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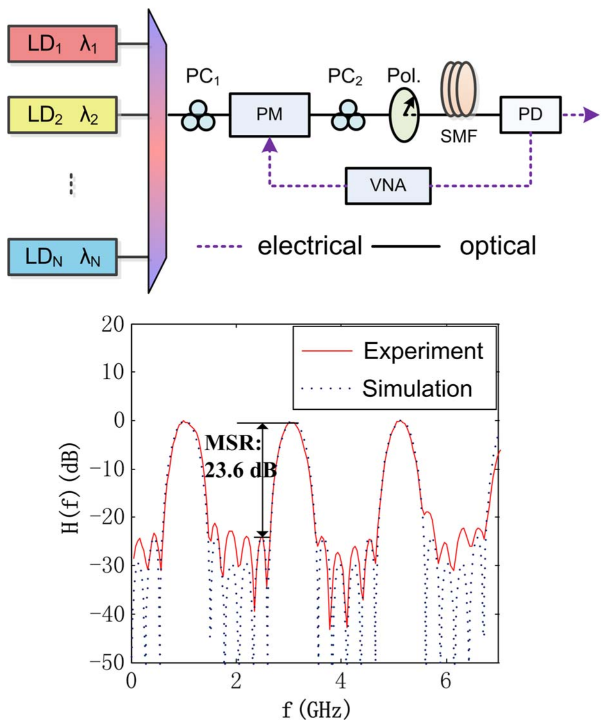

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Multitap Microwave Photonic Filter With Negative Coefficients Based on the Inherent Birefringence in a $LiNbO_3$ Phase Modulator

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Abstract: A novel technique to implement a multitap microwave photonic filter with positive and negative coefficients based on the inherent birefringence in a $LiNbO_3$ phase modulator is proposed and demonstrated. In the proposed filter, a microwave signal is applied to the phase modulator and an optical polarizer is connected at the output of the phase modulator to perform polarization interference and phase-modulation to intensity-modulation (PM–IM) conversion. Thanks to the inherent birefringence in the $LiNbO_3$ crystal, a π phase shift is obtained by adjusting the wavelength spacing between two adjacent wavelengths, which leads to the generation of a positive coefficient and a negative coefficient. An equivalent experiment is performed. Four-tap and six-tap microwave photonic filters with positive and negative coefficients are experimentally demonstrated. The reconfigurability of the four-tap and six-tap microwave photonic filters is also investigated.

Index Terms: Microwave photonics, microwave photonic filter, birefringence, phase modulator, polarization interference.

1. Introduction

The implementation of microwave filters in the optical domain with the advantageous features such as broad bandwidth and large tunability has attracted great interest in the last two decades, and numerous techniques have been proposed and demonstrated [1]–[4]. Usually, a microwave photonic filter has a delay-line structure with a finite impulse response (FIR). To avoid optical interferences, which are very sensitive to environmental perturbations, an FIR microwave photonic filter is usually designed to operate in the incoherent regime. It is known that a microwave photonic filter operating in the incoherent regime has all-positive coefficients, or a special design has to be employed to generate negative or complex coefficients [3]. Based on signal processing theory, an FIR filter with all-positive coefficients can only function as a low-pass filter. For many applications, however, bandpass filters are needed. To overcome this limitation, many approaches have been proposed to realize microwave photonic filters with negative coefficients [5]–[8]. A simple solution to implement a microwave photonic filter with negative coefficients is to use differential detection [5]. Since the negative coefficients are generated in the electrical domain, the systems are not all optical but hybrid. Numerous techniques have been proposed to achieve all-optical microwave photonic filters with negative coefficients. In [6], a microwave photonic filter with negative coefficients was demonstrated based on cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA). Negative coefficients can also be generated based on carrier depletion effects in a distributed-feedback laser diode (DFB-LD) [7]. The use of complementary light sources by filtering a broadband light source using cascaded fiber Bragg gratings (FBGs) can also generate negative coefficients [8]. A microwave photonic filter with negative coefficients can also be achieved using a phase modulator [9], [10], with the negative coefficients generated based on phase-modulation to intensity-modulation (PM–IM) conversion in a dispersive element such as a linearly chirped FBG (LCFBG) or in an optical frequency discriminator such as a Sagnac loop filter. However, an LCFBG and a Sagnac loop filter are both temperature sensitive, which may make the filter have poor stability. A microwave photonic filter with negative coefficients can also be realized by biasing a pair of Mach–Zehnder modulators (MZMs) at the positive and negative slopes of the transfer functions to achieve π phase inversion [11]. Due to the non-flat nature of the frequency response of an MZM, the two MZMs have to be perfectly matched to avoid frequency-dependent coefficients. In addition, the microwave signal applied to the MZMs must be precisely synchronized. A simplified technique using only a single MZM to achieve π phase inversion based on wavelength dependence of the half-wave voltage $(V_{\pi}(\lambda))$ was proposed [12]. It was shown that a $LiNbO_3$ MZM was biased at the positive and negative slopes for two wavelengths at the 1550-nm and 1300-nm windows. A two-tap microwave photonic filter with one negative coefficient was experimentally demonstrated. The large wavelength spacing, however, makes it difficult in achieving a microwave photonic filter with more than two taps. For a microwave photonic filter with multiple taps, a fixed time delay has to be introduced to the channels operating at 1550-nm or 1300-nm windows to offset the large time-delay difference due to the large wavelength spacing. In addition, two types of fibers such as a standard single-mode fiber (SSMF) and a dispersion-shifted fiber (DSF) have to be employed as two dispersive elements to introduce time delays with identical time-delay spacing at the 1550-nm and 1300-nm windows. This would significantly increase the system complexity and cost. Furthermore, due to the fact that the half-wave voltages for the two wavelengths are not identical, the transfer functions around the bias point are not exactly complementary; thus, the modulation gains and the dynamic ranges for the two wavelengths are not identical, which may reduce the performance of the filter.

In this paper, we propose and experimentally demonstrate a simple approach to implementing a multitap microwave photonic filter with negative coefficients using only a single $LiNbO_3$ phase modulator. The concept is similar to the one in [12], but the wavelength spacing for the taps with positive and negative coefficients is greatly reduced and the implementation of a microwave photonic filter with multiple taps is significantly simplified. Considering that a $LiNbO_3$ crystal is inherently birefringent and the birefringence is wavelength dependent, thus, a wavelength-dependent phase shift will be introduced, which would lead to a π phase shift if the wavelength spacing is properly selected. An optical polarizer is then connected after the phase modulator to perform polarization interference and PM–IM conversion. The proposed technique is verified by an equivalent experiment. Four-tap and six-tap microwave photonic filters with positive and negative coefficients are experimentally demonstrated. The reconfigurability and stability of the filter are also investigated.

2. Principle

The schematic of the proposed multitap microwave photonic filter is shown in Fig. 1. An LD array with N wavelengths multiplexed at a wavelength multiplexer is sent to a $LiNbO_3$ phase modulator via a polarization controller (PC). The light waves from the N LDs are linearly polarized with equal frequency interval. The polarization directions of the light waves are adjusted to be 45° relative to one principal axis of the phase modulator. For a z-cut $LiNbO_3$ phase modulator, the half-wave voltages of the two orthogonal principal polarization directions are different, which leads to two different phase modulation indices for two orthogonally polarized light waves (the o-wave and e-wave) [13]. In addition, since the birefringence is wavelength dependent, a wavelength-dependent

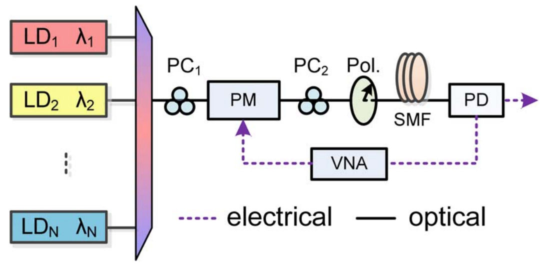

Fig. 1. Schematic of the proposed microwave photonic filter. LD: laser diode, PC: polarization controller, PM: phase modulator, Pol.: polarizer, VNA: vector network analyzer, PD: photodetector.

phase difference between the o-wave and e-wave will be introduced in the $LiNbO_3$ crystal. Applying the two orthogonally polarized signals to an optical polarizer with its polarization axis aligned at an angle of 45° relative to the principle axis of the phase modulator, a maximal polarization interference will happen and the phase-modulated signals will combine to generate an intensity-modulated signal. The optical intensity transfer function can be described as

$$T = \frac{1}{2}\left[1 + \cos\left(\frac{\pi V_{rf}}{V_\pi^{eff}} + \Delta\theta_{o,e}(\lambda)\right)\right] \tag{1}$$

where V_{rf} is the voltage of the radio-frequency (RF) signal applied to the phase modulator, V_π^{eff} is the effective half-wave voltage, and $\Delta\theta_{o,e}(\lambda)$ is the phase difference between the o-wave and e-wave at a wavelength of λ. The phase difference $\Delta\theta_{o,e}(\lambda)$ is given by

$$\Delta\theta_{o,e}(\lambda) = \frac{2\pi L}{\lambda}[n_o(\lambda) - n_e(\lambda)] \tag{2}$$

where L is the length of the $LiNbO_3$ crystal in the phase modulator, and n_o and n_e are the refractive indices along the slow and fast axes, respectively. The refractive indices versus wavelength for both the o-wave and e-wave can be expressed by the Sellmeier equations [14], given by

$$n_o^2(\lambda) - 1 = \frac{2.6734\lambda^2}{\lambda^2 - 0.01764} + \frac{1.2290\lambda^2}{\lambda^2 - 0.05914} + \frac{12.614\lambda^2}{\lambda^2 - 474.60} \tag{3.1}$$

$$n_e^2(\lambda) - 1 = \frac{2.9804\lambda^2}{\lambda^2 - 0.02047} + \frac{0.5981\lambda^2}{\lambda^2 - 0.0666} + \frac{8.9543\lambda^2}{\lambda^2 - 416.08}. \tag{3.2}$$

As can be seen from (1) and (2), two complementary signals with counter-phase intensity modulation can be achieved if the phase difference at different wavelengths satisfies the condition

$$\Delta\theta = \Delta\theta_{o,e}(\lambda_i) - \Delta\theta_{o,e}(\lambda_j) = (2n+1)\pi, n = 0, \pm 1, \cdots. \tag{4}$$

For a given length of the $LiNbO_3$ crystal in the phase modulator, according to (2)–(4), we can easily obtain the relationship between the phase difference and the wavelength in the C-band relative to a reference wavelength of 1530 nm, as shown in Fig. 2. As can be seen, the phase difference versus wavelength is linear, and a π phase shift can be achieved for a $LiNbO_3$ crystal with a given length if the wavelength spacing is 0.8 nm, corresponding to a frequency difference of 100 GHz, which indicates that the proposed filter can be implemented using a commercially available LD array and wavelength division multiplexer.

Assuming that the length of the $LiNbO_3$ crystal is 20 mm, 24 pairs of positive and negative coefficients can be generated in the whole C-band from 1530 nm to 1565 nm. When the length of the $LiNbO_3$ crystal increases (the typical length in a phase modulator and an MZM is 20 $\sim$ 50 mm) [15], the number of taps would also be increased, which is suitable for most of the applications.

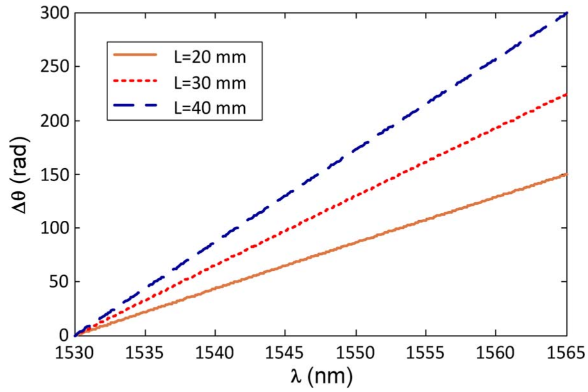

Fig. 2. Phase difference versus wavelength relative to a reference wavelength of 1530 nm for a $LiNbO_3$ crystal in the phase modulator with a length of 20, 30, and 40 mm.

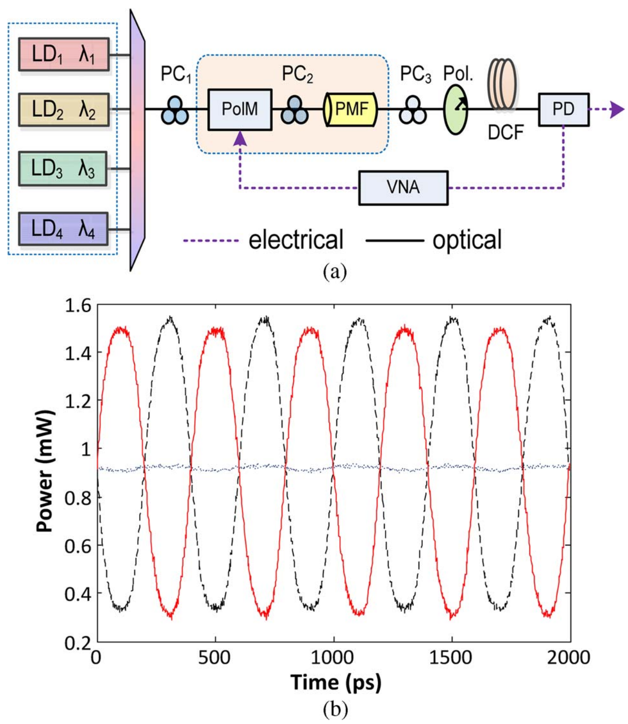

Fig. 3. (a) Experimental setup of the proposed microwave photonic filter. (b) Generation of two complementary microwave optical signals. LD: laser diode, PC: polarization controller, PolM: polarization modulator, PMF: polarization-maintaining fiber, Pol.: polarizer, DCF: dispersion-compensating fiber, VNA: vector network analyzer, PD: photodetector.

3. Experiment Setup

The proposed microwave photonic filter is experimentally demonstrated. Fig. 3(a) shows the experimental setup. Since a $LiNbO_3$ phase modulator is not available, in the experiment, the phase modulator is replaced by an AlGaAs–GaAs-based electro-optic polarization modulator (PolM; Versawave Technologies) [16] followed by a polarization-maintaining fiber (PMF). A PolM has similar modulation characteristics as a $LiNbO_3$ phase modulator, supporting both TE and TM modes but with opposite phase modulation indices. A PolM has a lower half-wave voltage (typical value $V_\pi = 3.5$ V) compared with a $LiNbO_3$ phase modulator, which has a typical half-wave voltage of about 6 V [17]. Since a PolM has negligible birefringence, to emulate the operation of a $LiNbO_3$ phase modulator, a length of PMF is connected to the PolM to introduce an equivalent birefringence, as shown in the dotted box of Fig. 3(a). First, a four-tap microwave photonic filter with two negative coefficients is implemented. To do so, four light waves from an LD array (Agilent N7714A) with four wavelengths at 1550.12, 1550.92, 1551.72, and 1552.52 nm are sent to the PolM through a 4×1 optical coupler and a PC (PC1). The four wavelengths are located at the ITU-T grid with a frequency spacing of 100 GHz (0.8 nm) so that a standard wavelength division multiplexer can also be used to replace the optical coupler to reduce the insertion loss. In addition, the four light waves have an identical state of polarization (SOP), and only one PC (PC1) is used to adjust the SOP of the four light waves, to make them aligned with an angle of 45° relative to one principal axis of the PolM.

Note that the setup here is simpler than the one reported in [18] where the SOP of each wavelength has to be independently controlled by a specific PC in the specific channel. For practical applications, however, the filter must be compact, and the use of multiple PCs to control the SOPs of the light waves would make the filter very bulky with poor stability. In addition, the ultimate goal is to implement the filter using a photonic integrated circuit (PIC), but it is extremely difficult to implement tunable PCs in a PIC. Note that the concept in [18] was recently extended by Xue *et al.* to have the ability to control not only the polarity of the coefficients but also the weights of the taps [19], which is realized by simply tuning the PCs to control the SOP of each wavelength to have an angle that is not always equal to 45° or 135°. Again, since the SOP of each wavelength has to be independently controlled by a specific PC, the implementation is complicated.

A PMF with a beat length of 3.75 mm is connected at the output of the PolM via a second PC (PC2). The length of the PMF is selected to be 3.63 m to ensure the frequency interval between two adjacent wavelengths is 100 GHz to introduce a π phase shift. The slow and fast axes of the PMF are aligned with the principal axes of the PolM by tuning PC2. A polarizer is connected after the PMF with its polarization axis aligned with an angle of 45° to one principal axis of the PolM by a third PC (PC3). At the polarizer, two orthogonally polarized components carried by the same wavelength would interfere, and an intensity-modulated microwave optical signal is obtained. A π phase shift between two adjacent channels is also introduced. The output microwave optical signal from the polarizer is monitored by an oscilloscope (Agilent 86100C) in which a built-in 53-GHz photodetector (PD) is employed to perform optical-to-electrical conversion. As shown in Fig. 3(b), two complementary microwave signals (solid and dashed curves) are generated for two light waves with a frequency spacing of 100 GHz, with the measurement done by injecting each of the light waves into the PolM at a time. When the two light waves are injected into the PolM simultaneously, the output would be a dotted curve (DC), since the two microwave signals are complementary and cancelled. This again confirms the fact that the two microwave signals are really identical in amplitude but out of phase. Note that, when performing the measurement, the optical power to the oscilloscope is keep constant. Then, a length of dispersion-compensating fiber (DCF) with a value of dispersion of -609 ps/nm at 1550 nm is used as a wavelength-dependent optical time-delay line. The time-delayed optical signals are detected by a 10-GHz PD, and the frequency response (S_{21} parameter) is measured by a vector network analyzer (VNA; Agilent E8364A).

4. Results

Fig. 4(a) shows the measured optical spectrum of the four light waves sent to the PolM, and the corresponding frequency response (solid curve) of the proposed four-tap microwave photonic filter is shown in Fig. 4(b). It is clearly seen that the microwave photonic filter is a typical four-tap bandpass filter with four coefficients of [1 -1 1 -1] and a free spectral range (FSR) of 2.1 GHz. The frequency response of a filter with the same coefficients of [1 -1 1 -1] is calculated in two cases, which is also shown in Fig. 4(b) (dotted and dashed curve). One difference between the two simulations is that whether the chromatic-dispersion-induced power fading is considered. It can be seen from Fig. 4 that the experimental results are in good agreement with the theoretical results, especially with those considering the dispersion-induced penalty. A slight deviation between the

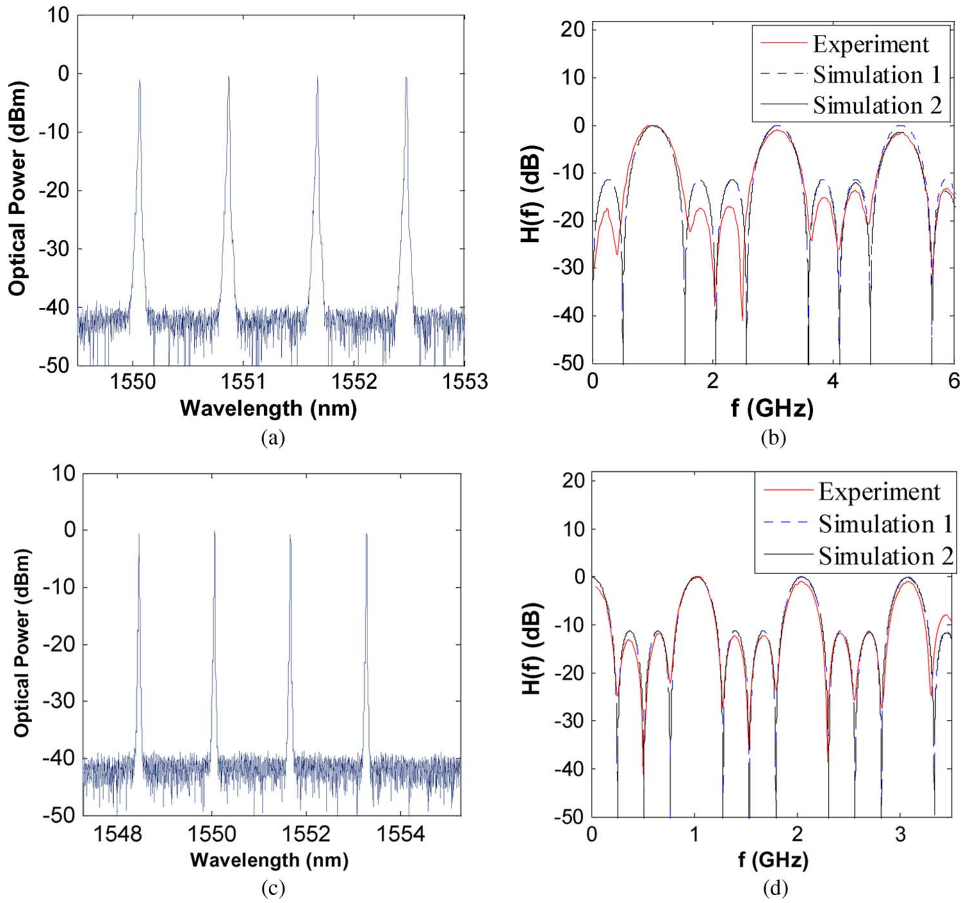

Fig. 4. Frequency responses of a four-tap filter with coefficients of [1 −1 1 −1] and [1 1 1 1]. (a) Optical spectrum of the four light waves sent to the PolM with a frequency spacing of 100 GHz (0.8 nm), and (b) the corresponding frequency response of the four-tap filter. (c) Optical spectrum of the four light waves sent to the PolM with a frequency spacing of 200 GHz (1.6 nm), and (d) the corresponding frequency response of the four-tap filter. ——— experiment results, ······ simulation results w/o considering the dispersion-induced penalty, − − − simulation results considering the dispersion-induced penalty.

experimental and theoretical results is observed, which is resulted from the misalignment of the input SOPs relative to the principal axes of the PolM and the PMF. A relative apparent power fading at the high frequency is observed, which is theoretically predicted by considering the dispersion-induced power penalty [20]. The power fading is about 1.5 dB in the 6-GHz modulation bandwidth of the filter response.

The proposed filter can be reconfigured. For example, a four-tap lowpass microwave photonic filter with coefficients of [1 1 1 1] can be implemented. To do so, the four wavelengths from the LD array are selected at 1548.52, 1550.12, 1551.72, and 1553.33 nm. All are locked to the ITU-T grid with a channel spacing of 200 GHz (1.6 nm), as shown in Fig. 4(c). Therefore, the phase shift between two adjacent channels is now 2π, which corresponds to a time-delay difference of 974 ps and an FSR of 1.026 GHz. The frequency response of the filter is shown in Fig. 4(d). Again, the experimental results agree well with the theoretical calculations.

The proposed filter can be extended to have more taps. It is known that a bandpass filter with narrower passband should have a higher Q factor, which can be achieved by using more taps. In the experiment, by adding two more wavelengths, a six-tap microwave photonic filter with coefficients of [1 −1 1 −1 1 −1] is implemented. These six wavelengths are 1549.32, 1550.12, 1550.92, 1551.72, 1552.52, and 1553.33 nm, as shown in Fig. 5(a). Fig. 5(b) shows the corresponding filter

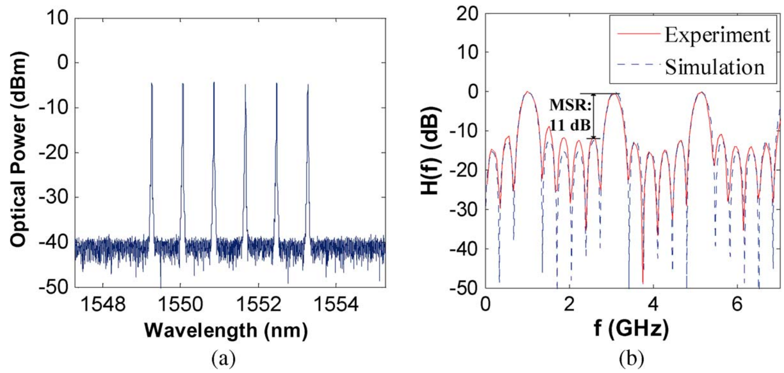

Fig. 5. Frequency response of a six-tap filter with coefficients of [1 −1 1 −1 1 −1]. (a) Optical spectrum of the six light waves sent to the PolM with a frequency spacing of 100 GHz (0.8 nm), and (b) the corresponding frequency response of the six-tap microwave photonic filter.

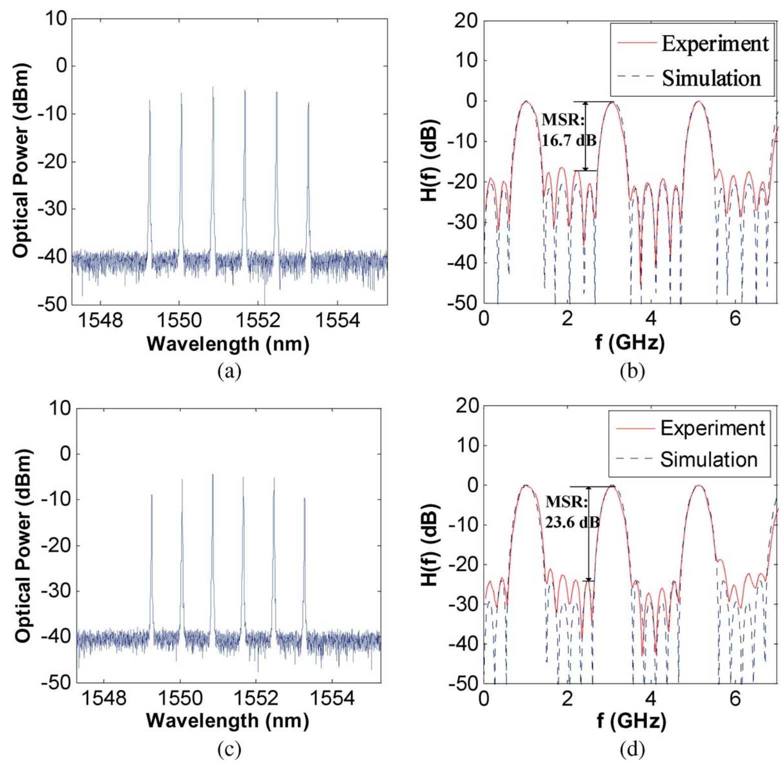

Fig. 6. Frequency responses of a six-tap filter with coefficients of [0.5 −0.75 1 −1 0.75 −0.5] and [0.35 −0.75 1 −1 0.75 −0.35]. (a) Optical spectrum of the six light waves sent to the PolM with a frequency spacing of 100 GHz (0.8 nm) with coefficients of [0.5 −0.75 1 −1 0.75 −0.5], and (b) the corresponding frequency response. (c) Optical spectrum of the six light waves sent to the PolM with a frequency spacing of 100 GHz (0.8 nm) with coefficients of [0.35 −0.75 1 −1 0.75 −0.35], and (d) the corresponding frequency response.

frequency response. The 3-dB bandwidth of the filter is 0.3 GHz. The theoretically calculated filter frequency response considering the dispersion-induced penalty is also shown as dotted line. Again, an excellent agreement with the theoretical results is achieved. It is worth noting that the proposed approach can also be extended to have more taps if a broadband incoherent light source and an optical comb filter are used. The light source can be an erbium-doped fiber amplifier (EDFA) or a light-emitting diode (LED), and the comb filter, employed to slice the broadband light source, can be an arrayed waveguide grating (AWG). Again, only one PC (PC1) is required. Thus, the approach here can be extended to have more taps but with a much simpler structure as compared with the approaches in [18] and [19]. However, it is also worth pointing out that this approach suffers from a limitation inherent to the proposed configuration, which results in the taps with alternate-sign or all-positive coefficients.

Then, the reconfigurability of the six-tap filter is evaluated. Two windowing functions are applied to make the coefficients be [0.5 -0.75 1 -1 0.75 -0.5] and [0.35 -0.75 1 -1 0.75 -0.35] by controlling the output optical powers of the LD arrays at each wavelengths. The optical spectra of the light waves sent to the PolM are shown in Fig. 6(a) and (c), and the corresponding frequency responses are shown in Fig. 6(b) and (d), respectively. Compared with the microwave photonic filter with uniform coefficients, the mainlobe-to-sidelobe ratio (MSR) of the filter with coefficients of [0.5 -0.75 1 -1 0.75 -0.5] is increased from 11 dB to 16.7 dB, and that of the filter with coefficients of [0.35 -0.75 1 -1 0.75 -0.35] is increased from 11 dB to 23.6 dB.

The stability of the proposed filter is an important feature for practical applications. The stability of the system is also evaluated. To do so, the system is allowed to operate for more than two hours at room temperature in a laboratory environment. The spectrum response of the proposed filter is monitored by a VNA (Agilent E8364A) with negligible amplitude fluctuations and frequency shifts. Compared with previous reported schemes, the excellent short-term stability of the proposed filter mainly owns to the simplicity of the structure, which consists of fewer PCs and an LD array. The long-term stability may be affected due to the SOP and wavelength drift of the light-wave output from the LD array. For real applications, the use of the wavelength-stabilized laser sources and PICs would increase the system long-term stability.

5. Conclusion

We have proposed and experimentally demonstrated a simple scheme to implement multitap microwave photonic filter with positive and negative coefficients based on a single $LiNbO_3$ phase modulator. Thanks to the inherent birefringence in the $LiNbO_3$ crystal and the wavelength dependence of the birefringence, a π phase shift between two taps can be obtained by adjusting the wavelength spacing of two adjacent wavelengths corresponding to two filter taps, with one having a positive coefficient and the other having a negative coefficient. An experiment has been performed, in which four- and six-tap microwave photonic filter with both positive and negative coefficients were demonstrated. The reconfigurability of the four-tap and six-tap microwave photonic filters has been also evaluated. By changing the wavelength spacing, a four-tap filter with all-positive coefficients has been achieved. By applying a windowing function to the coefficients of the six-tap filter through controlling the optical powers of the light waves from the LD array, a six-tap filter with an increased MSR has been realized.

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