Tunable Dual-Passband Microwave Photonic Filter Using Orthogonal Polarization Modulation

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***Abstract*— A microwave photonic filter (MPF) with two independently tunable passbands using a polarization modulator (PolM) and a phase-shifted fiber Bragg grating (PS-FBG) is proposed and experimentally demonstrated. By applying two orthogonally polarized optical waves from two tunable laser sources (TLSs) to the PolM, two phase-modulated optical signals that are orthogonally polarized are generated, which are sent to the PS-FBG that acts as an optical notch filter to suppress one sideband of the orthogonally polarized phase-modulated signals. Thus, the two phase-modulated signals are converted to two intensity-modulated single-sideband signals. The overall operation corresponds to a dual-passband MPF with the central frequencies of the two passbands independently tunable by changing the wavelengths of the optical carriers from the two TLSs. The proposed MPF is experimentally evaluated. A dual-passband MPF with a bandwidth for each passband of 140 MHz and a frequency tunable range of ∼6 GHz is demonstrated. The insertion loss and the dynamic range of the filter are also studied and measured experimentally.**

***Index Terms*— Microwave photonic filter, two passband filter, polarization modulator, phase-shifted fiber Bragg grating.**

I. INTRODUCTION

PROCESSING of microwave signals in the optical domain with the advantageous features such as broad bandwidth, large tunability and reconfigurability has been a topic of interest for the past few years [1], [2]. Among the many functions, frequency-tunable bandpass filtering is one major function that is widely used in modern radar, communications and warfare systems [3]. A bandpass microwave photonic filter (MPF) can be realized using a delay-line structure with a finite impulse response (FIR) [4]. However, the spectral response of an FIR delay-line filter is periodic with multiple passbands due to the discrete nature of the configurations. In addition, to avoid optical interferences which are extremely sensitive to environmental changes, an MPF with a delay-line structure should be implemented in the incoherent regime. On the other hand, an MPF can be implemented in the coherent regime if no delay-line structure is employed. For example, a single bandpass MPF was implemented using a phase modulator (PM) and an optical filter. By using the optical filter to remove one of the sidebands, the phase-modulated signal is converted to an intensity-modulated signal. The operation is equivalent to translating the spectral response of the optical filter to the electrical domain. The optical filter can be a ring resonator [5], two cascaded fiber Bragg gratings (FBGs) [6] or a phase-shifted fiber Bragg grating (PS-FBG) [7]. For some applications, a microwave filter with two passbands is needed [8]. For example, a microwave filter with two passbands at 2.4 and 5 GHz can be used in a Wi-Fi system to select the two bands of Wi-Fi signals. Recently, we demonstrated a dual-passband MPF using a PM and an equivalent phase-shifted fiber Bragg grating (EPS-FBG) [9]. The EPS-FBG has two notches at the $\pm1^{st}$ channels which are used to implement phase-modulation to intensity-modulation (PM-IM) conversion. The central frequencies of the two passbands can be tuned independently by changing the wavelengths of the two TLSs. The major problem of the approach in [9] is the wavelength spacing of the two wavelengths is small and the beating of the two wavelengths may generate a microwave signal falling in the frequency band of interest. To increase the wavelength spacing, the EPS-FBG must be designed to have a large wavelength spacing between the $\pm1^{st}$ channels, which required a high spatial sampling frequency, making the design more complicated.

In this letter, we propose and experimentally demonstrate a novel MPF with two independently tunable passbands using a polarization modulator (PolM) and a PS-FBG with a single notch. The PolM is a special PM that supports phase modulations along the two principal axes with opposite modulation indices. If two wavelengths from two TLSs that are orthogonally polarized are modulated at the PolM, two orthogonally polarized phase-modulated signals are generated. For one polarization direction, if one sideband is filtered out by the notch of the PS-FBG, a single passband MPF is implemented. The use of the two polarization directions would lead to the implementation of an MPF with two passbands. Due to the polarization orthogonality, the two wavelengths will not beat at the PD, thus no beat signal is generated. The proposed approach is experimentally studied. A dual-passband MPF with a bandwidth for each passband of 140 MHz and a microwave frequency tunable range of about 6 GHz is

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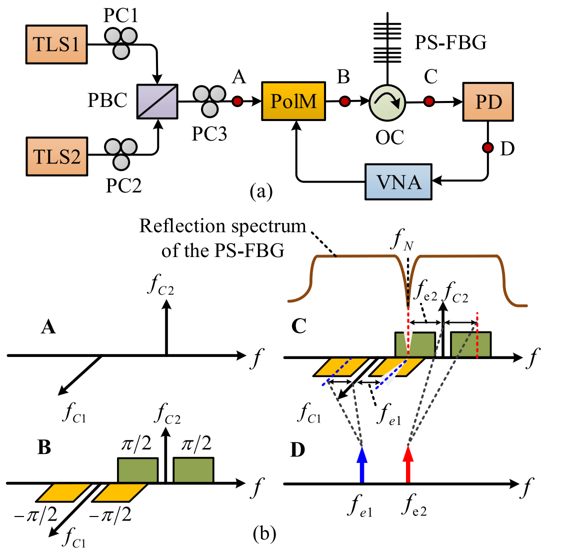


Fig. 1. (a) The schematic of the proposed MPF. (b) The spectra at A, B, C in the optical domain and D in the electrical domain. TLS, tunable laser source; PC, polarization controller; PBC, polarization beam combiner; PolM, polarization modulator; OC, optical circulator; PS-FBG, phase-shifted fiber Bragg grating; PD, photodetector; VNA, vector network analyzer.

demonstrated. The insertion loss and the dynamic range of the filter are also studied and measured experimentally.

II. Operation Principle

Figure 1(a) shows the schematic diagram of the proposed MPF. Two light waves at f_{C1} and f_{C2} from two TLSs (TLS1 and TLS2) that are orthogonally polarized achieved by using two polarization controllers (PC1 and PC2) are combined at a polarization beam combiner (PBC), and then sent to a PolM through a third PC (PC3). The PolM is a special phase modulator that supports both TE and TM modes with opposite phase modulation indices [10]. The polarization directions of the two orthogonally polarized light waves are aligned with the two principal axes of the PolM by adjusting PC3. A microwave signal $V_e \cos(2\pi f_e t)$ is applied to the PolM, where V_e is the amplitude and f_e is the frequency of the microwave signal. Two phase-modulated signals are obtained at the output of the PolM, and sent to the PS-FBG via an optical circulator (OC). For each phase modulated signal, one sideband is removed by the notch of the PS-FBG, and the phase-modulated signal is converted to an intensity-modulated signal, and then detected at a PD. The entire operation is equivalent to a bandpass MPF with the central frequency equal to the wavelength difference between the optical carrier and the notch of the PS-FBG. The spectral relationship between the two orthogonally polarized light waves is shown in Fig. 1(b).

The electrical fields of the phase-modulated signals at the output of the PolM along the two principal axes can be expressed as

$$\begin{bmatrix} E_{PolM,out,x}(t) \\ E_{PolM,out,y}(t) \end{bmatrix} = \begin{bmatrix} E_1 e^{[j2\pi f_{C1}t + jm\cos(2\pi f_e t) + j\varphi_0]} \\ E_2 e^{[j2\pi f_{C2}t - jm\cos(2\pi f_e t)]} \end{bmatrix} \quad (1)$$

where E_1 and E_2 are the amplitudes of the two light waves along the two principal axes of the PolM, respectively; φ_0 is the initial phase difference between the two light waves, $m = \pi V_e/V_\pi$ is the modulation index and V_π is the half-wave voltage of the PolM.

Assuming small signal modulation, and $\varphi_0 = 0$, $E_1 = E_2 = E_0$, (1) can be written with the Jacobi–Anger expansions as [11],

$$\begin{bmatrix} E_{PolM,out,x}(t) \\ E_{PolM,out,y}(t) \end{bmatrix} \approx \begin{bmatrix} -J_{-1}(m)\, e^{[j2\pi(f_{C1}-f_e)t]} e^{(j\frac{\pi}{2})} + J_0(m)\, e^{(j2\pi f_{C1}t)} \\ +J_1(m)\, e^{[j2\pi(f_{C1}+f_e)t]} e^{(j\frac{\pi}{2})} \\ -J_{-1}(m)\, e^{[j2\pi(f_{C2}-f_e)t]} e^{(-j\frac{\pi}{2})} + J_0(m)\, e^{(j2\pi f_{C2}t)} \\ +J_1(m)\, e^{[j2\pi(f_{C2}+f_e)t]} e^{(-j\frac{\pi}{2})} \end{bmatrix} \quad (2)$$

where J_0, J_1 and J_{-1} are the 0 and $\pm 1^{\text{st}}$ order Bessel functions of the first kind. As can be seen for each wavelength, the phase-modulated signal has two sidebands with the equal magnitude ($-J_{-1} = J_1$) and out of phase relationship (π or $-\pi$).

The two phase-modulated signals are then fed to the PS-FBG via the OC. The PS-FBG has an ultra-narrow notch in the reflection band. The notch is formed by introducing a π phase shift during the fabrication process [12]. Since the PS-FBG is fabricated in a single-mode fiber, the polarization states of the two phase-modulated signals will be maintained when reflected from the PS-FBG. For one polarization direction, one sideband of the phase-modulated signal along that polarization direction will be filtered out and the phase-modulated signal is converted to an intensity-modulated signal. After photodetection at the PD, a microwave signal with its frequency equal to the wavelength difference between the optical carrier and the notch is recovered. For the other polarization direction, a second microwave signal is recovered. The overall operation is equivalent to an MPF with two passbands, with the central frequencies of the two passbands being determined by the frequency difference between the optical carriers and the notch. Therefore, independent tuning of the central frequency of one passband can be done by changing the wavelength of the optical carrier from TLS1 or TLS2. Although the wavelengths of the two light waves from the two TLSs can be very close, due to the polarization orthogonality of the two light waves, no beat signal would be generated. This is the key advantage of the proposed approach which provides higher flexibility in frequency tuning of the MPF.

III. Experiment

An experiment based on the configuration shown in Fig. 1(a) is performed. Two light waves from TLS1 (YOKOGAMA AQ2200) and TLS2 (Agilent N7714A), both with a power of 9 dBm, are polarization multiplexed at the PBC and sent to the PolM (Versawave, 40 GHz, $V_\pi = 3.5$ V) through PC3. By adjusting PC1 and PC2, the polarization directions of two light waves are orthogonally polarized, and by tuning PC3, the polarization directions of the two light waves are aligned with the two principal axes of the PBC. A microwave signal from a VNA (Agilent E8364A) is applied to the PolM via the RF port. The phase-modulated signals are sent to the PS-FBG via the OC and reflected to the PD (New Focus, 20 GHz) for optical-to-electrical conversion. The total power

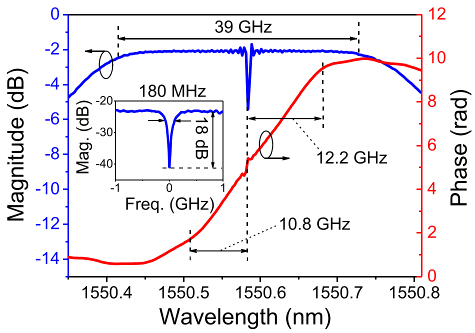


Fig. 2. The measured magnitude and phase responses of the PS-FBG.

of the two optical signals to the PD is 0 dBm. The generated electrical signal from the PD is sent back to the VNA for frequency response measurement.

The key device in the proposed MPF is the PS-FBG which is fabricated by UV illumination using a uniform phase mask. By introducing a π phase shift in the center of the FBG, an ultra-narrow passband is produced. Fig. 2 shows the magnitude and phase responses of the PS-FBG (in reflection) measured with an optical vector analyzer (LUNA) with a resolution of about 1.6 pm. The notch wavelength is 1550.588 nm and the 1-dB reflection bandwidth is about 39 GHz. In order to implement PM-IM conversion, the two sidebands of the phase-modulated signals should be within the linear phase response range to maintain their out of phase relationship generated by the PolM in the modulation process. The linear phase response region of the PS-FBG is about 23 GHz and is not symmetric relative to the notch wavelength, with the right section of about 12.2 GHz and the left section of about 10.8 GHz. The linear phase response ranges determine the maximum microwave frequency tunable ranges of the two passbands by changing the wavelength of TLS1 and TLS2. The inset in Fig. 2 gives a zoom-in view of the spectrum centered at the notch wavelength measured by a high-resolution method using single-sideband modulation [13]. The notch bandwidth is about 180 MHz and the rejection ratio is about 18 dB.

By incorporating the fabricated PS-FBG into the configuration in Fig. 1(a), a dual-passband MPF is implemented. In the experiment, the wavelengths of two light waves from TLS1 and TLS2 are set at 1550.600 and 1550.560 nm, respectively, located at the right and left side of the notch wavelength (1550.588 nm) of the PS-FBG. The frequency of the microwave signal from the VNA is swept from 0 to 6.5 GHz while maintaining a fixed power. The measured frequency response of the MPF is shown in Fig. 3. It can be seen that two passbands with the central frequencies at 1.5 and 3.5 GHz are produced and no beat signal (near 5 GHz) between the two optical carriers is observed. It demonstrates that the orthogonality of the two optical carriers guarantees the independence of the two passbands. The 3-dB bandwidth of each passband is about 140 MHz.

The frequency tunability of the MPF is then investigated. First, the 2nd passband with a central frequency of about 0.53 GHz is kept unchanged, and the 1st passband is tuned by changing the wavelength of TLS1 with a tuning step of 0.005 nm. The measured results are shown in Fig. 4(a).

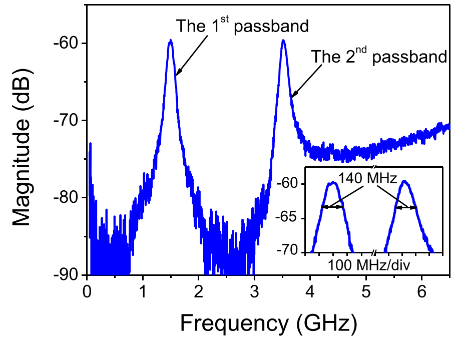
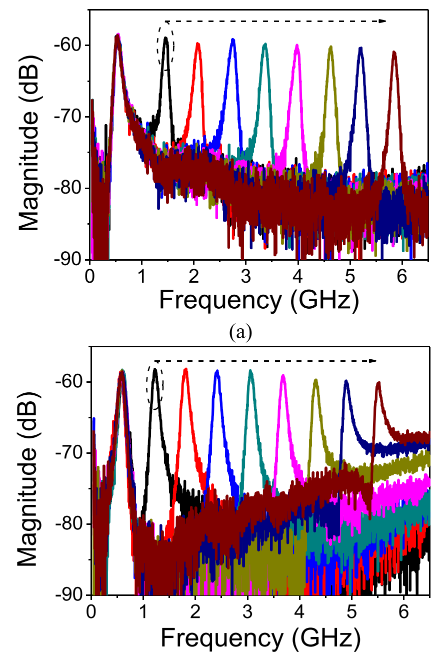


Fig. 3. Spectral response of the MPF. The two passbands are at 1.5 and 3.5 GHz without the beat signal near 5 GHz. The inset is the zoom-in view of the two passbands.



(b)

Fig. 4. The tuning of the frequency response of the MPF. (a) The 2nd passband is kept unchanged, and the 1st passband is tuned. (b) The 1st passband is kept unchanged, and the 2nd passband is tuned.

As can be seen, the central frequency of the 1st passband is changed from 1.45 to 5.95 GHz. Then, the 1st passband with a central frequency of about 0.58 GHz is kept unchanged, and the 2nd passband is tuned by tuning the wavelength of TLS2 with a tuning step of -0.005 nm. As can be seen, the central frequency of the 2nd passband is changed from 1.22 to 5.58 GHz. From Fig. 4, it can be seen that the central frequencies of the two passbands can be tuned independently within about 6 GHz by changing the wavelength of TLS1 or TLS2.

Note that during the tuning process, due to the nonlinear phase response of the PS-FBG near the two edges of the reflection band, the phase relationship between the two sidebands of a phase-modulated signal may not be always maintained, which may lead to the higher sidelobes of the passband. For example, as shown in Fig. 4(b), the highest sidelobe of the 2nd passband increases when the frequency approaches to 6 GHz. Therefore, to maintain a large ratio of the transmission peak to the sidelobe, the tunable range should be

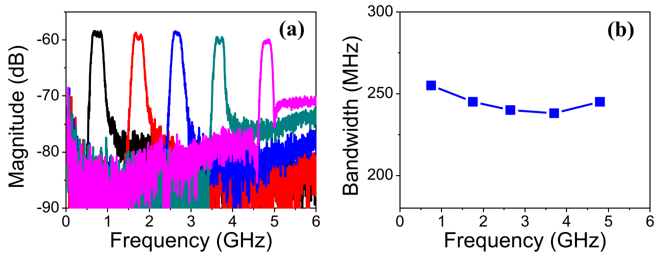


Fig. 5. (a) The frequency response of the MPF with a broadened bandwidth. (b) The 3-dB bandwidth of the passband.

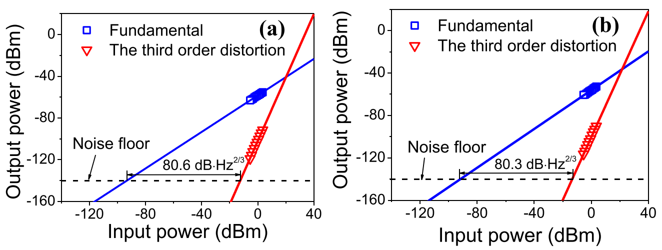


Fig. 6. The measured fundamental power and the third order intermodulation power for the (a) 1st passband and (b) 2nd passband of the MPF.

controlled within the linear region of the phase response of the PS-FBG. In the experiment, the right section with a width of about 12.2 GHz is used for the 1st passband, which leads to a maximum frequency tunable range of about 6.1 GHz, and the left section with a width of about 10.8 GHz is used for the 2nd passband, which leads to a maximum frequency tunable range of about 5.4 GHz. A broader frequency tuning range can be obtained by using a PS-FBG with a larger linear phase response range [7].

For some applications, a bandpass filter with a tunable passband width is also needed [8]. For the proposed MPF, if the two optical carriers are located close to each other, the two passbands will merge and the MPF becomes a single passband filter. The width of the passband can be tuned by tuning the wavelengths of the two optical carriers. Fig. 5 shows a measured frequency response of the MPF having a passband with a tunable width. It can be seen that the bandwidth of the MPF is broadened to be about 245 MHz by adjusting the two wavelengths with a wavelength spacing of 0.001 nm. When further increasing the wavelength spacing, the passband width will increase, but the flatness of the top of the passband will become poor.

The spurious-free dynamic range (SFDR) is an important performance measure for an MPF, which describes the range of microwave signal power that can be accommodated, taking into account the effects of noise and nonlinear distortions [9]. The 1st and 2nd passbands at 1.5 and 3.5 GHz, respectively, are chosen to characterize the SFDR. For the passband at 1.5 GHz, a two-tone microwave signal, at 1.5 and 1.51 GHz is applied to the MPF. The output fundamental signal and the third-order intermodulation (IMD3) term when the input two-tone signal is increased from −5.5 to 3.5 dBm are measured and the results are shown in Fig. 6(a). The measured SFDR for the 1st passband is 80.6 dB·Hz$^{2/3}$ for a noise floor of −140 dBm/Hz. The SFDR for the 2nd passband with a two-tone microwave signal at 3.5 and 3.51 GHz is also measured which is 80.3 dB·Hz$^{2/3}$ as shown in Fig. 6(b).

The insertion loss of the filter is −58 dB, which is very high. A solution to reduce the insertion loss is to use a high power handling PD. It was reported that a PD with an input power greater 30 dBm is now available [13]. If such a PD is used, the insertion loss of the filter will be greatly reduced by using an optical amplifier to increase the optical power to the PD.

IV. Conclusion

An MPF with two independently tunable passbands by using a PolM and a PS-FBG has been proposed and demonstrated. The PS-FBG was employed to suppress one sideband of a phase-modulated signal from the PolM, to convert a phase-modulated signal to an intensity-modulated signal. The entire operation is equivalent to a bandpass filter. Due to the use of two orthogonally polarized optical carriers, an MPF with two passbands was realized and the passband frequencies could be independently tuned by tuning the wavelengths of the two optical carriers. The proposed MPF was experimentally investigated. A dual passband MPF with a bandwidth for each passband of 140 MHz and a frequency tunable range of about 6 GHz was experimentally demonstrated.

References

[1] R. A. Minasian, "Photonic signal processing of microwave signals," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 2, pp. 832–846, Feb. 2006.
[2] J. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 1, 2009.
[3] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, "Microwave photonic signal processing," *J. Lightw. Technol.*, vol. 31, no. 4, pp. 571–586, Feb. 15, 2013.
[4] B. Vidal, T. Mengual, C. Ibanez-Lopez, and J. Marti, "WDM photonic microwave filter with variable cosine windowing based on a DGD module," *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2272–2274, Nov. 1, 2006.
[5] J. Palací, G. E. Villanueva, J. V. Galán, J. Martí, and B. Vidal, "Single bandpass photonic microwave filter based on a notch ring resonator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 17, pp. 1276–1278, Sep. 1, 2010.
[6] X. Yi and R. A. Minasian, "Microwave photonic filter with single bandpass response," *Electron. Lett.*, vol. 45, no. 7, pp. 362–363, Mar. 2009.
[7] W. Li, M. Li, and J. Yao, "A narrow-passband and frequency-tunable microwave photonic filter based on phase-modulation to intensity-modulation conversion using a phase-shifted fiber Bragg grating," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 5, pp. 1287–1296, May 2012.
[8] G. Chaudhary, Y. Jeong, and J. Lim, "Dual-band bandpass filter with independently tunable center frequencies and bandwidths," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 107–116, Jan. 2013.
[9] L. Gao, J. Zhang, X. Chen, and J. Yao, "Microwave photonic filter with two independently tunable passbands using a phase modulator and an equivalent phase-shifted fiber Bragg grating," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 2, pp. 380–387, Feb. 2014.
[10] J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, "40-GHz electro-optic polarization modulator for fiber optic communications systems," *Proc. SPIE*, vol. 5577, pp. 133–143, Dec. 2004.
[11] H. Chi, X. Zou, and J. Yao, "Analytical models for phase-modulation-based microwave photonic systems with phase modulation to intensity modulation conversion using a dispersive device," *J. Lightw. Technol.*, vol. 27, no. 5, pp. 511–521, Mar. 1, 2009.
[12] T. Erdogan, "Fiber grating spectra," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1277–1294, Aug. 1997.
[13] Z. Tang, S. Pan, and J. Yao, "A high resolution optical vector network analyzer based on a wideband and wavelength-tunable optical single-sideband modulator," *Opt. Exp.*, vol. 20, no. 6, pp. 6555–6560, Mar. 2012.
[14] E. Rouvalis *et al.*, "High-power and high-linearity photodetector modules for microwave photonic applications," *J. Lightw. Technol.*, vol. 32, no. 20, pp. 3810–3816, Oct. 15, 2014.