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Abstract. A reconfigurable microwave photonic filter based on a polarization modulator (PolM) is proposed and experimentally demonstrated. The PolM together with a polarization controller (PC) and a polarization beam splitter (PBS) implements two complementary intensity modulations in two separated branches. Then, optical components are inserted in the two branches to realize a bandpass filter and an allpass filter, respectively. When the two branches are combined by a second PBS, a filter with a frequency response that equals the subtraction of the frequency responses of the allpass filter and bandpass filter is achieved. By adjusting the PCs placed before the second PBS, a notch filter with a tunable notch depth or a bandpass filter can be achieved. [DOI: 10.1117/1.OE.55.3.031120]

Keywords: microwave photonics; microwave filters; optical signal processing.

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1 Introduction

Using photonic approaches to process microwave and radio frequency (RF) signals is attractive due to the inherent advantages such as low loss, broad bandwidth, immunity to electromagnetic interference, the possibility of good tunability, and reconfigurability.[1–3] Photonic processing of microwave signals has also the potential advantages of overcoming the existing electronic bottlenecks and provides functions in microwave systems that are very complex or even impossible to be carried out using pure electronic devices.

A microwave photonic filter is one of the basic elements in microwave photonic signal processing. Many photonic bandpass filters[4–7] and notch filters[8–11] have been proposed. However, these filters cannot be switched between a bandpass filter and a notch filter. The switchable filter can flexibly operate as one of the functions according to the required channel function. Thus, it can greatly increase the flexibility in practical application. Few techniques were proposed to realize a switchable filter.[12–14] A technique based on a phase modulator and two tunable optical bandpass filters (TOBFs) was proposed. The switchable transfer function is realized by adjusting two TOBFs, which is complex.[12] A technique based on a 2×1 Mach–Zehnder modulator (MZM) to generate two 180-deg RF phase difference modulated optical signals was proposed.[13] However, it needs two optical sources, and it cannot realize the frequency tunability. A technique based on stimulated Brillouin scattering has been proposed.[14] However, the structure is complex and costly due to using a common MZM, a dual-drive MZM, and an RF generator.

Recently, polarization modulator (PolM) has shown many advantages in microwave photonic processing due to the inherent special characteristics of supporting both transverse electric (TE) and transverse magnetic (TM) modes with opposite phase-modulation indices,[15,16] for instance, any microwave photonic signal processing based on phase modulation and intensity modulation can be realized based on the polarization modulation,[15,16] and the two modulation schemes can be implemented simultaneously.[16] In this paper, a reconfigurable filter based on a PolM is proposed and demonstrated. The PolM incorporating with a polarization controller (PC) and a polarization beam splitter (PBS) generates two 180-deg RF phase difference modulated optical signals in two separated branches. In one branch, an amplified recirculating delay line (RDL) loop achieves a bandpass filter; in the other branch, the directly passed signal achieves an allpass filter. When the two branches are combined by a second PBS, a filter with a frequency response that equals to the subtraction of the frequency responses of the allpass filter and bandpass filter is achieved. By adjusting the PCs placed before the second PBS, a notch filter with a tunable notch depth or a bandpass filter can be achieved.

2 Operation Principle

The schematic diagram of the proposed microwave photonic filter is shown in Fig. 1. A light wave from a laser diode (LD) is sent to a PolM. The PolM is a special phase modulator that can support both TE and TM modes with opposite phase-modulation indices.[15,16] When a linearly polarized incident light is oriented at an angle of 45 deg to one principal axis of the PolM by adjusting a PC (PC1), complementary phase-modulation signals are generated along two principal axes. The PolM incorporating with a PC (PC2) and a PBS implements two intensity-modulated optical signals with 180-deg RF phase difference in two branches. In the upper branch, the intensity-modulated signal is coupled into an RDL loop, comprising an optical coupler (OC), an erbium-doped fiber amplifier (EDFA), and a TOBF. The EDFA is used to compensate the loss of the RDL loop; however, the effective gain of the RDL loop should be less than

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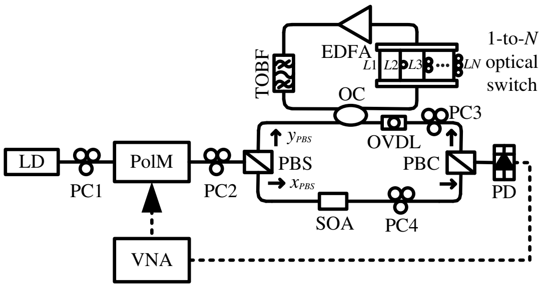

Fig. 1 Schematic diagram of the proposed microwave photonic filter.

one to avoid the lasing condition. The intensity-modulated signal circulating in the RDL loop realizes a bandpass filter. The bandpass frequency is determined by the RDL loop length. Therefore, the frequency tuning can be implemented by inserting two 1-to-N optical switches connected with different length of fiber in each port inside the RDL loop, as shown in Fig. 1. In the lower branch, the intensity-modulated signal passes through a section of delay line with a semiconductor optical amplifier (SOA) and a PC4 and only realizes an allpass filter. The two optical branches are combined by a polarization beam combiner (PBC). Since the two optical signals are with 180-deg RF phase difference, the bandpass filter and the allpass filter are subtracted after photodetection. The optical variable delay line (OVDL) in the upper branch is used to ensure that the delay times in the two branches are equal. PC3 is used to control the on–off state of the bandpass filter, i.e., when the polarization direction of light wave in the upper branch is aligned with one principal axis of the PBC, the bandpass filter is on; on the other hand, when the polarization direction is controlled to be vertical with the same principal axis of the PBC by adjusting PC3, the bandpass is off. For the same principle, PC4 is used to control the on–off state of the allpass filter. When the bandpass filter is off, and the allpass is on, the proposed filter operates as an allpass filter. When the bandpass filter is on, adjusting PC4 to control the on–off state of the allpass filter, the proposed filter can be switched between the bandpass filter and the notch filter. The SOA is used to balance the two signal powers in the two branches to achieve the maximum notch depth. On the other hand, the notch depth is reduced if the two signal powers are not equal. Thus, the notch depth can be tuned by adjusting PC4 to vary the power difference between the two branches.

When a linearly polarized incident light is oriented at an angle of 45 deg to one principal axis of the PolM, the normalized optical field at the output of the PolM along the two principal axes can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} e^{(j\omega_c t + j\beta \sin \omega_m t/2)} \\ e^{(j\omega_c t - j\beta \sin \omega_m t/2)} \end{bmatrix}, \tag{1}$$

where ω_c is the angular frequency of the optical carrier, ω_m is the angular frequency of the microwave signal, $\beta = \pi V_{RF}/V_\pi$, and V_π is the half-wave voltage.

When one principal axis of the PBS is oriented at an angle of α to one principal axis of the PolM, we obtain

$$\begin{aligned} E_1 &= \sin \alpha E_x + \cos \alpha E_y e^{-j\phi} \\ &= e^{j\omega_c t}(\sin \alpha e^{j\beta \sin \omega_m t/2} + \cos \alpha e^{(-j\beta \sin \omega_m t/2 - j\phi)}), \end{aligned} \tag{2}$$

$$\begin{aligned} E_2 &= \cos \alpha E_x - \sin \alpha E_y e^{-j\phi} \\ &= e^{j\omega_c t}(\cos \alpha e^{j\beta \sin \omega_m t/2} - \sin \alpha e^{(-j\beta \sin \omega_m t/2 - j\phi)}), \end{aligned} \tag{3}$$

where ϕ is the phase difference between E_x and E_y, which can be changed by adjusting the DC bias of the PolM or PC1 before the PolM.

The optical powers at the two outputs of the PBS are given by

$$P_1 = |E_1|^2 = E_1 E_1^* = 1 + \sin 2\alpha \cos(\beta \sin \omega_m t + \phi), \tag{4}$$

$$P_2 = |E_2|^2 = E_2 E_2^* = 1 - \sin 2\alpha \cos(\beta \sin \omega_m t + \phi). \tag{5}$$

Applying the Jacobi–Anger expansion to Eqs. (4) and (5), under a small-signal modulation condition, Eqs. (4) and (5) can be simplified as

$$\begin{aligned} P_1 = 1 &+ \sin 2\alpha J_0(m) \cos \phi \\ &- 2 \sin 2\alpha J_1(m) \sin \omega_m t \sin \phi, \end{aligned} \tag{6}$$

$$\begin{aligned} P_2 = 1 &- \sin 2\alpha J_0(m) \cos \phi \\ &+ 2 \sin 2\alpha J_1(m) \sin \omega_m t \sin \phi, \end{aligned} \tag{7}$$

where $J_i(\cdot)$ with $i = 0, 1$ are the first kind Bessel functions.

When $\phi = \pi/2$, $\alpha = \pi/4$

$$P_1 = 1 - 2J_1(m) \sin \omega_m t, \tag{8}$$

$$P_2 = 1 + 2J_1(m) \sin \omega_m t. \tag{9}$$

The overall filter transfer function can be written as

$$H(\omega) = K\left\{g' \cos \theta - \cos \gamma \left[\kappa + \frac{(1-\kappa)^2 g e^{-\omega_m T}}{1 - \kappa g e^{-\omega_m T}}\right]\right\}, \tag{10}$$

where $K = 2J_1(m)$, g' is the gain of the SOA, θ is the angle between the polarization direction of the light wave in the lower branch and one principal axis of the PBC, γ is the angle between the polarization direction of the light wave in the upper branch and the other principal axis of the PBC, κ is the OC coupling ratio, g is the gain of the EDFA, $T = (nL)/c$ is the delay time corresponding to the RDL loop length that is used to set the filter center frequency, n is the fiber refractive index, and c is the speed of light in vacuum.

Adjusting PC3, PC4, and the gain of the SOA to ensure

$$g' \cos \theta = \cos \gamma \left[\kappa + \frac{(1-\kappa)^2 g}{1 - \kappa g}\right]. \tag{11}$$

A notch filter response with a maximum notch depth is achieved. Since the notch depth depends on the power difference between the two branches, the notch depth can be tuned by adjusting PC4 to change the power difference between the two branches when PC3 is fixed.

3 Experimental Setup

An experiment based on the setup shown in Fig. 1 is carried out. In the experiment, a light wave from a tunable laser source with a wavelength of 1565.5 nm is sent to a PolM (JGKB, PL-40G-3-1550) with a half-wave voltage of 3.5 V. The electrically driven signal to the PolM is a sweeping RF signal generated by a 50-GHz vector network analyzer (VNA; Agilent N5245A). The power of the RF signal is 10 dBm, which ensures small-signal modulation. A TOBF (Yenista XTM-50) with an edge slope of more than 500 dB/nm and a top flatness of 0.2 dB is incorporated to reduce the amplified spontaneous emission noise of the EDFA. A PBS with a polarization extinction ratio of more than 35 dB serves as a power splitter. A PC2 is used to adjust the angle between the principal axis of the PolM and the principal axis of the PBS. The PBC is realized by the other PBS. A PD (New Focus10058B, 40 GHz) with a responsivity of 0.65 A/W is used to perform optical-to-electrical conversion. By adjusting PC3 and PC4, different filter response can be obtained, and the frequency response is measured by the VNA.

4 Experimental Results and Discussion

When the bandpass filter is off by adjusting PC3 and the allpass filter response is on by adjusting PC4, an allpass filter response is obtained, as shown in Fig. 2(a). In this case, the filter operates as a fiber-optic link. When the bandpass filter is on and the allpass filter is off, a bandpass filter response is obtained, as shown in Fig. 2(b). The total length of the RDL loop is about 34.5 m, which yields a free spectrum range (FSR) of about 6 MHz, and the 3-dB bandwidth is about 0.36 MHz. Thus, the Q factor is about 17. The rejection ratio is about 20 dB. When both the bandpass filter and the allpass filter are on, a notch filter response is obtained. With the two principal axes of the PBS aligned with the two principal axes of the PBC, respectively, and adjusting the gain of the SOA to make allpass filter power equal the bandpass filter power, a notch filter with a maximum notch depth is obtained, as shown in Fig. 2(c). The notch depth is about 35 dB, and the 3-dB bandwidth is about 0.30 MHz. Excellent agreement can be seen between the measured and simulated frequency response characteristics, as shown in Fig. 2. By varying the gain of the EDFA, the passband width and the stopband width of the filters could be changed.

The frequency tuning is demonstrated by inserting different lengths of fiber inside the RDL loop. Three different center frequencies for the bandpass filter and notch filter responses are obtained, as shown in Fig. 3. As can be seen, with the length of the fiber inserted in the RDL loop increased, the center frequency is shifted to the left. Since the notch depth is determined by the power difference between the two branches, the notch depth can be tuned by adjusting the polarization direction of PC4 to change the power of the allpass filter while the gain of the SOA and power of the bandpass filter are maintained. Adjusting PC4 to make θ increase, the allpass power is reduced; as a result, the notch depth is reduced, as shown in Fig. 4. The FSR is small due to long fiber pigtails of the optical components in the RDL loop, and the FSR can be further increased by reducing the length of the RDL loop in practical application.

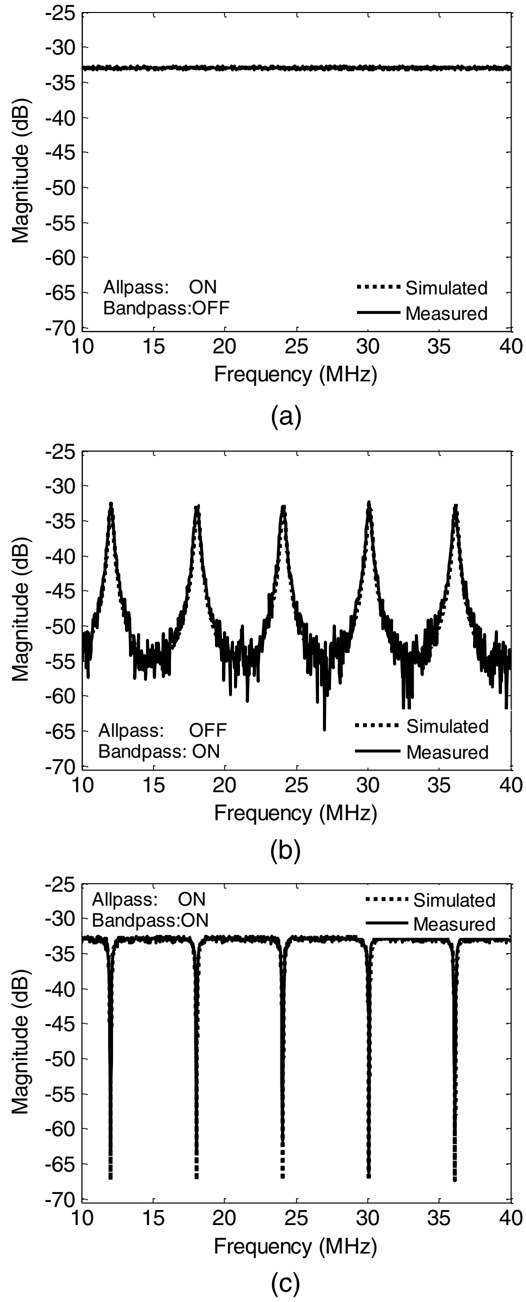

Fig. 2 Frequency responses: (a) allpass filter, (b) bandpass filter, and (c) notch filter.

From Fig. 2, it can be seen that the insertion loss is about 30 dB. Such a high insertion loss is mainly caused by the poor power handling capability of the PD. In this experiment, the average input optical power to the PD is attenuated to be about −1 dBm. By using a high-power handing PD, the insertion loss can be greatly reduced. Since the polarization directions of the optical light waves from the two branches are orthogonal after multiplexing, they would not interfere with each other, greatly reducing the instability of the filter. The instability is mainly a result of the environmental changes since the system is implemented using discrete fiber-optic components in a lab environment. The instability can be reduced if the system is well packaged or it is implemented using a photonic integrated circuit. In addition, the

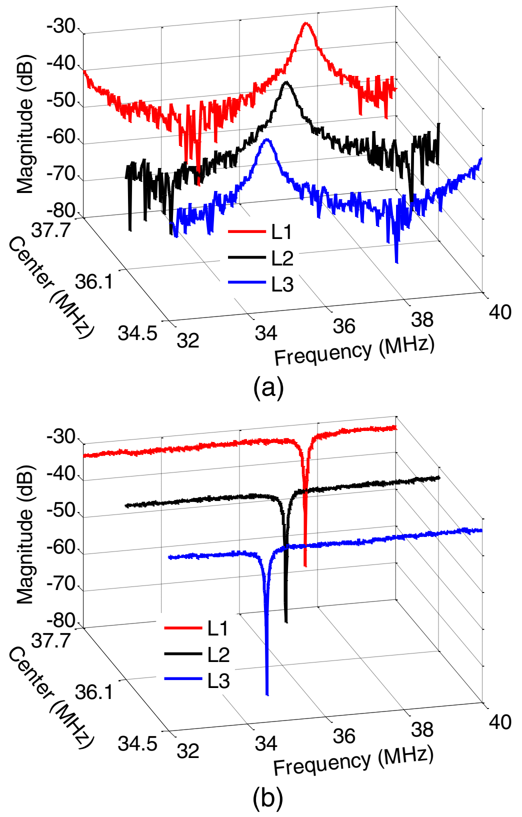

Fig. 3 Frequency tuning: (a) bandpass filter and (b) notch filter.

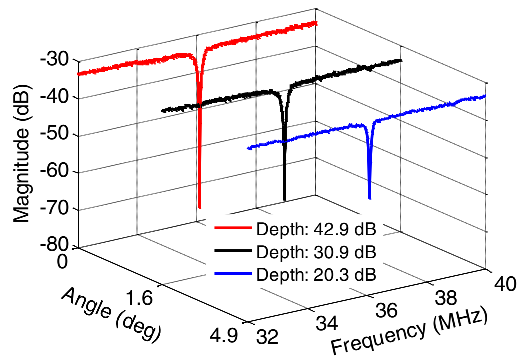

Fig. 4 Notch depth is tuned by adjusting PC4.

proposed filter structure can simultaneously implement a bandpass filter response and a notch filter response at different output ports.

5 Conclusion

A reconfigurable microwave photonic filter based on a PolM has been presented and demonstrated. The PolM incorporating with a PC and a PBS implemented two complementary intensity modulations in two separated branches. A RDL loop in the upper branch achieved a bandpass filter, and the directly passed signal in the lower branch achieved an allpass filter. The bandpass filter and the allpass filter are combined by a second PBS to realize the subtraction. By adjusting PC3 and PC4 to control the on–off states of the allpass filter and bandpass filter, respectively, the allpass filter response, the bandpass filter response, and notch filter response were obtained. The frequency tuning could be implemented by inserting two 1-to-N optical switches connected with different length of fiber in each port inside the RDL loop. The notch depth could be tuned by tuning PC4 to change the power difference between the two branches. In addition, the proposed filter structure could simultaneously implement a bandpass filter response and a notch filter response at different output ports.

Acknowledgments

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