All-Optical Microwave Mixing and Bandpass Filtering in a Radio-Over-Fiber Link

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***Abstract*—An all-optical signal processor that performs both microwave mixing and bandpass filtering in a radio-over-fiber link is proposed and demonstrated. The key device in the processor is an electrooptic phase modulator which performs all-optical microwave mixing. The microwave bandpass filtering is realized by passing the mixed microwave signals through a length of single-mode fiber, acting as a dispersive device. An up- or down-converted microwave signal is obtained and other unwanted frequency components are rejected at the end of the fiber span. The use of the proposed signal processor to perform an up-conversion of a microwave signal from 3 to 11.8 GHz in a 25-km fiber link is demonstrated.**

***Index Terms*—All-optical microwave filtering, all-optical microwave mixing, bandpass filter, chromatic dispersion, electrooptic phase modulation (PM), radio-over-fiber.**

I. Introduction

Radio-over-fiber technologies are of great interest for many potential applications such as broad-band wireless access networks, sensor networks, radar and satellite communication systems, and have been extensively studied in the last few years. The key function of a radio-over-fiber network is to distribute microwave and 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 also highly desired that the distributed signals can be processed directly in the fiber link without optical–electrical (O/E) and electrical–optical (E/O) conversions. Many papers have been published in the last two decades for all-optical microwave mixing [1]–[4] and filtering [5]–[9]. However, to the best of our knowledge, no approaches have been proposed to implement simultaneously all-optical microwave mixing and all-optical microwave filtering over a fiber link. In this letter, we propose an approach to perform both all-optical microwave mixing and bandpass filtering in a radio-over-fiber link using an electrooptic phase modulator (EOPM) and a length of single-mode fiber (SMF). The first function of the EOPM is to perform all-optical microwave mixing. The mixed signals at the output of the EOPM are then fed to the SMF link, which acts as a dispersive device for bandpass filtering, and distributes the mixed signal to a remote site. The combination of the EOPM, a multiwavelength laser source, and the SMF link forms an all-optical microwave bandpass filter [10], which can be designed to have a passband located at the up- or down-converted microwave frequency. Frequency components other than the up-converted or down-converted frequency component will be rejected. In addition to achieving bandpass filtering, the use of an EOPM has some other advantages over an intensity modulator, which include a lower insertion loss, no bias control, and simpler system design. Experiments are performed to evaluate the effectiveness of the proposed signal processor. The results show that an up-conversion of a microwave signal from 3 to 11.8 GHz is achieved while other unwanted signal components are rejected at the end of the fiber link of 25 km.

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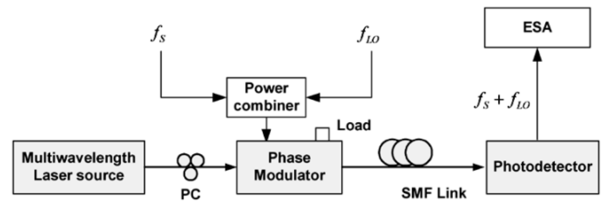

Fig. 1. Block diagram of the proposed all-optical microwave signal processor.

II. Principle

The block diagram of the proposed signal processor is shown in Fig. 1. The signal processor consists of a multiwavelength laser source, an EOPM, and a length of SMF. The light from the multiwavelength laser source is applied to the EOPM through a polarization controller. A microwave signal at frequency f_S is to be up-converted to $f_S + f_{\rm LO}$, where $f_{\rm LO}$ is the frequency of the local oscillator signal. Both signals are applied to one port of the phase modulator via a power combiner. The mixed optical signals after the EOPM are then applied to the SMF link serving as a dispersive device as well as a transmission medium. The up-converted (or down-converted) electrical signal is obtained at the output of a photodetector (PD) located at the end of the fiber link.

The phase modulated optical field can be expressed in terms of Bessel functions of the first kind

$$E(t) = \sum_{i=1}^{I} \sum_{n=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} J_n[m_p(\omega_S)V_S] \cdot J_k[m_p(\omega_{\rm LO})V_{\rm LO}] \cdot \cos\left[(\omega_{c,i} + n\omega_S + k\omega_{\rm LO})t + \frac{1}{2}n\pi + \frac{1}{2}k\pi\right] \quad (1)$$

where $\omega_{c,i}$ is the angular frequency of the ith optical carrier; $m_p(\omega)$ represents the effective phase modulation (PM) index, which is a function of the microwave frequency; V_S and $V_{\rm LO}$ are the amplitudes of the modulating microwave signals applied to the input port of the phase modulator at frequencies of ω_S and $\omega_{\rm LO}$, respectively; n and k are integers representing the orders of the harmonics; and $J_n[\cdot]/J_k[\cdot]$ denotes the nth/kth-order Bessel function of the first kind. To simplify, the argument $(m_p(\omega)V)$ will be omitted in the remainder of the letter. From (1), we can find that the phase modulated optical field consists of multiple carriers and a series of sidebands with amplitudes determined by the Bessel functions. For each carrier, the corresponding sidebands have frequency deviations from the carrier of $\pm\omega_S, \pm\omega_{\mathrm{LO}}, \pm 2\omega_S, \pm 2\omega_{\mathrm{LO}}, \ldots$, and $\omega_{\mathrm{LO}} \pm \omega_S, 2\omega_S \pm \omega_{\mathrm{LO}}, 2\omega_{\mathrm{LO}} \pm \omega_S, \ldots$. Meanwhile, based on the property of the Bessel function of the first kind,

$$\begin{aligned} J_n = -J_{-n}, J_k = -J_{-k}, &\qquad \text{when } n, k \text{ are odd} \\ J_n = J_{-n}, J_k = J_{-k}, &\qquad \text{when } n, k \text{ are even} \end{aligned} \tag{2}$$

we can see that the odd-order sidebands (when $|n+k|$ is odd) of each pair is π out of phase. If this phase-modulated optical signal is directly detected using a photodiode, no microwave signal but a dc can be obtained. However, if the phase modulated optical signal passes through a dispersive device, for example, a section of SMF, the phase relationship between any two optical frequency components will be changed due to the chromatic dispersion of the SMF. When this dispersed optical signal is fed to a PD, microwave signals with different frequencies may be obtained, which indicates that the PM is converted to intensity modulation (IM) by the dispersive SMF and a microwave mixing function is achieved.

Furthermore, since here we use a multiwavelength laser source and assume each lasing wavelength is independent, eventually the output radio frequency (RF) signal at each mixing frequency is a vector summation of all the corresponding electrical signals carried by the different wavelengths with different delays. This summation may be constructive or destructive depending on the frequency of the mixing product and the dispersion of the SMF: A transversal microwave filtering function is also achieved. The frequency response can be approximated as [10]

$$H(\omega) \propto \underbrace{\cos\left(\frac{\pi \bar{\chi_i} \bar{\lambda_i}^2 f^2}{c} + \frac{\pi}{2}\right)}_{H_1(\omega)} \cdot \underbrace{\sum_{i=1}^{I} P_i \cdot \exp[j2\pi f(i-1)T]}_{H_2(\omega)} \tag{3}$$

where $\bar{\chi_i}$ and $\bar{\lambda_i}$ denote the average accumulated dispersion and the mean value of the optical carrier wavelengths; P_i represents the power of the ith optical carrier; $T = \bar{\chi_i} \cdot \Delta\lambda$ is the time interval between any two adjacent taps; $H_1(\omega)$ represents the effects of PM-IM conversion, which has a quasi-periodic frequency response with a notch at the dc frequency and the first resonance peak at $f_1 = \sqrt{c/2\bar{\chi_i}\bar{\lambda_i}^2}$ (let $H_1(\omega) = -1$); and $H_2(\omega)$ is a typical frequency response of an all-optical transversal lowpass filter, which has a periodic frequency response with the first resonance peak at the dc and the second resonance peak at $f_2 = 1/T = 1/(\bar{\chi_i} \cdot \Delta\lambda)$ [(it is also the free-spectral range of $H_2(\omega)$]. The effective transfer function $H(\omega)$ of the proposed filter is expressed as the multiplication of these two responses. By choosing proper $\bar{\chi_i}, \bar{\lambda_i}$, and $\Delta\lambda$ to make $f_1 = f_2$, an equivalent bandpass filter is achieved, because the baseband resonance of $H_2(\omega)$ is eliminated by the notch of $H_1(\omega)$ at dc.

Based on the above analysis, if the passband peak of the proposed microwave bandpass filter is located at the frequency of the desired mixing product, the proposed system can perform simultaneously all-optical microwave mixing and bandpass filtering.

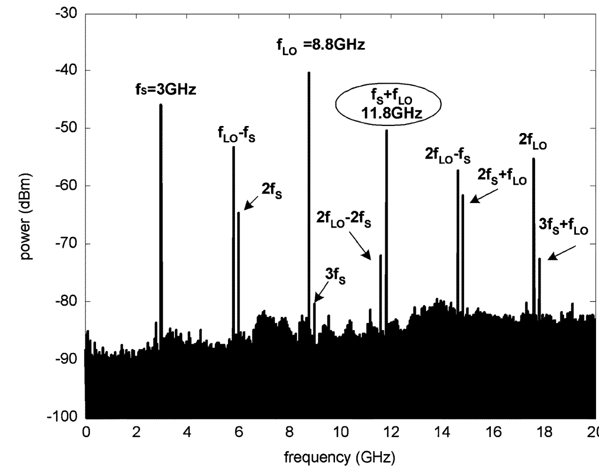

Fig. 2. Electrical spectrum of the signal at the output of the mixer, which consists of different mixing frequency components.

III. Experiment and Results

The experiment is carried in four steps.

Step 1: PM-IM conversion. Instead of using a multiwavelength laser, a single-wavelength laser diode (LD) with a wavelength of 1550 nm is used as the light source. A 25-km standard SMF-28 fiber is employed as the dispersive device. The SMF-28 fiber has a chromatic dispersion of 17 ps/nm$\cdot$km at 1550 nm. 25 km of this fiber has an accumulated dispersion of $\chi = 425$ ps/nm. To experiment the PM-IM conversion, a single microwave signal is applied to the phase modulator. By sweeping the modulating frequency from 45 MHz to 25 GHz while keeping the same output power of 3 dBm, we obtain the recovered microwave signal at the output of the PD [10].

Step 2: Microwave mixing. Keeping the LD as the light source instead of using a single microwave signal, we use two microwave signals operating at frequencies of $f_S = 3$ GHz and $f_{\mathrm{LO}} = 8.8$ GHz to drive the phase modulator. The power level for both signals is 17 dBm. The recovered microwave signals which consist of different frequency components are monitored using an electrical spectrum analyzer (ESA). As can be seen in Fig. 2, a series of microwave signals which correspond to the different frequency components of the mixing product are observed. Note that the power levels of the signals at f_S and f_{LO} are higher than the up-converted signal $f_S + f_{\mathrm{LO}}$. Also the power levels of the higher order harmonics $(2f_S, 3f_S, 2f_{\mathrm{LO}}, \ldots)$ and other unwanted intermodulation products $(f_{\mathrm{LO}} - f_S, 2f_{\mathrm{LO}} - 2f_S, 2f_{\mathrm{LO}} - f_S, 2f_S + f_{\mathrm{LO}}, 3f_S + f_{\mathrm{LO}}, \ldots)$ are comparable to that of the $f_S + f_{\mathrm{LO}}$ component. Therefore, a bandpass filter with narrow passband and high mainlobe-to-sidelobe ratio (MSR) must be used to suppress the unwanted frequency components.

Step 3: All-optical microwave bandpass filtering. To achieve microwave filtering with very narrow bandwidth, the number of taps must be large. Many taps can be realized by using an array of LDs, but with a complicated and costly system. To simplify the signal processor, in the experiment instead of using an array

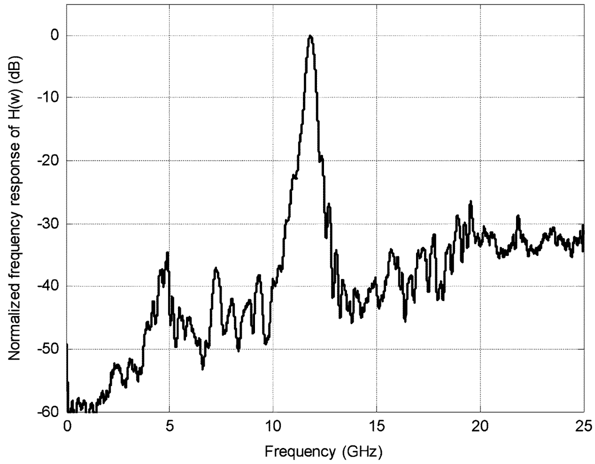

Fig. 3. Frequency response of the bandpass filter.

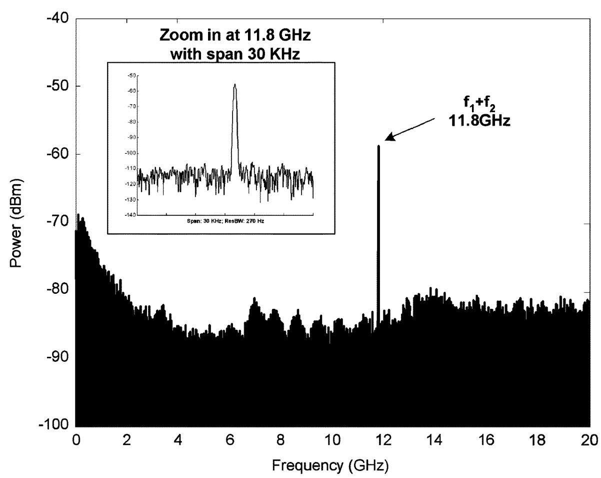

Fig. 4. Power spectrum at the output of the PD. Only the up-converted signal at 11.8 GHz is obtained and other frequency components are rejected.

of LDs, we use a multiwavelength fiber ring laser with about 30 wavelengths and a wavelength spacing of 0.2 nm proposed recently by us [11].

Using this multiwavelength laser as the light source and sweeping the modulating frequency from 45 MHz to 25 GHz, we obtain the frequency response of the proposed signal processor, as shown in Fig. 3. It can be seen that that the baseband resonance of the conventional intensity modulated direct detection based all-optical microwave lowpass filter is eliminated. A bandpass filter with a 3-dB mainlobe bandwidth of 330 MHz and an MSR of 30 dB is achieved. The RF frequency at the peak of the passband is of 11.8 GHz and is determined by the wavelength spacing of the multiwavelength light source and the accumulated dispersion of the 25-km SMF link, which agrees well with the theoretical value (11.9 GHz) calculated from (3).

Step 4: All-optical microwave mixing and bandpass filtering. Using the multiwavelength fiber ring laser as the light source, and applying the two signals ($f_S = 3$ GHz and $f_{\mathrm{LO}} = 8.8$ GHz) to the phase modulator, we obtain the up-converted microwave signal at the output of the PD. As can be seen from Fig. 4, only the up-converted component at $f_S + f_{\mathrm{LO}}$ is obtained while other frequency components are efficiently suppressed. The zoom-in spectrum with a span of 30 kHz at $f_S + f_{\mathrm{LO}}$ is also shown as an insert in Fig. 4, which exhibits a high-quality up-converted signal. Compared with the results shown in Fig. 2, a good rejection (better than 40 dB) of the unwanted frequency components is achieved. We should also note that thanks to the use of the SMF link as the dispersive device, the up-converted signal can be naturally distributed to a remote station over a 25-km span, which provides an added advantage of the proposed system. If further dispersion management is applied, the microwave distribution distance will be flexible. It should be mentioned here that due to the poor efficiency of the O/E and E/O conversions, a large RF conversion loss of about 70 dB is observed in our experimental implementation. However, we believe that this problem can be mitigated by applying either a PD with a better responsivity, or a phase modulator with a smaller half-wave voltage $V_\pi(f)$. The insertion loss can also be compensated by using an erbium-doped fiber amplifier.

IV. Conclusion

In this letter, we have demonstrated a novel all-optical signal processor that performed simultaneously all-optical microwave mixing and bandpass filtering in a radio-over-fiber link. Since a length of SMF was used in the system as a dispersive device, the up-converted microwave signal was generated at a remote site. Experimental results showed the up-converted signal was obtained at the remote site with a high rejection of other unwanted frequency components.

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