A Tunable Photonic Microwave Notch Filter Based on All-Optical Mixing

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

***Abstract*—A novel photonic microwave notch filter based on all-optical mixing using a single narrow-linewidth optical source is proposed. In the proposed filter, the optical carrier emitted from a laser source is externally intensity modulated by a subcarrier signal and then applied to a second intensity modulator, which is driven by a local radio-frequency (RF) source with a dc bias to suppress the even-order sidebands. Since the higher odd-order sidebands have a much lower power than the first-order sidebands, only two first-order sidebands are considered with the subcarrier signal transferred to the two sidebands via optical mixing. By using a linearly chirped fiber Bragg grating as a dispersive device to introduce time delays, a two-tap photonic microwave notch filter is realized. The tunability of the proposed filter is achieved by adjusting the frequency of the local RF signal. Based on the proposed architecture, a two-tap microwave notch filter with a free spectral range tunable from 2.1 to 4.2 GHz is experimentally demonstrated.**

***Index Terms*—All-optical mixing, chirped Bragg grating, electrooptic intensity modulator, photonic microwave notch filter.**

I. Introduction

PHOTONIC microwave filters (PMFs), with advantageous features such as high time-bandwidth products, low loss, and immunity to electromagnetic interferences, have attracted great interest. So far, in most reported filter architectures, a laser array or a low-coherence light source is used to implement PMFs that are operating in the incoherent regime, to avoid optical coherent interference [1], [2]. The frequency response of an incoherent photonic microwave filter is more robust than a filter that is operating in the coherent regime. However, for many applications, such as in a radio-over-fiber (RoF) link, a single narrow-linewidth laser source is used. Because of the high coherence, a PMF using a narrow-linewidth laser source would lead to optical interference, which is very sensitive to environmental changes. A solution to this problem is to use the filters proposed in [1] and [2]; however, in the use of the filters in [1] and [2] the radio-frequency (RF) signal carried by the narrow-linewidth optical carrier has to be first converted from an optical signal to electrical signal and then remodulated onto an array of laser diodes, which makes the system complicated and costly. PMFs using a single narrow-linewidth laser source suitable for a direct use in an RoF receiver without extra optical-to-electrical (O/E) conversion are highly desired.

Several approaches to realizing PMFs based on a single narrow-linewidth laser source have been proposed recently. One approach [3], [4] is to use a length of high birefringent (Hi-Bi) fiber to achieve the time delays. Since the two polarization modes excited within the Hi-Bi fiber are orthogonal, no optical interference will occur, even when an optical source with a very narrow linewidth is employed. The time delay difference between the two polarization modes is determined by the birefringence and the length of the Hi-Bi fiber. Another approach [5] is to use a dual-output electricoptic intensity modulator that undergoes a double-pass modulation. The remodulation of a single continuous wave (CW) carrier at different time instants would lead to a time delay difference. Since the delayed samples are carried by the same optical signal traveling in the same optical path, no optical interference is observed at the photodetector (PD). In [6], Polo *et al.* proposed an approach to implement a PMF using two external modulators. The first modulator is used to generate multiple modulation sidebands, with a spectral shape similar to that of an array of laser diodes. The RF signal to be processed is modulated on the multiple sidebands by the second modulator. By passing the multiple sidebands through a dispersive device, signals with different time delays are obtained. Since the RF signal to be processed is in the electrical domain, the filter in [6] cannot be directly employed at a receiver of an RoF link. For RoF applications, it is desirable that the subcarrier signal carried by a narrow-linewidth optical carrier traveling along an optical fiber be directly processed in the optical domain without extra O/E conversion. In [7], You and Minasian proposed a tunable photonic microwave notch filter. The input to the filter is a subcarrier signal modulated on a single optical carrier. It is, therefore, suitable for direct employment in a receiver of an RoF link. The tunability of the filter is realized by tuning the attenuations of three attenuators with three PDs connected after the attenuators, which increases the system cost.

In this letter, we propose a simple photonic microwave notch filter that is suitable for direct employment in a receiver of an RoF link without extra O/E conversion. The schematic diagram illustrating the proposed filter is shown in Fig. 1. In the proposed filter, the first intensity modulator (IM1) is used to modulate the subcarrier signal V_{RF} on a narrow-linewidth optical carrier. The output is then applied to a second intensity modulator (IM2), which is driven by a local RF signal V_{LO}. By properly biasing IM2, the even-order sidebands (including the optical carrier) are suppressed. Thanks to the optical mixing effect [8], [9], at the output of IM2, the subcarrier signal V_{RF} is transferred to the modulation sidebands. Since the higher odd-order sidebands have much lower power than the first-order sidebands, only two first-order sidebands are considered. By use of a linearly chirped fiber Bragg grating (LCFBG) to induce time delays, a two-tap photonic microwave notch filter is obtained. The free-spectral range (FSR) of the filter can be easily tuned by adjusting the frequency of V_{LO}. In our experiment, a two-tap microwave notch

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

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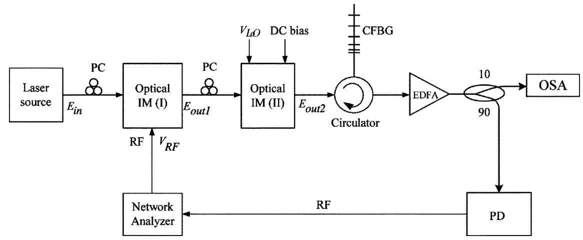

Fig. 1. Schematic diagram of proposed MPF. IM is intensity modulator, PC is polarization controller, PD is photodetector, and OSA is optical spectrum analyzer.

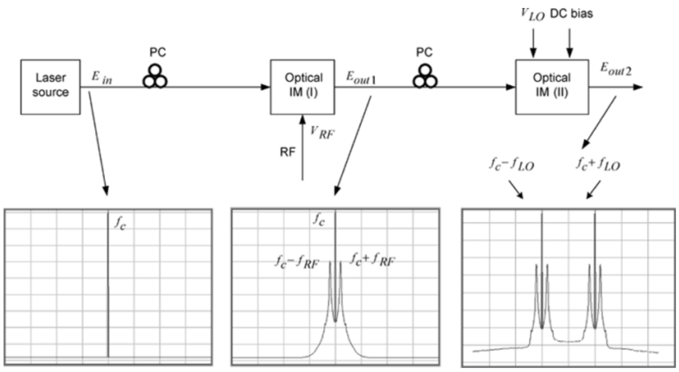

Fig. 2. Optical mixing using an intensity modulator.

filter with an FSR tunable from 2.1 to 4.2 GHz with a rejection as high as 35 dB at the first notch is demonstrated.

II. Principle

As shown in Fig. 1, an optical wave emitted from a narrow-linewidth laser diode is intensity modulated by a subcarrier signal $V_{\rm RF}$ at IM1; its output is then applied to IM2, to which a local RF signal $V_{\rm LO}$ and a dc bias are applied. By properly dc-biasing IM2, the even-order sidebands are suppressed. Considering the power levels of the higher odd-order sidebands are much lower than the first-order sidebands, only the two first-order optical sidebands need to be considered. The spacing between the two sidebands is twice the frequency of $V_{\rm LO}$. Thanks to the effect of optical mixing [8], [9], the subcarrier signal $V_{\rm RF}$ is transferred to the two optical sidebands, as shown in Fig. 2. After propagating through an LCFBG, the two optical sidebands experience different time delays. The time-delayed signals are then applied to a PD. By sweeping the frequency of $V_{\rm RF}$, a frequency response of the proposed filter is observed on a vector network analyzer.

Without loss of generality, the phase difference between the two arms of a Mach–Zender modulator (MZM) is assumed to be zero when no electrical signal is applied. Considering the case in which a single wavelength optical light is directly injected into the optical intensity modulator, the electric field at the output of IM2, $E_{\rm out2}(t)$, can be expressed by

$$E_{\rm out2}(t) = E_o \cos\left[\frac{\Phi\left[V(t)\right]}{2}\right]\cdot\cos(\omega_o t) \tag{1}$$

where E_o and ω_o are the electric field amplitude and angular frequency of the input optical carrier, respectively, $V(t)$ is the applied electrical drive voltage and $V(t)=V_{\rm DC}+V_{\rm LO}\cos(\omega_{\rm LO}t)$, where $V_{\rm DC}$ is the dc bias, $V_{\rm LO}$ and $\omega_{\rm LO}$ are the amplitude and angular frequency of the local RF signal, and $\Phi[V(t)]$ is the optical phase difference caused by $V(t)$ between the two arms of IM2, which is given by

$$\begin{aligned}\Phi\left[V(t)\right] &= \frac{\pi}{V_\pi}\left[V_{\rm DC}+V_{\rm LO}\cos\omega_{\rm LO}t\right)]\\ &= \phi_0 + \frac{\pi}{V_\pi}\cdot V_{\rm LO}\cos(\omega_{\rm LO}t)\end{aligned} \tag{2}$$

where V_π is the half-wave voltage of the MZM. We denote that the dc-bias-determined constant phase shift $(\pi/V_\pi)\cdot V_{\rm DC}$ in (2) as ϕ_0. Substituting (2) into (1), we have

$$\begin{aligned}&E_{\rm out2}(t)\\ &= E_o\cos\left(\frac{\phi_0}{2}\right)\\ &\quad\times\left\{J_0(\beta)+2\sum_{k=1}^{\infty}J_{2k}(\beta)\cos\left[2k\left(\frac{\pi}{2}-\omega_{\rm LO}t\right)\right]\right\}\cos(\omega_o t)\\ &\quad - E_o\sin\left(\frac{\phi_0}{2}\right)\\ &\quad\times\left\{2\sum_{k=1}^{\infty}J_{2k-1}(\beta)\sin\left[(2k-1)\left(\frac{\pi}{2}-\omega_{\rm LO}t\right)\right]\right\}\cos(\omega_o t)\\ &= E_o\cos\left(\frac{\phi_0}{2}\right)J_0(\beta)\cos(\omega_o t)+E_o\cos\left(\frac{\phi_0}{2}\right)\\ &\quad\times\left\{\sum_{k=1}^{\infty}J_{2k}(\beta)\left[\cos(\omega_o t-2k\omega_{\rm LO}t+k\pi)\right.\right.\\ &\qquad\qquad\left.\left.+\cos(\omega_o t+2k\omega_{\rm LO}t-k\pi)\right]\right\}\\ &\quad - E_o\sin\left(\frac{\phi_0}{2}\right)\\ &\quad\times\left\{\sum_{k=1}^{\infty}J_{2k-1}(\beta)\left[\sin\left(\omega_o t-(2k-1)\omega_{\rm LO}t+k\pi-\frac{\pi}{2}\right)\right.\right.\\ &\qquad\qquad\left.\left.-\sin\left(\omega_o t+(2k-1)\omega_{\rm LO}t-k\pi+\frac{\pi}{2}\right]\right.\right.\end{aligned} \tag{3}$$

where J_k is the Bessel function of the first kind of order k, and $\beta = (V_{\rm LO}/V_\pi)(\pi/2)$, which is the phase modulation depth. Based on (3), we can reach two important conclusions. First, when the MZM is driven by an electrical signal with adequate power, a large value of β is obtained. In this situation, (3) shows that the power in the input optical carrier will be transferred to the first-, second-, and higher order optical sidebands. The power distribution of these sidebands is governed by the Bessel functions parameterized by β. Second, the power distribution is also affected by ϕ_0, which is determined by the dc bias $V_{\rm DC}$. Consequently, by adjusting the dc bias applied to the second intensity modulator to make $\phi_0=\pi$, the even-order sidebands (including the optical carrier) are completely suppressed. In our implementation, by properly biasing the IM2, all even-order sidebands are suppressed. Since the higher odd-order sidebands have a much weaker power, only the two first-order sidebands are considered. By passing the two sidebands through an LCFBG, a two-tap microwave notch filter is thus realized.

The FSR of the filter is given

$$\text{FSR} = \frac{c}{\lambda_0^2\cdot 2f_{\rm LO}\cdot D} \tag{4}$$

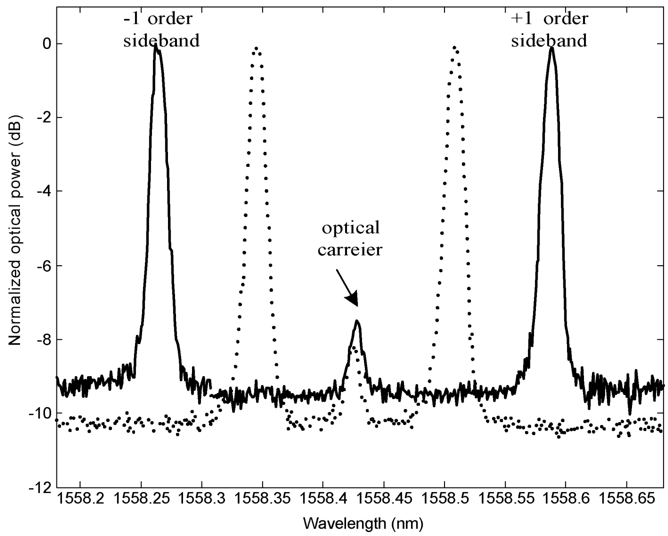

Fig. 3. Optical spectra at output of IM2 when optical carrier is strongly suppressed. Solid line shows local RF frequency at 20 GHz. Dotted line shows local RF frequency at 10 GHz.

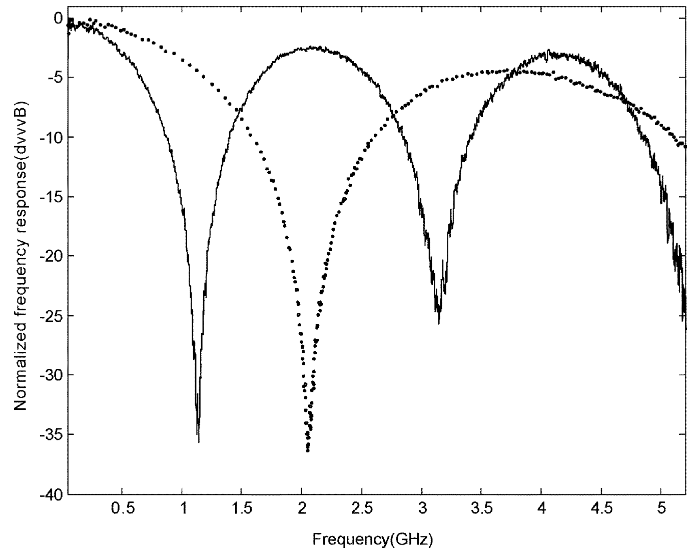

Fig. 4. Frequency responses of proposed two-tap filter. Solid line shows local RF frequency at 20 GHz. Dotted line shows local RF frequency at 10 GHz.

where λ_0 is the wavelength of the optical carrier, $f_{\rm LO}$ is the frequency of the local RF signal, c is the light velocity in vacuum, and D is the chromatic dispersion of the LCFBG. As can be seen from (4), by tuning the frequency of the local RF signal, the FSR can be tuned.

III. Experiment

The proposed microwave notch filter shown in Fig. 1 is built. A tunable laser source with a linewidth of 150 kHz is employed as the light source. Both optical intensity modulators are Mach–Zehnder electrooptic modulators with a typical V_π of around 12 V. The dc bias applied to IM2 is adjusted to suppress the optical carrier and the even-order sidebands. The local RF frequency generator used to drive the IM2 can operate up to 25 GHz with a maximum output power of 25 dBm, corresponding to a modulation depth $\beta = 0.5$. The LCFBG is fabricated in a hydrogen-loaded standard single-mode fiber using a linearly chirped phase mask by ultra-violet illumination. The LCFBG has a length of 8 cm. The dispersion value of the LCFBG is about 1450 ps/nm.

The optical spectrum at the output of IM2 is shown in Fig. 3. As can be seen, the optical carrier at 1558.45 nm is suppressed. The frequency response of the two-tap microwave notch filter is shown in Fig. 4. When the frequency of the local RF signal is tuned at 10 GHz, the FSR is 4.2 GHz; when the frequency of the local RF signal is tuned at 20 GHz, the FSR is 2.1 GHz. For both cases, a rejection higher than 35 dB at the first notch is observed. In the experiment, the observed degradation at the higher frequency is mainly caused by the power penalty induced by the chromatic dispersion of the LCFBG, which can be eliminated by using a single sideband modulation at the first modulator.

IV. Conclusion

In this letter, we have proposed and demonstrated a simple tunable photonic microwave notch filter based on all-optical mixing. The filter was implemented by using a second intensity modulator by biasing it to suppress the even-order sidebands. A two-tap tunable filter with an FSR tunable from 2.1 to 4.2 GHz and a rejection at the first notch up to 35 dB was demonstrated. A key feature of the proposed filter is that the filter can be directly employed in a receiver of an RoF link, without the need of extra O/E conversion. In addition, multitap filters based on the same principle are possible if the optical carrier is only partially suppressed (a three-tap filter) or if a modulator with higher modulation depth is employed as the second modulator.

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