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Performance-improved microwave photonic single-passband filter using birefringence of phase-shifted fiber Bragg grating

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ABSTRACT

A novel microwave photonic single-passband filter with an improved out-of-band rejection and an extended frequency tuning range is proposed and demonstrated, which is achieved by using birefringence of a phase-shifted fiber Bragg grating (PSFBG). If two polarization states of two phase-modulated signals with opposite modulation indices from a polarization modulator (PolM) are controlled to be aligned with two principal axes of the polarization-maintaining PSFBG (PM-PSFBG), respectively, two single-passband or two single-notch filters with slight frequency interval are achieved, depending on the position of the optical carrier relative to the notches of the PM-PSFBG. Through subtraction of the two filters, the out-of-band rejection is significantly improved, and the frequency tuning range is greatly extended. Analytical simulations are performed using an established theoretical model, which are verified by an experiment.

1. Introduction

Over the past few decades, microwave photonic filters have been widely investigated thanks to broad bandwidth, insensitivity to electromagnetic interference, flexible tunability, and reconfigurability [1–4]. Of the filters, the highly required is a single-passband filter since it can overcome the limitation of a periodic frequency response implemented by a delay-line-based filter [5,6]. A variety of approaches have been proposed for implementing single-passband filters [7–22]. The approaches can be mainly classified into two categories. One is based on a sliced [7–9] or non-sliced [10–12] broadband source in combination with a dispersive element. The limitation for this category is that the broadband source is usually a non-communicational source and the dispersive component is usually a kilometers long optical fiber. The other is based on phase modulation to intensity modulation conversion [13–22]. The conversion can be achieved by many techniques. One technique is the use of stimulated Brillouin scattering; however, it is complicated because a pump source and a dispersive component are required [13,14]. Another technique is based on a semiconductor device, such as Fabry–Pérot semiconductor optical amplifier (FP-SOA) [15], distributed-feedback SOA (DFB-SOA) [16], or FP laser diode (FP-LD) [17]. However, due to the use of the active component, the filter has a poor stability and low out-of-rejection ratio. Although the out-of-band rejection ratio could be improved with the assistance of one more optical source [18], the cost and complexity are increased. Recently, using a phase-shifted FBG (PSFBG) [19–21] to realize a single-passband filter has drawn an attractive attention thanks to the simple structure. However, the performances, especially the out-of-band rejection and the frequency tuning range, are restricted by the current conventional approach, and can be improved further.

In this work, a single-passband filter based on a PSFBG with small birefringence is proposed. The PSFBG with small birefringence here is also called polarization maintaining PSFBG (PM-PSFBG). Adjusting the polarization state of a light wave to be oriented 45° relative to one principal axis of a PolM, two phase-modulated signals with opposite phase modulation indices along the two orthogonal principal axes are generated. Then the two polarization states of the phase-modulated signals are controlled to be aligned with two orthogonal principal axes of the PM-PSFBG, respectively. After reflection from the PM-PSFBG, two single-passband filters or two single-notch filters with slight frequency interval are realized, depending on the position of the optical carrier relative to the notches of the PM-PSFBG. Since the two filters are out of phase by 180°, the subtraction is performed between either the two single-passband filters or two single-notch filters. Thus, the out-of-band rejection is improved and the frequency tuning range is extended, compared to the conventional filter based on a common phase modulator (PM) and a common PSFBG [19–21]. A theoretical analysis

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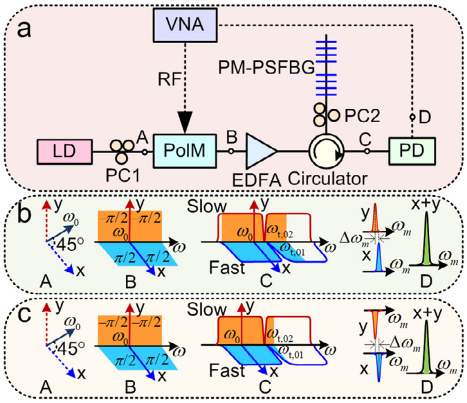

Fig. 1. (a) Block diagram of the proposed single-passband filter; the operation principle for achieving the improved filter through the subtraction of (b) two single-passband filters; (c) two single-notch filters. LD, laser diode; PC, polarization controller; PolM, polarization modulator; EDFA, erbium-doped fiber amplifier; PM-PSFBG, polarization maintaining phase-shifted fiber Bragg grating; PD, photodetector; VNA, vector network analyzer; RF, radio-frequency.

is performed, which is verified by an experiment. The simulated results are in good agreed with the experimental results.

2. Operational principle and theoretical analysis

The configuration and the operation principle of the proposed single-passband filter are depicted in Fig. 1. The proposed filter is composed of a laser diode (LD), a polarization controller (PC1), a PolM, an erbium-doped fiber amplifier (EDFA), a circulator, PC2, a PM-PSFBG with small birefringence and a photodetector (PD). The polarization state of the light wave from the LD is oriented 45° by PC1 with respect to one principal axis of the PolM, driven by a sweeping radio-frequency (RF) signal from a vector network analyzer (VNA), and two phase-modulated signals with opposite phase modulation indices along two principle axes (i.e. x, y) are generated. The modulated signals are amplified in the EDFA and subsequently input to the PM-PSFBG via a circulator, whose orthogonal polarization states are controlled by a second PC (PC2) to be aligned with the fast and slow axes of the PM-PSFBG, respectively. Thanks to the small birefringence existing in the PM-PSFBG, two ultra-narrow notches locating at $\omega_{t,01}$ (fast) and $\omega_{t,02}$ (slow) with slight spectral interval in reflection spectrum are obtained [23]. After reflection from the PM-PSFBG, the conversion from phase modulation to intensity modulation is achieved. Upon photodetection, two conventional single-passband filters or two single-notch filters with slight frequency interval are obtained, which depends on the position of the optical carrier relative to the notches of the PM-PSFBG, as shown in Fig. 1(b) and (c). The frequency interval between the two filters is determined by the spectral interval between the two notches of the PM-PSFBG. Since the phase modulation indices along the two principle axes of the PolM are opposite, and the two notches of the PM-PSFBG are located at the same side of the optical carrier, the realized two filters have a phase difference of 180°. Thus, subtraction between the two filters is performed, through subtraction, the out-of-band rejection is improved, and the frequency tuning range is extended.

Assuming a RF signal denoted as $\cos\omega_m t$ is applied to the PolM, and the polarization state of a light wave is oriented 45° relative to one principal axis of the PolM, the generated two complimentary phase-modulated signals are given by [22]

$$E_{x,y} = E_{in}\exp(\pm j\beta\cos(\omega_m t + \varphi_m)) \tag{1}$$

where $E_{in} = E_0\exp(j\omega_0 t)$, E_0 and ω_0 are the optical field and angular frequency of the LD, respectively; β is the phase modulation index, ω_m and φ_m represent the angular frequency and initial phase of the RF signal, respectively.

With the two polarization states of the two phase-modulated signals aligned with the fast and slow axes of the PM-PSFBG, after reflection, the expansion of the modulated signals under small signal modulation can be written as [20]

$$E_{x,y} = E_{in}\left(\begin{array}{l}\sqrt{r_{01,02}(\omega_0)}J_0(\beta)\exp\left(j\theta_{01,02}(\omega_0)\right)\\ +\sqrt{r_{01,02}(\omega_0+\omega_m)}J_1(\beta)\exp\left[j(\omega_m t+\varphi_m\pm\frac{\pi}{2})\right.\\ \left.+\,j\theta_{01,02}(\omega_0+\omega_m)\right]\\ +\sqrt{r_{01,02}(\omega_0-\omega_m)}J_1(\beta)\exp\left[-j(\omega_m t+\varphi_m\mp\frac{\pi}{2})\right.\\ \left.+\,j\theta_{01,02}(\omega_0-\omega_m)\right]\end{array}\right) \tag{2}$$

where $J_n(\cdot)$ with $n = 0, 1$ are the first kind Bessel functions, r_i and θ_i with $i = 01, 02$ represent, respectively, the reflective coefficient and phase response of the PM-PSFBG [20], which can be obtained using transmission-matrix approach [24], and the subscripts of $i = 01, 02$ denote the fast and slow axes, respectively. As seen from Eq. (2), both the amplitude and the phase of the optical carrier, as well as the sidebands, are changed by the PM-PSFBG, thus achieving phase modulation to intensity modulation conversion.

The overall power of the microwave signals can be expressed by

$$\begin{aligned}P(\omega_m) \propto\; & V_x^2 + V_y^2 - 2A_xA_y\\ & \times\left\{\begin{array}{l}\sqrt{r_{01}(\omega_0+\omega_m)}\left[\sqrt{r_{02}(\omega_0+\omega_m)}\cos(\theta'_{01}-\theta'_{02})\right.\\ \left.-\sqrt{r_{02}(\omega_0-\omega_m)}\cos(\theta'_{01}-\theta''_{02})\right]\\ -\sqrt{r_{01}(\omega_0-\omega_m)}\left[\sqrt{r_{02}(\omega_0+\omega_m)}\cos(\theta''_{01}-\theta'_{02})\right.\\ \left.-\sqrt{r_{02}(\omega_0-\omega_m)}\cos\left(\theta''_{01}-\theta''_{02}\right)\right]\end{array}\right\}\end{aligned} \tag{3}$$

In the above equation, the corresponding parameters are

$$\begin{aligned}V_{x,y}^2 = A_{x,y}^2\cdot & \left[r_{01,02}(\omega_0+\omega_m)+r_{01,02}(\omega_0-\omega_m)\right.\\ & \left.-\,2\sqrt{r_{01,02}(\omega_0+\omega_m)}\sqrt{r_{01,02}(\omega_0-\omega_m)}\cdot\cos(\theta'_{01,02}-\theta''_{01,02})\right]\end{aligned} \tag{4}$$

$$A_{x,y} = 2E_0^2J_0(\beta)J_1(\beta)\sqrt{r_{01,02}(\omega_0)} \tag{5}$$

$$\theta'_i = \varphi_m + \frac{\pi}{2} + \theta_i(\omega_0+\omega_m) - \theta_i(\omega_0) \tag{6}$$

$$\theta''_i = \varphi_m + \frac{\pi}{2} + \theta_i(\omega_0) - \theta_i(\omega_0-\omega_m) \tag{7}$$

Eq. (3) indicates that the proposed filter results from the combination of two filters determined by the shapes and phases of the two slightly separated notches along two principal axes given by the PM-PSFBG. The coherence between the two orthogonal filters is avoided in the optical domain, assuring a stable frequency response. It is noted that the effect induced by the time delay difference between the two filters on the performance-improved filter can be neglected thanks to small birefringence provided by the PM-PSFBG.

Numerical simulations are carried out using the above theoretical model. In the simulations, we select the effective refractive indices $n_{eff,01} = 1.45$, $n_{eff,02} = 1.450001$, and the refractive index modulation depths $\overline{\delta n_{eff,01}} = \overline{\delta n_{eff,02}} = 5.5\times10^{-4}$. Given that the Bragg wavelength of the fiber grating $\lambda_{01} = 1550$ nm is known, λ_{02} can be obtained from $\lambda_{02} = 2n_{eff,02}\Lambda$, Λ is the grating period. The total length of the PM-PSFBG is 8 mm. Two phase shifts are introduced along the fast and slow axes at the middle of the PM-PSFBG, and each phase shift is set at 1.05π. To obtain a smoothing reflection spectrum, the PM-PSFBG is apodized by a sinc function [22]. The simulated reflection spectra of the PM-PSFBG with a high resolution is presented in Fig. 2. As shown in Fig. 2, two ultra-narrow notches are clearly observed, and the two notches are located at about 1550.023 nm and 1550.024 nm, respectively.