Tunable multitap microwave photonic filter with all complex coefficients

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Architecture for the implementation of a tunable multitap microwave photonic filter (MPF) with all complex coefficients is proposed and demonstrated. The complex coefficients are realized by 360° tunable photonic microwave phase shifters based on single-sideband polarization modulation. The polarization modulator, wavelength-division multiplexers, polarizer, and photodetector required for achieving the tunable phase shift are shared by all taps. Only a polarization controller is required in each tap to adjust each phase shift independently, making the system simple and compact. A proof-of-concept experiment is performed. A four-tap MPF with full free spectral range tunability and adjustable filter shape is realized. © 2013 Optical Society of America

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Microwave photonic signal processing has been drawing particular attention thanks to the distinct features brought by the photonic technologies, such as large bandwidth, low loss, light weight, wide tunability, and immunity to electromagnetic interference. A microwave photonic filter (MPF) is one of the basic elements in microwave photonic signal processing. Different kinds of MPFs, such as low-pass filters with all-positive coefficients and bandpass filters with negative or complex coefficients, were proposed in the past few years, among which the center frequency of those with complex coefficients can be tuned without affecting the shape of the frequency response [1–3]. However, the implementation of the complex coefficient is always difficult in the optical domain because the optical-to-electrical conversion in a photodetector (PD) is square-law. As a result, most of the reported approaches can realize MPFs with only one complex tap [4–6]. In order to achieve tunable MPFs with more complex taps, M. Sagues *et al.* proposed a six-tap MPF based on stimulated Brillouin scattering (SBS) [7]. The key limitation associated with this method is the limited tuning range, i.e., less than one fifth of the free spectral range (FSR) of the MPF, due to the relatively small achievable phase shift by the SBS. The complex-valued multitap MPFs can also be realized using a phase-shifted fiber grating [8] or a microring resonator [9]. But the tuning range is still small, less than FSR/4.36 for the scheme in [8] and less than FSR/4 for the approach in [9]. Recently, Yi *et al.* reported a full-FSR tunable multitap MPF based on a programmable photonic processor comprising a 2D array of liquid crystal on silicon pixels [10]. The method is flexible since the photonic processor can manipulate the amplitude and phase of different optical spectral components independently. However, the state-of-the-art photonic processor is still complex, bulky, lossy, and costly. In addition, Xue *et al.* recently proposed a single passband MPF with arbitrary complex coefficients and large tuning range based on the programmable photonic processor [11]. Again, the method is sophisticated due to the use of the photonic processor.

In this Letter, a novel tunable multitap MPF with all-complex coefficients is proposed and demonstrated. In the proposed MPF, each tap is implemented by a LD, a shared polarization modulator (PolM), a polarization controller (PC), an optical delay line, three shared wavelength-division multiplexers (WDMs), a shared polarizer, and a shared PD. The wavelength of each LD is located at the edge of one passband of the WDMs. When a microwave signal is introduced to the PolM, one sideband of the polarization-modulated signal is suppressed. Single sideband (SSB) polarization modulation is thus realized. The combination of the SSB polarization modulation followed by a polarizer would form a phase shifter [12] with full-range tunability, flat magnitude response, large operation bandwidth, and high tuning speed. Since the phase shift of each tap can be adjusted independently, all the coefficients of the proposed MPF are complex. An experiment is carried out, and a four-tap MPF with full-FSR tunability and adjustable filter shape is experimentally realized.

Generally, the electrical transfer function of a N-tap MPF is given by

$$H(f) = \sum_{n=0}^{N-1} a_n \exp(-j2\pi f nT), \tag{1}$$

where a_n is the MPF tap coefficient, f is the frequency of the microwave signal, and T is the unit delay of the MPF. When the coefficients are positive, the center frequency of the transfer function is zero, which corresponds to a low-pass filter [1–3]. If phase shifts are introduced to the taps, i.e., the coefficients are complex, the transfer function becomes

$$\begin{aligned} H'(f) &= a_0 + a_1 \exp(j\theta)\exp(-j2\pi f T) \\ &\quad + a_2 \exp(j2\theta)\exp(-j2\pi f 2T) + \cdots \\ &\quad + a_n \exp(jn\theta)\exp(-j2\pi f nT) \\ &= \sum_{n=0}^{N-1} a_n \exp\left(jn2\pi T\left(\frac{\theta}{2\pi T} - f\right)\right), \end{aligned} \tag{2}$$

where θ is the phase difference between the adjacent taps (suppose the phase shift of the first tap is 0). From

Eq. (2), we can see that the center frequency changes to be $\theta/2\pi T$. By changing the phase difference, the center frequency can be tuned. Therefore, to implement the tunable N-tap filter, the key is to realize N photonic microwave phase shifters with the smallest amount of devices.

Figure 1 shows the schematic diagram of the proposed N-tap MPF which consists of a laser array, a PolM, three WDMs, N PCs, N optical delay lines, a polarizer, and a PD. The lightwaves with wavelengths of λ_i ($i = 1, 2, \ldots N$) from the laser array are combined at WDM1 and injected into the PolM to be modulated by a microwave signal for processing. The polarization-modulated signals are split into N paths by WDM2, undergo time delays of $(n - 1)$ T at the optical delay lines, and then are combined by WDM3. The wavelength of each LD is located at the edge of one passband of the WDMs, so one sideband of the polarization-modulated signal is suppressed. When the SSB polarization-modulated signals are sent to a polarizer and detected by the PD, 360° tunable phase shifters are formed [12]. To adjust the phase shift of each tap independently, N PCs are incorporated between WDM2 and WDM3. A tunable multitap MPF with all complex coefficients is therefore realized.

To verify the principle of the multitap MPF, a four-tap MPF is built based on the setup shown in Fig. 1. A multichannel tunable laser source (Agilent N7714A) is used as the laser array to provide four wavelengths for the four taps. The WDMs have eight passbands with 3 dB bandwidths of 0.6 nm. The edge slopes of the passbands are about 190 dB/nm at the right edges. By properly setting the laser array, four wavelengths separated by 1.6 nm (1548.06, 1549.66, 1551.26, and 1552.86 nm) located at four right edges of the WDMs are obtained. The PolM (Versawave Inc.) has a bandwidth of 40 GHz and a half-wave voltage of 3.5 V, and the PD has an effective bandwidth of 43 GHz and a responsivity of 0.65 A/W. The frequency response of the four-tap MPF is measured by a 40 GHz vector network analyzer (VNA, Agilent N5230). The output port of the VNA is connected to the PolM and the input port is connected to the PD. The RF power of the VNA is 10 dBm. In addition, an optical spectrum analyzer (AQ6370C) is employed to observe the optical spectra.

Figure 2 shows the transmission responses of the selected four passbands of the WDMs and the optical spectra before and after the WDMs. Due to the steep slope of the right edge, and because the four wavelengths are located at the right edges, the right sidebands of the double sideband polarization-modulated signals are suppressed by more than 35 dB. SSB polarization modulations required for the phase shifters are realized [12].

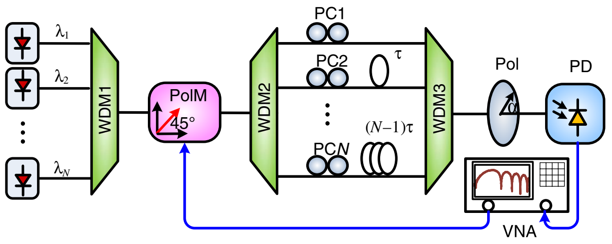

Fig. 1. (Color online) Schematic of the proposed N-tap MPF. PolM, polarization modulator; WDM, wavelength division multiplexer; PC, polarization controller; Pol, polarizer; PD, photodetector; and VNA, vector network analyzer.

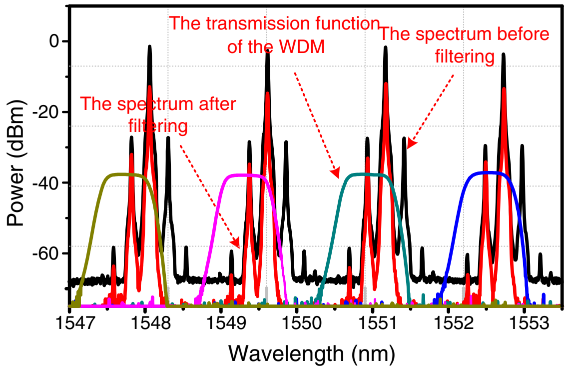

Fig. 2. (Color online) Transmission response of the four passbands of the WDM and the optical spectra of the signals before and after the WDMs.

Figure 3(a) shows the frequency responses of three two-tap filters when only two of the four channels are switched on. Selecting the two taps at wavelengths of (1548.06 and 1549.66 nm), (1548.06 and 1551.26 nm), and (1548.06 and 1552.86 nm), the unit time delays of the three two-tap filters are τ, 2τ, and 3τ, and the corresponding FSRs are $1/\tau$, $1/(2\tau)$, and $1/(3\tau)$, respectively. In the experiment, τ is about 4.6 ns, so the FSR is about 216.8 MHz for the MPF with (1548.06 and 1549.66 nm), 108.4 MHz for the MPF with (1548.06 and 1551.26 nm), and 72.3 MHz for the MPF with (1548.06 and 1552.86 nm). By letting the three filters have the same

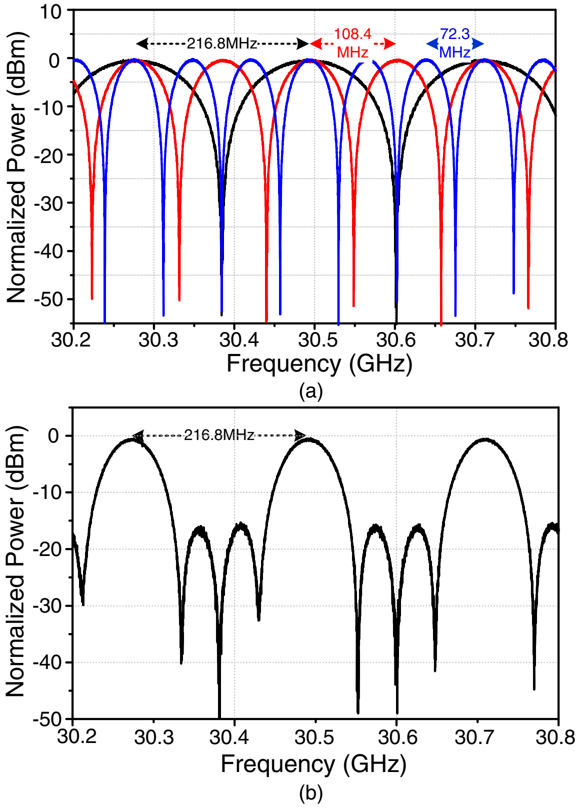

Fig. 3. (Color online) (a) Frequency responses of the three two-tap MPFs and (b) the frequency response of the four-tap MPF.

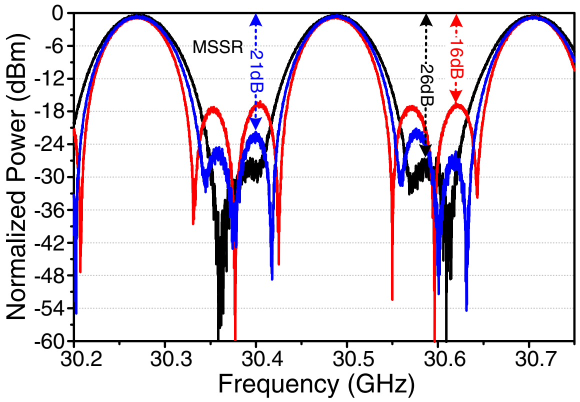

Fig. 4. (Color online) Frequency responses of the four-tap MPF with different shapes and MSSRs.

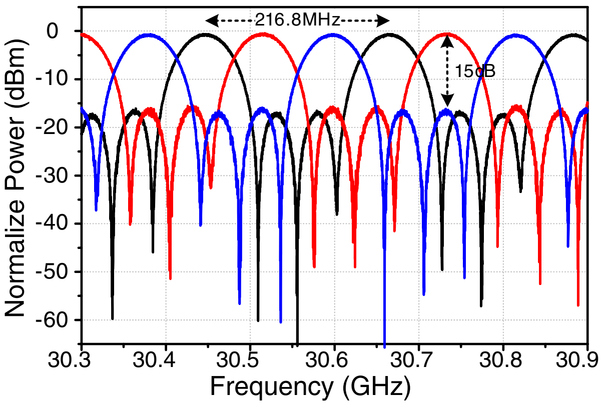

Fig. 5. (Color online) Frequency responses of the four-tap MPF with different center frequencies.

center frequency and enabling all the four taps, a four-tap MPF is generated. Figure 3(b) shows the frequency response of the four-tap MPF, which has a mainlobe and two sidelobes. The mainlobe-to-sidelobe suppression ratio (MSSR) is about 15 dB. The FSR is about 216.8 MHz, indicating that the unit time delay of the four-tap filter is τ. The 3 dB bandwidth of the filter is 53 MHz. By changing the currents of the laser sources, the magnitudes of the coefficients are adjusted, which would results in frequency responses with different shapes and different MSSRs. For instance, the MSSR could be as large as 26 dB and the 3 dB bandwidth could be 59 MHz, as shown in Fig. 4.

To confirm the tunability of the filter, the PCs in the four taps are adjusted to introduce different phase shifts. Figure 5 shows the frequency responses of the four-tap MPF with different center frequencies. As can be seen, the center frequency of the filter can be tuned over the full FSR without changing the shape of the frequency response.

It should be noted that the PC in each tap can be replaced by an electronically controlled PC. By using a microprocessor to set the PC settings and the currents of the laser sources, the multitap MPF can be electronically reconfigured at a high speed. The filter can work over a broad frequency range. The lower bound is determined by the edge slope of the WDMs, and the upper limit is related to the wavelength spacing of the WDMs and the bandwidth of the PolM and the PD.

In conclusion, a novel tunable multitap MPF with all complex coefficients was proposed and demonstrated. By simply adjusting the PC in each tap, the center frequency is tuned in the full FSR while the shape of the frequency response keeps unchanged. On the other hand, by tuning the magnitudes of the coefficients via changing the optical powers, the shape of the frequency response is altered while the center frequency remains the same. A four-tap MPF with a FSR of 216.8 MHz was constructed. The 3 dB bandwidth of the filter is 53 MHz, and the MSSR is 15 dB. Full-FSR tunability as well as the tuning of the filter shape were confirmed. The proposed MPF is simple and compact, and can find applications in high-speed and reconfigurable photonic microwave signal processing.

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