Multitap Photonic Microwave Filters With Arbitrary Positive and Negative Coefficients Using a Polarization Modulator and an Optical Polarizer

Qing Wang and Jianping Yao, *Senior Member, IEEE*

***Abstract*—A novel multitap photonic microwave filter with arbitrary positive and negative coefficients implemented using an electrooptic polarization modulator (PolM) and an optical polarizer is proposed and experimentally demonstrated. In the proposed filter, the optical polarizer is connected at the output of the PolM with its transmission axis aligned at an angle of 45° to one principal axis of the PolM. By adjusting the polarization direction of the input lightwave to be 45° or 135° to one principal axis of the PolM, an inverted or noninverted intensity-modulated optical microwave signal is obtained at the output of the optical polarizer, which leads to the generation of a negative or positive coefficient. A time delay difference between adjacent taps is generated by using a wavelength-dependent delay line. A five-tap photonic microwave filter with arbitrary positive and negative coefficients is demonstrated. The reconfigurability of the filter is also investigated.**

***Index Terms*—Microwave photonics, optical processing of microwave signals, photonic microwave filter, polarization modulation.**

I. Introduction

THE implementation of microwave filters in the optical domain has been a topic of interest in the last few years thanks to the advantageous features such as low loss, light weight, broad bandwidth, large tunability, and immunity to electromagnetic interferences provided by photonics [1], [2]. Photonic microwave filters are usually implemented based on a delay line structure, in which a microwave input signal is modulated onto one or multiple optical carriers via an optical modulator; the modulated lightwaves are then sent to a time delay device to introduce different time delays; the time delayed microwave signals are then recovered at a photodetector (PD). To avoid the optical interference, most of the approaches proposed in the past are based on incoherent detection, which lead to the implementation of microwave filters with all positive coefficients. A microwave filter with all positive coefficients can only operate as a low-pass filter [1]. To implement a microwave filter that functions as a bandpass filter, negative coefficients must be generated. Various designs have been proposed to realize microwave filters with negative coefficients [3]–[12]. Recently, we proposed a simple approach to implementing a microwave bandpass filter with negative coefficients using an electrooptical polarization modulator (PolM) [11]. In the proposed filter, a linearly polarized lightwave generated by a laser diode (LD) is sent to the PolM with its polarization direction aligned at an angle of 45° to one of the principal axes of the PolM. Thanks to the polarization modulation in the PolM, two complementary microwave signals with identical amplitudes carried by two orthogonally polarized lightwaves are generated. The two orthogonally polarized lightwaves are then sent to a section or two sections of high-birefringence (Hi-Bi) fibers to generate a time delay difference between two adjacent taps thanks to the birefringence of the Hi-Bi fiber. A two- or four-tap photonic microwave filter with one or two negative coefficients was demonstrated. The approach in [11] can realize a microwave filter with negative coefficients, but the positive and negative coefficients are generated in pairs, which limited the design of the filter response. In addition, the filter is not reconfigurable as the weights of the positive and negative coefficients are always identical. In [12], a photonic microwave filter with arbitrary positive and negative coefficients by using the cross-gain modulation effect in a semiconductor optical amplifier (SOA) was proposed. One major difficulty in implementating the filter is the need of a careful balance of the optical powers at the input of the SOA, to guarantee the same output power saturation response.

In this letter, we propose a photonic microwave filter with a simple architecture using a PolM with arbitrary positive and negative coefficients. The key difference of the proposed approach from an earlier approach in [11] is that the filter here has arbitrary positive and negative coefficients; therefore, the filter is reconfigurable. In the proposed filter, a polarizer is incorporated after the PolM, with its transmission axis aligned at an angle of 45° to one principal axis of the PolM. By adjusting the polarization directions of the input lightwaves at an angle of 45° or 135° with the principal axis of the PolM, an inverted or noninverted optical microwave signal is obtained. A time delay difference between adjacent taps is generated by using a wavelength-dependent optical delay line. The time-delayed signals are then combined and sent to a PD to recover the time-delayed microwave signals. The entire system functions as a multitap microwave filter with arbitrary positive and negative coefficients, with the signs of the coefficients determined by the polarization directions of the input lightwaves and the weights determined by the input optical powers.

Manuscript received September 15, 2007; revised October 15, 2007. This work was supported by The Natural Sciences and Engineering Research Council of Canada (NSERC).

The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca)

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2007.912562

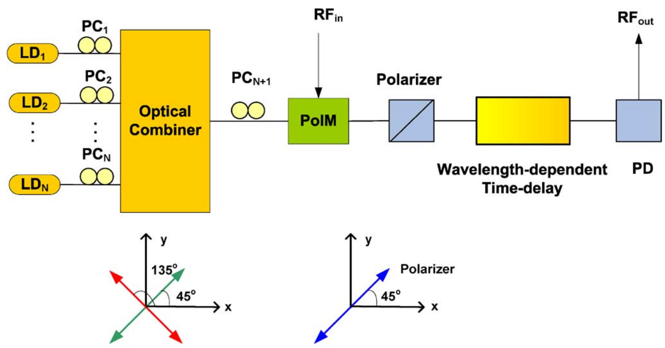

Fig. 1. Schematic diagram of a multitap photonic microwave filter with arbitrary coefficients.

II. Theoretical Analysis

The schematic diagram of the proposed N-tap microwave filter is shown in Fig. 1. In the proposed scheme, an array of N LDs generates linearly polarized lightwaves that are sent to a PolM through N polarization controllers (PCs), to adjust the polarization directions of the lightwaves to have an angle of either 45° or 135° to one principal axis of the PolM. The PolM operates as an electrically tunable arbitrary retarding wave plate [13]. With a microwave signal applied, the refractive indexes of the PolM along the two principal axes are modulated, but with different modulation indexes. Therefore, the two polarization modes would experience different phase shift, which leads to the change of the polarization states of the input lightwaves. When the voltage applied to the PolM is increased from zero to V_π, the polarization state of the input lightwave would be changed from linear polarization to orthogonal linear polarization through elliptical and circular polarization states. When a polarizer is placed at the output of the PolM with its polarization axis aligned at an angle of 45° to the same principal axis of the PolM, the polarization modulation is converted to intensity modulation. Depending on the polarization direction of the input lightwave at an angle of 45° or 135° to the principal axis of the PolM, an inverted or noninverted intensity-modulated optical microwave signal would be obtained. For a microwave filter with N taps, N wavelengths would be used, with the polarization direction of each wavelength being independently adjusted to 45° or 135° to realize N negative and positive coefficients. In the proposed filter, the time delay difference between adjacent taps is generated using a wavelength-dependent time-delay device, which can be either an array of fiber Bragg gratings or a dispersive fiber.

The key advantage of the proposed approach is that the filter is reconfigurable. The reconfigurability is realized by tuning the optical powers and the polarization directions of the incident lightwaves to the PolM, to adjust the magnitudes and the signs of the coefficients. For an N-tap microwave delay-line filter, its frequency response is given by

$$H_N(j\omega) = \sum_{k=0}^{N-1} \Re P_k a_k e^{-jk\omega\Delta\tau} \quad (1)$$

where $\Re$ is the responsivity of the PD, $\Delta\tau$ is the time delay difference between two adjacent taps, P_k is the optical power of the kth lightwave at the input of the PD, and $a_k \in \{1, -1\}$ is determined by the polarization state of the kth lightwave. If the kth lightwave is aligned with a polarization direction of 45° to the principal axis of the PolM, the intensity modulated microwave signal at the output of the polarizer would be inverted compared to the modulating microwave signal, and we have $a_k = -1$. On the contrary, if the kth lightwave is aligned with a polarization direction of 135° to the principal axis of the PolM, the intensity modulated microwave signal at the output of the polarizer would be in phase with the modulating microwave signal, and we have $a_k = 1$. Therefore, the magnitudes and signs of the coefficients can be reconfigured by adjusting the powers and polarization states of the incident lightwaves.

The filter is also tunable. The tunability is realized by tuning the time delay difference. If a dispersive fiber is used as the delay line device, the time delay difference can be continuously tuned by tuning the wavelength spacing of the input lightwaves. The time delay difference for two wavelengths with a wavelength spacing $\Delta\lambda$ traveling in a dispersive fiber with a length L and a dispersion parameter D is

$$\Delta\tau = D\Delta\lambda L. \quad (2)$$

The corresponding free spectral range (FSR) is given by FSR $= 1/\Delta\tau$.

III. Experimental Results and Discussion

A five-tap photonic microwave filter is experimentally demonstrated. The output lightwaves from five LDs with wavelengths of 1543.05, 1544.01, 1544.97, 1545.93, and 1546.89 nm are sent to the PolM via five PCs. The wavelength spacing between two adjacent taps is 0.96 nm. The PCs are used to adjust the polarization directions of the lightwaves. The PolM used in the experiment is an AlGaAs–GaAs 40-Gb/s mode-converter-based modulator (Versawave Technologies), which can operate up to 45 GHz with a wavelength range from 1530 to 1560 nm. A polarizer is connected after the PolM with its polarization axis aligned with an angle of 45° to one principal axis of the PolM by using an additional PC. Thanks to the polarization modulation at the PolM and polarization discrimination at the polarizer, intensity-modulated optical microwave signals carried by the five optical wavelengths are obtained at the output of the polarizer, with their polarities dependent on the polarization directions of the input lightwaves. In the experiment, a 9.4-km standard single-mode fiber (SMF) is used as the wavelength-dependent time optical delay line. The time delay difference between two adjacent taps is calculated to be about 160 ps, which corresponds to an FSR of 6.1 GHz.

First, we demonstrate the five-tap photonics microwave filter with five positive coefficients of (1, 1, 1, 1, 1). To do so, the polarization directions of the lightwaves from the five LDs are adjusted to be 135° with the principal axis of the PolM and the optical powers of different wavelengths at the input of the PDs are maintained identical. The frequency response of the microwave filter is shown in Fig. 2(a), which is measured using an Agilent vector network analyzer. As can be seen, the microwave filter is a typical five-tap filter with an FSR of 6.1 GHz. A theoretical frequency response with five identical positive coefficients is also shown in Fig. 2(a), which is in excellent agreement with the experimental result. Then, the five-tap photonic microwave filter is reconfigured as a microwave bandpass filter with coefficients of $(1, -1, 1, -1, 1)$. To generate the negative coefficients, we adjust the polarization direction of the lightwaves from LD_2

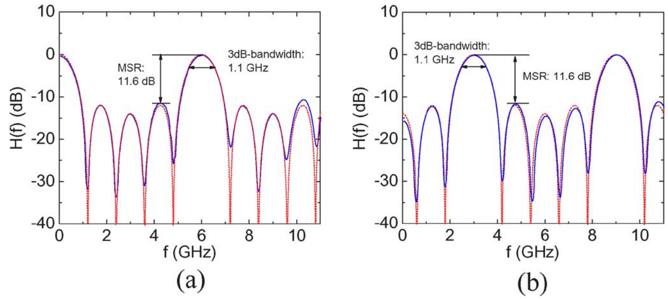

Fig. 2. Experimental (solid line) and simulated (dashed line) frequency responses of the five-tap photonic microwave bandpass filter with even coefficients; (a) coefficients (1, 1, 1, 1, 1); (b) coefficients (1,−1,1,−1,1).

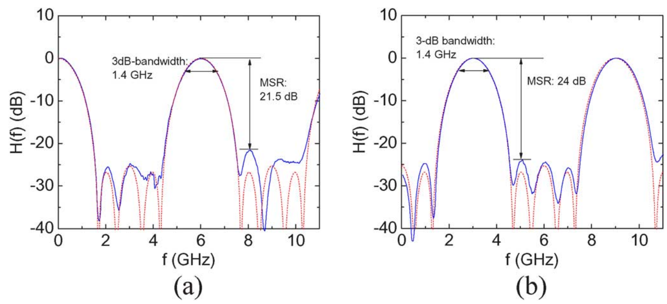

Fig. 3. Experimental (solid line) and simulated (dashed line) frequency responses of the five-tap photonic microwave bandpass filter with windowing; (a) coefficients (0.37, 0.78, 1, 0.78, 0.37); (b) coefficients (0.37,−0.78,1,−0.78, 0.37).

and LD_4, to make it be parallel to the transmission axis of the polarizer. The frequency response of the microwave bandpass filter is shown in Fig. 2(b). The 3-dB bandwidth of the mainlobe is measure to be 1.1 GHz and the mainlobe-to-sidelobe ratio (MSR) is measured to be 11.6 dB. Again, the experimental result agrees well with the theoretical frequency response.

Then, we demonstrate the reconfigurability of the filter. It is known that for a microwave delay-line filter, the MSR can be increased by applying an appropriate windowing function. In the experiment, a Gaussian function is used as the windowing function. The microwave filter after windowing has coefficients of (0.37, 0.78, 1, 0.78, 0.37) and (0.37, −0.78, 1, −0.78, 0.37), with the filter responses shown in Fig. 3(a) and (b), respectively. Comparing Fig. 2 and Fig. 3, it can be seen that after windowing, the MSR of the photonic microwave bandpass filter for the two sets of coefficients has been improved by over 10 dB.

IV. Conclusion

A novel multitap photonic microwave filter with arbitrary positive and negative coefficients implemented using a PolM and an optical polarizer was proposed and experimentally demonstrated. Depending on the polarization directions of the input lightwaves to the PolM, positive and negative coefficients were generated. A five-tap microwave filter functioning as a microwave low-pass filter with all positive coefficients and a microwave bandpass filter with both positive and negative coefficients was experimentally demonstrated. The reconfigurability of the filter was demonstrated by applying a windowing function to the weights of the taps, which was realized by controlling the powers from the LDs. The results showed that by applying a Gaussian windowing function, the MSR of the filter could be increased by over 10 dB.

References

[1] J. Capmany, B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 201–229, Jan. 2006.

[2] R. A. Minasian, "Photonic signal processing of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 832–846, Feb. 2006.

[3] F. Coppinger, S. Yegnanarayanan, P. D. Trinh, and B. Jalali, "All-optical RF filter using amplitude inversion in a semiconductor optical amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1473–1477, Aug. 1997.

[4] J. Capmany, D. Pastor, A. Martinez, B. Ortega, and S. Sales, "Microwave photonic filters with negative coefficients based on phase inversion in an electro-optic modulator," *Opt. Lett.*, vol. 28, no. 16, pp. 1415–1417, Aug. 2003.

[5] E. H. W. Chan and R. A. Minasian, "Sagnac-loop-based equivalent negative tap photonic notch filter," *IEEE Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1740–1742, Aug. 2005.

[6] Y. Yan, F. Zeng, Q. Wang, and J. P. Yao, "Photonic microwave filter with negative coefficients based on cross polarization modulation in a semiconductor optical amplifier," presented at the OFC'07, Anaheim, CA, Mar. 2007, Paper OWU6.

[7] X. Wang and K. T. Chan, "Tunable all-optical incoherent bipolar delay-line filter using injection-locked Fabry–Perot laser and fibre Bragg gratings," *Electron. Lett.*, vol. 36, no. 24, pp. 2001–2003, Nov. 2000.

[8] S. Li, S. Chiang, W. A. Gambling, Y. Liu, L. Zhang, and I. Bennion, "A novel tunable all-optical incoherent negative tap fiber-optic transversal filter based on a DFB laser diode and fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 12, no. 9, pp. 1207–1209, Sep. 2000.

[9] F. Zeng, J. Wang, and J. P. Yao, "All-optical microwave bandpass filter with negative coefficients based on a phase modulator and linearly chirped fiber Bragg gratings," *Opt. Lett.*, vol. 30, no. 17, pp. 2203–2205, Sep. 2005.

[10] Q. Wang, J. P. Yao, and J. D. Bull, "Negative tap photonic microwave filter based on a Mach–Zehnder modulator and a tunable optical polarizer," *IEEE Photon. Technol. Lett.*, vol. 19, no. 21, pp. 1750–1752, Nov. 1, 2007.

[11] J. P. Yao and Q. Wang, "Photonic microwave bandpass filter with negative coefficients using a polarization modulator," *IEEE Photon. Technol. Lett.*, vol. 19, no. 9, pp. 644–646, May 1, 2007.

[12] J. Mora, A. Martinez, M. D. Manzanedo, J. Capmany, B. Ortega, and D. Pastor, "Microwave photonic filters with arbitrary positive and negative coefficients using multiple phase inversion in SOA based XGM wavelength converter," *Electron. Lett.*, vol. 41, no. 16, pp. 921–922, Aug. 2005.

[13] J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, "40 GHz electro-optic polarization modulator for fiber optic communications systems," *Proc. SPIE*, vol. 5577, no. 1, pp. 133–143, Sep. 2004.