All-Optical Microwave Bandpass Filter With Negative Coefficients Based on PM-IM Conversion

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***Abstract*—A novel technique for obtaining negative coefficients for the implementation of all-optical microwave bandpass filters is presented. In the proposed approach, the negative coefficients are obtained by locating the optical carriers at the opposite slopes of the transfer function of an optical filter, to convert the phase-modulated signal to intensity-modulated signal, with phase inversion of the radio-frequency modulating signals. A two-tap microwave bandpass filter with negative coefficients is demonstrated.**

***Index Terms*—Bandpass filter, electrooptic phase modulation, microwave filter, optical filter, phase-modulation to intensity-modulation (PM-IM) conversion.**

I. INTRODUCTION

ALL-OPTICAL microwave filters with the advantageous features of large time-bandwidth products, low loss, light weight, and immunity to electromagnetic interferences have been investigated by many researchers. To avoid the optical interferences, most of the proposed filters are operating in the incoherent regime with only positive coefficients. All-optical filters with all positive coefficients can only function as low-pass filters. Several techniques have been proposed in the last few years to achieve bandpass filtering [1]–[7]. Recently, we have reported an approach to implementing an all-optical microwave bandpass filter using an electrooptic phase modulator in combination with a dispersion device [8]. The baseband resonance is eliminated by the phase modulation (PM) to intensity modulation (IM) conversion; a bandpass-equivalent filter is thus obtained. Since no negative taps are actually generated in the filter [8], bandpass filters with improved performance, such as flattop passband and high mainlobe-to-sidelobe ratio, are still impossible to implement.

In this letter, we propose a novel and simple technique to realize all-optical microwave bandpass filters with negative coefficients. In our approach, the positive and negative coefficients are obtained by letting two phase-modulated optical carriers pass through an optical filter which serves as a PM-IM conversion device. Because the center wavelengths of the two carriers are tuned at the quadrature frequencies of the positive and negative slopes of the transfer function of the optical filter, the envelopes of the two PM-IM converted signals will be π out of phase. The PM-IM converted signals are then applied to a length of single-mode fiber (SMF) serving as a dispersive device to achieve different time delays. A two-tap bandpass transversal microwave filter with one negative coefficient is obtained.

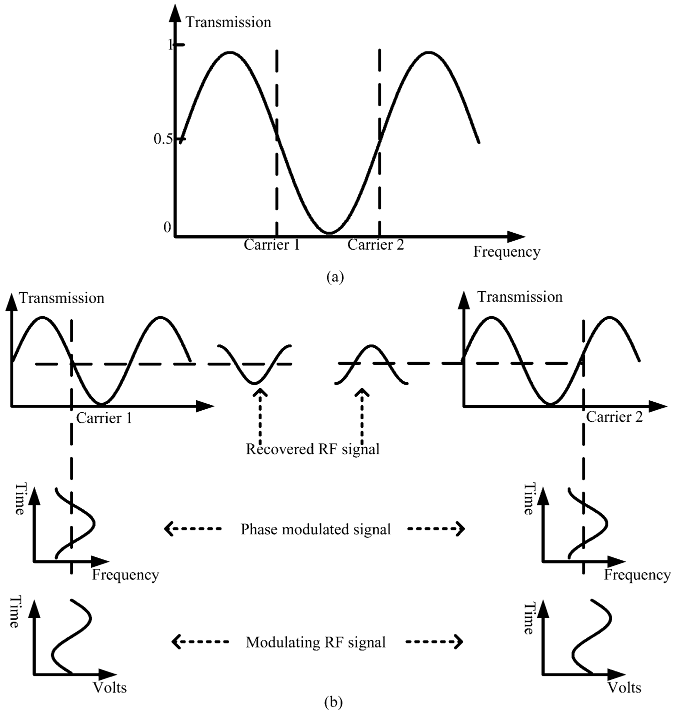

Fig. 1. Fundamental concept for the implementation of negative coefficients based on PM-IM conversion using an optical filter. (a) Intensity transfer function of an optical filter. (b) Illustration of the generation of RF modulating signals in counterphase.

II. PRINCIPLE

The fundamental concept for the implementation of negative coefficients is shown in Fig. 1. Fig. 1(a) shows a typical intensity transmission function of an optical filter, such as an unbalanced Mach–Zehnder interferometer or a Sagnac loop. Two optical carriers, namely Carrier 1 and Carrier 2, are tuned at the opposite slopes of the filter transfer function. As shown in Fig. 1(b), the same radio-frequency (RF) modulating signal is modulated onto the two carriers via a phase modulator, which will introduce an instant frequency shift to the carriers. The value of the frequency shift is proportional to the differential of the RF modulating signal. In this situation, the optical filter is equivalent to a frequency discriminator, by which the frequency shift is converted to the variation of optical intensity. It can be seen from Fig. 1, if the two carriers are phase modulated, the output optical signals from the optical filter will be with the same average power but reverse envelopes, negative coefficients are thus obtained.

In theory, the phase-modulated signal can be given in the form of (1) when the modulation depth is small

$$E_{\mathrm{PM}}(t) \approx E_0 \left\{ J_0(\beta)\cos\omega_0 t + J_1(\beta)\cos\left[(\omega_0+\Omega)t+\frac{\pi}{2}\right] - J_1(\beta)\cos\left[(\omega_0-\Omega)t-\frac{\pi}{2}\right]\right\} \quad (1)$$

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where E_0 and ω_0 are the amplitude and angular frequency of the optical carrier, Ω is the angular frequency of the RF modulating signal, $J_n(\beta)$ is the Bessel function of the first kind of order n with argument of β, and β is related to the modulation depth.

On the other hand, the transfer function of the optical filter can be described by (2). For simplicity, only filters based on an unbalanced Mach–Zehnder interferometer and a Sagnac loop with one section polarization-maintaining (PM) fiber will be considered here

$$H(\omega) = \cos\frac{\omega\tau}{2} \cdot e^{-j\frac{\omega\tau}{2}} \tag{2}$$

where ω is the angular frequency of the input optical signal, and τ is the time delay difference between two optical paths. Consequently, the signal after the optical filter is

$$\begin{aligned} E_{\mathrm{IM}}(t) \approx E_0 \Big\{ & J_0(\beta)\cos\frac{\omega_0\tau}{2} \cdot \cos\left(\omega_0 t - \frac{\omega_0\tau}{2}\right) \\ & + J_1(\beta)\cos\frac{(\omega_0+\Omega)\tau}{2} \\ & \times \cos\left[(\omega_0+\Omega)t + \frac{\pi}{2} - \frac{(\omega_0+\Omega)\tau}{2}\right] \\ & - J_1(\beta)\cos\frac{(\omega_0-\Omega)\tau}{2} \\ & \times \cos\left[(\omega_0-\Omega)t - \frac{\pi}{2} - \frac{(\omega_0-\Omega)\tau}{2}\right] \Big\}. \end{aligned} \tag{3}$$

If the photodetector has a responsivity R, the recovered RF signal at the output of the photodetector is given by

$$\begin{aligned} I_\Omega \propto \mathrm{RE}_0^2 \Big[& J_0(\beta)\cdot J_1(\beta) \cdot \cos\frac{\omega_0\tau}{2} \cdot \cos\frac{(\omega_0+\Omega)\tau}{2} \\ & \cdot \cos\left(\Omega t + \frac{\pi}{2} - \frac{\Omega\tau}{2}\right) - J_0(\beta)\cdot J_1(\beta) \\ & \cdot \cos\frac{\omega_0\tau}{2} \cdot \cos\frac{(\omega_0-\Omega)\tau}{2} \cdot \cos\left(\Omega t + \frac{\pi}{2} - \frac{\Omega\tau}{2}\right) \Big] \\ = & -M\sin(\omega_0\tau) \cdot \sin\frac{\Omega\tau}{2} \cdot \cos\left(\Omega t + \frac{\pi}{2} - \frac{\Omega\tau}{2}\right). \end{aligned} \tag{4}$$

M is used to stand for the constant $\mathrm{RE}_0^2 \cdot J_0(\beta) \cdot J_1(\beta)$. From (4), it is easily seen that for a specific value of Ω, the corresponding I_Ω can have different signs by adjusting the carrier frequency ω_0 to let the value of $\sin(\omega_0\tau)$ have different signs.

In our proposed approach, the ideal arrangement of a two-tap filter with one negative coefficient is based on the placement of the two optical carriers at the quadrature points of the opposite slopes of the transfer function. For example, let the center frequencies of Carrier 1 and Carrier 2, namely ω_1 and ω_2, satisfy the equation $\cos^2(\omega\tau/2) = 1/2$, which also means $\sin(\omega\tau) = \pm 1$. Without loss of generality, we suppose that $\omega_1\tau = (\pi/2) + 2n\pi$ and $\omega_2\tau = -(\pi/2) + 2n\pi$, where $n = 0, \pm 1, \pm 2, \ldots$. By using a length of fiber to induce a time delay difference between the two taps, the overall recovered RF signal is given by

$$\begin{aligned} I_\Omega \propto M \cdot \sin\frac{\Omega\tau}{2} \Big[& -\cos\left(\Omega t + \frac{\pi}{2} - \frac{\Omega\tau}{2}\right) \\ & + \cos\left(\Omega(t-\Gamma) + \frac{\pi}{2} - \frac{\Omega\tau}{2}\right) \Big] \end{aligned} \tag{5}$$

where Γ is the fiber-induced time delay difference between the two taps, is equal to the product of the accumulated dispersion χ and the wavelength spacing $\Delta\lambda$ between the two carriers. Therefore, the normalized transfer function of the optical microwave filter is

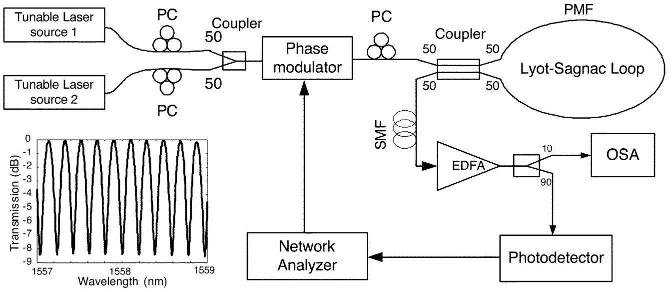


Fig. 2. Block diagram of the proposed all-optical microwave bandpass filter. Inset: Intensity transfer function of the Sagnac-loop optical filter. PC: polarization controller. PMF: polarization-maintaining fiber. OSA: optical spectrum analyzer.

$$H(\Omega) \propto \left| \sin\frac{\Omega\tau}{2} \cdot \left(1 - e^{j\Omega\Gamma}\right) \right|. \tag{6}$$

The term $\sin(\Omega\tau/2)$ in (6) is determined by the frequency response of the PM-IM conversion; the term $(1 - e^{j\Omega\Gamma})$ is induced by the summation of the recovered RF signals from the two taps. On the contrary, if the two carriers are located at the quadrature frequencies with equal slopes, the normalized transfer function of the optical microwave filter is

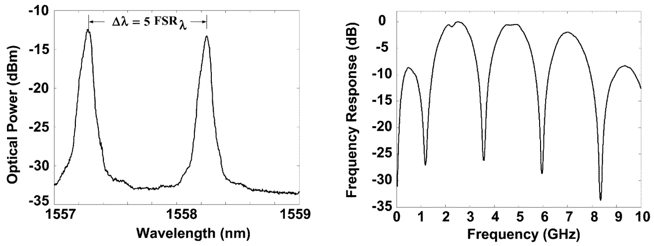
$$|H(\Omega)| \propto \left| \sin\frac{\Omega\tau}{2} \cdot \left(1 + e^{-j\Omega\Gamma}\right) \right|. \tag{7}$$

Comparing (6) and (7), it can be found that a negative coefficient is obtained in (6) when the two optical carriers are tuned to be at the quadrature points of the opposite slopes. Although in (7), the filter has only positive coefficients, the baseband resonance is suppressed by the dc notch caused by the PM-IM conversion; the filter is equivalent to a bandpass filter [8]. Since no negative taps are actually generated in the bandpass-equivalent filter, the performance such as passband flatness and mainlobe-to-sidelobe ratio is poorer compared to that of a bandpass filter with negative coefficients.

III. EXPERIMENT AND RESULTS

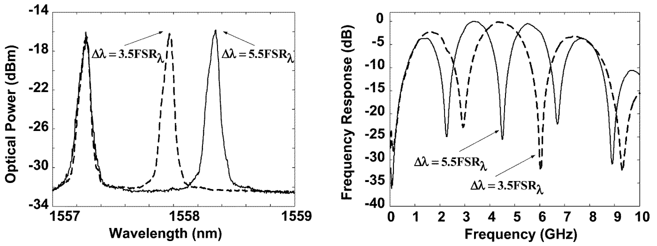
The block diagram of the experimental setup is shown in Fig. 2. Two tunable laser sources are used to provide the tunable carriers. The two carriers are phase modulated by an RF signal generated by a network analyzer and then fed into a Sagnac loop optical filter. The intensity transfer function of the Sagnac loop is shown in the inset of Fig. 2. It can be seen that the optical filter has a free spectral range FSR_λ of around 0.19 nm. A time delay difference is obtained by passing the optical carriers through a 25-km SMF, which has an accumulated dispersion of 425 ps/nm at 1550 nm. Note that except its inherent insertion loss of about 1 dB, the optical filter will induce an extra 3-dB insertion loss since the optical carriers are located at the quadrature points.

Based on the analysis, if the wavelength of the first tunable laser source, namely λ_1, is fixed at the quadrature point of one positive slope, different microwave transfer functions will be achieved when the wavelength of the second tunable laser source, namely λ_2, is tuned to satisfy the conditions $|\lambda_1 - \lambda_2| = (2n+1)(\mathrm{FSR}_\lambda/2)$ or $|\lambda_1 - \lambda_2| = (2n)\cdot(\mathrm{FSR}_\lambda/2)$,



(a) (b)

Fig. 3. Bandpass-equivalent filter with only positive coefficients. (a) Optical spectrum of the two tunable laser sources; (b) frequency response of the bandpass-equivalent filter.



(a) (b)

Fig. 4. Tunability of the true bandpass filter with negative coefficient. (a) Optical spectra of the two tunable laser sources. (b) Frequency response of the true bandpass filter.

where $n = 0, 1, 2, 3, \ldots$. In the first case, a bandpass frequency response is expected since λ_1 and λ_2 are at the opposite slopes; in the second case, a lowpass frequency response will be obtained because λ_1 and λ_2 are at the equal slopes. In the following experiments, two different cases are demonstrated.

First, λ_1 is fixed at 1557.282 nm, and λ_2 is tuned to 1558.246 nm, as shown in Fig. 3(a). The spacing between λ_1 and λ_2 is 0.964 nm, which is five times the FSR_λ. Since the wavelengths of the two carriers are located at the points with equal slopes, no negative coefficients are obtained. As discussed earlier, the baseband resonance is suppressed by the PM-IM conversion, a bandpass-equivalent filter is obtained. The filter frequency response is shown in Fig. 3(b). As can be seen, a high sidelobe at the baseband is observed; the sidelobe is caused by the baseband resonance, which is only partially suppressed by the dc notch. The FSR of the microwave filter is 2.4 GHz, corresponding to a time delay of 410 ps.

Then λ_2 is tuned to 1558.336 nm; the difference between λ_1 and λ_2 is now 1.054 nm, 5.5 times of the FSR_λ. Since the two carriers are now located at the points with opposite slopes, a negative coefficient is obtained. The frequency response of the microwave filter is shown in Fig. 4(b) (solid line). It is a true bandpass filter with a negative coefficient. No sidelobe is observed at the baseband. The FSR of the filter is 2.2 GHz, which corresponds to a time delay of 448 ps.

The tunability of the proposed microwave filter is also investigated. When λ_2 is tuned to 1557.964 nm, the spacing between λ_1 and λ_2 is 0.682 nm, 3.5 times the FSR_λ, as shown in Fig. 4(a) (dashed line). In this case, a negative coefficient is still obtained, but with a smaller time delay difference, the FSR is thus increased. As shown in Fig. 4(b) (dashed line), the FSR of the microwave filter is 3.3 GHz, corresponding to a time delay of 290 ps.

In Figs. 3 and 4, the degradation of the magnitude response shown in higher frequencies is mainly due to the power penalty induced by the chromatic dispersion of the 25-km SMF.

We should note that the performance of the proposed microwave filter, especially the notch rejection level, depends highly on the stability of the optical sources and the optical filter. The use of state-of-the-art optical sources will solve the laser stability problem. For example, the wavelength drift of JDS-Uniphase laser diodes with case temperature is much better than 1 pm/°C. In our experiment, the performance of the proposed microwave filter is mainly affected by the instability of the optical filter. We believe that this problem can be solved by using an optical filter with proper packaging and temperature control or by using a temperature-insensitive Sagnac loop, as reported recently in [9].

IV. CONCLUSION

In this letter, a novel approach to obtaining negative coefficients through PM-IM conversion using an optical phase modulator and an optical filter was presented; a two-tap bandpass filter with one negative tap was demonstrated. The tunability of the proposed filter was also investigated. The proposed approach has the potential to implement all-optical multitap microwave filters with arbitrary positive and negative coefficients.

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