Complex Coefficient Microwave Photonic Filter Using a Polarization-Modulator-Based Phase Shifter

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***Abstract*— A continuously tunable microwave photonic filter with a complex coefficient is proposed and demonstrated. The complex coefficient is implemented by a polarization-modulator-based photonic microwave phase shifter, which enables a tunable phase shift from −180° to 180° in 10–40 GHz. An experiment is carried out. By simply controlling the photonic microwave phase shifter, the frequency response of the microwave photonic filter is tuned over the full free spectral range (FSR) without changing the shape and the FSR of the frequency response. The proposed filter shows a rich set of features, including simple operation, large bandwidth, and high tuning speed.**

***Index Terms*— Analog optical signal processing, microwave photonic filter, microwave photonic phase shifter, microwave photonics.**

I. INTRODUCTION

PROCESSING microwave or millimeter-wave signal in the optical domain has been a field of increasing interest thanks to the inherent characteristics brought by the photonic technologies, such as broad bandwidth, low loss, light weight, and immunity to electromagnetic interference [1]–[3]. In the microwave photonic signal processing, microwave photonic filtering is one of the most important applications. Extensive efforts have been directed to implement microwave photonic delay-line filters with positive coefficients or negative coefficients in the last few years [1]–[3]. However, to tune the center frequency of the filter without affecting the shape of the frequency response, at least one complex coefficient is required [2]. The complex coefficient can be achieved by the stimulated Brillouin scattering in optical fiber [4], [5], or the slow light effect in a semiconductor optical amplifier (SOA) [6], but their operational bandwidth is limited, or careful control of the optical powers and wavelengths is required. In addition, it is very difficult to tune the filter over the entire free spectral range (FSR) because the maximal phase shift in most of the approaches is less than 360°. To realize the full-range tunability, W. Li *et al.* proposed a configuration to achieve the complex coefficient by a dual-parallel Mach–Zehnder modulator (DP-MZM) and an optical bandpass filter (OBPF) [7]. The key limitations associated with the method are the large insertion loss, complex bias setting and the bias drifting problem of the DP-MZM. The tunability of the microwave photonic filters can also be realized by a reconfigurable optical filter [8], [9]. However, it requires a careful adjustment of both wavelength and amplitude of the laser source or the phase and amplitude responses of the optical filter, making the operation complicated. Recently, M. H. Song *et al.* proposed a reconfigurable microwave photonic filter with the complex taps realized by an optical comb and a pulse shaper [10]. This approach can principally realize microwave photonic filters with any frequency response, but in the current stage, the system is complex and the operation is sophisticated.

In this letter, we propose and demonstrate a simple two-tap microwave photonic filter with a complex coefficient realized by a polarization-modulator-(PolM)-based photonic microwave phase shifter. The phase shifter features wideband operation, flat power response, large tuning speed, and compact configuration, which generates a continuously tunable phase shift from −180° to 180°. When the phase shift is controlled by a polarization controller (PC) in one arm, the frequency response of the filter can be tuned over the full FSR while keeping the shape and the FSR unchanged.

II. PRINCIPLE

Fig. 1 shows the schematic diagram of the proposed tunable two-tap microwave photonic filter. The key component in the microwave photonic filter is a photonic microwave phase shifter, which is implemented by a PolM, an OBPF and a polarizer, as shown in the dashed box of Fig. 1. The PolM is a special phase modulator that can support both TE and TM modes with opposite phase modulation indices. When a linearly polarized incident light that is oriented at an angle of 45° to one principal axis of the PolM is sent to the PolM, two complementary phase-modulated signals are generated

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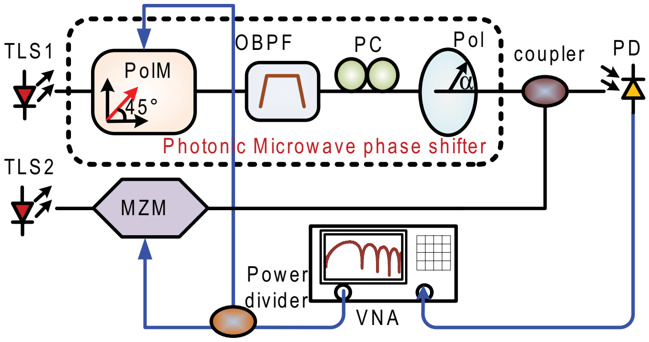

Fig. 1. Schematic diagram of the proposed tunable microwave photonic filter. TLS: tunable laser source. PC: polarization controller. PolM: polarization modulator. Pol: polarizer. MZM: Mach–Zehnder modulator. PD: photodetector. VNA: vector network analyzer.

along the two principal axes. If a modulating signal expressed by $\cos\omega_m t$, is applied to the PolM, the normalized optical fields at the output of the PolM along the two principal axes can be written as

$$\begin{bmatrix}E_x\\E_y\end{bmatrix} \propto \begin{bmatrix}\exp j\left(\omega_o t+\gamma\cos\omega_m t+\phi\right)\\ \exp j\left(\omega_o t-\gamma\cos\omega_m t\right)\end{bmatrix} \propto \begin{bmatrix}\exp(j\phi)\Big[J_0(\gamma)+jJ_1(\gamma)\exp(j\omega_m t) \\ \qquad -jJ_{-1}(\gamma)\exp(-j\omega_m t)\Big] \\ J_0(\gamma)-jJ_1(\gamma)\exp(j\omega_m t) \\ \qquad +jJ_{-1}(\gamma)\exp(-j\omega_m t)\end{bmatrix} \quad (1)$$

where ω_o is the angular frequency of the optical carrier, γ is the phase modulation index, ϕ is the phase difference between E_x and E_y which can be controlled by the DC bias of the PolM, and J_n is the Bessel function of the first kind of order n. In writing (1), small-signal modulation is assumed so that the higher-order (≥ 2) sidebands are ignored. Then, the OBPF removes one sideband of the signals, converting the double-sideband (DSB) phase-modulated signals into two single-sideband (SSB) intensity-modulated signals with a π phase difference,

$$\begin{bmatrix}E_x\\E_y\end{bmatrix} \propto \begin{bmatrix}\exp(j\phi)[J_0(\gamma)+J_{-1}(\gamma)\exp(-j(\omega_m t+\frac{\pi}{2}))]\\ J_0(\gamma)+J_{-1}(\gamma)\exp(-j(\omega_m t-\frac{\pi}{2}))\end{bmatrix}. \quad (2)$$

The two orthogonally polarized SSB signals are combined by the polarizer. When the combined signal is sent to a PD for square-law detection, the output current is given by

$$\begin{aligned} I(t) &\propto \left[\cos\alpha E_x+\sin\alpha E_y\right]\left[\cos\alpha E_x+\sin\alpha E_y\right]^* \\ &= (1+\sin 2\alpha\cos\phi)J_0^2(\gamma)+(1-\sin 2\alpha\cos\phi)J_{-1}^2(\gamma) \\ &\quad -2(\cos 2\alpha\sin\omega_m t+\sin 2\alpha\cos\omega_m t\sin\phi) \\ &\quad \times J_0(\gamma)J_{-1}(\gamma) \end{aligned} \quad (3)$$

where α is the angle between the polarization direction of the polarizer and one principal axis of the PolM. Let $\phi=\pi/2$, which can be implemented by tuning the DC bias of the PolM, (3) can be simplified to

$$I(t) \propto J_0(\gamma)J_{-1}(\gamma)\cos\left(\omega_m t+2\alpha+\frac{\pi}{2}\right). \quad (4)$$

As can be seen from (4), when α changes in the range of $[0, \pi]$, the phase of the signal would be varied in $[0, 2\pi]$. As a result, a tunable microwave photonic phase shifter is achieved with the phase shift adjusted by placing a PC before the polarizer. When the photonic radio frequency (RF) phase shifter is used in one tap of a filter, it would generate a complex coefficient. In general, the transfer function of a conventional two-tap microwave photonic filter with both real coefficients is written as

$$\begin{aligned} H(f) &= \sum_{n=0}^{1} a_n \exp(-j2\pi n f T) \\ &= a_0 + a_1\exp(-j2\pi f T) \end{aligned} \quad (5)$$

where a_0 and a_1 are the coefficients of the two taps, f is the frequency of the microwave signal, and T is the time delay between the two taps. When the phase shifter incorporated in one tap introduces an additional phase shift φ, the frequency response of the filter can be expressed as

$$\begin{aligned} H'(f) &= a_0 + a_1\exp(j\varphi)\exp(-j2\pi f T) \\ &= H\left(f-\frac{\varphi}{2\pi T}\right). \end{aligned} \quad (6)$$

As can be seen from (6), the center frequency of the filter is changed by $\varphi/2\pi T$, and the FSR and shape of the filter keep unchanged. Since the phase shifter can achieve a phase shift up to 2π, the center frequency of the filter can be tuned over the FSR of the frequency response.

III. EXPERIMENT RESULTS AND DISCUSSION

An experiment based on the schematic diagram shown in Fig. 1 is carried out. Two lightwaves with wavelengths of 1551.140 and 1550.140 nm are generated by a four-channel tunable laser source (TLS, Agilent N7714A), which is sent to the two arms of the microwave photonic filter, respectively. In the upper arm, the 1551.140-nm lightwave is launched to a microwave photonic phase shifter, which consists of a PolM, an OBPF, a PC and a polarizer. The PolM (Versawave Inc.) has a 3-dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. The OBPF (Yenista XTM-50) has an edge slope of more than 500 dB/nm, which can effectively remove the positive sidebands of the signals. A polarization beam splitter (PBS) with a polarization extinction ratio of more than 35 dB is used as the polarizer. The PC is placed before the PBS to adjust the angle between the polarization direction of the PBS and one principal axis of the PolM. In the lower arm, the 1551.140-nm lightwave is sent to a MZM biased at the quadrature point. Both the PolM and the MZM are driven by a RF signal generated by a 50-GHz vector network analyzer (VNA, Agilent N5245A) with a power of 10 dBm. The signals from the two arms are combined by a 3-dB coupler. A PD with a bandwidth of 40 GHz and a responsivity of 0.65 A/W is used to perform optical-to-electrical conversion. The frequency response of the proposed system is measured by the VNA.

Fig. 2 shows the phase responses of the PolM-based phase shifter. By adjusting the angle between the polarization direction of the PBS and one principal axis of the PolM, the phase of the RF signal is tuned from −180° to 180°. The phase response is flat within 10–40 GHz. The lower

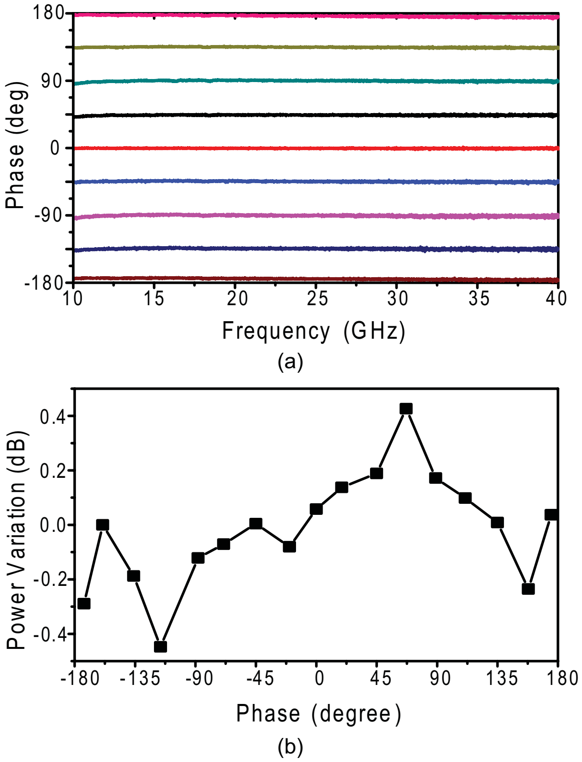

Fig. 2. (a) Phase responses of the phase shifter in the frequency range of 10–40 GHz at different PC settings. (b) Power variation for different phase shifts.

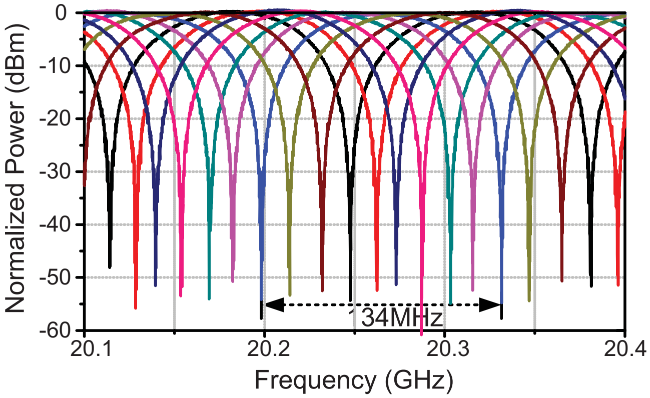

Fig. 3. Frequency responses of the proposed photonic filter by changing the setting of the PC.

boundary of the response is restricted by the edge slope of the OBPF, and the upper limit is governed by the bandwidth of the devices used in the scheme. The insertion losses of the phase shifter at different phase shifts are also measured at 30 GHz for 200 seconds. The variation is within ± 0.5 dB.

With the full-range tunable phase shifter, the tunable microwave photonic filter can be implemented. Fig. 3 shows the frequency responses of the filter when the phase shifter provides different phase shifts. From Fig. 3 we can see that the FSR is 134 MHz, which corresponds to about 1.5-m length difference of the optical fibers in the two arms. When adjusting the phase shifter, the notch center changes over the entire FSR, and the shape and FSR of the frequency response remains unchanged. In addition, more than 48-dB rejection ratio is obtained over the entire tuning range. Because the filter is tuned by a PC and the state-of-the-art electrical polarization converter can reach a tuning speed of more than 40 GHz [11], the proposed microwave photonic filter is suitable for ultra-high-speed photonic microwave signal processing. In addition, the microwave photonic filter is possibly multi-octave tunable, since the photonic microwave phase shifter can operate over 10–40 GHz. This range can be further extended if an OBPF with a steeper edge slope, and a PD with higher bandwidth are used.

IV. Conclusion

A tunable two-tap microwave photonic filter with a complex coefficient implemented by a PolM-based photonic microwave phase shifter was proposed and demonstrated. By adjusting the phase shifter, the frequency response of the filter was continuously tuned over the full FSR while keeping the FSR and the shape unchanged. The proposed filter features simple operation, large operational bandwidth and high tuning speed, which can find application in ultra-high-speed photonic microwave signal processing.

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