Fully Reconfigurable Silicon CMOS Photonic Lattice Filters

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Abstract
We present reconfigurable CMOS-compatible silicon-photonic lattice-filters consisting of Mach-Zehnder structures and ring resonators configured as high resolution bandpass and notch filter shapes. Arbitrary filter synthesis and CMOS-compatible fabrication process are also discussed.

Introduction
All-optical processing of RF and microwave signals impressed on optical carriers using reconfigurable optical filters can obtain higher operation bandwidth, tuning bandwidths, and lower power consumption than their pure electrical counterparts. To match the diverse signal processing capabilities of electrical systems, an optical system must be easily reconfigurable, must have control over a large number of zeros and poles in the filter transfer function, and must achieve high resolution (~50 MHz). The lattice filter construction builds high-order filters with many poles and zeros by cascading many identical unit cells, each cell providing a single pole and zero. Here, we demonstrate reconfiguration of single- and four-cell photonic lattice filters on the silicon-on-insulator (SOI) platform consisting of tunable couplers and ring resonators into filter shapes including those with pure finite impulse response (FIR) and infinite impulse response (IIR).

Design and Fabrication
Fig. 1(a) presents the lattice filter unit cell which provides a fully controllable pole and zero to the filter transmission function by controlling four parameters: the ring phase shift, the coupling strength between the upper waveguide and the ring, the lower waveguide phase shifter, and the output coupler. Fig. 1(b) shows the four unit cell lattice filter with four tuneable poles and zeros. Rapid reconfiguration of the filter is possible using phase shifters that utilize the free-carrier plasma dispersion effect from current injection into p-i-n diodes (< 20 ns measured switching time) at the expense of some additional insertion loss from free carrier absorption. The tuneable couplers are 2×2 Mach-Zehnder interferometers with phase shifters in each arm.

In the lattice filter construction, the two inputs and outputs of adjacent unit cells are coupled together. Within a unit cell, the upper arm contains a waveguide coupled to a ring which produces both a pole and zero. The pole is fully defined by the ring coupler (pole magnitude) and ring phase shifter (pole phase), however the zero is not controllable. In FIR/IIR filter design, the pole magnitude which ranges between zero (FIR) and one (IIR) for passive devices is inversely proportional to the minimum spectral feature. The pole magnitude of the unit cell is equal to the power transmittance of one round-trip through the ring and is $10^{-\gamma/10(1 - \kappa)}$ where $\gamma$ is the excess losses in dB and $\kappa$ is the power coupling coefficient of the ring coupler. IIR functionality occurs when the ring stores light (i.e., near 0% coupling out of the ring or a pole with near unity magnitude). In this case, the ring...
outputs an impulse every $T$ seconds (i.e., the propagation delay time of the ring or lattice constant) which extends the filter impulse response much longer than the delay provided by the physical path length of the device. Realizing a pure FIR filters requires 100% coupling into and out of the ring (i.e., a pole with a magnitude of zero). In this case, the ring simply acts as a delay line and the impulse response duration is no longer than $T$.

The unspecified zero provided by the upper waveguide and ring is adjustable to a specified value by properly combining the signals on the upper and lower waveguides. A recursive algorithm\cite{3-4} determines the settings for the output couplers’ and lower waveguide’s phase shifters to adjust the zero to the desired location.

Realizing pole magnitudes near unity require low excess losses in the ring (i.e., $\gamma$ is 0). Therefore, Fig. 1(c,d) show the two types of silicon rib-waveguides used in the unit-cell design: a 3-µm wide waveguide for reduced waveguide losses and nonlinearities in the straight sections of the ring and a 0.5-µm wide waveguide for single-mode confinement, strong lateral evanescent coupling, and low current tuning operation\cite{7}. The chips are fabricated at the BAE Systems CMOS foundry\cite{6} using a procedure similar to Ref. 7. In addition, these devices use angled facets to reduce facet reflections and heat-isolating trenches to reduce thermal crosstalk between electrodes. The 0.5-µm waveguide losses are ~0.3 dB/cm.

**Measurements and Tuning of a Single Cell**

Fig. 2(a) shows the measured optical intensity and phase transmission of a single-unit cell filter tuned to form a 400-MHz wide bandpass filter. The data are obtained using a frequency-domain swept coherent interferometer\cite{8-9} that enables simultaneous complex spectral transmission measurements across 10 nm with 100 dB dynamic range and an update rate of 10 Hz. The filter’s free spectral range (FSR) is 10 GHz which is the inverse of $T$. The thin lines overlaid in Fig. 2(a) depict the best-fit filter containing only the pole and zero shown in Fig. 2(b) obtained using the MATLAB system identification toolbox\cite{10}. The excellent match between the measurement and fit indicates that the unit cell provides only a single pole and zero without undesired features or behaviours.

Fig. 2(c) shows the extracted pole magnitude of the filter versus separate sweeps of the drive current to each phase shifter in Fig. 1(a). To obtain maximal reconfigurability of the unit cell, the pole magnitude must tune from zero to one to convert the filter from a pure FIR filter to a FIR/IIR filter with vanishingly narrow spectral features. In addition, simple reconfiguration requires low crosstalk between the phase shifters. In our devices, the pole magnitude does not change when driving the lower waveguide phase shifter and the output coupler (i.e., electrodes 1 and 4) which is strong evidence of low crosstalk. The wide measured pole tuning range of 0.1 to 0.93 ($\gamma$ between 13% and 99%) is demonstrated by injecting current into the ring coupler (electrodes 2 and 3). The maximum pole magnitude is inversely proportional to the total ring round-trip loss due to both the necessary coupling to the upper waveguide and unwanted excess losses. Therefore, assuming that excess loss limits the maximum pole magnitude, a worst-case estimate of the ring round trip loss is 0.6 dB. Controlling the ring phase shifter (electrode 6) changes the pole angle over 2π rad for 13 mA of injected current; however the pole magnitude decreases due to undesired free-carrier absorption. Nevertheless, the unit cell provides a large pole tuning range due to the low-loss waveguides and tunable couplers.
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Fig. 3: Four unit-cell filter tuning examples. (a) No tuning. Bandpass filters optimized for (b) $H_{21}(\omega)$ with a $-1$ dB bandwidth of 600 MHz, $-3$ dB bandwidth of 1 GHz, and $-20$ dB bandwidth of 2.8 GHz. (c) $H_{11}(\omega)$ optimized transmission with $-1$ dB bandwidth of 1.8 GHz, $-3$ dB bandwidth of 2.5 GHz and $-20$ dB bandwidth of 7.6 GHz.

Fig. 2(d,e) show the transmission from the upper input port to the upper and lower outputs [$H_{11}(\omega)$ and $H_{21}(\omega)$] for a near-FIR filter (pole magnitude is 0.11) and a FIR/IIR filter with a large pole magnitude near 0.9 optimized for the $H_{21}(\omega)$ transmission. The filter tuning procedure is as follows: first, use the ring coupler and ring phase shifter to set the pole magnitude and phase. Then, use the lower waveguide phase shifter and output coupler to position the zero’s magnitude and phase. The ideal FIR filter’s impulse response [top of Fig.2(d)] should contain two peaks of equal magnitude; the first peak from the light in the lower waveguide and the second peak from the ring delayed by $T$. Here, the unwanted impulses contribute to less than 1% of the transfer function. The spectral transmission is sinusoidal for both outputs and if the input coupler were adjusted, both transmissions could be identical with large extinction (e.g., an ideal delay interferometer).

Fig. 2(e) shows a high-resolution 400-MHz wide bandpass filter (-3 dB bandwidth) created using a pole with magnitude near 0.9. Here, the impulse response rolls off at about 1 dB per impulse and extends beyond 5 ns before reaching the noise floor of the measurement. The insertion loss of the FIR/IIR filter is 10 dB lower than the pure FIR filter due to compensation of the excess losses in the ring with the output coupler. These examples demonstrate full functionality of the unit cell.

**Four Unit Cell Filters**

Fig. 3 displays the transmission of the four unit cell filter under three configurations. Fig. 3(a) shows the case with no tuning. Each dip in the transmission corresponds to a pole. The phase of the pole sets its location within the FSR. Since three dips are visible within a single FSR, two poles have the same phase. Arbitrary filter shapes require control of the 26 phase shifters.

Fig. 3(b) shows the filter manually reconfigured to have a flat-top bandpass shape with sharp rolloff for the $H_{21}(\omega)$ transmission. The filter has an extinction of 30 dB and its flat-top -1 dB bandwidth is 600 MHz. Fig. 3(c) shows a filter optimized for the $H_{11}(\omega)$ transmission. As expected, the four unit cell devices achieved more complex and versatile filter shapes when compared to the single unit cell filter.

**Conclusions**

We demonstrated reconfiguration of high order photonic lattice filters fabricated on a CMOS-compatible SOI platform. The high-quality transmission of the four-unit cells shows strong potential for eight- and even 16 unit-cell structures. Inherent <20 ns switching speed, development of automatic routines, and fast digital-to-analog converters will enable sub-100 ns switching between arbitrary filter shapes. Such rapidly reconfigurable filters are highly desirable in microwave-photonic signal processing, optical communications, and optical label switching.

**References**


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