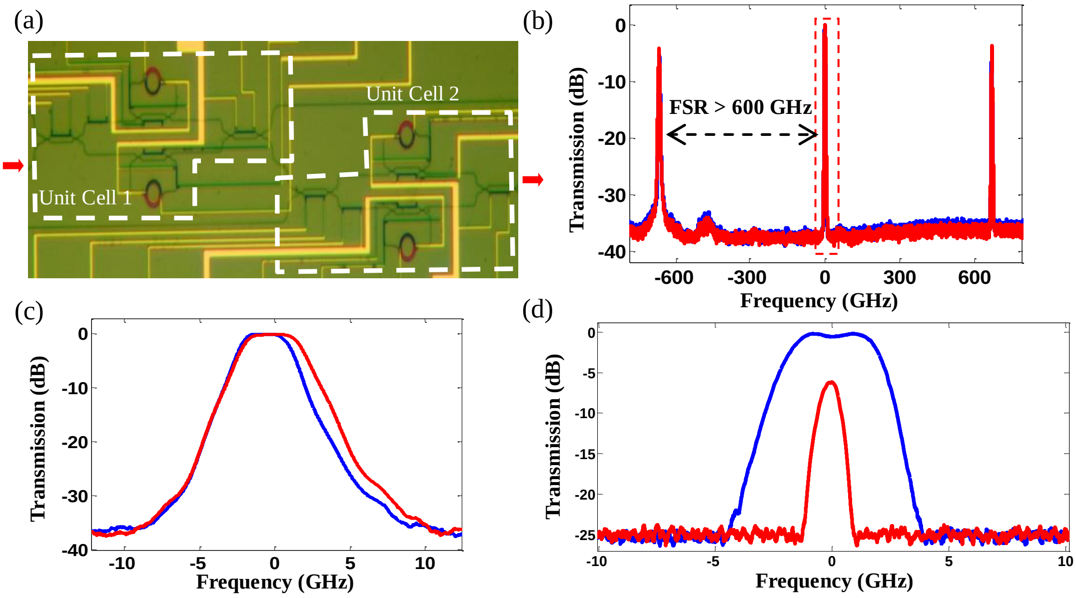

Fig. 2. (a) Optical micrograph of the two-stage cascaded filter. (b) Band-pass filter response showing an FSR > 600 GHz and an out-of-band rejection > 38 dB. (c) Close-up view of the area in the dashed rectangle in (b). Blue and red curves show two filter settings with slightly different bandwidths. (d) Tuning the bandwidth from 4 GHz to 900 MHz.

References

[1] J. Capmany, B. Ortega, and D. Pastor, "A Tutorial on Microwave Photonic Filters," J. Lightwave Technol. **24**, 201-229 (2006).

[2] M. S. Rasras, K. Y. Tu, D. M. Gill, Y. K. Chen, A. E. White, S. S. Patel, A. Pomerene, D. Carothers, J. Beattie, M. Beals, J. Michel, and L. C. Kimerling, "Demonstration of a Tunable Microwave-Photonic Notch Filter Using Low-Loss Silicon Ring Resonators," J. Lightwave Technol. **27**, 2105-2110 (2009).

[3] E. Shah Hosseini, S. Yegnanarayanan, A. H. Atabaki, M. Soltani, and A. Adibi, "Systematic design and fabrication of high-Q single-mode pulley-coupled planar silicon nitride microdisk resonators at visible wavelengths," Opt. Express **18**, 2127-2136 (2010).

[4] A. H. Atabaki, E. Shah Hosseini, A. A. Eftekhar, S. Yegnanarayanan, and A. Adibi, "Optimization of metallic microheaters for high-speed reconfigurable silicon photonics," Opt. Express **18**, 18312-18323 (2010).