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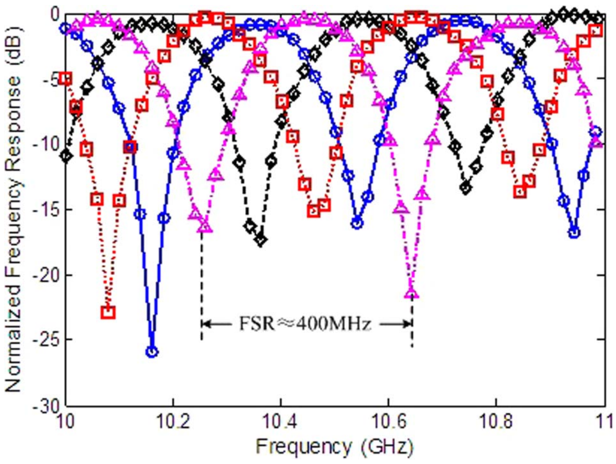

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A Tunable Microwave Photonic Filter With a Complex Coefficient Based on Polarization Modulation

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Abstract: A tunable microwave photonic filter with a complex coefficient based on polarization modulation and a single laser source is proposed and demonstrated. Two out-of-phase microwave signals with orthogonal polarization states are generated using a polarization modulator and then combined into one special polarization state to introduce certain phase shifts after filtering out one sideband. The tunability of the filter with the complex coefficient is achieved by adjusting the phase shifts between two taps. In addition, the frequency response of the proposed filter from 10 to 11 GHz with FSR of 400 MHz is measured.

Index Terms: Microwave photonic filter, complex coefficient, polarization modulation, frequency response.

1. Introduction

Microwave signal processing has attracted considerable interests in the last few years due to its intrinsic features such as broad bandwidth, tunability, low loss and immunity to electromagnetic interference compared to conventional radio-frequency (RF) techniques [1]–[3]. Microwave photonic filters (MPFs) play an important role in various applications. Recently, many approaches have been demonstrated to provide MPFs with different coefficients. In general, MPFs with positive coefficients can only function as low-pass filters with limited applications, while MPFs with negative coefficients can be used as band-pass filters and could be achieved using semiconductor optical amplifiers (SOAs) or fiber Bragg gratings (FBGs), facilitated by wavelength conversion or polarization modulation [4]–[8]. The tunability of such MPFs is generally limited. A tunable photonic filter with an arbitrary number of coefficients has been demonstrated based on a spatial light modulator [9]. Considering that most MPFs rely on discrete-time signal processing with real coefficients, which require the use of tunable optical true time delays, a microwave photonic filter with dynamic reconfigurations based on stimulated Brillouin scattering slow light and separate carrier tuning method has been brought up [10]. Even so, the tunability may lead to changes of the free spectral range (FSR) during the tuning process. Therefore, different kinds of microwave photonic filters with complex coefficients have been proposed in recent years to solve such problems by introducing a phase shift between the taps [11] using either a wideband 90° hybrid coupler [12], a

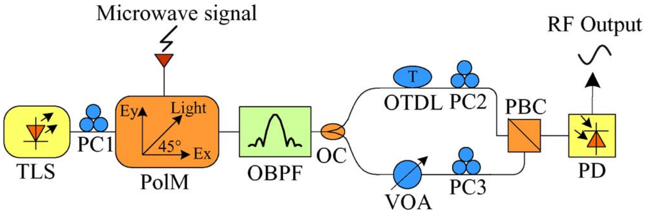


Fig. 1. Schematic diagram of the proposed tunable microwave photonic filter. TLS: tunable laser source. PolM: polarization modulator. OBPF: optical band-pass tunable filter. OC: optical coupler. OTDL: optical time delay line. VOA: variable optical attenuator. PC: polarization controller. PBC: polarization beam combiner. PD: photodetector.

dual-parallel Mach-Zehnder modulator [13], a phase-shift FBG [14], an all-optical differentiator [15], or an SOA with slow and fast light effects [16]. Note that most schemes are achieved utilizing two laser sources that may bring about certain disadvantages, including increased cost and complexity.

In this paper, we propose and experimentally demonstrate a novel microwave photonic filter with a complex coefficient based on polarization modulation. Compared with previous approaches, the proposed scheme only requires one single laser source. Meanwhile, a two-tap structure is designed in which the phase of the RF signal at either tap can be varied to provide a tunable microwave photonic phase shifter. The phase shifter can be continuously tuned in a full 360° range by changing the center frequency while keeping the shape of the frequency response unchanged. The phase shift and frequency response of the proposed filter are measured.

2. Principle of the Filter

The schematic diagram of the proposed tunable microwave photonic filter is shown in Fig. 1. The polarization modulator (PolM) that acts as a special phase modulator can achieve complementary phase modulation to the microwave signals that propagate along its two orthogonal polarization axes [7], [9]. In the proposed system, linearly polarized light that is generated by a tunable laser source (TLS) is sent into the PolM, with its polarization being aligned at an angle of 45° to the principal axis of the PolM. A microwave signal is applied onto the PolM via its RF port.

The normalized optical field at the output of the PolM along the x and y directions can be expressed as [9]

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \exp[j\omega_c t + j\beta\cos(\omega_m t)]\exp(j\phi) \\ \exp[j\omega_c t - j\beta\cos(\omega_m t)] \end{bmatrix} \tag{1}$$

where ω_c is the angular frequency of the optical carrier, ω_m is the angular frequency of the microwave signal, β is the phase modulation index of the PolM, and φ is the phase difference between E_x and E_y, which can be controlled by the DC bias of the PolM.

In order to analyze the frequency response of the microwave photonic filter, we use the model under small signal modulation. Based on the Jacobi-Anger expansion, Eq. (1) can be expanded as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \left\{J_{-1}(\beta)\exp\left[j(\omega_c - \omega_m)t - \frac{\pi}{2}\right] + J_0(\beta)\exp(j\omega_c t) + J_1(\beta)\exp\left[j(\omega_c + \omega_m)t + \frac{\pi}{2}\right]\right\}\exp(j\phi) \\ J_{-1}(\beta)\exp\left[j(\omega_c - \omega_m)t + \frac{\pi}{2}\right] + J_0(\beta)\exp(j\omega_c t) + J_1(\beta)\exp\left[j(\omega_c + \omega_m)t - \frac{\pi}{2}\right] \end{bmatrix} \tag{2}$$

where $J_n(\beta)$ is the nth-order Bessel function of the first kind. Under the condition of small signal modulation, the higher order (2nd-order and above) sidebands can be ignored while only the carrier and first-order sidebands are considered.

If the signals at the output of the PolM suffer beating effects at the photoelectric detector (PD), the data carried by the double sideband (DSB) signals will be lost. Consequently, we could use a tunable optical band-pass filter (OBPF) to remove one sideband of the DSB signals, converting the phase-modulated (PM) signals into intensity-modulated (IM) signals. The corresponding output after the OBPF can be written as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \left\{J_{-1}(\beta)\exp\left[j(\omega_c-\omega_m)t-\frac{\pi}{2}\right]+J_0(\beta)\exp(j\omega_c t)\right\}\exp(j\phi) \\ J_{-1}(\beta)\exp\left[j(\omega_c-\omega_m)t+\frac{\pi}{2}\right]+J_0(\beta)\exp(j\omega_c t) \end{bmatrix}. \tag{3}$$

If a polarizer is connected after the OBPF with its polarization direction controlled by a polarization controller (PC), the polarization angle between the polarizer and the principal axes of the PolM can be written as α. Subsequently after the polarizer, the intensity-modulated signals in Eq. (3) can be expressed as

$$E_{out}(t) = E_x\cos\alpha + E_y\sin\alpha \tag{4}$$

where α could be adjusted from 0 to π.

When the signal in Eq. (4) is sent into the PD, the recovered RF signal can be obtained. By taking only the RF signal centered at the modulation frequency ω_m into account and ignoring the DC current and higher order harmonics, we could write the signal after the PD as

$$E_{RF}(t) \propto \cos 2\alpha \sin\omega_m t - \sin 2\alpha \cos(\omega_m t)\cos\left(\phi-\frac{\pi}{2}\right). \tag{5}$$

When $\phi = \pi/2$, Eq. (5) can be rewritten as

$$E_{RF}(t) \propto \cos\left(\omega_m t - 2\alpha - \frac{\pi}{2}\right). \tag{6}$$

Since the angle α could be changed from 0 to π, the phase shift of the recovered RF signal can vary from 0 to 2π according to Eq. (6). Note here that if the PolM is replaced by an intensity modulator, the phase shift of the recovered RF signal is unchanged, because there won't be two out-of phase microwave signals with orthogonal polarization states combined by a polarizer, as expressed by Eq. (4).

Once there are two paths of optical signals sent to the PD in the incoherent regime, a two-tap microwave photonic filter could be obtained. As two paths are in orthogonal polarization states, the recovered RF signal after PD can be expressed as

$$E_{RF}(t) \propto \sum_{n=1}^{2} a_n \cos[\omega_m t - 2\alpha_n + \omega_m(n-1)T] \tag{7}$$

where a_n is the output power in the n-th tap, α_n is the angle between the polarization direction of the polarizer and the principal axes of the PolM in the n-th tap, and T is the time delay difference between the optical signals that travel along two paths.

According to the Fourier transform expression, the transfer function of the proposed microwave photonic filter can be expressed as

$$H(\omega_m) \propto a_0 + a_1\exp(j\omega_m T)\exp(j\Delta\alpha) \tag{8}$$

where $\Delta\alpha$ is the phase shift difference between the recovered RF signals of two taps and can be adjusted from 0 to 2π.

The transfer function of a two-tap microwave photonic filter is usually given by

$$H'(\omega_m) \propto a_0 + a_1\exp(j\omega_m T). \tag{9}$$

As can be seen from Eq. (8), a tunable microwave photonic filter with a complex coefficient $e^{j\Delta\alpha}$ is achieved. The frequency response of the proposed microwave photonic filter can be expressed as

$$H(f) = H'\left(f + \frac{\Delta\alpha}{2\pi T}\right) \tag{10}$$

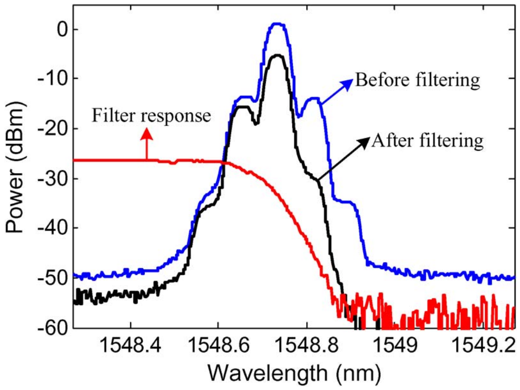


Fig. 2. Measured spectra of the OBPF (red line) and polarization modulated signals (before-blue and after-black the OBPF).

where f is the frequency of the microwave signal. It can be seen from Eq. (10) that once the time delay between the two taps is fixed, the center frequency of the microwave photonic filter is changed by $\Delta\alpha/2\pi T$ while the shape and the FSR of the microwave photonic filter keep unchanged.

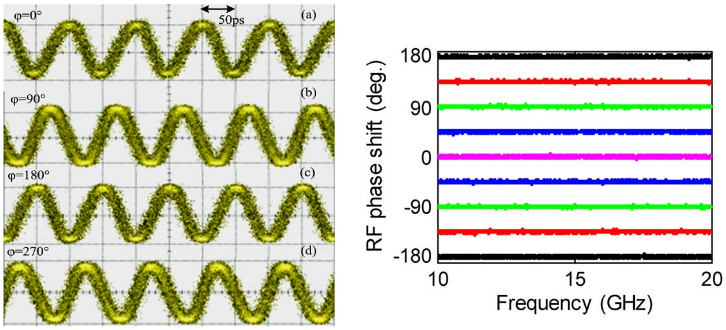
3. Experimental Results and Discussion

Fig. 1 shows the experimental setup we built to verify the proposed filter. A continuous-wave (CW) optical signal generated by a TLS (Agilent 8164B) with a wavelength of 1548.77 nm was sent into the PolM. The polarization state of the CW light was adjusted by PC1 to keep an angle of 45° to the principal axis of the PolM. A 10-GHz microwave signal generated by a microwave signal generator (MG3694B) was applied onto the PolM to achieve polarization modulation. The power of the RF signal was set at 8 dBm to ensure the condition of small-signal modulation.

After the polarization modulation, a DSB signal was obtained. In order to achieve the conversion from phase modulation to intensity modulation, a tunable OBPF was used to filter out the $+1$st-order sideband. The range of the RF frequency was determined by the roll-off property of the OBPF. However, for the microwave photonic filter with a complex coefficient, the minimum RF frequency was not important; what we need to do was just keep the optical carrier at the right location to ensure the $+1$st-order sideband being removed. Fig. 2 shows the spectral response of the OBPF and the spectra of the modulated signal (before and after the OBPF). The $+1$st-order sideband of the modulated signals was suppressed by more than 15 dB after optical filtering. Subsequently we could obtain a single sideband signal.

In order to create a microwave photonic filter with two taps, an optical coupler (OC) was used to split the SSB modulated signal after the OBPF into two branches. An optical delay line was employed in one of the branches to introduce a relative time delay, while a variable optical attenuator (VOA) was used in another branch to balance the power between two branches. A polarization beam combiner (PBC) was used to combine the optical signals from two branches without additional interference before sending into the PD.

As can be seen from Eq. (4), the polarization angle between the polarizer and the principal axes of the PolM (i.e., α) can be controlled by a PC. To analyze the phase shift of the recovered RF signal in every branch, we used a PBC to substitute the polarizer and recorded the phase change of the recovered RF signal in the upper branch by adjusting PC2 while the lower branch was disconnected. Fig. 3(a) shows the phase change of the recovered 10-GHz RF signal from the upper branch. It can be seen that the phase of the recovered RF signal can be changed from 0 to 2π. Furthermore, to evaluate the stability of the phase change, we measured the phase response from 10 GHz to 20 GHz as shown in Fig. 3(b) and adjusted for the filter response of the OBPF and the bandwidth of the PD. The phase shift exhibits a very stable performance over a wide range of the frequency shift.



(a) (b)

Fig. 3. (a) Measured phase change of the recovered 10-GHz RF signal; (b) RF phase shift in different frequencies (from 10 to 20-GHz).

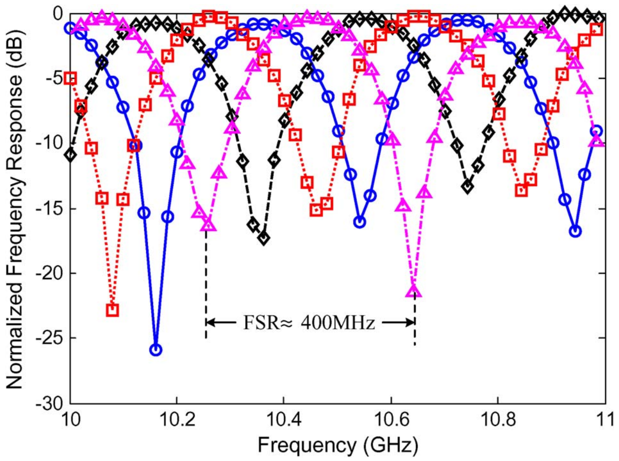


Fig. 4. Frequency response of the proposed microwave photonic filter.

Therefore, a two-tap microwave photonic filter could be obtained by connecting every branch to the PBC. The phase of the RF signal at either branch could be varied to provide a tunable microwave photonic phase shifter. Once the adjustment of PC2 was completed,the phase of the RF signal in the upper branch was fixed and the phase of the RF signal in the lower branch could be changed from 0 to 2π by simply adjusting PC3 in the lower branch. Subsequently we could obtain a two-tap microwave photonic phase shifter with a continuous shifting range over a full 360°.

As we set the frequency sweep range from 10 GHz to 11 GHz with an interval of 0.02-GHz, we could measure the frequency response of the proposed filter using a spectrum analyzer. Since the phase shifter could be continuously tuned within a full 360° range, we did the measurements as the phase shift difference between the recovered RF signals in two branches increased by 90° (i.e., by adjusting PC3). Fig. 4 shows the measured frequency response of the proposed microwave photonic filter. Some notches are deeper than others in the curves is due to the method that we record the frequency response using a spectrum analyzer with an interval of 0.02-GHz (i.e., not fully continuous).

As can be seen from Fig. 4, the FSR of the proposed microwave photonic filter is about 400 MHz. When the center frequency changed, the shape of the frequency response remained unchanged. Therefore, a tunable microwave photonic filter with a complex coefficient only using a single optical source was obtained, which reduced the complexity compared to previous schemes. Moreover, the filter could be tuned by simply tuning a PC to introduce a certain phase shift between the recovered RF signals in two branches. The maximum RF frequency in the measurements was 20 GHz, which was limited by the bandwidth of the PD. Therefore, it was feasible to apply such a microwave photonic filter at higher frequencies.

In addition, we should note that the optical time delay line that was employed in one branch could be adjusted to change the time-delay difference between two branches. This provided an additional flexibility to the filter, i.e., to vary the FSR of the filter. As the main purpose of the filter with complex coefficients was to provide tunable center frequencies without modifying the FSR, here we did not demonstrate the tunability of FSR.

4. Conclusion

A tunable microwave photonic filter with a complex coefficient based on polarization modulation is proposed and experimentally demonstrated. Such a configuration requires just one single optical source and is therefore less complex than previous schemes. The experimental results indicate the tunability of the frequency response shape without FSR changes. The filter also exhibits good stability in terms of the phase shift within a wide frequency range. Such an approach could find applications in microwave photonic links.

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