Tunable Microwave Photonic Filter With a Narrow and Flat-Top Passband

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***Abstract*—A frequency-tunable microwave photonic filter (MPF) with a narrow and flat-top passband implemented using a phase modulator (PM) and a superstructured fiber Bragg grating (SFBG) is proposed and experimentally demonstrated. The key component in the MPF is the SFBG, which is designed and fabricated based on the equivalent phase shift (EPS) technique. Two phase shifts are introduced, and the combination of the two phase shifts would lead to a flat-bottom notch in the reflection band. By incorporating the SFBG into the MPF, a frequency response with a narrow and flat-top passband is achieved. The reflection bandwidth and the notch width of the SFBG, which determine the frequency tunable range and passband width, can be controlled by the length and maximum index modulation (MIM) of the SFBG. An experiment is performed. An MPF with a 3 dB bandwidth of 143 MHz, a 20 dB bandwidth of 370 MHz, and a tunable range from 0.4 to 6.4 GHz is demonstrated.**

***Index Terms*—Equivalent phase shift (EPS), fiber Bragg grating (FBG), microwave photonic filter (MPF).**

I. Introduction

MICROWAVE photonic filters (MPFs) with advantageous features, such as high central frequency and large frequency tunable range, have attracted great interest and have been extensively researched in the past few years [1], [2]. An MPF can be implemented based on a Mach–Zehnder interferometer [3], a ring resonator [4], or stimulated Brillouin scattering (SSB) in a nonlinear fiber [5]. The key limitation of the MPFs demonstrated in [3]–[5] is the poor flatness of the passband. For many applications, it is highly required that the passband is flat [6]. A flat-top MPF with a 3 dB bandwidth of 2 GHz can be obtained by using a fiber Bragg grating (FBG) to optically filter out one of the sidebands of a phase-modulated signal [7]. The major limitation of the approach is that the passband is wide, which is determined by the bandwidth of the FBG. A flat-top MPF can also be implemented based on optical frequency comb shaping using a pulse shaper to control each comb line from a comb source [8]. However, the system is complicated, and the bandwidth is also very wide, usually greater than 2 GHz. An MPF with a narrow and flat-top passband was demonstrated using a two-dimensional liquid crystal on silicon (LCoS) pixel array to control the spectral profile of a broadband source to achieve a flat-top frequency response [9]. Again, the system is complicated, and the frequency tunable range is less than 1 GHz. Recently, we proposed an MPF with both a narrow bandwidth and a wide frequency tunable range, which was implemented based on phase-modulation to intensity-modulation (PM-IM) conversion using a phase modulator (PM) and a phase-shifted FBG (PS-FBG) [10]. An MPF with a passband width of 60 MHz and a frequency tunable range of 15 GHz was demonstrated. The incorporation of the MPF in an optoelectronic oscillator (OEO) to achieve tunable microwave generation was reported [11]. The major limitation of the MPF is the poor flatness of the passband due to the Lorentz-shaped notch in the reflection band of the PS-FBG.

In this letter, we propose and experimentally demonstrate a tunable MPF with a narrow and flat-top passband using a PM and a specially designed superstructured FBG (SFBG). An SFBG is special FBG that is spatially modulated by a periodic sampling function. Due to the spatial sampling, the spectral response has multiple channels. If one period of the sampling function is intentionally increased by a half period, a π phase shift is equivalently introduced to the grating, leading to a narrow notch. The technique is called equivalent phase shift (EPS) technique [12]. In the proposed filter, the SFBG has two notches which are achieved by introducing two EPSs to the structure. Each phase shift would produce a Lorentz-shaped notch and the combination of the two Lorentz-shaped notches would lead to a notch with a flat bottom. When the SFBG with a flat-bottom notch is incorporated into an MPF to perform PM-IM conversion, a passband with a flat top is achieved. The reflection bandwidth and notch width of the SFBG, which determine the frequency tunable range and bandwidth of the passband, can be controlled by controlling the length and maximum index modulation (MIM) of the SFBG. An experiment is performed. An MPF with a 3 and 20 dB bandwidths of 143 and 370 MHz, respectively, is demonstrated. The flatness of the passband is within ± 0.25 dB and the central frequency of the passband is tunable from 0.4 to 6.4 GHz by tuning the wavelength of the optical carrier.

II. Principle

A PS-FBG with a single phase shift has a Lorentz-shaped notch in the reflection band, as shown in Fig. 1(a). When it is incorporated into an MPF, to use the notch to suppress one of the sidebands of a phase-modulated optical signal for PM-IM conversion, a Lorentz-shaped passband would be generated [10], [11]. To obtain an MPF with a flat top, a special PS-FBG with a

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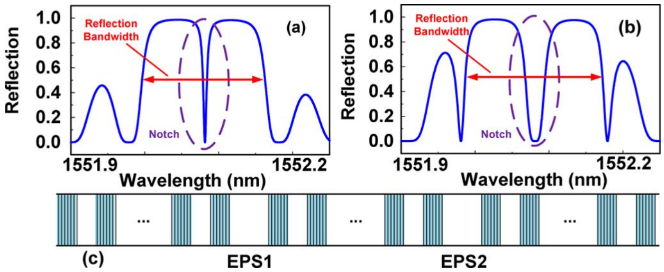

Fig. 1. (a) Simulated reflection spectrum of a PS-FBG with a single phase shift. (b) Simulated reflection spectrum of an SFBG with two phase shifts. (c) Structure of an SFBG.

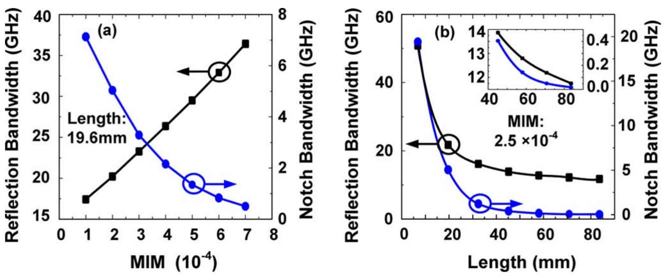

Fig. 2. (a) Reflection bandwidth and notch width versus the MIM. (b) Reflection bandwidth and notch width versus the grating length.

flat-bottom notch is required. A simple solution is to introduce two phase shifts to obtain two notches, which are spectrally separated such that the overall notch has a flat bottom [13].

Instead of introducing the phase shifts directly to the grating structure, in our work the phase shifts are introduced with the EPS technique [12]. The key advantage of employing the EPS technique is that the phase shifts can be equivalently introduced by controlling the sampling periods, which simplifies the fabrication process greatly, since the control of the sampling periods requires only micrometer accuracy while the conventional phase shift technique requires nanometer accuracy. In addition, only a uniform phase mask is needed, which would reduce the fabrication cost.

Mathematically, the index modulation of an SFBG along the z direction is given by

$$\Delta n(z) = \underbrace{\sum_m F_m \exp\left(j\frac{2\pi m}{P}z\right)}_{S(z)} \exp\left(j\frac{2\pi}{\Lambda}z\right) + c.c \qquad (1)$$

where Λ is the period of the grating, $S(z)$ is the sampling function, F_m is the Fourier coefficient of the mth channel, $|F_0| = 0.5$, $|F_{\pm1}| = 0.32$ [14], and P is the sampling period, which is 0.4 mm in our design. When the ith sampling period is increased by ΔP, an EPS is introduced to the SFBG at the mth channel

$$\theta_m = 2\pi m\left(\frac{\Delta P}{P}\right). \qquad (2)$$

In our design, the -1st channel is considered. According to (2), by choosing ΔP to be half the sampling period, a π phase shift is introduced. Assume that the total number of the sampling periods is k, two EPSs are introduced at the $k/4$-th and $3k/4$-th sampling periods, as shown in Fig. 1(c). The reflection spectrum of the -1st channel of the SFBG is shown in Fig. 1(b). As can be seen, there is a flat-bottom notch in the reflection band. When it is incorporated in the MPF, the notch is directly translated to the passband and a flat-top passband is achieved.

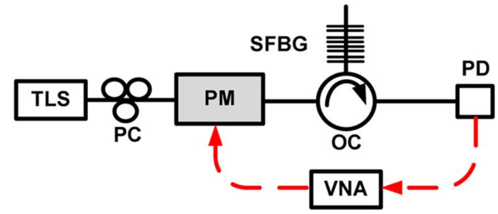

Fig. 3. Schematic of the proposed MPF. TLS: tunable laser source, PC: polarization controller, PM: phase modulator, SFBG: superstructured fiber Bragg grating, OC: optical circulator, PD: photodetector, VNA: vector network analyzer.

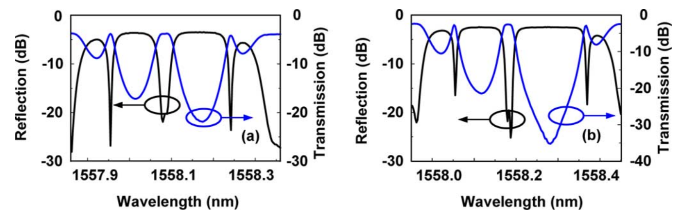

Fig. 4. Measured reflection spectrum and transmission spectrum of (a) SFBG1 and (b) SFBG2.

The frequency tunable range and the width of the passband depend on the reflection bandwidth and the notch width of the SFBG, which are determined by the length and the MIM of the SFBG [10]. Fig. 2 shows the simulated results of an SFBG with different grating length and MIM. As can be seen from Fig. 2(a), the reflection bandwidth would increase with the increase of the MIM, while the notch width would decrease with the increase of the MIM. On the other hand, the reflection bandwidth and notch width would both decrease with the increase of the grating length, as shown in Fig. 2(b). Therefore, by selecting an appropriate grating length and MIM, an MPF with the desired frequency tunable range and passband width can be obtained.

By incorporating the SFBG into a system shown in Fig. 3, an MPF is implemented. In Fig. 3, a light wave from a tunable laser source (TLS) is sent to a PM via a polarization controller (PC), which is used to minimize the polarization-dependent loss. The PM is driven by a sinusoidal microwave signal with a tunable frequency generated by a vector network analyzer (VNA). The phase-modulated signal is reflected by the SFBG via an optical circulator (OC) with one sideband being eliminated. Thus, PM-IM conversion is achieved, and the intensity-modulated optical signal at the output of the SFBG is converted to an electrical signal at a photodetector (PD), and then sent back to the VNA for frequency response measurement.

III. Experiment and Results

An SFBG (SFBG1) with a length of 13.2 mm and an MIM of 4×10^{-4} is fabricated. The optical spectrums in reflection and transmission measured by an optical vertical analyzer (OVA, LUNA) are shown in Fig. 4(a). Note that the optical powers at the notch are very low, thus the measurement at the notch may not correctly reflect the actual shape of the bottom. To clearly see the flatness of the notch, an alternative way is to measure the transmission spectrum. As can be seen, SFBG1 has a transmission band with a very flat top, which confirms the notch has a flat bottom. As discussed in Section II, to achieve an SFBG with a narrow notch, we may increase the MIM. Based on this concept, a second SFBG (SFBG2) with a greater MIM of 5.5×10^{-4} is fabricated. The length is kept the same. As expected, SFBG2 has larger reflection bandwidth and a narrower notch width than

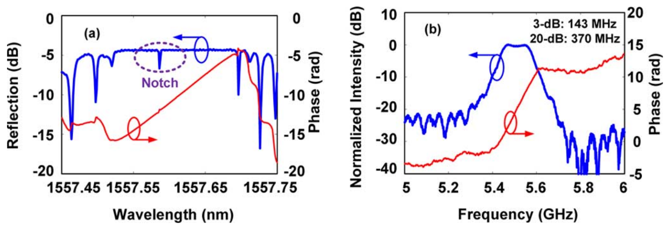

Fig. 5. (a) Measured reflection spectrum and phase response of SFBG3. (b) Frequency response and phase response of the MPF using SFBG3.

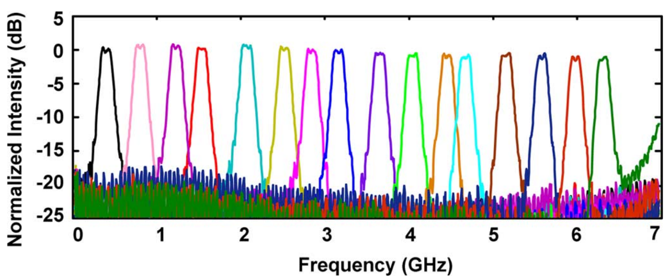

Fig. 6. Measured frequency response of the narrow and flat-top MPF with a tunable passband from 0.4 GHz to 6.4 GHz.

SFBG1. However, for a fiber with a given photosensitivity, the MIM is finite. Thus, to further reduce the passband width, another solution is to increase the grating length. A third SFBG (SFBG3) with an increased length (32.4 mm) is fabricated (the MIM is controlled at 5.2×10^{-4}). The reflection spectrum and phase response are shown in Fig. 5(a). Due to the limited resolution of the OVA, the notch depth and shape cannot be precisely shown.

Then, SFBG3 is incorporated into the MPF shown in Fig. 3. A light wave at 1557.63 nm from the TLS (Anritsu MG9638A) is sent to the PM via the PC. A microwave signal from a VNA (Agilent E8364A) is applied to the PM. The phase-modulated signal is sent into SFBG3 where one of the two sidebands is suppressed by the notch, and the phase-modulated signal is thus converted to an intensity-modulated signal. The reflected intensity-modulated optical signal is sent to the PD for optical-to-electrical conversion. An electrical signal at the output of the PD is generated and it is sent back to the VNA for frequency response measurement.

Fig. 5(b) shows the frequency response of the MPF. As can be seen, it has a narrow passband with a flat top. The flatness of the passband is within $\pm$ 0.25 dB. The phase response of the MPF is also measured and shown in Fig. 5(b). As can be seen the phase response is linear in the passband. The 3 dB bandwidth is 143 MHz, which is close to the theoretical value of 136 MHz. The 20 dB bandwidth is 370 MHz. The shape factor, defined as the ratio between the 20 dB and 3 dB bandwidths, is calculated to be 2.6, which is much smaller than those reported in [10]. A smaller shape factor represents a better selectivity. By tuning the wavelength of the optical carrier, the central frequency of the passband is tuned from 0.4 to 6.4 GHz, as shown in Fig. 6, which is close to the theoretical tunable range of 6.2 GHz. The magnitude and bandwidth of the passband keep almost unchanged during the tuning, a feature that is important for applications where the loss and bandwidth are required to be constant. The insertion loss is measured, which is about 28 dB. The use of a high power-handling PD can reduce the loss [10]. The spurious free dynamic range (SFDR) of the MPF is also measured, which is about 83 dB$\cdot$Hz$^{2/3}$.

IV. Conclusion

In the fabrication of an SFBG, if the multi-exposure technique is used, the effective MIM of the -1st channel can still be increased, despite of the limit of the finite photo-sensitivity of a fiber [14]. Hence, a wider frequency tunable range and a narrower bandwidth can be achieved.

In conclusion, a novel approach to implementing an MPF with a narrow and flat-top passband based on PM-IM conversion using an SFBG was proposed and experimentally demonstrated. The key component in the proposed MPF was the SFBG, which was fabricated based on the EPS technique through equivalent sampling. By introducing two phase shifts into the structure, an SFBG with a narrow and flat-bottom notch was obtained. By incorporating the SFBG into the MPF, a flat-top MPF with a narrow 3 dB bandwidth of 143 MHz was achieved. The central frequency of the passband was tunable from 0.4 to 6.4 GHz. The tuning range and the width of the passband could be controlled by selecting the length and the MIM in the design and fabrication of the SFBG.

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