Photonic Microwave Bandpass Filter With Negative Coefficients Using a Polarization Modulator

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***Abstract*—A novel photonic microwave bandpass filter with negative coefficients implemented using a polarization modulator (PolM) is proposed and experimentally demonstrated. In the proposed filter, a lightwave from a tunable laser source (TLS) is sent to a PolM, with the incident lightwave adjusted to have its polarization direction aligned at an angle of ±45° to the principal axes of the PolM. A microwave signal is applied to the PolM through its RF port. Thanks to the polarization modulation in the PolM, two complementary microwave signals with identical amplitudes carried by two optical carriers with orthogonal polarizations are generated. The two complementary optical microwave signals are then sent to an optical delay line consisting of one section or two sections of polarization-maintaining fiber (PMF), with the polarization directions aligned with the fast and slow axes of the PMF. A photonic microwave bandpass filter with two or four taps is obtained.**

***Index Terms*—Bandpass filter, microwave photonics, photonic microwave filter, polarization-maintaining fiber (PMF), polarization modulation.**

I. Introduction

PROCESSING of microwave and millimeter-wave signals in the optical domain with the advantageous features such as broad bandwidth, low loss, light weight, and immunity to electromagnetic interference offered by optics has been a topic of interest for over two decades [1], [2]. In general, photonic microwave filters are implemented based on a delay line structure, in which different time delays are generated using optical delay line devices. The major difficulty associated with the implementation of an optical delay line microwave filter is the optical interference which is very sensitive to environmental changes, leading to poor system stability. A straightforward solution to the problem is to use incoherent detection, such as using a low coherent light source. Photonic microwave filters based on incoherent detection have only positive coefficients, with lowpass filtering only. For many applications, such as in a radio-over-fiber link, bandpass filters are required. In the last few years, many approaches have been proposed to implement microwave bandpass filters. An approach to achieve bandpass filtering is to employ differential photodetection using a balanced photodetector (PD) [3]. Microwave filters with negative coefficients can also be achieved based on cross-gain modulation in a semiconductor optical amplifier [4], or carrier depletion effect in a laser diode [5], [6]. The use of a complementary light source obtained by filtering a broadband light source using fiber Bragg gratings (FBGs) can also achieve bandpass filtering with negative coefficients [7]. Photonic microwave bandpass filters can also be realized by biasing a pair of intensity modulators at the opposite slopes to achieve phase inversion [8], or by using a single dual-output intensity modulator with a double-pass modulation [9]. Recently, we demonstrated a microwave bandpass filter with negative coefficients based on optical phase modulation to intensity modulation conversion in an optical filter or chirped FBGs. By locating the phase-modulated optical signals at the opposite slopes of the transfer function of the optical filter or by passing the phase-modulated optical signals through chirped FBGs with group-delay responses of positive and negative slopes [10], [11], microwave bandpass filters with negative coefficients were generated.

In this letter, we propose and demonstrate a new and simple photonic microwave bandpass filter with negative coefficients based on polarization modulation in an electrooptic polarization modulator (PolM). In the proposed system, a lightwave generated by a tunable laser source (TLS) is sent to the PolM, with its polarization direction aligned at an angle of ±45° to the principal axes of the PolM. A microwave signal is applied to the modulator via its RF port. Thanks to the polarization modulation at the PolM, two out-of-phase microwave signals carried by two optical carriers with orthogonal polarizations are obtained at the output of the PolM. The out-of-phase optical microwave signals are then sent to a section or two sections of polarization-maintaining fiber (PMF) to generate time delays. By applying the time-delayed optical microwave signals to a PD, a photonic microwave bandpass filter with two or four taps is obtained.

II. Principle

The proposed microwave bandpass filter with negative coefficients based on a PolM is shown in Fig. 1. The key component in the filter is the PolM [12], which operates as an electrically variable wave plate, capable of changing a linearly polarized laser light to an orthogonal linear polarization, passing through elliptical and circular polarization states [12]. In the system, a linearly polarized lightwave generated by a TLS is sent to the PolM through a polarization controller (PC1) to adjust its polarization direction to make it aligned with the transmission axis of a polarizer that is integrated in the PolM. The direction of the internal polarizer is oriented at an angle of ±45° to the principle axes of the PolM. A microwave signal generated from a

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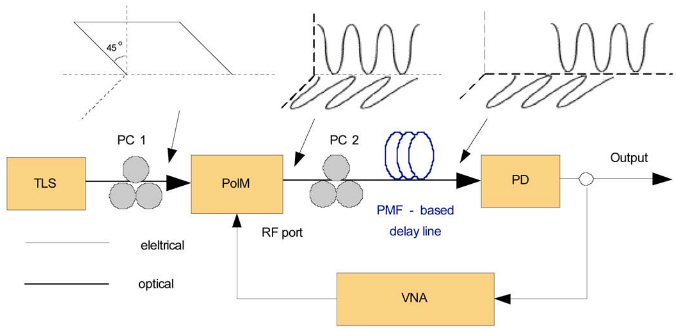

Fig. 1. Schematic diagram of the proposed photonic microwave filter.

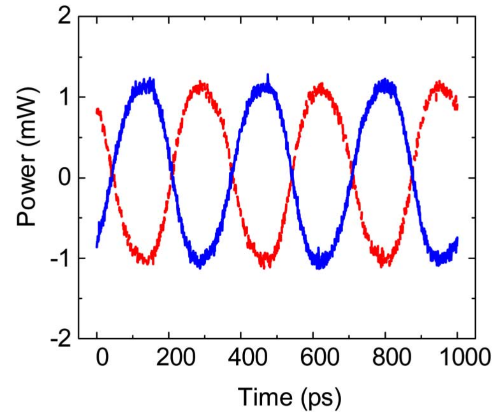

Fig. 2. Generation of two complementary microwave signals based on polarization modulation.

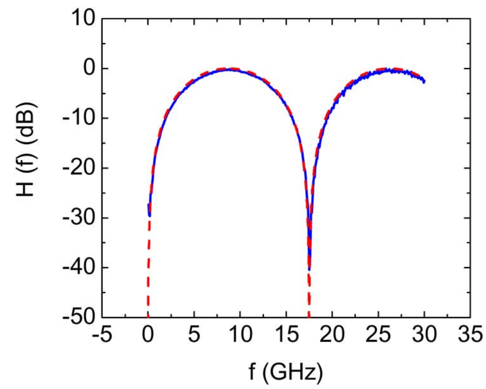

Fig. 3. Frequency responses of the two-tap microwave bandpass filter with one negative coefficient. (Solid curve: experimental results. Dashed line: simulation results).

vector network analyzer (VNA) (Agilent E8364A) is applied to the PolM via its RF port. Thanks to the polarization modulation, two complementary microwave signals modulated on two orthogonally polarized optical carriers are generated. The optical microwave signals are then sent to a PMF-based delay line through a second PC (PC2) to align its polarization directions with the principal axes of the PMF. The delay line can be one or two sections of PMF to obtain two or four time-delayed optical microwave signals. The time delay difference between two adjacent time-delayed optical microwave signals is determined by the birefringence of the PMF and the length of the shorter section of the PMF (if the delay line has multiple sections). The time-delayed signals are then sent to a 45-GHz PD. A two- or four-tap microwave filter with one or two negative coefficients is thus achieved.

III. Experimental Results and Discussion

The proposed microwave filter shown in Fig. 1 is built. A TLS with a linewidth of 150 kHz is employed as the light source. The PolM is an AlGaAs–GaAs 40-Gb/s mode-converter-based modulator (Versawave Technologies). The PolM can operate from 1530 to 1560 nm, with a polarization extinction ratio better than 28 dB [12]. In the experiment, we first verify the generation of two complementary microwave signals by polarization modulation. To do so, we use a 3-GHz microwave tone generated from a VNA to modulate the PolM. A tunable polarizer is connected at the output of the PolM to select one of the two orthogonally polarized optical carriers, by tuning the transmission axis of the tunable polarizer. When the transmission axis of the tunable polarizer is aligned with the polarization direction of one of the two optical carriers, a microwave signal is generated at the PD. The output microwave signal is monitored by an oscilloscope. As can be seen from Fig. 2, the two microwave signals are identical in amplitude, but out of phase. This verifies that the polarization modulation at the PolM generates two complementary microwave signals.

Then, a PMF-based delay line is connected to the PolM through PC2. The function of PC2 is to align the polarization directions of the two orthogonal optical carriers with the principal axes of the PMF. In the experiment, we first use a delay line with one section of PMF. A two-tap microwave filter is thus realized. The beat length of the PMF is 3.75 mm; a total length of 42 m would generate a time-delay difference of 57 ps between the two orthogonal optical carriers traveling along the fast and slow axes, which corresponds to a free-spectral range (FSR) of 17.5 GHz. The frequency response of the microwave filter is measured again by the VNA by scanning the frequency of the microwave signal applied to the PolM while keeping the power constant. The frequency response is shown in Fig. 3, which is equal to a frequency response of a microwave filter with coefficients $[1 \quad -1]$. It is clearly seen that it is a bandpass filter with a notch as deep as 30 dB at dc. A frequency response with coefficients $[1 \quad -1]$ calculated by numerical simulation is also shown in Fig. 3 (dashed line). An excellent agreement is observed.

When the one-section PMF is replaced by a two-section PMF with the second section having a length that is twice that of the first section, a four-tap bandpass filter is obtained. The two sections are spliced by a polarization-maintaining splicer, with a splicing angle of 45° between the two principal axes of the two sections. The lengths of the first and the second sections in the experiment are, respectively, 62.9 and 125.8 m. If the polarization directions of the two orthogonal optical carriers at the output of the PolM are aligned with the principal axes of the shorter section of the PMF, four coefficients $[1 \quad -1 \quad 1 \quad -1]$ are generated. The filter is a bandpass filter with two negative coefficients. The time-delay difference between two adjacent taps is about 80 ps. Therefore, a bandpass filter with an FSR of 12.5 GHz is obtained. The experimental frequency response is

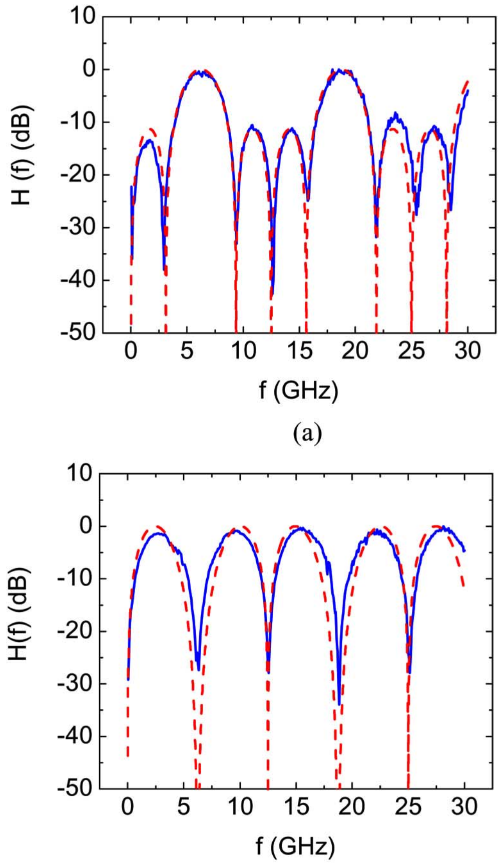

Fig. 4. Frequency responses of the four-tap microwave bandpass filter. (a) Frequency response with coefficients $[1\quad -1\quad 1\quad -1]$. (b) Frequency response with coefficients $[1\quad 1\quad -1\quad -1]$.

shown in Fig. 4(a) (solid curve). Again, it agrees very well with the simulated frequency response (dashed curve). If the polarization directions of the two optical carriers at the output of the PolM are aligned with the principal axes of the longer section of the PMF, four coefficients $[1\quad 1\quad -1\quad -1]$ are generated. The experimental frequency response is shown in Fig. 4(b). A slight discrepancy between the experimental and simulation results is observed, which is resulted from the misalignment between the polarization directions of the two optical carriers at the output of the PolM and the principal axes of the longer section of the PMF.

Note that along each principal axis of the second section of the PMF there are two degenerated lightwave components; interferences would happen along each principal axis. However, since the time-delayed optical microwave signals are traveling within the same optical fiber, environmental changes imposed on the different optical microwave signals are identical; therefore, a stable operation is still ensured [13], [14].

Note also that although the coefficients of the filter can be switched from $[1\quad -1\quad 1\quad -1]$ to $[1\quad 1\quad -1\quad -1]$ by adjusting PC2, they cannot be adjusted independently. Therefore, the filter is not reconfigurable. In addition, the FSR of the filter is determined by the lengths of the sections of the PMF. Once the lengths are fixed, the FSR cannot be changed. The filter is not tunable.

IV. Conclusion

We have proposed and experimentally demonstrated a new photonic microwave filter with negative coefficients based on polarization modulation in a PolM. Thanks to the polarization modulation, two complementary microwave signals modulated on two optical carriers that were orthogonally polarized were obtained at the output of the PolM. Different time delays introduced to the optical microwave signals were generated by using a PMF-based delay line, which in our demonstration was a section or two sections of PMF. A microwave bandpass filter with two or four taps was experimentally demonstrated.

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