Full-field technique for measuring the spectral evolution of reconfigurable photonic filters

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This Letter demonstrates a measurement technique based on frequency-to-time mapping and coherent detection, which enables the complete (i.e., amplitude and phase) characterization of dynamically reconfigurable photonic filters. We apply this technique to a unit cell from a silicon CMOS-compatible photonic lattice filter that has a rapidly changing transfer function with an 8.33 ns update time, 120 MHz spectral resolution, and 12 GHz bandwidth. These dynamic measurements allow characterization of transients, thermal effects, filter fidelity, and other time-dependent phenomena during switching. © 2012 Optical Society of America

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Characterizing the dynamic switching performance of complex optical devices is important for applications in optical switching systems, waveform generation, and radiofrequency-photonic signal processing [1–3]. This Letter reports on a full-field measurement technique for characterizing the spectral evolution of reconfigurable optical devices. Specifically, application of the measurement technique to a reconfigurable silicon photonics unit cell filter enables characterization of the transition between a notch filter and a bandpass filter, the thermal effects of current injection, and the filter shape fidelity while switching. Among many optical filter architectures, optical lattice filters are an attractive solution for synthesizing high-order filters by cascading many identical unit cells. Previous studies have shown the static performance of high-order reconfigurable lattice filters that use thermal tuning [3] or current tuning [4] in silicon-on-insulator (SOI) platforms, or gain and phase tuning in InP-InGaAsP [5]. This work introduces a coherent measurement technique with an 8.33 ns update time, >40 dB dynamic range, and 120 MHz optical spectral resolution to characterize the switching dynamics of a unit cell filter based on current tuning. This technique is general and may be applied to characterizing the spectral evolution (i.e., switching) of other types of reconfigurable optical devices.

Figure 1(a) shows a schematic of a unit-cell silicon photonic filter [4], which is configurable as a finite impulse response filter, an infinite impulse response filter, or variations in between by adjusting phase shifters (labeled as R1, L1, etc.). Each unit cell consists of three major parts: an input coupler, a “main” 2 × 2 Mach–Zehnder interferometer (MZI) with a ring resonator in the upper arm and a phase shifter in the lower arm, and an output coupler. Within the main MZI, phase shifters can adjust the coupling coefficient into the ring, which has a free spectral range of 10 GHz (i.e., a 100 ps lattice constant or ring delay). The phase shifters operate by current injection into p-i-n diode regions to provide a fast phase change via the free-carrier plasma dispersion effect [6]. The input and output couplers are tunable MZIs, and they control the amount of power coupled to the upper and lower waveguides that follow.

Each unit cell provides one pole and one zero to the transfer function in which the pole sets the filter minimum feature width and the zero adjusts the filter shape. In this unit cell, the pole magnitude is set by varying the coupling strength into the ring (R2 and R3), and its phase is set by the phase shifter in the ring resonator (R6). The unit cell zero value is a function of the pole setting and can be tuned after setting the pole value by controlling R1, R4, and R5. A recursion algorithm can be used to fully reconfigure the filter shape [7]. Following Fig. 1(b) and (c), the filter shape can change between a bandpass filter (A) and notch filter (B) by moving the zero by π rad (10 mA current injection). Here, we show rapid switching between notch and bandpass filters by tuning R1 to adjust the zero position. Figure 2 shows the experimental arrangement used to measure the dynamic reconfiguration of the unit cell. The measurement involves passing a train of linearly chirped optical pulses through the unit cell filter and characterizing the amplitude and phase of the pulses before [Fig. 2(a)] and after [Fig. 2(b)] the filter. Thus, the complex transfer function is \( H(\omega) = O(\omega)/I(\omega) \), where \( I(\omega) \) is the spectral amplitude and phase of the input pulse and \( O(\omega) \) is the filtered output pulse. This technique has several advantages, including lower induced optical nonlinearities because a chirped pulse has a lower peak-to-average power ratio and each frequency of the chirped pulse arrives at a different time. The optical spectrum is efficiently mapped to the time domain for direct display of the filter shape.

![Figure 1](https://example.com/figure1.png)
The train of linearly chirped pulses was created using an in-phase and quadrature-phase modulator (I/Q modulator) that was driven by an electronic arbitrary waveform generator (eAWG) with two independent outputs (5.5 GHz of analog bandwidth). For these measurements, the optical pulses had 12 GHz of optical bandwidth and a period of either 16.66 or 8.33 ns. A separate electrical function generator was used to apply a square wave current signal [Fig. 2(c)] to R1 to vary the filter shape. Optical waveform measurements were performed with a coherent receiver based on a 90° optical hybrid, balanced photodetectors, and a real-time oscilloscope with up to a 2 μs record length and 20 GHz electrical bandwidth [8].

Figure 3(d) shows the intensity of the pulses (16.67 ns period) measured after the unit cell while a 2.5 MHz square wave is applied to R1. Since the filter’s spectral transmission is mapped onto the temporal waveform, Fig. 3(a) shows that there is a complete switch from a notch to bandpass filter within one period at 220 ns. Digital signal processing (DSP) enables filter characterization on a pulse-by-pulse basis. Figure 3(b) shows the amplitude and phase of pulse A [see Fig. 3(a)] after isolation by DSP. Figure 3(c) shows the spectrum of pulse A computed using a Fourier transform. Normalization of pulse A’s spectrum against \( I(\omega) \) yields the filter’s complex transfer function, \( H(\omega) \) [Fig. 3(d)]. Figure 3(e) is a spectrogram that shows the normalized filter shape present within each chirped pulse in Fig. 3(a). The major transition between filter shapes occurs within one 16.67 ns waveform period. However, after each transition the center frequency takes 30–50 ns to fully stabilize, likely due to changes in the device’s power dissipation (15–30 mW).

Figure 4 shows dynamic filter results for a 15 MHz switching rate between low [Fig. 4(a), (b), and (c)] and high [Fig. 4(d), (e), and (f)] pole magnitudes (set by dc current to R2) with an 8.33 ns measurement update time. Figure 4(a) and (d) show the measured temporal intensity for the two cases with a 15 MHz switching rate. There are four pulses (measurements) for each filter shape, and since three of them appear nearly identical, an ∼8 ns switching time is indicated. From the points indicated in Fig. 4(a), Fig. 4(b) and (c) show the normalized transmission of the notch and bandpass filters overlaid with a plot of a one pole and one zero mathematical model. The fitting of this model to the measured filter results allows extraction of the amplitude and phase of the zero and pole. A useful filter fidelity metric is normalized energy error (NEE) [9], which is the ratio between the energy of the error spectrum [i.e., \( |H_m(\omega) - H_f(\omega)|^2 \)] and the energy of the fitted spectrum [i.e., \( |H_f(\omega)|^2 \)], where \( H_m(\omega) \) and \( H_f(\omega) \) are defined as the measured and fitted spectrums, respectively. In Fig. 4(b) and (c), the NEE for the fitted bandpass and notch filter results are 0.24% and 0.03% and the pole magnitudes are 0.25 and 0.26 (i.e., \( Q \)-factor of \( 4.2 \times 10^6 \)), respectively. The phase of the zero was changed from −0.26 rad (notch) to 2.65 rad (bandpass). Figure 4(e) and (f) show measured intensity and...
phase and the fitted magnitude filter. The NEE for the fitted bandpass and notch filters are 0.18% and 0.03% and the fitted pole magnitudes are 0.48 and 0.47 ($Q$-factor of $\sim 5.7 \times 10^4$), respectively. The phases of the zeros for high pole filter switching are changed from $-0.14$ (notch) to $-1.91$ rad (bandpass).

The waveform (filter) distortion shown in Figs. 4 and 5 is related to imperfections in the modulation signal [Fig. 2(d)] caused by the chip probing arrangement and the limited free-carrier lifetime of the phase shifters. An independent measurement of the function generator with its probing arrangement showed $\sim 1$ ns modulation rise and fall times. A free-carrier lifetime simulation using a commercial software showed a 7.09 ns full time for a 500-μm-long p-i-n diode under forward bias. This is consistent with the measured 8.33 ns filter switching time for a 700-μm-long p-i-n diode shown in Fig. 4(d). Incorporating pre-emphasis into the modulation signal may improve the filter shape during switching and further reduce the NEE.

In summary, this Letter presents a technique for characterizing dynamically changing filter shapes using frequency-to-time mapping and coherent detection. The amplitude and phase of the filter’s transfer function were measured with an optical resolution of 120 MHz while being switched at 30 MHz. The measured filter shapes match well with the mathematical pole-zero model, indicating high-fidelity filters under dynamic conditions.

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References