Tunable Photonic Microwave Bandpass Filter With Negative Coefficients Implemented Using an Optical Phase Modulator and Chirped Fiber Bragg Gratings

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***Abstract*—A continuously tunable photonic microwave bandpass filter with positive and negative coefficients implemented using an optical phase modulator and chirped fiber Bragg gratings (FBGs) is proposed and experimentally demonstrated. The positive and negative coefficients are generated through optical phase-modulation to intensity-modulation conversion by reflecting the phase-modulated optical carrier from linearly chirped FBGs (LCFBGs) with positive and negative dispersions. The tunability of the filter is realized by changing the wavelength of the optical carrier such that it is reflected at different physical locations in the LCFBGs. A two-tap microwave bandpass filter with a free spectral range tunable from 1.14 to 4.55 GHz is experimentally demonstrated.**

***Index Terms*—Chirped fiber Bragg grating (CFBG), electro-optic phase modulation, microwave photonics, phase-modulation to intensity-modulation (PM–IM) conversion, photonic microwave filter.**

I. INTRODUCTION

PROCESSING of microwave and millimeter-wave signals in the optical domain has been an active research topic for many years due to the advantageous features offered by optics, such as large time–bandwidth product, low loss, light weight, and immunity to electromagnetic interference. Among the many microwave signal processing functionalities, microwave filtering is of particular interest since photonic microwave filters can provide a large tunability and a high Q factor, which are difficult to realize using conventional electronic methods. In general, photonic microwave filters are implemented based on a delay line structure, in which different time delays are generated by various delay-line devices. The key problem associated with delay-line-based microwave filters is that the detection at a photodetector (PD) has to be incoherent to avoid optical interferences. The use of incoherent detection limits the coefficients of the optical delay-line filters to be all positive, resulting in low-pass filtering only. For many applications such as radar and wireless communications systems, bandpass filtering is highly desirable. Various approaches have been reported to tackle this problem [1]–[10]. One approach [1] is to use differential photodetection to realize bandpass filtering. Other approaches to achieve negative coefficients include wavelength conversion using cross-gain modulation in a semiconductor optical amplifier [2] and a carrier depletion effect in a distributed-feedback laser diode (LD) [3] or in a Fabry–Pérot LD [4]. Using the transmission of a broadband source through uniform fiber Bragg gratings (FBGs), negative coefficients can also be obtained [5]. It was also reported that a microwave bandpass filter can be realized by biasing a pair of electrooptic modulators (EOMs) to achieve phase inversion [6] or by using a single dual-output EOM with a double-pass modulation [7]. Photonic microwave bandpass filters can also be implemented based on electrooptic phase modulation [8], [9]. It was demonstrated that the phase-modulation to intensity-modulation (PM–IM) conversion would have a frequency response with a notch at dc. The baseband resonance of a conventional photonic microwave filter with all positive coefficients would be eliminated by the PM–IM notch [8], [9], leading to a bandpass-equivalent filter. Although the filters in [8] and [9] are bandpass filters, they have all positive coefficients, which leads to the filter responses with a nonflat top and high sidelobes. To design a bandpass filter with a frequency response that has a flat top and low sidelobes, a true bandpass filter with negative coefficients should be implemented. In [10], we proposed a true bandpass filter. The negative coefficients were generated by reflecting the phase-modulated optical carriers from linearly chirped FBGs (LCFBGs) with group-delay responses having positive or negative slopes. The phase-modulated signals were converted to intensity-modulated signals at the LCFBGs with phase inversion, leading to the generation of negative coefficients.

On the other hand, it is highly desirable that the microwave filters be tunable. Various configurations have been reported for the implementation of tunable optical microwave filters [11]–[16]. In general, the tunability can be achieved by using variable optical delay lines [11], [12], by tuning optical wavelengths combined with dispersive optical devices having fixed chromatic dispersions [13]–[15], or by tuning chromatic dispersions combined with fixed optical wavelengths [16]. The filters demonstrated in [11]–[16] are tunable microwave filters, but all with positive coefficients only, making them function as low-pass filters.

In this paper, we propose a novel photonic microwave bandpass filter with negative coefficients that is tunable. In the proposed filter, the microwave signal is modulated on an

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Manuscript received February 17, 2007; revised August 7, 2007. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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Digital Object Identifier 10.1109/JLT.2007.906821

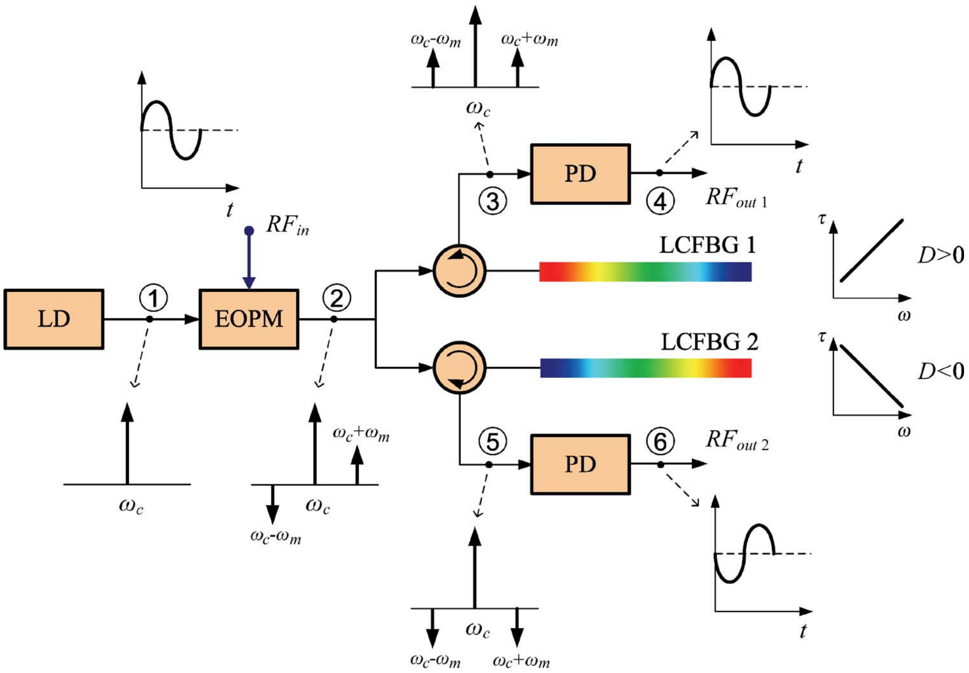


Fig. 1. Generation of positive and negative coefficients based on PM–IM conversion using LCFBGs. LD: laser diode; EOPM: electrooptic phase modulator; PD: photodetector.

optical carrier using an optical phase modulator. The positive and negative coefficients are generated through optical PM–IM conversion by reflecting the phase-modulated optical carrier from LCFBGs with group-delay responses having positive or negative slopes. The tunability is realized by changing the wavelength of the optical carrier, which is reflected at different physical locations in the LCFBGs, leading to the generation of different time delays. Therefore, the LCFBGs in the proposed filter have two functions: 1) to generate positive and negative coefficients and 2) to make the filter tunable.

This paper is organized as follows. In Section II, the generation of positive and negative coefficients based on PM–IM conversion using LCFBGs is discussed; then, a tunable microwave bandpass filter with positive and negative coefficients implemented based on PM–IM conversion using LCFBGs is proposed and analyzed. In Section III, experimental implementation of a two-tap tunable microwave bandpass filter using two LCFBGs is presented. A conclusion is drawn in Section IV.

II. PRINCIPLES

A. *Generation of Positive and Negative Coefficients Based on PM–IM Conversion Using LCFBGs*

The schematic diagram illustrating the generation of positive and negative coefficients based on PM–IM conversion using LCFBGs is shown in Fig. 1. In the system, the electrooptic phase modulator (EOPM) is driven by a microwave signal. Under a small-signal condition, the phase-modulated optical field $E(t)$ can be expressed as [17]

$$E(t) = J_0(m_pV)\cos(\omega_c t) + J_1(m_pV)\cos\left[(\omega_c+\omega_m)t + \frac{\pi}{2}\right] - J_1(m_pV)\cos\left[(\omega_c-\omega_m)t - \frac{\pi}{2}\right] \quad (1)$$

where $J_n(m_pV)$ is the nth-order Bessel function of the first kind, m_p is the phase-modulation index, V is the amplitude of the microwave modulating signal, ω_c is the angular frequency of the optical carrier, and ω_m is the angular frequency of the microwave modulating signal. It can be seen that the two sidebands of the phase-modulated signal at the output of the EOPM are π out of phase (point ② in Fig. 1). If this phase-modulated optical signal is directly applied to a PD, the beating between the carrier and the upper sideband will exactly cancel the beating between the carrier and the lower sideband. Therefore, no microwave signal other than a dc can be obtained at the output of the PD. However, as shown in Fig. 1, if the phase-modulated optical signal passes through an LCFBG, the chromatic dispersion of the LCFBG will change the phase relationships of the carrier and the two sidebands. Therefore, the two sidebands of the phase-modulated signal can be partially or totally in phase after experiencing the chromatic dispersion. When the optical signal after the dispersion is applied to the PD, the microwave modulating signal can thus be recovered. As a result, the PM signal is converted to an IM signal. Mathematically, the electrical field of the recovered microwave signal is given by

$$E_{RF}(t) \propto \sin\left(\frac{\pi D\lambda_c^2 f_m^2}{c}\right) \cdot \cos\left(\omega_m t + \theta\right) \quad (2)$$

where D is the chromatic dispersion of the LCFBG, λ_c is the wavelength of the optical carrier, f_m is the microwave modulating frequency, c is the optical velocity in free space, and θ is the phase delay of the recovered microwave signal, which is also determined by D and f_m [17].

As shown in Fig. 1, two LCFBGs are employed to generate a positive coefficient and a negative coefficient. To do so, the two LCFBGs are connected in opposite directions. Assume

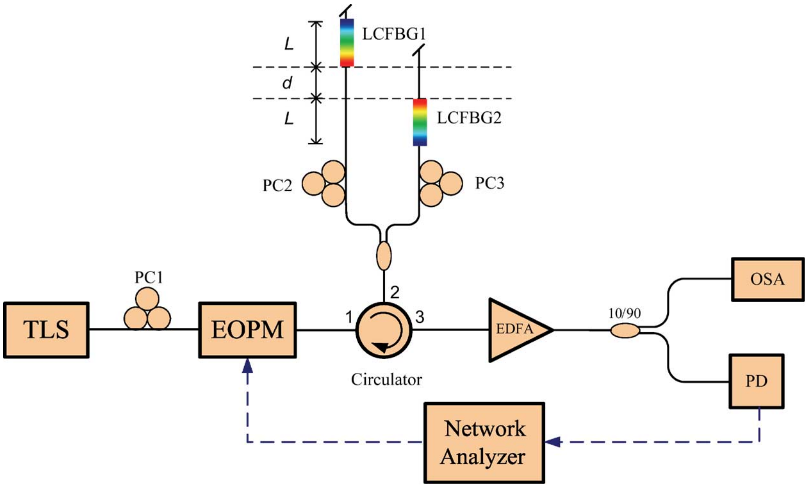


Fig. 2. Experimental setup of the proposed microwave bandpass filter. TLS: tunable laser source; PC: polarization controller; OSA: optical spectrum analyzer.

that LCFBG1 is connected such that its chromatic dispersion $D = \partial\tau/\partial\omega > 0$, where τ is the group delay. In this case, the higher optical frequency component will experience more phase shift due to the positive chromatic dispersion. For a specific microwave frequency, e.g., ω_m, the phase relationships of the two sidebands and the carrier may be changed to totally in phase (point ③ in Fig. 1) after the chromatic dispersion; thus, the PM signal is converted to an IM signal, which can be detected by the PD (point ④ in Fig. 1). On the other hand, if LCFBG2 is connected such that its chromatic dispersion $D = \partial\tau/\partial\omega < 0$, the lower frequency component would experience more phase shift. After the chromatic dispersion, the two sidebands will be in phase but are π out of phase with respect to the optical carrier (point ⑤ in Fig. 1). After the photodetection at the PD, the beating between the carrier and the two sidebands will recover the microwave modulating signal but with a phase difference of π (point ⑥ in Fig. 1). The use of the two out-of-phase microwave signals with a proper time-delay difference between them would achieve a two-tap microwave filter with one positive coefficient and one negative coefficient.

The phase inversion can also be easily explained mathematically. As can be seen in (2), if the sign of the chromatic dispersion D is changed, the sign of the recovered microwave signal will also be changed because $\sin(\pi D\lambda_c^2 f_m^2/c)$ is an odd function of D.

B. Tunable Photonic Microwave Bandpass Filter Based on PM–IM Conversion

Based on the aforementioned analysis, we propose a tunable photonic microwave bandpass filter based on PM–IM conversion using LCFBGs. To demonstrate the concept, only two LCFBGs are used. Therefore, the filter is a two-tap filter. The filter can be extended to multiple taps if more LCFBGs are used. The configuration of the proposed filter is shown in Fig. 2. In the system, a lightwave from a tunable laser source (TLS) is phase modulated by an EOPM. A polarization controller (PC1) is connected between the TLS and the EOPM to align the polarization direction of the laser beam with the principle axis of the EOPM to minimize the polarization-dependent loss. The phase-modulated optical signal is then sent to two LCFBGs through an optical circulator and an optical coupler. The two LCFBGs are connected in such a way that one has a positive dispersion, and the other has a negative dispersion. The spacing d between the two LCFBGs, as shown in Fig. 2, determines the smallest time-delay difference between the two taps. When the wavelength is tuned, the time-delay difference will be changed, and the free spectral range (FSR) of the filter is thus changed. The filter is tunable.

Since the two optical signals reflected by the two LCFBGs are from the same laser source, when they recombine at the PD, optical interference would happen. To eliminate the optical interference, in the proposed filter, we use two PCs (PC2 and PC3) to make the two reflected optical signals orthogonally polarized. Another solution to avoid optical interference is to use an optical source that has a low coherence, such as a sliced amplified spontaneous emission or a sliced superluminescent light-emitting diode source.

Assuming that the reflection coefficients of the LCFBGs are identical, the frequency response of the proposed filter is then given by

$$H(\omega) \propto \sum_{n=1}^{2} \sin\left(\frac{\pi D_n \lambda_c^2 f_m^2}{c}\right) \exp\left[j\omega_m(n-1)\Delta\tau\right] \quad (3)$$

where $\Delta\tau$ is the time delay between the two taps, which is given by

$$\Delta\tau = \frac{2n_{\text{eff}}}{c} \cdot \Delta L = \frac{2n_{\text{eff}}}{c} \cdot \left(l_0 + \frac{2(\lambda_0 - \lambda_c)L_g}{\Delta\lambda_g}\right) \quad (4)$$

where n_{eff} is the effective refractive index of the gratings; l_g is the length of the LCFBGs; ΔL is the distance between the reflection points of the gratings, which is a function of the carrier wavelength; l_0 is the distance between the reflection points at the central wavelength λ_0; and $\Delta\lambda_g$ is the bandwidth of the LCFBG. Assume that the lengths and the chirp rates of the two gratings are identical and that the bandwidth of each grating is less than 1 nm; then, $\lambda_c^2 \approx \lambda_0^2$ (3) can now be rewritten as

$$H(\omega) \propto \underbrace{\sin\left(\frac{\pi D \lambda_0^2 f_m^2}{c}\right)}_{H_1(\omega)} \cdot \underbrace{\left\{1 - \exp\left[j\omega_m \frac{2n_{\mathrm{eff}}}{c} \cdot \left(l_0 + \frac{2(\lambda_0 - \lambda_c)L_g}{\Delta\lambda_g}\right)\right]\right\}}_{H_2(\omega)}. \quad (5)$$

The frequency response of the filter is the multiplication of two frequency responses $H_1(\omega)$ and $H_2(\omega)$. $H_1(\omega)$ is the frequency response of the PM–IM conversion using an LCFBG, and $H_2(\omega)$ is the frequency response of an ideal two-tap bandpass filter with one positive coefficient and one negative coefficient. The FSR of the filter can be given as

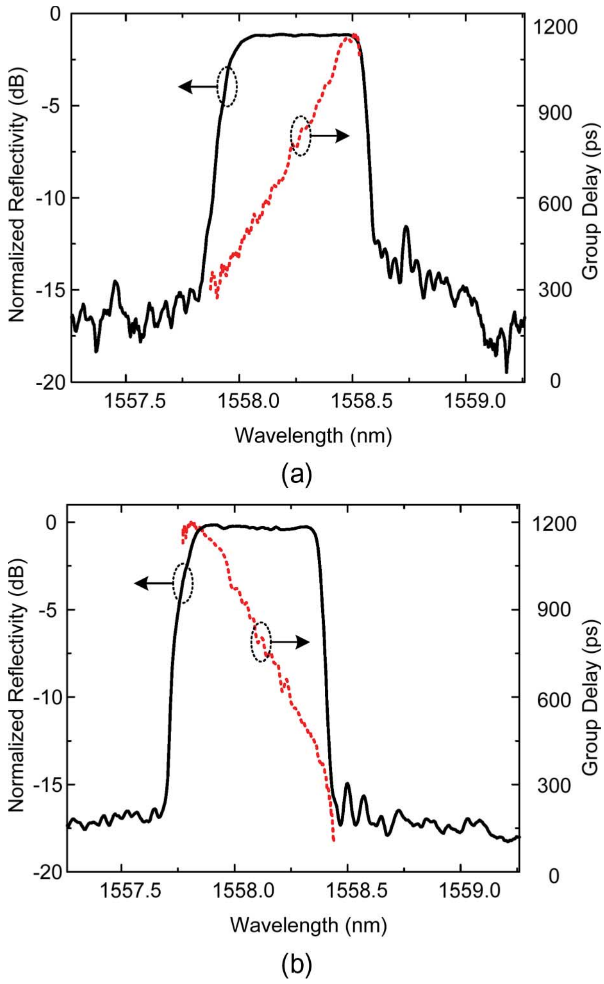
$$\mathrm{FSR} = \frac{1}{\Delta\tau} = \frac{c}{2n_{\mathrm{eff}}} \frac{1}{\left(l_0 + \frac{2(\lambda_0 - \lambda_c)L_g}{\Delta\lambda_g}\right)}. \quad (6)$$

By tuning the wavelength λ_c of the optical carrier, the FSR can be changed; thus, the filter is tunable.

Note that the proposed filter has only two taps, which can be extended to a multitap microwave filter by adding more LCFBGs. The light source can be a tunable laser array or a broadband source sliced by a tunable optical filter. In the latter case, the PCs to maintain the orthogonality between the two reflected lightwaves from one CFBG are not needed since no optical interference would be generated when using a broadband source with low coherence. The tunability is realized by simply tuning the wavelength of the tunable optical filter. The chirp rates of the LCFBGs for both cases should be carefully designed to ensure that the time-delay differences between any two adjacent taps are identical. The insertion loss due to a large number of taps could be compensated by incorporating an optical amplifier in the filter before photodetection.

III. EXPERIMENT

An experimental setup based on the configuration in Fig. 2 is built. A TLS with a typical linewidth of 150 kHz is used as the light source. Two LCFBGs are fabricated in a hydrogen-loaded standard single-mode fiber using the phase-mask technique. The lengths of the two LCFBGs are 8 cm. The chromatic dispersions of the LCFBGs are 1344 and −1370 ps/nm. The reflection spectrum and the group delay response of the two LCFBGs are shown in Fig. 3. As can be seen, the reflection spectra of the two gratings have an overlap of about 0.6 nm. By tuning the wavelength of the TLS within this overlapping region, two optical signals will be reflected by the two gratings, with different time-delay differences.



(a)

(b)

Fig. 3. Measured reflectivity and group delay responses of (a) LCFBG1 and (b) LCFBG2.

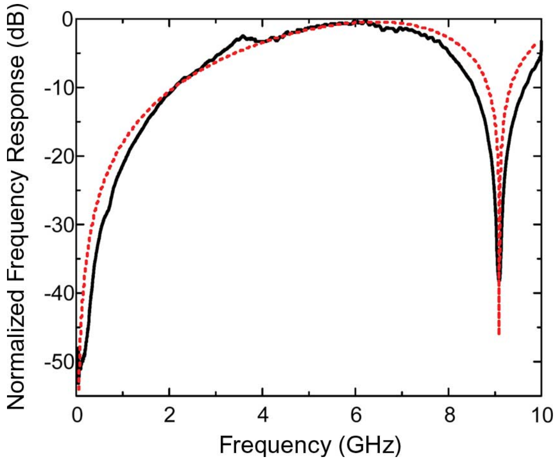


Fig. 4. Measured (solid curve) and simulated (dotted curve) frequency responses of the PM–IM conversion based on an LCFBG.

Before we measure the frequency response of the two-tap microwave filter, we first investigate the PM–IM conversion using an LCFBG. To do so, we disconnect LCFBG2 and measure the frequency response of the system with only one grating (LCFBG1) being connected. The frequency response is measured using a vector network analyzer (VNA), which is shown in Fig. 4 (solid curve). As can be seen, a deep notch is observed at dc. A theoretical frequency response calculated based on (2) is also shown in the figure (dotted curve). An excellent agreement is observed.

Based on (5), the overall frequency response of the filter is the multiplication of $H_1(\omega)$ and $H_2(\omega)$. Since the bandwidth

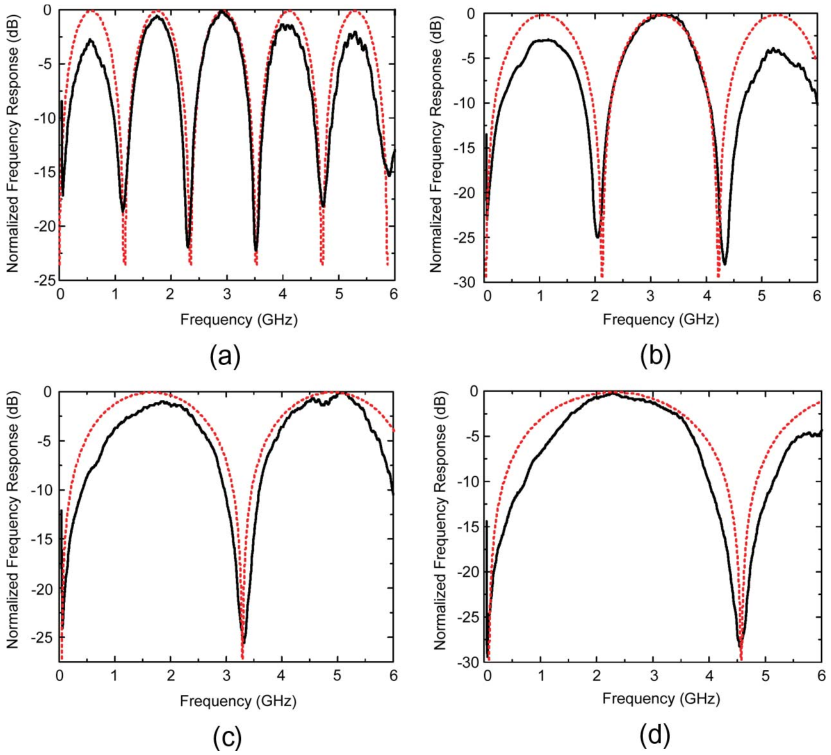


Fig. 5. Measured frequency response (solid curve) and ideal frequency response (dotted curve) of a two-tap bandpass microwave filter with one positive coefficient and one negative coefficient. The FSRs are (a) 1.14 GHz, (b) 2.18 GHz, (c) 3.31 GHz, and (d) 4.55 GHz.

of $H_1(\omega)$ is very wide, its impact on the overall frequency response can be negligible, particularly for a microwave bandpass filter with many taps (narrow passband).

Then, we reconnect LCFBG2 to the system. This filter is now a two-tap filter with one positive coefficient and one negative coefficient. The filter frequency response is again measured using the VNA. To demonstrate the tunability, the wavelength of the TLS is tuned at four different wavelengths. The frequency responses at 1557.83, 1557.99, 1558.20, and 1558.39 nm are shown in Fig. 5 (solid curve). The dotted line shows the frequency response of an ideal two-tap microwave filter with one positive coefficient and one negative coefficient with a time-delay difference of 879.5, 458.7, 302.1, and 219.8 ps. The FSRs for the four different measurements are 1.14, 2.18, 3.31, and 4.55 GHz, corresponding to the distances between the two reflection points of 17.59, 9.17, 6.04, and 4.4 cm or the time-delay differences of 879.5, 458.7, 302.1, and 219.8 ps, respectively. The tunable range can be further increased if the bandwidths of the two LCFBGs are increased.

IV. CONCLUSION

A novel continuously tunable optical microwave bandpass filter with a negative coefficient implemented based on PM–IM conversion using LCFBGs was proposed and experimentally demonstrated. The positive and negative coefficients were generated based on PM–IM conversion by reflecting the phase-modulated optical carriers from the LCFBGs with positive or negative dispersions. The tunability was realized by tuning the wavelength of the optical carrier. The major advantage of this filter is that it has a simple structure with a continuous tunability and a large tunable range. A two-tap microwave bandpass filter with an FRS tunable from 1.14 to 4.55 GHz was experimentally demonstrated.

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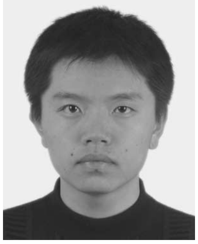

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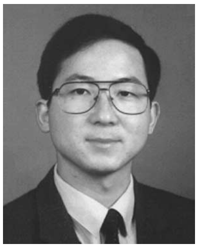

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