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Microwave photonic single-passband filter with highly flexible tunability of bandwidth and frequency

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ABSTRACT

A microwave photonic single-passband filter with highly flexible tunability of bandwidth and frequency is proposed and demonstrated. Two different light waves with their polarizations aligned with two principal axes of a polarization modulator are modulated, and two phase-modulated signals with opposite phase modulation indices are generated. Two different lower parts of the lower sidebands are removed by a fiber Bragg grating to convert two phase-modulated signals into two intensity-modulated signals. Two high-pass frequency responses with different cut-off frequencies are realized. Since the two converted intensity-modulated signals are out of phase, the overlapped frequency responses are cancelled, and a single-passband filter is realized. The bandwidth and the central frequency can be tuned independently by properly adjusting the two wavelengths simultaneously. Furthermore, both the bandwidth and the central frequency can be simultaneously tuned by adjusting one of the two wavelengths.

1. Introduction

Photonic approaches for the processing of microwave and radio frequency signals have attracted significant interest because they have advantages of high bandwidth capability, flexible tunability, light weight and electromagnetic interference immunity [1,2].

Various delay-line based microwave photonic filters have been reported [3,4]; however, due to the discrete nature of the sampling process in the time domain, the frequency response is periodic. If the time delay difference between two adjacent taps is large, which is true for most implementation, especially an implementation using fiber-delay lines, the free spectral range is small, which may make the filter have multiple passbands within the spectral range of interest. Thus, it is highly demanded to implement a microwave photonic filter with only a single passband. Many techniques have been proposed to achieve a single-passband filter [5–17]. A technique based on a sliced broadband source and a long fiber is largely used to achieve single-passband filters [5–8], and a technique based on a phase modulation incorporated with an optical notch filter [9,10], a stimulated Brillouin scattering (SBS) [11,12], or a distributed-feedback semiconductor optical amplifier assisted optical carrier recovery [13] is employed to implement single-passband filters. However, the bandwidth is not adjustable. A technique based on the SBS incorporated with variation of the number of pump spectral lines can achieve a bandwidth adjustment [14–16]. However, an extra arbitrary waveform generator and a dual parallel Mach–Zehnder modulator are needed to control the number of pump spectral lines, which is complex. Recently a simple structure to achieve the bandwidth adjustment by tuning the wavelength of the laser source has been proposed [17]. However, the central frequency is tuned by varying the bandwidth of an optical bandpass filter (OBPF), and the reduction of the bandwidth of the OBPF would have a limitation on the tunable bandwidth range of the single-passband filter.

In this paper, a new simple structure to realize a single-passband filter with highly flexible tunability of bandwidth and frequency is proposed and demonstrated. Two light waves from two different laser diodes (LDs) with their polarizations aligned with two principal axes of the polarization modulator (PolM) are modulated in the PolM, a pair of complementary phase-modulated signals are generated along the two principal axes. Two different lower parts of the lower sidebands are removed by a fiber Bragg grating (FBG), converting two phase-modulated signals into two intensity-modulated signals. Two high-pass frequency responses with different cut-off frequencies are realized after photodetection. Since the two converted intensity-modulated signals are out of phase, the overlapped frequency responses are cancelled, and a single-passband filter is realized. An adjustable bandwidth and a tunable frequency can be achieved

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independently by properly adjusting the two wavelengths simultaneously, and both the bandwidth and the central frequency can be tuned simultaneously by adjusting one of the two wavelengths.

2. Operation principle

The schematic diagram of the proposed microwave photonic single-passband filter is shown in Fig. 1, and the illustration of the principle of the filter is shown in Fig. 2. It consists of two tunable LDs, two polarization controllers (PCs), an optical coupler (OC), a PolM, an FBG and a photodetector (PD). The PolM is a special phase modulator that can support both transverse-electric (TE) and transverse-magnetic (TM) modes with opposite phase modulation indices [18]. If a modulating signal expressed by $\cos\omega_m t$, is applied to the PolM, two optical fields with different wavelengths at the output of the PolM along the two principal axes can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_1 \exp(j\omega_1 t + j\beta\cos\omega_m t) \\ E_2 \exp(j\omega_2 t - j\beta\cos\omega_m t) \end{bmatrix} \tag{1}$$

where E_1 and E_2 are the amplitudes of LD1 and LD2, respectively, ω_1 and ω_2 are the corresponding angular frequencies, ω_m is the angular frequency of the microwave signal, β is the phase modulation index.

Based on the Jacobi-Anger expansion, Eq. (1) can be rewritten as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_1 \exp(j\omega_1 t)(J_0(\beta) + jJ_1(\beta)\exp(j\omega_m t) - jJ_{-1}(\beta)\exp(-j\omega_m t)) \\ E_2 \exp(j\omega_2 t)(J_0(\beta) - jJ_1(\beta)\exp(j\omega_m t) + jJ_{-1}(\beta)\exp(-j\omega_m t)) \end{bmatrix} \tag{2}$$

where $J_i(\cdot)$ with $i = 0, 1$ are the first kind Bessel functions. In Eq. (2), small-signal modulation is assumed so that high order sidebands are ignored. If the phase-modulated signals are beat at the PD, only a dc can be generated because the two first-order sidebands have equal amplitudes and a phase difference of π. If two different lower parts of the two lower sidebands of the complementary phase-modulated signals are removed by the FBG, two optical fields at the output of the FBG can be written as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_1 \exp(j\omega_1 t)\begin{pmatrix} J_0(\beta) + J_1(\beta)\exp j(\omega_m t + \frac{\pi}{2}) \\ +H(\omega_1 - \omega_m)J_{-1}(\beta)\exp\left(-j(\omega_m t + \frac{\pi}{2})\right) \end{pmatrix} \\ E_2 \exp(j\omega_2 t)\begin{pmatrix} J_0(\beta) + J_1(\beta)\exp j(\omega_m t - \frac{\pi}{2}) \\ +H(\omega_1 - \omega_m)J_{-1}(\beta)\exp\left(-j(\omega_m t - \frac{\pi}{2})\right) \end{pmatrix} \end{bmatrix} \tag{3}$$

where $H(\omega_1 - \omega_m)$ and $H(\omega_2 - \omega_m)$ represent the transmission response of the FBG for -1 order optical sidebands of ω_1 and ω_2, respectively. After the square-law detection, the generated microwave component can be written as

$$\begin{aligned} I = |E_x|^2 + |E_y|^2 = E_1^2[1 - H(\omega_1 - \omega_m)]J_0(\beta)J_1(\beta)\cos\left(\omega_m t + \tfrac{\pi}{2}\right) \\ +E_2^2[1 - H(\omega_2 - \omega_m)]J_0(\beta)J_1(\beta)\cos\left(\omega_m t - \tfrac{\pi}{2}\right) \end{aligned} \tag{4}$$

As can be seen from Eq. (4), the generated two microwave signals have a phase difference of π, leading to a destructive combination of the overlapped frequency responses. Thus, a single-passband filter is realized.

Adjusting two optical powers of the two LDs to make $E_1^2 = E_2^2 = E^2$, and applying the Fourier transform to both sides of Eq. (4), the transfer function can be expressed by

$$H(\omega) \propto K[H(\omega_1 - \omega_m) - H(\omega_2 - \omega_m)] \tag{5}$$

where $K = E^2 J_0(\beta)J_1(\beta)$. As can be seen from Eq. (5), the shape of the single-passband filter is mainly determined by the shape of the FBG. A FBG with a steeper edge can make the single-passband filter have a better shape factor.

Since the two orthogonally polarized modulated signals are incoherent, the stability of the single-passband filter is ensured. The time delay difference between two principal axes is ignored due to small wavelength difference and short fiber length. Since the bandwidth of the single-passband filter is determined by the wavelength difference between the two light waves, the bandwidth can be tuned by adjusting the two wavelengths in opposite direction, and the central frequency can be tuned by adjusting the two wavelengths in the same direction. Furthermore, both bandwidth and central frequency can be tuned simultaneously by adjusting one of the two wavelengths.

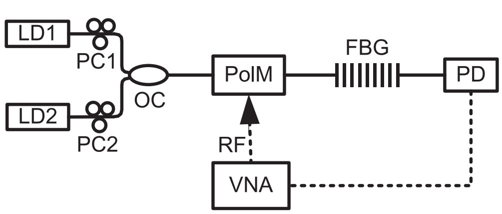

Fig. 1. Schematic diagram of the microwave photonic single-passband filter.

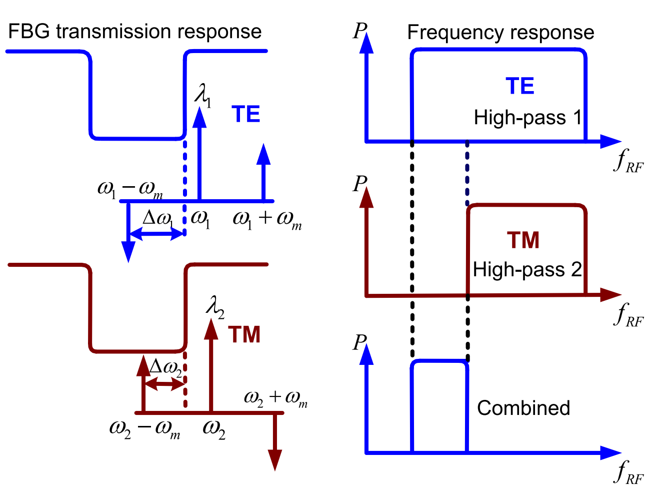

Fig. 2. Illustration of the principle of the microwave photonic single-passband filter.

3. Experimental setup

The experiment setup is shown in Fig. 1. Two light waves from LD1 and LD2 are combined by an OC and then sent into a PolM (JGKB, PL-40G-3-1550). The polarizations of the two light waves controlled by PC1 and PC2 are aligned with the two principal axes of the PolM, which is driven by a microwave sinusoidal signal from a VNA (Agilent E8364A) with a sweeping frequency from 45 MHz to 20 GHz. Two phase-modulated signals with opposite phase modulation indices are generated and sent to a uniform FBG, which is apodized by a sinc function to achieve a steep edge. The apodized FBG has a steep edge with a slope of about 950 dB/nm and a central wavelength of 1553.42 nm. The 30-dB bandwidth is about 0.15 nm, as shown in Fig. 3 (black). Two optical carriers are located on the left side of the FBG, as shown in Fig. 3 (red and blue), so that the lower sidebands are removed. The processed optical signals are sent to a PD, and the frequency response is measured by the VNA.