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A reconfigurable microwave photonic filter with flexible tunability using a multi-wavelength laser and a multi-channel phase-shifted fiber Bragg grating

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ABSTRACT

We propose a photonic scheme to realize a reconfigurable microwave photonic filter (MPF) with flexible tunability using a multi-wavelength laser (MWL) and a multi-channel phase-shifted fiber Bragg grating (PS-FBG). The proposed MPF is capable of performing reconfigurability including single bandpass filter, two independently bandpass filter and a flat-top bandpass filter. The performance such as the central frequency and the bandwidth of passband is tuned by controlling the wavelengths of the MWL. In the MPF, The light waves from a MWL are sent to a phase modulator (PM) to generate the phase-modulated optical signals. By applying a multi-channel PS-FBG, which has a series of narrow notches in the reflection spectrum with the free spectral range (FSR) of 0.8 nm, the $+1^{st}$ sidebands are removed in the notches and the phased-modulated signals are converted to the intensity-modulated signals without beating signals generation between each two optical carriers. The proposed MPF is also experimentally verified. The 3-dB bandwidth of the MPF is broadened from 35 MHz to 135 MHz and the magnitude deviation of the top from the MPF is less than 0.2 dB within the frequency tunable range from 1 GHz to 5 GHz.

1. Introduction

Microwave photonic filter (MPF) have been an essential part of the photonic processing system in the modern radar and warfare systems with the advantage of broadband, reconfiguration, flexibility and immunity to electromagnetic interference (EML) [1–5]. In the past few years, numerous techniques have been proposed to implement an MPF either in the coherent operational regime [6–14] or in the incoherent operational regime [1,3]. An MPF is usually implemented using a delay-line configuration with a finite-impulse response (FIR) or infinite-impulse response (IIR). The numbers of taps determine the width of the passband. To obtain a narrow passband, the number of the taps should be large or an IIR filter is implemented. Since the spectral response of an MPF with FIR or IIR is periodic, the tunability is limited by the time delay and the stability is also poor. In the incoherent operational regime, two aspects of the microwave photonic filter (MPF) have been extensively researched in the last few years. Generally, an MPF with one good performance such as the high Q factor and the small shape factor has been reported in Refs. [5,6]. For some applications such as communication system and warfare system, the MPF with excellent flexibility and reconfigurability has also been attracting researcher' interest [7–17]. To realize flat-top frequency response, several methods have been proposed to implement such filter, including fiber Bragg grating (FBG) [1], tunable optical bandpass filter (TOBF) [13], Fabry–Perot (F–P) filter [11] and Stimulated Brillouin scattering (SBS) effect [15]. Among them, the first technique is to achieve a flatness filter using a flat-top optical filter such as the FBG, the TOBF and the F–P filter. The tunability of the MPF is achieved either by changing the optical wavelength and the central frequency of the optical filter that makes the system easy to operate due to the flatness frequency response of the optical filter. But, to meet the reconfiguration, extra optical filter is needed to cascade in the system. The SBS-based flat-top MPF has also been reported in Ref. [15] with a spectral resolution of 20 MHz. The filter bandwidth can be changed by controlling the pump spectrum based on the optical frequency comb. To improve a flatness shape, a feedback compensation process is used to decrease the ripple of optical frequency comb. The main limitation of this approach is the complicated and bulky of system which makes the system cost and unstable. A spool of optical fiber is used to stimulate the SBS effect

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with strong pump power in which the gain region is used to amplify the sideband of the phase-modulated signal. To improve a flatness shape, a feedback compensation process is used to decrease the ripple of optical frequency comb. The main limitation of this approach is the complicated and bulky of system which makes the system cost and unstable.

In the rapid development of the microwave wireless communication, the microwave system needs to meet the demand for multiband and multifunction. A dual-passband MPF is needed in some applications [6,7]. For example, in a Wi-Fi system, dual passband filter with the central frequency of 2.4 GHz and 5 GHz can be used to select the two bands of the wireless signals. Dual-passband MPF has also been demonstrated using an optical filter and a PM [15] or a polarization modulator (PoIM) [16]. In Ref. [15], tunable dual-passband MPF is reported using a PM and an equivalent phase-shifted fiber Bragg grating (EPS-FBG). The central frequency of the dual-passband can be tunable independently by changing the optical wavelength. However, the beating signal between two wavelengths may fall in the passband of the MPF due to the small wavelength spacing of two optical carriers. To overcome this problem, a dual-passband MPF is demonstrated using a PoIM and a PS-FBG [16]. Two wavelengths with two orthogonal polarization directions are phase modulation with opposite modulation indices, respectively. Therefore, the beating signal of two wavelengths is not generated at the photodetector (PD). Since the polarization state of the light wave propagating in the fiber is easily influenced by the external environment and need to be strictly controlled by a polarization controller, the tail fiber of the component is fixed in the experimental platform and the polarization state is adjusted before each experiment.

In this paper, a reconfigurable MPF with three filter response characteristics is proposed and experimentally demonstrated using a MWL and a multi-channel PS-FBG. The transfer function of the proposed MPF can be switched among single passband, dual-passband and flat-top passband filter by tuning the wavelengths of the MWL. The multi-channel PS-FBG as the main device has multiple notches with the FSR of 0.8 nm which is used to remove one sideband in each phased-modulated optical signal. The phase-modulated signal is converted to intensity-modulated signal and the beating signal of two optical carriers is not generated at the PD due to the frequency interval of two adjacent optical carriers up to 100 GHz. when one $+1$st sideband of the phase-modulated signals is falling in one notch of the multi-function PS-FBG, a single bandpass MPF is generated. Double $+1$st sidebands are removed in the reflection spectrum, which leads to PM-IM conversion and generates two independently band passes MPF. The flat MPF with a tunable passband can be implemented when four band passes are overlapped with each other to become a single passband filter. The advantage of the proposed MPF is that the filter shape is well reconfigured by controlling the wavelengths of the MWL. The results show that the 1-dB bandwidth of the MPF is expanded to be over 135 MHz and the magnitude deviation of the flatness of the MPF is less than 0.2 dB within the frequency tunable range of 5 GHz. with the flexible tunability of the central frequency.

2. Principle

The schematic diagram of the proposed MPF is shown in Fig. 1(a). Four light waves with the frequency of f_{C1}, f_{C2}, f_{C3} and f_{C4} from a MWL are sent to a PM via a polarization controller (PC) to adjust the polarization state of light waves along the principal axes of the PM. The PM is driven by the microwave signal with the sweep frequency f_e generated by a vector network analyzer (VNA). The phase-modulated signals are injected into the multi-channel PS-FBG. If either the upper sidebands or the lower sidebands of the phase-modulated signals are falling in the notch, the magnitude and the phase of the sideband can be modified. Therefore, the phase-modulated signals are converted to intensity-modulated signals, generating multiple ultra-narrow passbands. The multi-channel PS-FBG in the proposed MPF is the main component, which are carved by UV illumination using a series of uniform phase mask. A seriesπphase shifts are introduced in the FBGs. Multiple narrow notches with the wavelength spacing of 0.8 nm are generated in the multi-channel PS-FBG. Fig. 1(b) shows the reflection spectrum and the phase response of a single channel PS-FBG, respectively. Since the frequency interval of two adjacent notch is approximately 100 GHz, the beating signal between each adjacent optical carrier is not detected at the PD due to the limited bandwidth.

Fig. 2 illustrate the operation of the proposed MPF. Four wavelengths are used in the theoretical analysis. Mathematics, the optical field at the output of the PM can be expressed as

$$E_{PM}(t) = \sum_{i=1}^{i=4} A_i e^{[j\omega_{Ci}t + jm\cos(\omega_{ei}t)]} \tag{1}$$

where A_i, $\omega_{Ci}(i = 1, 2, 3, 4)$ are the magnitude and the angular frequency of the optical carrier, respectively. $m = \frac{\pi V_{RF}}{V_\pi}$ is the phase modulation index, where V_{RF} is magnitude of the microwave signal and V_π is the half-wave voltage of the phase modulator. ω_{ei} is the angular frequency of the microwave signal. Under small signal modulation, only first order sidebands are considered. Eq. (1) can be expanded by Jacobi–Anger expansion as follows

$$E_{PM}(t) = \sum_{i=1}^{i=4} A_i \left[J_1(m) e^{j(\omega_{Ci}-\omega_{ei})t + j\pi} + J_0(m) e^{j(\omega_{Ci}t)} + J_1(m) e^{j(\omega_{Ci}+\omega_{ei})t} \right] \tag{2}$$

where $J_0(m)$ and $J_1(m)$ are the zero order and first order Bessel functions of the first kind. The optical spectrums of four phase-modulated signals are shown in Fig. 2(B). When four phase-modulated optical signals are fed to a multi-channel PS-FBG via the optical circulator (OC), which are located in the four channels of the multi-channel PS-FBG, respectively, four reflection optical spectrums from the multi-channel PS-FBG as shown in Fig. 3(C) can be written as

$$\begin{aligned} E_{out}(t) &= E_{PM}(t)\sqrt{H(\omega)} \\ &= A_1 \Big[J_1(m)\sqrt{H(\omega_{C1}-\omega_{e1})} e^{[j(\omega_{C1}-\omega_{e1})t + j\pi]} \\ &\quad + J_0(m)\sqrt{H(\omega_{C1})} e^{j(\omega_{C1}t)} + J_1(m)\sqrt{H(\omega_{C1}+\omega_{e1})} e^{[j(\omega_{C1}+\omega_{e1})t]} \Big] \\ &\quad + A_2 \Big[J_1(m)\sqrt{H(\omega_{C2}-\omega_{e2})} e^{[j(\omega_{C2}-\omega_{e2})t + j\pi]} \\ &\quad + J_0(m)\sqrt{H(\omega_{C2})} e^{j(\omega_{C2}t)} + J_1(m)\sqrt{H(\omega_{C2}+\omega_{e2})} e^{[j(\omega_{C2}+\omega_{e2})t]} \Big] \\ &\quad + A_3 \Big[J_1(m)\sqrt{H(\omega_{C3}-\omega_{e3})} e^{[j(\omega_{C3}-\omega_{e3})t + j\pi]} \\ &\quad + J_0(m)\sqrt{H(\omega_{C3})} e^{j(\omega_{C3}t)} + J_1(m)\sqrt{H(\omega_{C3}+\omega_{e3})} e^{[j(\omega_{C3}+\omega_{e3})t]} \Big] \\ &\quad + A_4 \Big[J_1(m)\sqrt{H(\omega_{C4}-\omega_{e4})} e^{[j(\omega_{C4}-\omega_{e4})t + j\pi]} \\ &\quad + J_0(m)\sqrt{H(\omega_{C4})} e^{j(\omega_{C4}t)} + J_1(m)\sqrt{H(\omega_{C4}+\omega_{e4})} e^{[j(\omega_{C3}+\omega_{e3})t]} \Big] \end{aligned} \tag{3}$$

where $H(\omega)$ is the power reflection function of the multi-channel PS-FBG. After PM-IM conversion at PD, four microwave signals are recovered at the output of the PD. It is note that beating signal between two optical carriers is not detected at the PD since the frequency spacing of each adjacent light waves is up to 100 GHz. the recovered microwave signals are given by

$$\begin{aligned} i(t) &= \gamma E(t) \cdot E^*(t) \\ &= C + C_1 \Big\{ \sqrt{H(\omega_{C1})} \Big[-\sqrt{H(\omega_{C1}-\omega_{e1})}\cos(\omega_{e1}t) + \sqrt{H(\omega_{C1}+\omega_{e1})}\cos(\omega_{e1}t) \Big] \\ &\quad + \sqrt{H(\omega_{C2})} \Big[-\sqrt{H(\omega_{C2}-\omega_{e2})}\cos(\omega_{e2}t) + \sqrt{H(\omega_{C2}+\omega_{e2})}\cos(\omega_{e2}t) \Big] \\ &\quad + \sqrt{H(\omega_{C3})} \Big[-\sqrt{H(\omega_{C3}-\omega_{e3})}\cos(\omega_{e3}t) + \sqrt{H(\omega_{C3}+\omega_{e3})}\cos(\omega_{e3}t) \Big] \\ &\quad + \sqrt{H(\omega_{C4})} \Big[-\sqrt{H(\omega_{C4}-\omega_{e4})}\cos(\omega_{e4}t) + \sqrt{H(\omega_{C4}+\omega_{e4})}\cos(\omega_{e4}t) \Big] \Big\} \end{aligned} \tag{4}$$

where γ is the responsivity of the PD.C is the direct current (DC) term and C_1 is the magnitude of the generated microwave signal with the