A Microwave Bandpass Differentiator Implemented Based on a Nonuniformly-Spaced Photonic Microwave Delay-Line Filter

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***Abstract*—A microwave bandpass differentiator implemented based on a finite impulse response (FIR) photonic microwave delay-line filter with nonuniformly-spaced taps is proposed and experimentally demonstrated. To implement a microwave bandpass differentiator, the coefficients of the photonic microwave delay-line filter should have both positive and negative coefficients. In the proposed approach, the negative coefficients are equivalently achieved by introducing an additional time delay to each of the taps, leading to a π phase shift to the tap. Compared with a uniformly-spaced photonic microwave delay-line filter with true negative coefficients, the proposed differentiator features a greatly simplified implementation. A microwave bandpass differentiator based on a six-tap nonuniformly-spaced photonic microwave delay-line filter is designed, simulated, and experimentally demonstrated. The reconfigurability of the microwave bandpass differentiator is experimentally investigated. The employment of the differentiator to perform differentiation of a bandpass microwave signal is also experimentally demonstrated.**

***Index Terms*—Differentiator, finite impulse response (FIR), microwave photonics, nonuniformly-spaced delay-line filter.**

I. Introduction

MICROWAVE signal processing based on photonic techniques has been a topic of interest in the past few years [1]. Due to the limited speed of the currently available digital electronics, the processing of high-frequency and broadband signal based on photonic techniques has been considered a promising solution. Among the numerous signal processing schemes, the one based on a delay-line architecture with a finite impulse response (FIR) has been widely investigated, which can find applications such as spectral filtering, phase coding, chirped microwave signal generation, and chirped pulse compression. To avoid optical interference, a photonic microwave delay-line filter is usually operating in the incoherent regime. The major limitation of a photonic microwave delay-line filter operating in the incoherent regime is that the tap coefficients are all positive, which makes the FIR delay-line filter to be low-pass only. For many applications, however, a bandpass filter with negative or complex coefficients is needed [1].

Manuscript received April 24, 2011; revised August 25, 2011; accepted September 20, 2011. Date of publication September 29, 2011; date of current version November 16, 2011. This work was supported by Natural Sciences and Engineering Research Council of Canada (NSERC).

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Digital Object Identifier 10.1109/JLT.2011.2169939

Numerous techniques have been proposed to achieve a photonic microwave delay-line filter with positive and negative tap coefficients [2]–[5]. A microwave photonic filter with positive and negative coefficients can be implemented based on cross-gain modulation (XGM) [2] or cross-polarization modulation (XPolM) [3] in a semiconductor optical amplifier (SOA). Positive and negative tap coefficients can also be realized using a pair of Mach–Zehnder modulators (MZMs) that are biased at the positive and negative linear slopes of the transfer functions to achieve amplitude inversion [4]. A pair of positive and negative tap coefficients can be generated based on phase modulation and phase-modulation to intensity-modulation (PM-IM) conversion by passing a phase-modulated optical signal through a pair of chirped fiber Bragg gratings (CFBGs) with complementary group velocity dispersion (GVD) responses [5]. Photonic microwave delay-line filters with complex tap coefficients have also been proposed [6], [7]. In [6], a complex coefficient is generated by introducing a phase shift to the microwave signal to be processed, which is realized based on a combined use of optical single-sideband modulation (SSB) and stimulated Brillouin scattering (SBS). In [7], a complex coefficient is generated using a wideband tunable optical microwave phase shifter that consists of two electro-optic MZMs. A continuous tuning of a phase shift from -180° to $+180^\circ$ was demonstrated. A comprehensive review of photonic microwave filters with negative or complex coefficients can be found in [8].

A photonic microwave delay-line filter with complex coefficients can have an arbitrary spectral response, which is highly needed for advanced signal processing. Although the schemes in [6], [7] can provide complex coefficients, the implementation is extremely complicated, especially when the number of taps is large. To solve this problem, we have recently developed a concept to design and realize a bandpass microwave photonic delay-line filter with equivalent negative or complex tap coefficients [9], [10] with nonuniformly-spaced taps. By introducing an additional time delay to a tap, an additional phase shift will be introduced to the tap coefficient, making the tap have an equivalent negative or complex coefficient. Based on this concept, advanced signal processing functions, such as phase coding, chirped microwave signal generation and chirped pulse compression, have been demonstrated [10].

Due to the wide applications in radar and modern communication systems, temporal differentiation is one of the most important signal analyzing and processing functions. A temporal differentiator can be implemented using digital electronics, but at a lower speed and narrower wideband compared with the implementation in the optical domain. Numerous photonically assisted temporal differentiators have been proposed and demon-

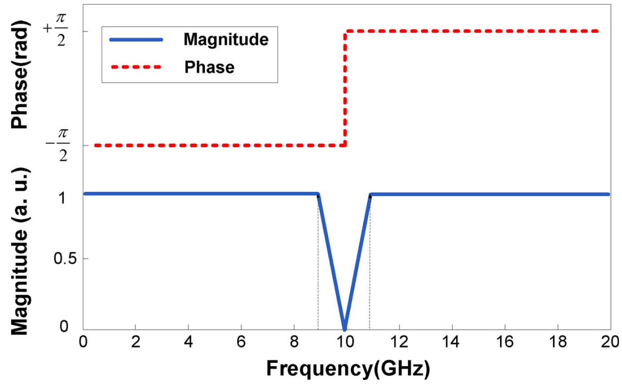

Fig. 1. Frequency response of a bandpass microwave differentiator.

strated. In general, depending on the applications, temporal differentiators [11]–[17] can be classified into two categories: optical differentiators [11]–[13], [17] and microwave differentiators [14]–[16]. A photonic microwave temporal differentiator could be achieved based on PM and PM-IM conversion in an FBG serving as a frequency discriminator [14], [15]. A temporal differentiator using other schemes such as the XGM [16] and the XPolM [17] in a SOA has also been reported.

In this paper, we propose and experimentally demonstrate a microwave bandpass differentiator based on a photonic microwave delay-line filter. A first-order bandpass temporal differentiator has a transfer function of the form given by $j(\omega-\omega_0)$, where ω_0 is the angular frequency of the microwave carrier, which can be implemented using a photonic microwave delay-line filter with a linear magnitude response within the bandwidth and a π phase shift at ω_0. A photonic microwave delay-line filter with such a spectral response should have both positive and negative coefficients [18]. The techniques proposed for the generation of negative coefficients in [2]–[5] can be employed for the implementation of a temporal differentiator, but the system is very complicated and costly. Although the filter structure in [4] is relatively simpler, an additional MZM is still needed. In addition, the requirement for a strict match of the branch lengths at the outputs of the two MZMs and a perfect match of the two MZMs would also increase the complexity of the system. In this paper, we propose to implement a temporal differentiator based on a photonic microwave delay-line filter with nonuniformly-spaced taps. The negative taps are equivalently achieved through nonuniform spacing. The key advantage of a photonic microwave filter with nonuniformly-spaced taps is its simple structure. A microwave bandpass differentiator based on a six-tap nonuniformly-spaced microwave delay-line filter is designed. Its performance is evaluated based on numerical simulations. An experimental demonstration of the differentiator is also performed. The reconfigurability of the differentiator is investigated. The differentiation of a bandpass microwave signal using the differentiator is also experimentally demonstrated.

The remainder of the paper is organized as follows. In Section II, the principle of a microwave bandpass differentiator based on a nonuniformly-spaced photonic microwave delay-line filter is presented. A microwave bandpass differentiator based on a six-tap nonuniformly-spaced photonic microwave delay-line filter is designed and its performance is evaluated based on numerical simulations. In Section III, a proof-of-concept experiment is performed, in which a microwave bandpass differentiator based on a six-tap nonuniformly-spaced photonic microwave filter is demonstrated. In Section IV, the differentiation of a bandpass microwave signal using the differentiator is experimentally demonstrated. In Section V, a conclusion is drawn.

II. Principle

A temporal differentiator can be implemented using a filter having a frequency response given by

$$H_D(\omega) = j(\omega-\omega_0) = \begin{cases} (\omega-\omega_0)e^{j\frac{\pi}{2}} & (\omega-\omega_0)>0 \\ -(\omega-\omega_0)e^{j\left(-\frac{\pi}{2}\right)} & (\omega-\omega_0)<0 \end{cases} \quad (1)$$

where ω_0 is the angular frequency of the microwave carrier. From (1) we can see that the temporal differentiator has a linear magnitude frequency response and a π phase jump at $\omega=\omega_0$. Considering that a differentiator should always have a finite bandwidth, the transfer function can be further defined by applying a window function, with the magnitude response shown in Fig. 1, where a window function with a width of 2 GHz is applied to the magnitude response.

The impulse response of a temporal differentiator implemented based on a regular FIR filter can be written by

$$h(t) = \sum_{n=0}^{M-1} a_n \delta(t-nT) \quad (2)$$

where M is the number of taps, a_n is the tap coefficient of the n-th tap, and T is the time delay between adjacent taps. If we apply Fourier transform to (2), we have the frequency response of the FIR filter,

$$H(\omega) = \sum_{n=0}^{M-1} a_n e^{-j\omega nT} \quad (3)$$

From (3) we can see that the FIR filter has multiple spectral channels and any adjacent channels are separated by a FSR given by $\Omega = 2\pi/T$. The center frequency of the m-th channel of the filter is $m\Omega$. If the FSR of the filter is set to be 9.95 GHz, the time delay between adjacent taps is $T = 100.5$ ps.

The impulse response of a regular FIR filter with six uniformly-spaced taps to achieve the frequency response shown in Fig. 1 can be calculated through the Remez algorithm [18], with the coefficients shown in Fig. 2(a). As can be seen the tap coefficients have both positive and negative values. The implementation of the microwave photonic delay-line filter using the regular uniformly-spaced FIR structure will make the system extremely complicated. A solution to simplify the implementation is to use the structure having nonuniformly-spaced taps.

If an additional time delay $\Delta\tau_n$ is introduced to the n-th tap, the filter becomes a nonuniformly-spaced FIR filter [7]. The frequency response is given by

$$H_N(\omega) = \sum_{n=0}^{M-1} a_n \exp\left[-j\left(n\frac{2\pi}{\Omega}+\Delta\tau_n\right)\omega\right] \quad (4)$$

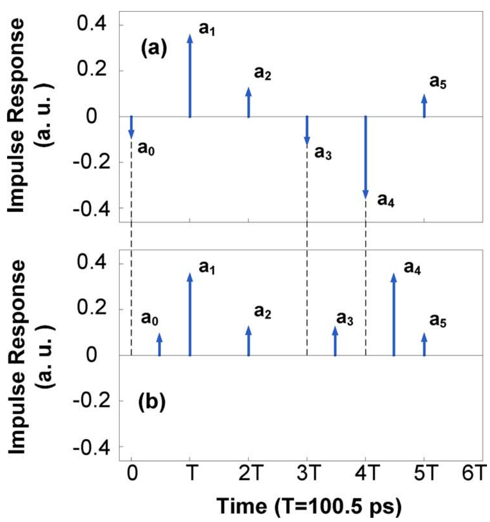

Fig. 2. Design of the temporal differentiator based on a six-tap FIR filter. (a) Impulse response of the six-tap uniformly-spaced FIR filter. (b) Impulse response of the six-tap nonuniformly-spaced FIR filter.

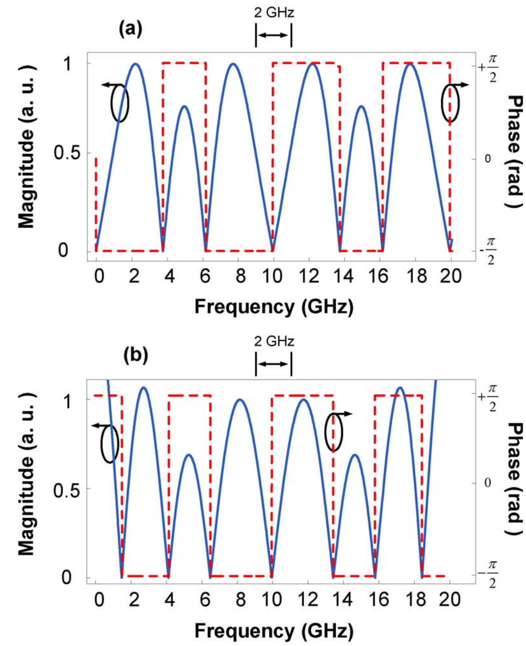

Fig. 3. Frequency response of a differentiator based on a six-tap uniformly-spaced and nonuniformly-spaced FIR filter. (a) Frequency response of the six-tap FIR filter with uniformly-spaced taps. (b) Frequency response of the six-tap nonuniformly-spaced FIR filter with nonuniformly-spaced taps.

Assume the passband of interest is narrow and the central frequency is $m\Omega$, then the frequency response in (4) can be approximated as

$$H_N(\omega) \approx \sum_{n=0}^{M-1} a_n \exp(-jm\Omega\Delta\tau_n) \cdot \exp\left(-jn\frac{2\pi}{\Omega}\omega\right) \quad (5)$$

where we have $\exp(-j\omega\Delta\tau_n) \approx \exp(-jm\Omega\Delta\tau_n)$.

An equivalent phase shift introduced by the additional time delay $\Delta\tau_n$ at the passband of interest is

$$\phi_n \approx -\Delta\tau_n \times m\Omega \quad (6)$$

If the FIR filter is implemented using all positive coefficients, the phase term of n-th tap ϕ_n can be equivalently realized by an additional time delay, with the time delay of the n-th tap given by

$$\tau_n = nT - \frac{\phi_n}{m\Omega} \quad (7)$$

Based on (7), an FIR filter with all-positive coefficients to achieve the same function as a regular FIR filter can be designed. Fig. 2(b) shows the tap coefficients of a six-tap FIR filter with nonuniformly-spaced taps for the implementation of the microwave bandpass differentiator shown in Fig. 1. It can be seen from Fig. 2(b) that the tap coefficients are all positive, but with nonuniformly-spaced taps.

The frequency responses of the six-tap FIR filter with uniformly and nonuniformly spaced taps are shown in Fig. 3(a) and (b). As can be seen from Fig. 3(a), the filter has a linear magnitude response within the 2-GHz bandwidth from 8.96 to 10.95 GHz and a π phase jump at the center frequency of 9.95 GHz. The frequency response of the nonuniformly-spaced FIR filter is shown in Fig. 3(b). Within the 2-GHz bandwidth from 8.96 to 10.95 GHz, the magnitude response of the filter is approximately linear, and a π phase jump also occurs at the center frequency of 9.95 GHz.

If we compare the frequency responses in Fig. 3(a) and (b), we can see that the frequency response of the regular FIR filter is periodic and any two adjacent channels are separated by the FSR of the filter. However, the frequency response of the nonuniformly spaced FIR filter is aperiodic. The aperiodicity is resulted due to the fact that the phase shift is introduced based on an additional time delay, which is frequency dependent. The phase shift is accurate only for the frequency at $m\Omega$ and approximately accurate at the passband centered at $m\Omega$ [7]. To ensure an accurate phase shift in the passband of interest, the filter should have a narrow bandwidth. The filter shown in Fig. 3(b) is designed to have a bandwidth of 2 GHz, the normalized root mean square (NRMS) error between the magnitude responses shown in Fig. 3(a) and (b) within the 2-GHz bandwidth is calculated to be 2.44%, which is very small. Therefore, it is feasible to implement a differentiator using a nonuniformly spaced photonic microwave delay-line filter, with a significantly reduced complexity.

III. Experiment

A proof-of-concept experiment is then carried out to demonstrate the microwave bandpass differentiator based on the six-tap nonuniformly spaced FIR filter. The center frequency is 9.95 GHz, and the bandwidth is 2 GHz from 8.96 GHz to 10.95 GHz.

Based on the Remez algorithm, the tap coefficients of a regular six-tap microwave photonic FIR filter are calculated to be $[-0.099, 0.362, 0.129, -0.129, -0.362, 0.099]$. The implementation is complicated due to the three negative values of the tap coefficients. If the differentiator is implemented using a nonuniformly-spaced microwave photonic delay-line filter, the coefficients can be all positive, with the negative coefficients equivalently achieved by additional time delays. Based on (5), the tap coefficients are

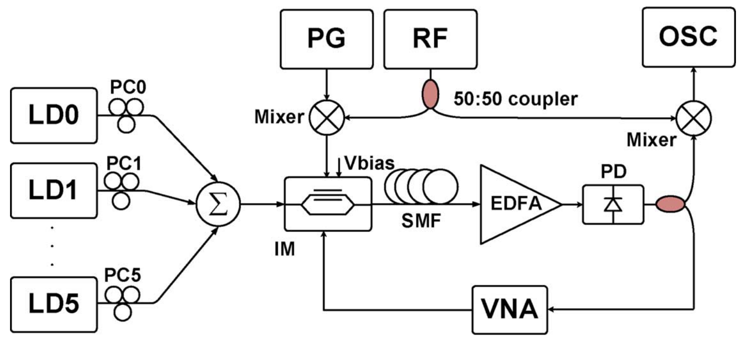

Fig. 4. Experimental setup for the implementation of a photonic microwave differentiator based on a six-tap nonuniformly-spaced delay-line filter. PC: polarization controller; VNA: vector network analyzer; EDFA: erbium-doped fiber amplifier; PG: pulse generator; RF: radio frequency source; OSC: real-time oscilloscope, PD: photodetector.

$[0.099, 0.362, 0.129, 0.129, 0.362, 0.099]$ and the time delays for the six taps are $[0.5\ \mathrm{T}, \mathrm{T}, 2\ \mathrm{T}, 3.5\ \mathrm{T}, 4.5\ \mathrm{T}, 5\ \mathrm{T}]$, where T is the time delay difference between two adjacent taps in a regular uniformly-spaced FIR filter, which is 100.5 ps.

Fig. 4 shows the experimental setup to implement the six-tap nonuniformly-spaced microwave photonic delay-line filter. The six taps are generated using six wavelengths. When the six wavelengths are traveling through a dispersive fiber, a time delay difference between two adjacent taps is generated. In the experiment, the six wavelengths are generated by a laser array, which are multiplexed using an optical coupler and sent to an intensity modulator (IM) which is biased at the linear transmission point. Six polarization controllers (PCs) are used to adjust the polarization directions of the light waves to minimize the polarization dependent loss at the IM. A 9.8-km single-mode fiber (SMF) connected at the output of the IM is used to serve as a dispersive element. Assume that the first wavelength is λ_0 and the n-th wavelength is λ_n, the time delay for the n-th tap due to the dispersive element is given by $\tau_n = D(\lambda_n - \lambda_0) L$, where D is the chromatic dispersion parameter of the SMF and L is the length of the SMF. If λ_0 is given, the n-th wavelength is calculated by

$$\lambda_n = \lambda_0 + \frac{\tau_n}{D \cdot L} = \lambda_0 + \frac{nT - \phi_n/m\Omega}{D \cdot L} \tag{8}$$

The six wavelengths are $\lambda_0 + [0, 0.5, 1.5, 3, 4, 4.5] \cdot \Delta\lambda$, where $\Delta\lambda = T/D \cdot L$ is the wavelength spacing of two adjacent wavelengths corresponding a regular uniformly spaced FIR filter.

For a standard SMF, the chromatic dispersion parameter is $D = 17$ ps/nm/km. In the experiment, the first wavelength is selected to be 1543.860 nm, based on (8) the other five wavelengths are calculated to be 1544.160, 1544.760, 1545.660, 1546.260, and 1546.560 nm. The spectrum of the six-wavelength laser array is measured and shown in Fig. 5(a). The measured magnitude and phase responses of the differentiator are shown in Fig. 5(b) and (c), respectively. The center frequency of the passband is measured, which is 9.95 GHz. The simulated magnitude and phase response of the six-tap FIR filter with uniformly-spaced taps generated by the same filter coefficients are also shown in Fig. 5(b) and (c) for comparison. The NRMS error between the experimental and simulated magnitude response shown in Fig. 5(b) is 2.69%, which is slightly higher than the theoretical value of 2.44%. The additional error is resulted from the errors in the experiment. As can be seen from Fig. 5(c), a π phase shift also occurs at 9.95 GHz. The experimental results agree well with the simulated results.

The reconfigurability of the differentiator is then investigated. The center frequency of the differentiator is tuned to 8.53 GHz, thus the wavelength spacing corresponding to a regular uniformly spaced FIR filter is $\Delta\lambda = 0.7$ nm. As shown in Fig. 5(d), the wavelengths for the six taps are 1543.860, 1544.210, 1544.910, 1545.960, 1546.660, and 1547.010 nm. The measured magnitude and phase responses are shown in Fig. 5(e) and (f). The measured center frequency is 8.53 GHz. The simulated magnitude and phase responses of the differentiator are also shown in Fig. 5(b) and (c) for comparison. The NRMS error between the simulated and experimental magnitude response is 2.71%, which is small. As can be seen from Fig. 5(f), a π phase shift also occurs at 8.53 GHz. The experimental results again agree well with the simulated results.

IV. Differentiation of a Bandpass Signal

To further evaluate the microwave bandpass differentiator, the differentiation of a bandpass microwave signal is experimentally performed. In the experiment, a Gaussian pulse is used as an input. It is known that the first-order derivative of a Gaussian pulse is a monocycle. A monocycle pulse can find applications in ultra-wideband (UWB) communications [19].

The proposed photonic microwave differentiator is a bandpass filter. To differentiate a baseband signal, a microwave up-convertor consisting of a RF signal source and a microwave mixer, as shown in Fig. 4, is employed to convert the baseband signal to a bandpass signal which is then applied to the input of the differentiator. The signal after differentiation is then converted to the baseband by using a microwave down-convertor. A Gaussian pulse with a full-width at half-maximum (FWHM) of 270 ps generated by a pattern generator (Tektronix AWG7102), shown in Fig. 6(a), is mixed with a microwave carrier at 9.95 GHz generated by a microwave signal generator (Agilent E8254A), and then sent to the IM. The spectral width of the bandpass microwave signal is 1.6 GHz, which is smaller than the bandwidth of the microwave bandpass differentiator. The differentiated bandpass microwave signal is obtained at the output of the photodetector (PD). To compare the original baseband waveform and the differentiated baseband waveform,

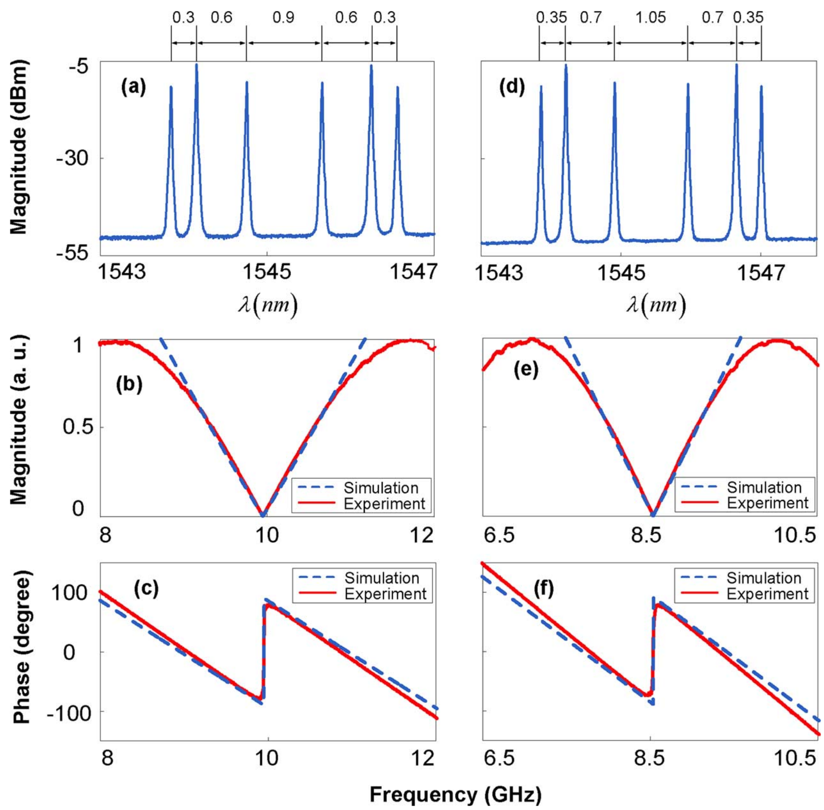

Fig. 5. Experimental results. (a) The measured spectrum of the six-wavelength laser array. Theoretically calculated (dashed line) and experimentally measured (solid line) (b) magnitude response of the 9.95-GHz differentiator, and (c) phase response of the 9.95-GHz differentiator. (d) The measured spectrum of the six-wavelength laser array for the differentiator with a center frequency at 8.53 GHz. Theoretically calculated (dashed line) and experimentally measured (solid line) (e) magnitude response of the 8.53-GHz differentiator, and (f) phase response of the 8.53-GHz-differentiator.

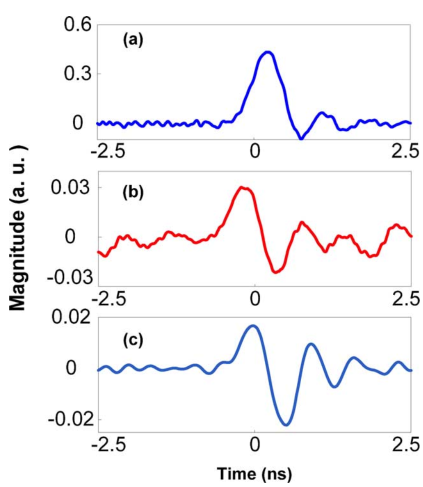

Fig. 6. Differentiation of a bandpass microwave signal based on the photonic microwave bandpass differentiator. (a) Waveform of the microwave baseband signal. (b) Experimental differentiation result of the input signal shown in (a). (c) Ideal differentiation result of the input signal shown in (a).

a second microwave mixer is employed, to which the same microwave carrier at 9.95 GHz is applied. The differentiated baseband waveform is measured by an oscilloscope (Tektronix TDS7704B), which is shown in Fig. 6(b).

As a comparison, the waveform based on ideal differentiation is shown in Fig. 6(c). In obtaining the waveform in Fig. 6(c), a bandpass filter with a 3-dB bandwidth of 2 GHz is employed to remove the high-frequency noise resulted from the differentiation process. The NRMS error between the experimented and the simulated waveforms in Fig. 6(b) and (c) is 12.11%.

V. Discussion and Conclusion

For the experimented differentiator, the power penalty function due to the chromatic dispersion of the SMF has a 3-dB bandwidth of 13.72 GHz, which is greater than 9.95 GHz. Therefore, power fading due to the chromatic dispersion of the fiber is small and can be ignored. However, for the same chromatic dispersion, if the differentiator is designed to operate at a much higher frequency, for example, if the 4th channel of the spectral response is used to perform the differentiation, the center frequency is 39.8 GHz, then the power fading effect must be taken into consideration. A simple solution to this problem is to use single-sideband (SSB) modulation scheme [20] instead of the double-side band (DSB) modulation scheme employed here.

In summary, a microwave bandpass differentiator implemented based on a FIR photonic microwave delay-line filter with nonuniformly-spaced taps was proposed and experimentally demonstrated. The key contribution of this work is that a differentiator was designed and demonstrated using a photonic microwave delay-line filter with all positive coefficients, which greatly simplified the implementation. The negative coefficients were equivalently achieved by introducing additional time delays, leading to a π phase shift to each of the negative taps. A microwave bandpass differentiator based on a six-tap FIR microwave photonic delay-line filter was designed, simulated and experimentally demonstrated. The reconfigurability of the differentiator was experimentally investigated. The differentiation of a bandpass microwave signal using the six-tap differentiator was also experimentally demonstrated.

REFERENCES

[1] J. Capmany, B. Ortega, D. Pastor, and S. Sales, "Discrete-time optical processing of microwave signals," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 702–723, Feb. 2005.

[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] Y. Yan, F. Zeng, Q. Wang, and J. P. Yao, "Photonic microwave filter with negative coefficients based on cross polarization modulation in a semiconductor optical amplifier," *Proc. OFC 2007* Paper OWU6.

[4] J. Capmany, D. Pastor, A. Martinez, B. Ortega, and S. Sales, "Microwave photonic filters with negative coefficients based on phase inversion in an electro-optic modulator," *Opt. Lett.*, vol. 28, no. 16, pp. 1415–1417, Aug. 2003.

[5] F. Zeng, J. Wang, and J. P. Yao, "All-optical microwave bandpass filter with negative coefficients based on a phase modulator and linearly chirped fiber Bragg gratings," *Opt. Lett.*, vol. 30, no. 17, pp. 2203–2205, Sep. 2005.

[6] A. Loayssa, J. Capmany, M. Sagues, and J. Mora, "Demonstration of incoherent microwave photonic filters with all-optical complex coefficients," *IEEE Photon. Technol. Lett.*, vol. 18, no. 16, pp. 1744–1746, Aug. 2006.

[7] Y. Yan and J. P. Yao, "A tunable photonic microwave filter with complex coefficient using an optical RF phase shifter," *IEEE Photon. Technol. Lett.*, vol. 19, no. 19, pp. 1472–1474, Oct. 2007.

[8] J. P. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.

[9] Y. Dai and J. P. Yao, "Nonuniformly-spaced photonic microwave delay-line filter," *Opt. Exp.*, vol. 16, no. 7, pp. 4713–4718, Mar. 2008.

[10] Y. Dai and J. P. Yao, "Nonuniformly spaced photonic microwave delay-line filters and applications," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3279–3289, Nov. 2010.

[11] N. K. Berger, B. Levit, B. Fischer, M. Kulishov, D. V. Plant, and J. Azaña, "Temporal differentiation of optical signals using a phase-shifted fiber Bragg grating," *Opt. Exp.*, vol. 15, no. 2, pp. 371–381, Jan. 2007.

[12] M. Kulishov and J. Azaña, "Long-period fiber gratings as ultrafast optical differentiators," *Opt. Lett.*, vol. 30, no. 20, pp. 2700–2702, Oct. 2005.

[13] M. Li, D. Janner, J. P. Yao, and V. Pruneri, "Arbitrary-order all-fiber temporal differentiator based on a fiber Bragg grating: Design and experimental demonstration," *Opt. Exp.*, vol. 17, no. 22, pp. 19798–19807, Oct. 2009.

[14] F. Zeng and J. P. Yao, "Ultrawideband impulse radio signal generation using a high-speed electrooptic phase modulator and a fiber-Bragg-grating-based frequency discriminator," *IEEE Photon. Technol. Lett.*, vol. 18, no. 19, pp. 2062–2064, Oct. 2006.

[15] J. Xu, X. Zhang, J. Dong, D. Liu, and D. Huang, "High-speed all-optical differentiator based on a semiconductor optical amplifier and an optical filter," *Opt. Lett.*, vol. 32, no. 13, pp. 1872–1874, Jul. 2007.

[16] J. Xu, X. Zhang, J. Dong, D. Liu, and D. Huang, "All-optical differentiator based on cross-gain modulation in semiconductor optical amplifier," *Opt. Lett.*, vol. 32, no. 20, pp. 3029–3031, Oct. 2007.

[17] Z. Li and C. Wu, "All-optical differentiator and high-speed pulse generation based on cross-polarization modulation in a semiconductor optical amplifier," *Opt. Lett.*, vol. 34, no. 6, pp. 830–832, Mar. 2009.

[18] J. G. Proakis and D. G. Manolakis, "Design of digital filters," in *Digital Signal Processing*, 4th ed. Englewood Cliffs, NJ: Prentice Hall, 2009, ch. 10.

[19] J. P. Yao, F. Zeng, and Q. Wang, "Photonic generation of ultra-wideband signals," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3219–3235, Nov. 2007.

[20] G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1410–1415, Aug. 1997.

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