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Negative Tap Photonic Microwave Filter Based on a Mach–Zehnder Modulator and a Tunable Optical Polarizer

Qing Wang, Jianping Yao, *Senior Member, IEEE*, and Jeffrey D. Bull, *Member, IEEE*

***Abstract*—A negative tap photonic microwave filter based on a Mach–Zehnder modulator (MZM) and a tunable optical polarizer is proposed. In the proposed filter, the output light from the MZM, after experiencing a time delay difference between the two orthogonal modes in a polarization-maintaining fiber, is sent to the tunable optical polarizer. By adjusting the dc bias of the MZM and the polarization angle of the tunable polarizer with respect to the two orthogonal modes, two positive or one positive and one negative coefficient are generated. A theoretical analysis is presented which is verified by experiments. A two-tap microwave filter with two positive or one positive and one negative coefficient is demonstrated.**

***Index Terms*—Mach–Zehnder modulator (MZM), negative tap, photonic microwave filter, ultrawideband.**

I. Introduction

PHOTONIC microwave filtering, with the advantageous features such as low loss, light weight, broad bandwidth, large tunability, and immunity to electromagnetic interference, has been considered a very promising technique for microwave and millimeter-wave signal processing [1], [2]. Photonic microwave filters are usually implemented based on a delay line structure, in which a microwave signal is modulated on one or multiple optical carriers via an optical modulator; the modulated optical signals are sent to a time delay device to introduce time delays and then fed to a photodetector (PD). To avoid optical interference, photonic microwave filters are usually designed to operate in the incoherent regime, with only positive coefficients. It is known that a delay line filter with all positive coefficients can only function as a low-pass filter. For many applications, bandpass filters are highly desired. Recently, many approaches have been proposed and demonstrated to realize photonic bandpass filters with negative coefficients. These filters are implemented based on cross-gain modulation [3] or cross-polarization modulation [4] in a semiconductor optical amplifier, microwave phase inversion by biasing two intensity modulators to operate at the opposite slopes of the transfer functions [5], phase modulation to intensity modulation conversion by using two chirped fiber Bragg gratings with opposite dispersions [6], and polarization modulation in a polarization modulator [7]. In [3]–[6], multiple wavelengths are required to realize a bandpass filter with multiple taps, which increases the cost and complexity of the system. In [7], although a single wavelength is used, the negative coefficients are generated using a specially designed and presently high-cost polarization modulator.

In this letter, we propose and demonstrate a novel and cost-effective approach to realizing a negative tap photonic microwave filter. The key components in the proposed filter are a low-cost commercially available Mach–Zehnder modulator (MZM) and a tunable optical polarizer. The fundamental principle is to use the tunable optical polarizer to produce positive or negative coefficients. By adjusting the bias voltage of the MZM and the polarization angle of the polarizer, a two-tap microwave filter with two tunable positive or one positive and one negative coefficient is implemented.

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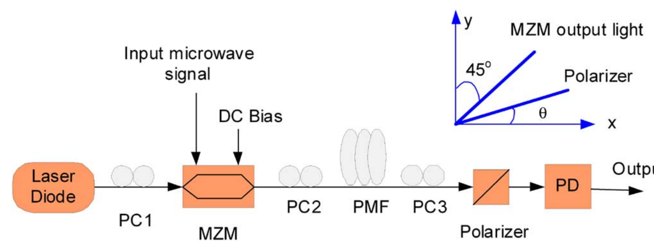

Fig. 1. Schematic diagram of the negative tap photonic microwave filter.

II. Theoretical Analysis

The schematic diagram of the proposed filter is shown in Fig. 1. The system consists of a laser diode (LD), an MZM, a length of polarization-maintaining fiber (PMF), a tunable optical polarizer, and a PD. In the system, a linearly polarized lightwave from the LD is modulated by a microwave signal at the MZM and is then sent to the PMF, with an incident polarization angle of 45° with respect to the fast axis of the PMF. In the PMF, the lightwave is decomposed into two orthogonal polarization modes. The two polarization modes travel in the PMF at different velocities due to the birefringence of the PMF, leading to the generation of a time delay difference. The two time-delayed polarization modes are then recombined at the tunable optical polarizer. By adjusting the dc bias of the MZM and the polarization angle of the tunable polarizer with respect to the two orthogonal polarization modes, two coefficients that are all positive or one positive and one negative are generated.

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With a microwave modulation signal applied, the optical field at the output of the MZM, ignoring push–pull drive for simplicity, can be mathematically expressed as

$$E(t) = E_0 \left[\frac{e^{j\omega_c t}}{\sqrt{2}} + \frac{e^{j\omega_c t + j\beta \sin \omega_e t - j\delta}}{\sqrt{2}} \right] \quad (1)$$

where ω_c is the angular frequency of the optical carrier, $\sin \omega_e t$ is the microwave modulation signal, β is the modulation index, δ is the initial phase difference between the two branches of the MZM, which can be controlled by adjusting the dc bias of the MZM. When the modulated lightwave at the output of the MZM is sent to the PMF at an incident polarization angle of 45°, it is decomposed into two orthogonal polarization modes

$$\mathbf{E}_{\text{in}}(t) = \frac{E_0 e^{j\omega_c t}}{2} [(1 + e^{-j\delta} e^{j\beta \sin \omega_e t})\hat{\mathbf{x}} + (1 + e^{-j\delta} e^{j\beta \sin \omega_e t})\hat{\mathbf{y}}] \quad (2)$$

where $\mathbf{x}$ and $\mathbf{y}$ denote the polarization directions of the fast and slow axes of the PMF, respectively. The PMF basically functions as a delay line, which generates a time-delay difference between the two polarization modes. The optical field at the output of the PMF is

$$\mathbf{E}_{\text{out}}(t) = \frac{E_0 e^{j\omega_c t}}{2} (1 + e^{-j\delta} e^{j\beta \sin \omega_e t})\hat{\mathbf{x}} + \frac{E_0 e^{j\omega_c (t+T)}}{2} [1 + e^{-j\delta} e^{j\beta \sin \omega_e (t+T)}]\hat{\mathbf{y}} \quad (3)$$

where T is the time-delay difference between the two polarization modes traveling along the fast and the slow axes of the PMF. For a small modulation index, namely $\beta \ll 1$, the output optical field of the PMF can be approximated as

$$\mathbf{E}_{\text{out}}(t) = \frac{E_0 e^{j\omega_c t}}{2} [1 + e^{-j\delta}(1 + j\beta \sin \omega_e t)]\hat{\mathbf{x}} + \frac{E_0 e^{j\omega_c (t+T)}}{2} \left\{1 + e^{-j\delta}[1 + j\beta \sin \omega_e (t+T)]\right\} \hat{\mathbf{y}}. \quad (4)$$

If $\mathbf{E}_{\text{out}}(t)$ is directly sent to the PD, since the polarizations of the two polarization modes are orthogonal, no interference would occur between the two modes. The total photocurrent is thus the sum of the photocurrents generated by the two polarization modes. Neglecting the dc and the second-order harmonics, the photocurrent is

$$I_{\text{incoh}}(t) = R\,|\mathbf{E}_{\text{out}}(t)|^2 = \frac{R E_0^2 \beta \sin \delta}{2} \times [\sin \omega_e t + \sin \omega_e (t+T)] \quad (5)$$

where R is the responsivity of the PD. Equation (5) shows that if only an MZM and a length of PMF are used, the system is generally a microwave filter with two positive coefficients when $\sin \delta \neq 0$; therefore, the filter is only a low-pass filter. The maximum amplitude response is achieved when $\delta = \pi/2$, corresponding to the case that the MZM is biased at the quadrature point of the transfer function.

If an optical polarizer is connected after the PMF, the two polarization modes would be projected to the direction of the polarization axis of the polarizer, and add coherently. The optical field at the output of the polarizer is given by

$$E_p(t) = \mathbf{E}_{\text{out}}(t) \cdot (\hat{\mathbf{x}} \cos \theta + \hat{\mathbf{y}} \sin \theta) \quad (6)$$

where θ is the polarization angle between the transmission axis of the polarizer and the fast axis of the PMF, as shown in Fig. 1. For simplicity, let $e^{j\omega_c T} = a_1 + j a_2$ and $a_3 = \tan \theta$. Substituting (4) into (6), we have

$$\begin{aligned} E_p(t) = \frac{e^{j\omega_c t} \cos \theta}{2} \{ & 1 + \cos \delta + a_1 a_3 + a_1 a_3 \cos \delta \\ & + a_2 a_3 \sin \delta + \beta \sin \delta \sin \omega_e t \\ & + \beta (a_1 a_3 \sin \delta - a_2 a_3 \cos \delta) \sin \omega_e (t+T) \\ & + j[a_2 a_3 + a_2 a_3 \cos \delta \\ & \quad - a_1 a_3 \sin \delta - \sin \delta] + j\beta \cos \delta \sin \omega_e t \\ & + j\beta [a_2 a_3 \sin \delta + a_1 a_3 \cos \delta \sin \omega_e (t+T)] \\ & \times \sin \omega_e (t+T) \}. \end{aligned} \quad (7)$$

Again, neglecting the dc and the second-order harmonics, the photocurrent at the output of the PD is

$$\begin{aligned} I_{\text{coh}}(t) = \frac{R\beta \cos^2 \theta}{2} \{ & [a_2 a_3 + a_1 a_3 \sin \delta + a_2 a_3 \cos \delta \\ & + \sin \delta] \sin \omega_e t \\ & + [a_3^2 \sin \delta + a_1 a_3 \sin \delta \\ & - a_2 a_3 \cos \delta - a_2 a_3] \sin \omega_e (t+T) \}. \end{aligned} \quad (8)$$

The two coefficients are

$$C_1 = \frac{R\beta \cos^2 \theta}{2} (a_2 a_3 + a_1 a_3 \sin \delta + a_2 a_3 \cos \delta + \sin \delta) \quad (9)$$

$$C_2 = \frac{R\beta \cos^2 \theta}{2} (a_3^2 \sin \delta + a_1 a_3 \sin \delta - a_2 a_3 \cos \delta - a_2 a_3). \quad (10)$$

From (9) and (10), we can see that the coefficients C_1 and C_2 can be adjusted to have the same or opposite signs by adjusting δ and θ. Therefore, by adjusting δ and θ, a two-tap photonic microwave filter with either two positive coefficients or one positive and one negative coefficient can be realized. For example, when the MZM is biased at the lowest transmission point $(\delta = 0), C_1 = -C_2 = a_2 a_3 R\beta \cos^2 \theta$, the microwave filter is a two-tap filter with one positive and one negative coefficient. The negative coefficient is generated from the optical interference of the two polarization modes using the polarizer.

III. Experimental Results and Discussion

The system shown in Fig. 1 is experimentally evaluated. A tunable laser source (TLS) with a linewidth of 150 kHz, a wavelength at 1550 nm, and an output power of 5 dBm is used as the optical source. The MZM used in the experiment is a JDS-Uniphase 10-Gbit/s modulator. In order to adjust the polarization states of the lightwaves, three polarization controllers (PCs) are used. PC1 is used to align the TLS output light with the

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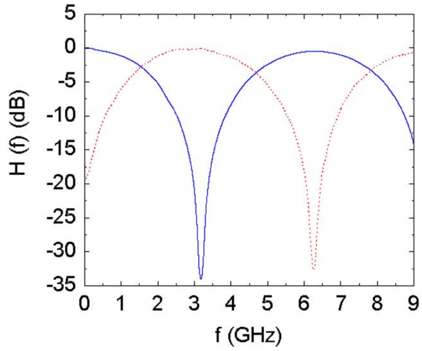

Fig. 2. Frequency response of a two-tap photonic microwave filter; solid line, with coefficients (1, 1); dashed line, with coefficients (1, -1).

transmission axis of the MZM. PC2 is used to adjust the polarization angle between the transmission axis of the MZM and the fast axis of the PMF to be 45°. PC3 and the polarizer serve as a tunable optical polarizer with the angle θ adjusted by tuning PC3. To compensate for the optical loss of the system, an erbium-doped fiber amplifier (EDFA) is connected after the polarizer. The output power from the EDFA is about 1 mW. The PMF (Corning PM1550) has a length of 126 m and a beat length of 4.0 mm, giving a time-delay difference between the fast and the slow axes of about 160 ps, corresponding to a free spectral range (FSR) of 6.3 GHz. The microwave modulation signal is generated using a vector network analyzer. The frequency response of the microwave filter is obtained by scanning the microwave frequency while maintaining the output power constant.

In the experiment, a photonic microwave filter with two positive coefficients (1, 1) or one positive and one negative (1, -1) is realized by adjusting PC3 and the dc bias of the MZM. When the MZM is biased at 0 V, which corresponds to the case where the MZM is biased at the quadrature point ($\delta = \pi/2$), by adjusting PC3 to maximize the notch depth of the filter response, a microwave filter with two positive coefficients of (1, 1) is realized. When the bias voltage is adjusted to 8.53 V, which corresponds to the case where the MZM is biased at the lowest transmission point ($\delta = 0$), a microwave filter with one positive and one negative coefficient of (1, -1) is realized. The frequency responses of the filter with the two different pairs of coefficients are shown in Fig. 2. The FSR of the filter is measured to be 6.3 GHz, which agrees with the value calculated according to the time-delay difference generated by the PMF. A direct application of the proposed two-tap microwave filter is to generate ultrawideband Gaussian monocycle. Mathematically, a Gaussian monocycle is the first-order derivative of a Gaussian pulse. The first-order derivative can be approximated using a first-order difference, which can be implemented using the proposed two-tap microwave filter with coefficient of (1, -1).

IV. Discussion and Conclusion

The proposed filter is a coherent-type filter; the stability must be studied to evaluate the usability of the filter. In our experimental study, the filter shows an excellent short-term stability. This is understandable since the two projected polarization modes after the polarizer are traveling in the same fiber, and would experience the same environmental changes. The long-term stability of the filter is also studied. From (9) and (10) it can be seen that the filter coefficients are dependent on the bias voltage of the MZM (term δ), the polarization angle between the principle axis of the PMF and the polarizer (term θ), and the optical phase difference between the two polarization modes (term $e^{j\omega_c T}$). Each term could contribute to the long-term instability of the filter response. In the experimental setup, no bias controller is used and the temperature of the MZM is not controlled. Therefore, the MZM bias point would be drifting, which would affect the long-term stability of the filter response. We believe that the bias drifting problem could be solved by using a bias and a temperature controller. In the experiment, to adjust the polarization angle θ, paddle-type fiber PCs are used. It is known that paddle-type PCs are sensitive to physical disturbances, which contributes to the long-term instability of the filter. A direct solution to this problem is to use temperature-insensitive PCs. For the term $e^{j\omega_c T}$, $\omega_c T$ is calculated to be 1.9×10^5 (rad). The frequency stability of the LD (Anritsu MG 9541A) is 100 MHz/h, the relative stability of the LD is $\Delta\omega_c/\omega_c = 5 \times 10^{-7}$; therefore, the variation of $\omega_c T$ caused by the LD wavelength drift is 0.095 rad/h, which is very small and can be neglected. The thermal coefficient of the PMF used in the setup is $6.1 \times 10^{-6}/°C$ [8]. The relative variation of $\omega_c T$ versus temperature is 1.15 rad/°C, which could have a noticeable effect on the long-term stability. By using photonic crystal PMF [8] that has a thermal coefficient as small as $0.55 \times 10^{-6}/°C$, the long-term stability could be significantly improved.

In conclusion, a cost-effective approach to realizing a negative-tap photonic microwave filter based on an MZM and a tunable optical polarizer was proposed and experimentally demonstrated. The key component in the system was the tunable optical polarizer, which was used to generate negative coefficient. A theoretical analysis was presented. A photonic microwave filter with coefficients of (1, 1) and (1, -1) was demonstrated. The short-term and long-term stability of the proposed filter was also studied.

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