All-Optical Microwave Bandpass Filters Implemented in a Radio-Over-Fiber Link

Jun Wang, Fei Zeng, *Student Member, IEEE*, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—An all-optical microwave bandpass filter implemented in a radio-over-fiber (RoF) link is proposed and demonstrated. The filter consists of an optical phase modulator, a length of high birefringence (Hi-Bi) fiber, a 25-km single-mode fiber and a narrow linewidth laser source. Different time delays are achieved when the two orthogonal polarization modes are traveling along the Hi-Bi fiber. The baseband resonance is eliminated by use of the optical phase modulator in combination with the 25-km single-mode fiber serving as a dispersive device. The proposed filter is immune to optical interference because of the orthogonality of the two polarization modes. A two-tap all-optical microwave bandpass filter with a null-to-null bandwidth of 8.7 GHz and a notch rejection level greater than 30 dB implemented in the 25-km RoF link is demonstrated.**

***Index Terms*—All-optical microwave filter, bandpass filter, chromatic dispersion, electrooptic phase modulation, high birefringence (Hi-Bi) fiber, optical interference, polarization mode.**

I. INTRODUCTION

DISTRIBUTION of microwave and millimeter-wave signals over optical fiber is of great interest for many applications such as broad-band wireless access networks, wireless sensor networks, radar, and satellite communication systems, and has been extensively studied in the past few years. The primary function of a radio-over-fiber (RoF) network is to distribute microwave or millimeter-wave signals over optical fiber to take the advantages of the low loss, low dispersion, and large bandwidth of optical fiber links. On the other hand, it is highly desired that the distributed microwave and millimeter-wave signals can be processed directly in the optical domain without optical–electrical and electrical–optical conversions. Among the numerous signal processing functions, bandpass filtering is one of the most often used in a communication system. A lot of effort has been directed to implement microwave filtering directly in the optical domain. However, most of the reported approaches are based on the incoherent operation, in which only the intensity of the optical signal can be manipulated and, hence, negative taps are difficult to obtain. Therefore, bandpass or highpass functions cannot be realized. Several approaches have been proposed to solve this problem [1]–[7]. One approach [1] is to use a differential photodetection scheme to achieve bandpass filtering. Other approaches with negative coefficients include wavelength conversion based on cross-gain saturation modulation in a semiconductor optical amplifier [2], carrier depletion effect in a Fabry–Pérot laser diode (LD) [3] or in a distributed-feedback LD [4]. It was reported recently that a microwave bandpass filter could also be realized by employing either a pair of electrooptic modulators (EOMs) by biasing the EOMs to achieve phase inversion [5] or a single dual-output EOM that undergoes a double-pass modulation [6]. In addition, negative taps can also be obtained by use of the transmission of a broad-band source through uniform Bragg gratings [7]. We have recently demonstrated an all-optical microwave bandpass filter based on an electrooptic phase modulator [8]. It is different from the approaches in [1]–[7]; the bandpass filtering is realized by passing the phase-modulated signal through a dispersive device to eliminate the baseband resonance. In our proposed approach [8], to achieve microwave filtering with multiple taps, a light source with multiple wavelengths was used. In RoF networks, however, the microwave or millimeter-wave signals are usually modulated on a narrow linewidth optical carrier. The approaches using incoherent or multiwavelength light sources are not suitable for this application.

In this letter, we propose a novel approach that implements all-optical microwave bandpass filtering with a single narrow linewidth laser source. The proposed filter consists of an optical phase modulator, a length of high birefringence (Hi-Bi) fiber, a 25-km single-mode fiber (SMF), and a narrow linewidth laser source. The key problem when using a narrow linewidth optical source to achieve all-optical microwave filtering is the strong environment-dependent optical interference among the time-delayed optical signals because of the high coherence of the narrow linewidth laser source [9]–[11]. To solve this problem, in the proposed filter, a length of Hi-Bi fiber is used to excite the two polarization modes of the injected linear-polarization light. Thanks to the birefringence, the two polarization modes will experience different time delays in the Hi-Bi fiber; meanwhile, the optical interference is avoided because the two polarization modes are orthogonal. The baseband resonance is eliminated by use of the optical phase modulator in combination with the 25-km SMF serving as a dispersive device. A two-tap all-optical microwave bandpass filter with a null-to-null bandwidth of 8.7 GHz and a notch rejection level greater than 30 dB implemented in the 25-km RoF link is demonstrated.

II. PRINCIPLE

The block diagram of the all-optical microwave bandpass filter is shown in Fig. 1. A linearly polarized light emitted from an LD is fed to a phase modulator, which is driven by a microwave signal generated by a vector network analyzer. The polarization controller (PC) after the phase modulator is used to adjust the azimuth angle θ of the launched light with respect to the fast axis of the Hi-Bi fiber, in which two orthogonal polarization modes are excited provided that the azimuth angle is not equal to 0° or 90°, as depicted in the inset

Manuscript received January 27, 2005; revised April 7, 2005.

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).

Digital Object Identifier 10.1109/LPT.2005.851956

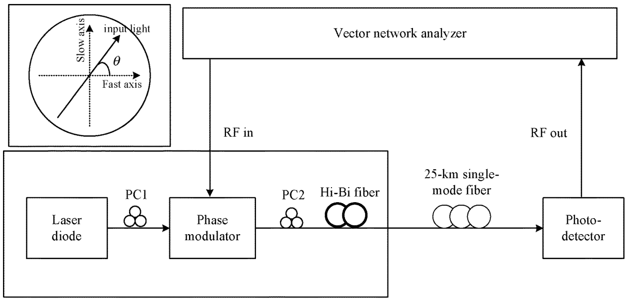

Fig. 1. Block diagram of the proposed all-optical microwave bandpass filter. Insert: Linearly polarized light launch into the Hi-Bi fiber.

in Fig. 1. Because of the birefringence, the two polarization modes will experience different time delays after traveling along the Hi-Bi fiber. The time-delayed optical signals are then distributed over a 25-km standard SMF. The SMF in the proposed filter plays two roles, as a dispersive device to eliminate the lowpass resonance, and as a transmission medium to distribute the signal. The distributed optical signal is then converted to electrical signal by a photodetector.

Without loss of generality, the phase-modulated signal is given in the form of (1) when the modulation depth is small

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

where E_c and ω_c are the amplitude and angular frequency of the optical carrier; ω_e is the angular frequency of the microwave 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 phase modulation depth. It can be seen that the first-order upper and lower sidebands at the output of the phase modulator are π out of phase. The signals generated by beating the two sidebands with the optical carrier will cancel each other completely if the phase modulated signal is directly detected by the photodetector. In the proposed filter, the phase modulated signal is then transmitted over the Hi-Bi fiber and the SMF. Due to the birefringence of the Hi-Bi fiber, a time delay difference between the two polarization modes will be generated. The two time-delayed polarized optical signals are then fed to the 25-km SMF. Thanks to the chromatic dispersion of the SMF, the phase relationship between the upper and lower sidebands is changed; they are now partially or totally in phase. Since the length of the Hi-Bi fiber is very short, the chromatic dispersion of the Hi-Bi fiber can be ignored. If the polarization-mode dispersion induced by the SMF is also ignored, the frequency response of the proposed system shown in Fig. 1 can be approximated as [8]

$$H(\omega) \propto \underbrace{\cos\left(\frac{\pi D\lambda_c^2 f_e^2 L_{\mathrm{SMF}}}{c}+\frac{\pi}{2}\right)}_{H_1(\omega)} \cdot \underbrace{\left[\cos^2\theta\cdot\cos 2\pi f_e t+\sin^2\theta\cdot\cos 2\pi f_e(t-T)\right]}_{H_2(\omega)} \quad (2)$$

where λ_c and f_e denote the wavelength of the optical carrier and the frequency of the microwave signal; D and L_{SMF} represent the chromatic dispersion and the length of the SMF; θ is the azimuth angle between the polarization of the light and the fast axis of the Hi-Bi fiber; $T = \Delta n \cdot L_{\mathrm{PMF}}/c$ is the time delay difference between the two polarization modes, where Δn and L_{PMF} are the birefringence and the length of the Hi-Bi fiber; and c is the light velocity in vacuum.

As can be seen from (2), the overall transfer function of the proposed filter is the multiplication of the two transfer functions $H_1(\omega)$ and $H_2(\omega)$ in the frequency domain. $H_1(\omega)$ is obtained when the phase-modulated signal is undergoing a chromatic dispersion. The spectrum of $H_1(\omega)$ has a notch at the dc frequency. $H_2(\omega)$ is the transfer function of a microwave lowpass filter resulted from the Hi-Bi fiber with a time delay difference of T between the two polarization modes. The free spectral range (FSR) of $H_2(\omega)$ is $1/T$. The notch depth varies with the azimuth angle. The multiplication of the two transfer functions leads to a cancellation of the baseband resonance of $H_2(\omega)$. An all-optical microwave equivalent bandpass filter is consequently achieved.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental implementation of the proposed filter is shown in Fig. 1. A laser source with a typical linewidth of 150 kHz is employed. The light is applied to the phase modulator via a polarization controller (PC1). A 42-m Hi-Bi fiber (Corning PM1550, beating length = 3.75 mm) is connected to the output of the phase modulator via a second polarization controller (PC2), which gives a time delay of 57 ps, corresponding to an FSR of 17.4 GHz. The second PC is used to adjust the azimuth angle between the polarization of the phase-modulated signal and the fast axis of the Hi-Bi fiber. By tuning this angle, the tap weights can be changed. From (2), we can see that the maximum notch depth appears only when the two polarization modes are equally excited, i.e., $\theta = 45^\circ$. This is verified by the experimental results shown in Fig. 2(a).

The time delayed signals after the Hi-Bi fiber is applied to a 25-km standard SMF (Corning SMF-28), which has a chromatic dispersion of 17 ps/nm/km at 1550 nm. Thanks to the chromatic dispersion, a transfer function $H_1(\omega)$ with the first notch at dc and a second notch at 17.1 G Hz is obtained. The experimental result is shown in Fig. 2(b).

The overall filter frequency response of the proposed filter is shown in Fig. 3(a). As expected, an equivalent bandpass filter with null-to-null bandwidth of 8.7 GHz and a notch depth over 30 dB is obtained. Meanwhile, no obvious interferences are observed in our experiment, which indicates that by use of the two orthogonal polarization modes, a filter without optical coherence limitations is feasible in an RoF link. The degradation of the response in higher frequencies is mainly caused by the degraded responses of the phase modulator and the photodetector.

The demonstrated filter here is obtained by matching the FSR of $H_2(\omega)$ to the second notch of $H_1(\omega)$; therefore, in order to achieve the tunability, both $H_1(\omega)$ and $H_2(\omega)$ are required to be tunable. The tunability of $H_2(\omega)$ can be obtained by use of a differential group-delay module, which has six phase delay sections and each section consists of a birefringent crystal and a magneto-optic polarization switch [12]. To tune $H_1(\omega)$, an equivalent nonlinearly chirped fiber Bragg grating (FBG) with linear dispersion, as presented in [13], could be cascaded with the SMF. Because the dispersion of the FBG varies in the order of several hundred picoseconds/nanometers, an acceptable tuning range of $H_1(\omega)$ can be achieved by using a laser source with small wavelength tuning range.

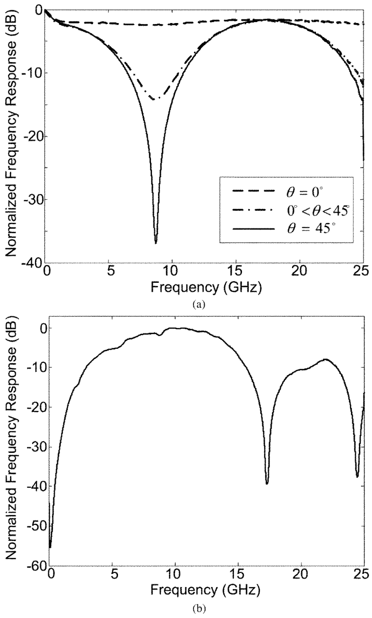

Fig. 2. (a) Frequency responses $H_2(\omega)$. (b) Frequency response $H_1(\omega)$.

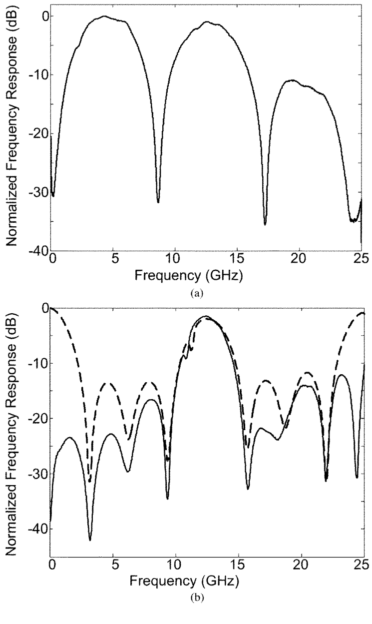

Fig. 3. (a) Frequency response $H(\omega)$ of the proposed microwave bandpass filter with one section of Hi-Bi fiber. (b) Frequency response $H(\omega)$ of the proposed filter with two sections of Hi-Bi fibers (solid line), frequency response $H_2(\omega)$ of the corresponding low pass filter (dashed line).

If a single section of Hi-Bi fiber is replaced by two sections of Hi-Bi fiber, a four-tap bandpass filter is obtained. The frequency response of the four-tap filter is shown in Fig. 3(b). Here, the lengths of the first and the second section Hi-Bi fiber are 62.9 and 125.8 m, respectively. If the linearly polarized light enters the first section of Hi-Bi fiber at an azimuth of 45°, and the spiced angle between the two Hi-Bi sections is also 45°, four taps with identical weights are achieved. The time delay between the adjacent taps is determined by the shorter Hi-Bi fiber; it is about 86 ps, corresponding to an FSR of 11.7 GHz, which matches the first peak of $H_1(\omega)$. Because on each polarization plane of the second Hi-Bi fiber there are two degenerated light components, interferences will happen on each polarization plane. However, since all the optical taps travel within the same optical link, environmental perturbations imposed on the different taps are identical; therefore, a stable operation is possible [11].

IV. CONCLUSION

In this letter, we have demonstrated an all-optical microwave bandpass filter using a narrow linewidth light source. A stable bandpass transfer function free of optical interference was realized based on a particularly simple structure, in which only a length of Hi-Bi fiber and a dispersive medium were required after the phase modulator. A bandpass filter using a section and two sections of Hi-Bi fiber were demonstrated. There are two key advantages of the proposed filter. First, the use of a single telecommunication-type laser ensures that the proposed filter can be directly incorporated in an RoF link for all-optical bandpass filtering. Second, the bandpass filtering function was realized in a 25-km fiber link, which ensures that the microwave or millimeter-wave signals are not only processed but also distributed by the proposed filter. The proposed filter has the potential to be tunable. A discussion on the tunability was presented.

REFERENCES

[1] S. Sales, J. Capmany, J. Marti, and D. Pastor, "Experimental demonstration of fiber-optic delay line filters with negative coefficients," *Electron. Lett.*, vol. 31, pp. 1095–1096, Jul. 1995.

[2] 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.

[3] X. Wang and K. T. Chan, "Tunable all-optical incoherent bipolar delay-line filter using injection-locked Fabry–Perot laser and fiber Bragg gratings," *Electron. Lett.*, vol. 36, pp. 2001–2002, Dec. 2000.

[4] S. Li, K. 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.

[5] J. Capmany, D. Pastor, A. Martinez, B. Ortega, and S. Sales, "Microwave photonics filters with negative coefficients based on phase inversion in an electro-optic modulator," *Opt. Lett.*, vol. 28, pp. 1415–1417, Aug. 2003.

[6] E. H. W. Chan and R. A. Minasian, "Novel all-optical RF notch filters with equivalent negative tap response," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1370–1372, May 2004.

[7] J. Mora, M. V. Andres, J. L. Cruz, B. Ortega, J. Capmany, D. Pastor, and S. Sales, "Tunable all-optical negative multitap microwave filters based on uniform fiber Bragg gratings," *Opt. Lett.*, vol. 28, pp. 1308–1310, Aug. 2003.

[8] F. Zeng and J. P. Yao, "All-optical bandpass microwave filter based on an electro-optic phase modulator," *Opt. Express*, vol. 12, no. 16, pp. 3814–3819, Aug. 2004.

[9] E. H. W. Chan and R. A. Minasian, "Photonic notch filter without optical coherence limitations," *J. Lightw. Technol.*, vol. 22, no. 7, pp. 1811–1817, Jul. 2004.

[10] W. Zhang, J. A. R. Williams, and I. Bennion, "Optical fiber delay line filter free of limitation imposed by optical coherence," *Electron. Lett.*, vol. 35, no. 24, pp. 2133–2134, Nov. 1999.

[11] Y. Lai, W. Zhang, and J. A. R. Williams, "A novel all-fiber bipolar transversal filter with complementary outputs," in *Proc. Microwave Photonics 2002*, Nov. 2002, pp. 173–176.

[12] J. X. Chen, Y. Wu, J. Hodiak, and P. K. L. Yu, "A novel digitally tunable microwave-photonic notch filter using differential group-delay module," *IEEE Photon. Technol. Lett.*, vol. 15, no. 2, pp. 284–286, Feb. 2003.

[13] Y. Dai, X. Chen, L. Xia, Y. Zhang, and S. Xie, "Sampled Bragg grating with desired response in one channel by use of a reconstruction algorithm and equivalent chirp," *Opt. Lett.*, vol. 29, no. 12, pp. 1333–1335, Jun. 2004.