A Microwave Photonic Signal Processor for Arbitrary Microwave Waveform Generation and Pulse Compression

Jiejun Zhang, *Student Member, IEEE*, and Jianping Yao, *Fellow, IEEE, Fellow, OSA*

***Abstract*—A microwave photonic signal processor for arbitrary microwave waveform generation and pulse compression based on a microwave photonic filter (MPF) and a time reversal module (TRM) is proposed and experimentally demonstrated. In the proposed signal processor, an arbitrary microwave waveform is generated by allowing an ultrashort microwave pulse to pass through an MPF and a TRM, to get a microwave waveform to have a spectrum that is the complex conjugate of the spectral response of the MPF. When the generated microwave waveform is transmitted and received, by passing the received microwave waveform through the same MPF, matched filtering is performed and the microwave waveform is compressed. The proposed microwave photonic signal processor is verified by two experiments, in which a linearly chirped microwave waveform (LCMW) with a bandwidth of 7.7 GHz and a 7-bit phase-coded microwave waveform (PCMW) with a carrier frequency of 4.08 GHz are generated and compressed. The temporal durations of the generated LCMW and PCMW are 5.57 and 5.4 ns, respectively, and the widths of the compressed pulses are 0.27 and 0.58 ns, corresponding to pulse compression ratios of 20.6 and 9.3, respectively.**

***Index Terms*—Arbitrary waveform generation, matched filter, microwave photonics, pulse compression, radar, time reversal.**

I. Introduction

PULSE compression has been widely used in modern radar systems to increase the range resolution [1]. Pulse compression is implemented by radiating a spread-spectrum microwave waveform, such as a linearly chirped microwave waveform (LCMW) or a phase-coded microwave waveform (PCMW), to the free space. When the radiated waveform is reflected by a target and received at a receiver, the waveform is largely compressed by passing it through a matched filter, resulting in a significantly increased range resolution. The pulse compression involves two operations, spread-spectrum microwave waveform generation at a transmitter and matched filtering at a receiver. Assume a radiated microwave waveform is $x(t)$ and its Fourier transform is $X(\omega)$, a matched filter to compress this waveform should have a spectral response given by $X^*(\omega)$, which is a complex conjugate version of the spectrum of the radiated waveform, or an impulse response $x(-t)$, which is a time reversed version of the radiated signal. Based on the convolution commutative property, if the radiated sign is time reversed, $x(-t)$, the impulse response of the matched filter should be $x(t)$. As can be seen, to achieve pulse compression, we may first generate a time reversed microwave waveform $x(-t)$, and the pulse compression can be done by passing the received time-reversed signal through a matched filter with an impulse response $x(t)$. Based on this concept, a microwave photonic signal processor to achieve spread-spectrum arbitrary microwave waveform generation and pulse compression is proposed and demonstrated.

Photonic techniques have been extensively investigated for the generation of spread-spectrum microwave waveforms [2]. For example, an LCMW can be generated based on photonics. Photonics-based techniques can be generally classified into five categories: 1) space-to-time pulse shaping [3]–[5], 2) spectral-shaping and wavelength-to-time (SS-WTT) mapping [6], [7], 3) temporal pulse shaping [8], 4) photonic delay-line filtering with non-uniform tap spacing [9], [10], and 5) optical heterodyning [11]. Among the different techniques, the SS-WTT mapping technique is of particular interest, since the bandwidth of a generated microwave waveform can be tuned by changing the spectral response of the spectral shaper or simply changing the dispersion of the dispersive element. The optical heterodyning technique has been demonstrated to generate a microwave waveform with the longest temporal duration. So far, an LCMW with a time-bandwidth product (TBWP) of 600 [7] or 4200 [11] has been achieved using photonic techniques, which can satisfy the requirements for advanced radar applications. For PCMW generation, solutions based on an optical phase modulator [12], an opto-electronic oscillator [13] and an pulse shaper using a specially designed fiber Bragg grating (FBG) [14] have been proposed and demonstrated.

On the other hand, very few photonic techniques have been proposed for microwave pulse compression. For the compression of an LCMW in the electrical domain, a dispersive filter with its spectral response that is a complex conjugate version of the spectrum of the LCWM can be used as a matched filter, which can be implemented using a surface acoustic wave (SAW) device [15], a C-section delay line [16] or a synthesized microwave phaser [17]. However, the bandwidth of an electrical matched filter based on the techniques reported in [15]–[17] is limited, usually less than a few GHz. A photonic matched filter has the potential to overcome the bandwidth limitation when used for pulse compression in a radar system. In [18], a microwave photonic filter (MPF) with a quadratic phase response

Manuscript received August 9, 2016; revised October 4, 2016; accepted October 17, 2016. Date of publication October 18, 2016; date of current version November 22, 2016. This work was supported by the Natural Sciences and Engineering Research Council of Canada. The work of J. Zhang was supported by a scholarship from the China Scholarship Council.

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

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2016.2619159

was demonstrated for LCMW compression, in which the MPF was implemented by passing a single sideband modulated optical signal through an FBG that has a quadratic phase response. Thanks to optical phase to microwave phase conversion through single sideband modulation and heterodyne detection, an MPF with a quadratic phase response was achieved. The bandwidth of the MPF was 3 GHz, which can be much wider if the FBG is design to have a wider bandwidth. In [19], a four-tap MPF was experimentally demonstrated to function as a matched filter for pulse compression of a binary PCMW with a carrier frequency of 6.75 GHz. The filter can be reconfigured by changing the wavelength spacing of the optical carriers to compress a microwave waveform encoded with a different phase code. Since the tap number is determined by the code length of the PCMW, which can be long, thus the system is complicated for pulse compression with a long length code. In [20], an MPF with a quadratic phase response was demonstrated based on a broadband optical source sliced by an Mach-Zehnder interferometer (MZI). By passing the sliced optical wave through a nonlinear dispersive element, a finite impulse response (FIR) filter with nonuniform tap spacing corresponding to a quadratic phase response was implemented. A bandwidth of 2.5 GHz and a dispersion of 12 ns/GHz were experimentally achieved. A similar approach was proposed in [21]. To eliminate the dispersion induced power penalty, a phase modulator placed in one arm of the MZI was used instead of an intensity modulator that was placed at the output of the MZI. The bandwidth of the MPF was 4 GHz. The photonic approaches proposed in the last few years can be used for either pulse generation or pulse compression, but no approaches have been proposed to perform the two functions simultaneously.

In this paper, we propose a microwave photonic signal processor to achieve simultaneously spread-spectrum microwave waveform generation and pulse compression based on an MPF and a time reversal module (TRM). In the proposed processor, an arbitrary microwave waveform is generated by allowing an ultra-short microwave pulse to pass through the MPF and the TRM, to get a microwave waveform to have a spectrum that is the complex conjugate of the spectral response of the MPF. When the generated microwave waveform is transmitted and received, by passing the received microwave waveform through the same MPF, matched filtering is performed and the microwave waveform is compressed. The operation of the proposed microwave photonic signal processor is verified by two experiments, in which an LCMW with a bandwidth of 7.7 GHz and a 7-bit PCMW with a carrier frequency of 4.08 GHz are generated and compressed. The temporal durations of the generated LCMW and PCMW are 5.57 and 5.4 ns, respectively, and the widths of the compressed pulses are 0.27 and 0.58 ns, corresponding to pulse compression ratios of 20.6 and 9.3, respectively.

II. Principle

Fig. 1 shows the schematic diagram of the proposed microwave photonic signal processor for spread-spectrum microwave waveform generation and pulse compression. The signal processor consists of an MPF and a TRM. A light wave from

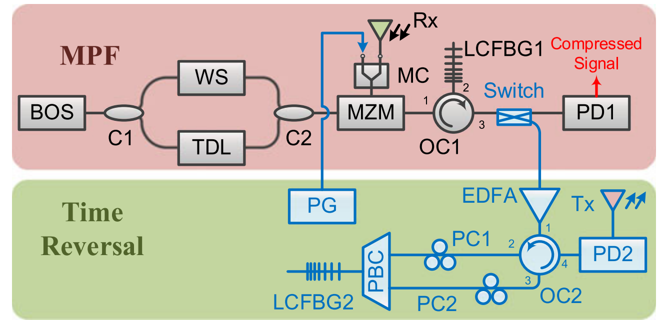

Fig. 1. Schematic diagram of the microwave photonic signal processor. MPF: microwave photonic filter; TRM: time reversal module; BOS: broadband optical source; C1, C2: 3-dB optical couplers; WS: waveshaper; TDL: tunable delay line; MZM: Mach-Zehnder modulator; Rx: receiving antenna; MC: microwave combiner; OC: optical circulator; LCFBG: linearly chirped fiber Bragg grating; PD: photodetector; EDFA: erbium doped fiber amplifier; PC: polarization controller; PBC: polarization beam combiner; PG: pulse generator; Tx: transmitting antenna.

a broadband optical source (BOS) is sent to a fiber-optic MZI, with the two arms connected by two 3-dB optical couplers (C1 and C2). A waveshaper (WS) as a programmable optical filter is incorporated in the upper arm to change the transmission spectrum of the MZI by applying a phase coding signal to the light wave travelling in the upper arm and an optical tunable delay line (TDL) is incorporated in the lower arm to adjust the length difference between two arms of the MZI. A Mach-Zehnder modulator (MZM) is connected at the output of the MZI at which the optical carrier is modulated by an ultra-short microwave pulse for waveform generation or by a received microwave waveform for pulse compression. The optical signal from the MZM is reflected by a linearly chirped fiber Bragg grating (LCFBG1) via an optical circulator (OC1) and sent through a 2 $\times$ 2 switch to a TRM. When the switch is in the cross state, the processor is configured for waveform generation. When the switch is in the bar state, the processor is configured for pulse compression. The setup can be considered as an MPF when the switch is in the bar state. The spectral response of the MPF can be reconfigured by applying a phase coding signal to the WS, to make the MPF operate as a reconfigurable matched filter for a pre-defined microwave signal.

First, we investigate the generation of an LCMW in which the system is operating as an MPF and a TRM. To generate an LCMW, the MPF is configured to have a group delay response with a linearly increasing time delay. If an ultra-short microwave pulse is applied to the MPF, an LCMW will be generated. The chirp rate of the generated LCMW is determined by the group delay response of the MPF. As shown in Fig. 1, an ultra-short microwave pulse generated by an electrical pulse generator (PG) is applied to the MZM via a 2 $\times$ 1 microwave combiner (MC). The receiving antenna is also connected to the MZM via the 2 $\times$ 1 MC. To generate an LCMW that can be compressed by the MPF, the waveform should have a spectral response that is a complex conjugate version of the spectral response of the MPF, which is done by passing the waveform through a TRM. In this case, the optical switch is in the cross state. The redirected signal is amplified by an erbium-doped fiber amplifier (EDFA) and sent to port 1 of a 4-port optical circulator (OC2). The second and third ports of OC2 are connected to a polarization beam combiner (PBC), at the output of which LCFBG2 is incorporated. This configuration allows the light wave from Part 1 of OC2 to be reflected by LCFBG2 twice, and when the dispersion coefficient of LCFBG2 is opposite to that of LCFBG1, the optical signal carrying the impulse response of the MPF will be temporally reversed [22]. Two polarization controllers (PC1 and PC2) are employed between the second and third ports of OC2 and the PBC to ensure a maximum coupling efficiency to LCFBG2. The optical signal is finally detected by a photodetector (PD2) to generate a microwave waveform, which is a time reversed version of the impulse response of the MPF. The microwave signal can then be amplified, sent to an antenna Tx and radiated to the free space. After being reflected by a target, the waveform will be received by an antenna Rx and compressed by the MPF, which functions as a matched filter. It should be noted that, in a radar system, the transmitter and receiver share one antenna, which can be realized by a duplexer switch in the system.

Assume that the BOS has a broadband flat spectrum with a unity magnitude, the optical spectrum at the output of the MZI can then be denoted as $s(\omega)$, where $s(\omega)$ is also the frequency response of the MZI and ω is the optical angular frequency. Note that $s(\omega)$ can be seen as the spectrum of the optical carrier for the microwave signal modulated at the MZM. For the microwave signals modulating on different optical angular frequencies ω, different time delays will be resulted when detected at PD1 due to the dispersion of LCFBG1. The signal at the output of PD1 should be the summation of all the time delayed signals carried by all the optical carrier frequencies. First, we consider a microwave signal $e(t) = \exp(j2\pi\Omega t)$ with an angular frequency of Ω, the signal at the output of PD1 can be written as

$$\begin{aligned} y(t) &= \int_0^{+\infty} \exp\left[j2\pi\Omega\left(t - \beta\omega\right)\right] s(\omega) d\omega \\ &= \exp\left(j2\pi\Omega t\right) \int_0^{+\infty} s(\omega) \exp\left(-j2\pi\Omega\beta\omega\right) d\omega \end{aligned} \quad (1)$$

where $\beta\omega$ is a carrier frequency dependent time delay induced by LCFBG1 and β (in ps^2) is the dispersion coefficient of LCFBG1. Here, the beat signals between the optical carriers are ignored, as they are not phase-correlated. Note that in (1), $\exp(j2\pi\Omega t)$ is the input microwave signal, the integration is time-independent and thus is the response of the system to the input microwave signal. The frequency response of the MPF is then given by

$$\begin{aligned} H(\Omega) &= \int_0^{+\infty} s(\omega) \exp\left(-j2\pi\Omega\beta\omega\right) d\omega \\ &= S(\xi)|_{\xi=\beta\Omega} \end{aligned} \quad (2)$$

where $S(\xi)$ is the Fourier transform of $s(\omega)$. Since the frequency response of the MPF is simply the Fourier transformation of the optical spectrum at the output of the MZI, we can program the WS to have a certain phase response, which would lead to a frequency response of the MPF that can be used to compress an input microwave waveform.

Here, the MPF is also used in conjunction with the TRM for the generation of an arbitrary microwave waveform. To do so, we apply a short pulse to the MZM, a microwave signal that is the impulse response of the MPF will be achieved at the output of PD1. The impulse response of the system can be derived by the inverse Fourier transformation of its frequency response, given by

$$h(t) = s\left(\frac{t}{\beta}\right) \quad (3)$$

According to (3), an electrical signal with a shape identical to the spectrum of the optical carrier will be generated at PD1 when a short pulse is applied to the MZM. The system can be seen as an SS-WTT mapping system that is commonly used for the generation of microwave arbitrary waveforms [6], [7]. For example, if the MZI has a linearly increasing or decreasing free spectral range (FSR), an LCMW will be generated if a short pulse is applied to the MZM.

It is known that the frequency response of a matched filter should be the complex conjugate of the spectrum of the input signal. In our system, the TRM is employed to perform complex conjugation. First, an electrical short pulse is applied to the MZM, the optical signal containing the impulse response of the MPF is directed to LCFBG2 by setting the 2×2 switch at the cross state, and reflected twice due to the use of the PBC and the 4-port OC (OC2). The dispersion coefficient of LCFBG2 is chosen to be opposite to that of LCFBG1. A time reversed version of the MPF impulse response will be obtained at the output of PD2, which can be expressed as $g(t) = h(-t) = s(-t/\beta)$ [22]. It is easy to prove that for the signal $g(t)$ that contains only real values, the Fourier transform is

$$G(\Omega) = \int_{-\infty}^{+\infty} h\left(-t\right) \exp\left(-j2\pi\Omega t\right) dt = \left[H(\Omega)\right]^* \quad (4)$$

As can be seen, the Fourier transform (spectrum) of $g(t)$ is complex conjugate to the frequency response of the MPF $H(\Omega)$. If $g(t)$ is a radar signal being transmitted into the free space, the MPF can be used as a matched filter for the detection and compression of the returned signal.

III. Experiments

The proposed processor is experimentally evaluated. In the experiments, the BOS is a spectrally flattened amplified spontaneous emission (ASE) source using an EDFA. A WS (Finisar 4000s) is employed in the upper arm of the MZI. The MZM (JDSU OC-192) has a bandwidth of 10 GHz. A microwave arbitrary waveform (Keysight M8195A) is used to generate a 62.5-ps electrical pulse. The electrical pulse and the received microwave signal are both applied to the MZM via a microwave power combiner. The two LCFBGs have a length of 1 m, and the dispersion coefficients of LCFBG1 and LCFBG2 are +2500 ps/ nm and −2500 ps/ nm, respectively, within an identical bandwidth of 40 nm centered at 1545 nm. Two PDs, PD1 (New Focus 1414) and PD2 (New Focus 1014), are used to measure the compressed electrical waveform and generate the microwave waveform to be transmitted into the free space, respectively. For

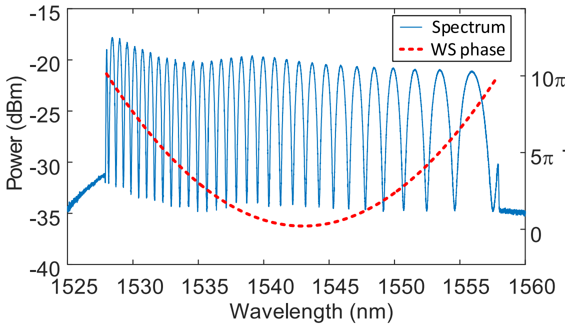

Fig. 2. The spectrum of the optical carrier measured at the output of the MZI when a quadratic phase is applied to the WS.

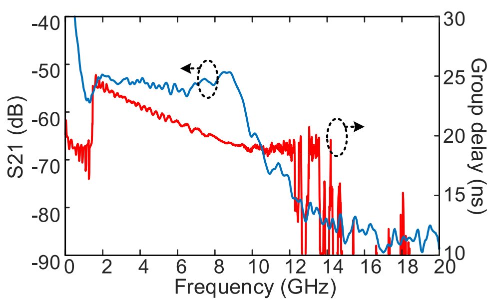

Fig. 3. The magnitude and group delay response of the MPF when a quadratic phase is applied to the WS.

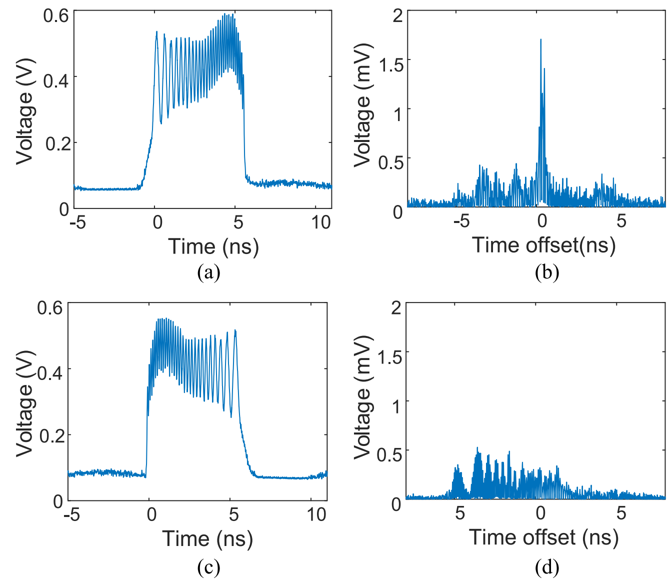

Fig. 4. (a) The LCMW generated at the output of PD2 with the TRM connected. (b) The signal at the output of PD1 with the signal in (a) as the input signal to the MPF. (c) The LCMW at the output of PD2 with the TRM disconnected. (d) The signal at the output of PD1, with the signal in (c) as the input signal to the MPF.

simplicity, we use a microwave cable to replace the receiving and transmitting antennas by connecting the output port of PD2 to the power combiner, of which the output is connected to the microwave port of the MZM. A real-time oscilloscope (Agilent DSO-X 93204A) is used to sample the output signal from PD1 (receiver mode) or PD2 (transmitter mode). A digital high pass filter with a cutoff frequency at 50 MHz is connected to the output of PD1, to remove the strong DC component in the compressed pulse. The sample data after the digital filtering are converted to its absolute value digitally.

We firstly configure the system to generate an LCMW. To do so, the 2×2 switch is in the cross state. The WS is configured to have a quadratic phase response centered at 1543 nm with a maximum phase of 10π, which is shown as red dotted line in Fig. 2. The MZI has an arm length difference of 1.7 mm. The transmission spectrum of the MZI is then measured to have a linearly increasing FSR, as also shown in Fig. 2. The frequency response of the MPF is measured by a vector network analyzer (Agilent E8364A) with the switch in the bar state. Fig. 3 shows the S21 parameter of the MPF, which is the power ratio between the output and the input signals at different frequencies. A passband from 1.55 to 9.22 GHz and a group delay dispersion of -0.691 ns/ GHz are observed.

When the electrical pulse with a duration of 62.5 ps is applied to the MZM and the switch is set at the cross state, a chirped microwave waveform with a shape similar to the transmission spectrum of the MZI is generated at the output of PD2, as shown in Fig. 4(a), which has a frequency range from around 2 to 10 GHz and a chirp rate of 1.44 GHz/ ns.

We then configure the system to perform pulse compression. To do so, the switch is changed to the bar state and the generated chirped microwave waveform is applied to the MZM as a received signal. The chirped microwave waveform is then compressed by the matched filter. A compressed pulse is measured at the output of PD1, as shown in Fig. 4(b), which has a temporal width of 0.27 ns, corresponding to a compression ratio of 20.7 considering the duration of the original pulse is 5.57 ns. Theoretically, perfect matched filtering can compress the chirped pulse to have a temporal width of 0.20 ns or a compression ratio of 27.9. The slightly poorer pulse compression is caused by the limited bandwidths of the electro-optic components and the measurement equipment, which makes the generated chirped microwave waveform slightly different from an idea waveform (smaller amplitude for the high frequency components). To verify that the MPF is able to reject a microwave waveform that is different from the transmitted waveform, here, for simplicity, a different waveform is generated by simply disconnecting the TRM, which is done by connecting PD2 directly to the output of the EDFA. In this case, the microwave waveform generated at the output of PD2 is no longer a time reversed impulse response of the MPF, but the impulse response itself $h(t)$, as shown in Fig. 4(c), which should not be compressed by the MPF. The signal at the output of PD1 when $h(t)$ is applied to the MZM and the switch is set at the bar state is shown in Fig. 4(d). No compressed pulse is observed, which confirms that the MPF is a matched filter which is able to reject a microwave signal that is different from the transmitted signal.

A significant advantage of the proposed signal processor is that it can generate and compress not only a chirped microwave waveform, but a truly arbitrary waveform by simply changing the phase response of the WS. Here we verify the operation of

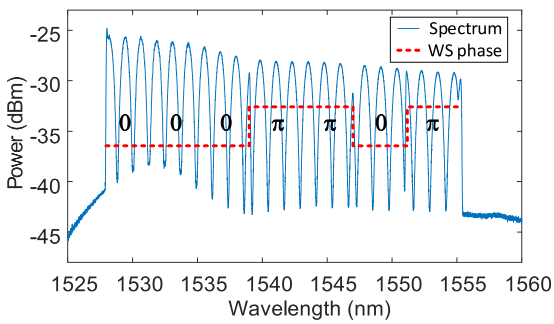

Fig. 5. The spectrum of the optical carrier measured at the output of the MZI when a 7-bit binary phase code is applied to the WS.

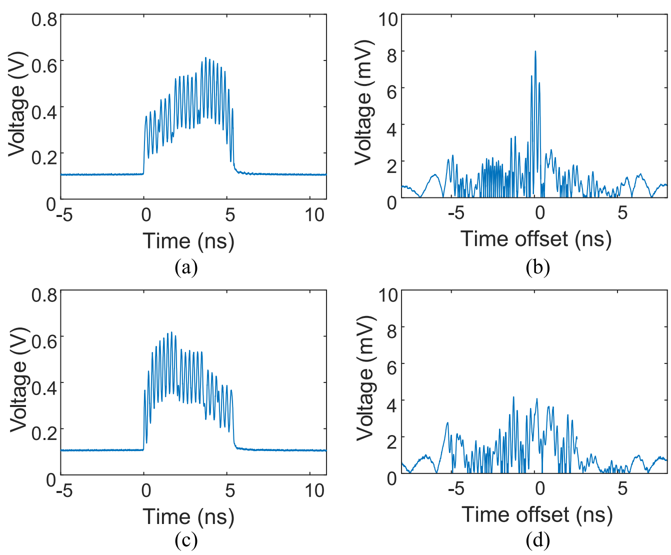

Fig. 6. (a) The PCMW generated at the output of PD2 with the TRM connected. (b) The signal at the output of PD1 with the signal in (a) as the input to the MPF. (c) The PCMW at the output of PD2 with the TRM disconnected. (d) The signal at the output of PD1 with the signal in (c) as the input to the MPF.

the system for a PCMW generation and compression. Instead of a quadratic phase, here we configure the WS to have a 7-bit Barker phase, as indicated in the red dotted line in Fig. 5. The MZI then has an optical transmission spectrum that corresponds to the desired PCMW (blue solid line).

Fig. 6(a) shows the generated PCMW when a short electrical pulse is applied to the MZM and that the switch is set at the cross state. The signal is measured to have a carrier frequency of 4.08 GHz and a duration of 5.4 ns. The PCMW is then fed to the MZM and the switch is set at the bar state. Fig. 6(b) shows the compressed pulse measured at the output of PD1, in which a peak with a temporal width of 0.58 ns is observed. The compression ratio is calculated to be 9.3. Theoretically, a perfect matched filter can compress the PCMW to a temporal width of 0.42 ns or a compression ratio of 12.9. Again, the slightly poorer pulse compression is caused by the limited bandwidths of the electrical components and the measurement equipment. Similarly, here we also test the ability of the MPF to reject a signal that is different from the transmitted signal. With PD2 connected to the EDFA directly, we get a generated waveform which is shown in Fig. 6(c). The microwave waveform is then applied to the MZM and the switch is set at the bar state. Fig. 6(d) shows the measured signal at the output of PD1. No pulse compression is observed, which confirms again that the MPF is a matched filter which is able to reject a microwave signal that is different from the transmitted signal.

IV. Conclusion

A microwave photonic signal processor for arbitrary microwave waveform generation and pulse compression based on an MPF and a TRM was proposed and experimentally demonstrated. An arbitrary microwave waveform was generated by allowing an ultra-short microwave pulse to pass through an MPF and a TRM, to get a microwave waveform to have a spectrum that is the complex conjugate of the spectral response of the MPF. When the generated microwave waveform was transmitted and received, by passing the received microwave waveform through the same MPF, matched filtering was performed and the microwave waveform is compressed. The proposed microwave photonic signal processor was verified by two experiments, in which a 7-bit phase-coded microwave waveform (PCMW) with a carrier frequency of 4.08 GHz, and a LCMW with a bandwidth of 7.7 GHz were generated and compressed. The durations of the generated LCMW and PCMW were 5.57 and 5.4 ns, respectively. The widths of the compressed pulses were 0.27 and 0.58 ns and the pulse compression ratios were 20.6 and 9.3. The proposed microwave photonic signal processor can also be configured to generate and compress other waveforms such as a nonlinearly chirped microwave waveform. It can find applications in radar systems to generate and compress wideband and high speed microwave signals.

References

[1] A. W. Rihaczek, *Principles of High-Resolution Radar*. Norwood, MA, USA: Artech House, 1996.

[2] J. P. Yao, “Photonic generation of microwave arbitrary waveforms,” *Opt. Commun.*, vol. 284, no. 15, pp. 3723–3736, Jul. 2011.

[3] J. D. McKinney, D. Seo, D. E. Leaird, and A. M. Weiner, “Photonically assisted generation of arbitrary millimeter-wave and microwave electromagnetic waveforms via direct space-to-time optical pulse shaping,” *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3020–3028, Dec. 2003.

[4] S. T. Cundiff and A. M. Weiner, “Optical arbitrary waveform generation,” *Nature Photon.*, vol. 4, no. 11, pp. 760–766, Nov. 2010.

[5] A. Vega, D. E. Leaird, and A. M. Weiner, “High-speed direct space-to-time pulse shaping with 1 ns reconfiguration,” *Opt. Lett.* vol. 35, no. 10, pp. 1554–1556, May 2010.

[6] A. Zeitouny, S. Stepanov, O. Levinson, and M. Horowitz, “Optical generation of linearly chirped microwave pulses using fiber Bragg gratings,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 660–662, Mar. 2005.

[7] Y. Li, A. Rashidinejad, J.-M. Wun, D. E. Leaird, J.-W. Shi, and A. M. Weiner, “Photonic generation of W-band arbitrary waveforms with high time-bandwidth products enabling 3.9 mm range resolution,” *Optica*, vol. 1, no. 6, pp. 446–454, Dec. 2014.

[8] J. Azaña, N. K. Berger, B. Levit, and B. Fischer, “Reconfigurable generation of high-repetition-rate optical pulse sequences based on time-domain phase-only filtering,” *Opt. Lett.*, vol. 30, no. 23, pp. 3228–3230, Dec. 2005.

[9] Y. Dai and J. P. Yao, “Chirped microwave pulse generation using a photonic microwave delay-line filter with a quadratic phase response,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 9, pp. 569–571, May 2009.

[10] M. Rius, M. Bolea, J. Mora, B. Ortega, and J. Capmany, “Experimental photonic generation of chirped pulses using nonlinear dispersion-based incoherent processing,” *Opt. Express.*, vol. 23, no. 10, pp. 13634–13640, May 2015.

[11] O. L. Coutinho, J. Zhang, and J. P. Yao, "Photonic generation of a linearly chirped microwave waveform with a large time-bandwidth product based on self-heterodyne technique," in *Proc. 2015 Int. Top. Meet. Microw. Photon.*, Paphos, Cypru, Oct. 2015, pp. 1–4.

[12] M. Li and J. P. Yao, "Photonic generation of a precisely π phase shifted binary phase-coded microwave signal," *IEEE Photon. Technol. Lett.*, vol. 24, no. 22, pp. 2001–2004, Nov. 2012.

[13] W. Li, F. Kong, and J. P. Yao, "Arbitrary microwave waveform generation based on a tunable optoelectronic oscillator," *J. Lightw. Technol.*, vol. 31, no. 23, pp. 3780–3786, Dec. 2013.

[14] C. Wang and J. P. Yao, "Phase-coded millimeter-wave waveform generation using a spatially discrete chirped fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 24, no. 17, pp. 1493–1495, Sep. 2012.

[15] A. M. Kawalec, "SAW dispersive delay lines in radar signal processing," in *Proc. Rec. IEEE 1995 Int. Radar Conf.*, Alexandria, VA, May 1995, pp. 732–736.

[16] S. Gupta, D. L. Sounas, H. V. Nguyen, Q. Zhang, and C. Caloz, "CRLH–CRLH C-section dispersive delay structures with enhanced group-delay swing for higher analog signal processing resolution," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 12, pp. 3939–3949, Dec. 2012.

[17] Q. Zhang, S. Gupta, and C. Caloz, "Synthesis of narrowband reflection-type phasers with arbitrary prescribed group delay," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 8, pp. 2394–2402, Aug. 2012.

[18] C. Wang and J. P. Yao, "Chirped microwave pulse compression using a photonic microwave filter with a nonlinear phase response," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 2, pp. 496–504, Feb. 2009.

[19] Y. Dai and J. P. Yao, "Microwave correlator based on a nonuniformly spaced photonic microwave delay-line filter," *IEEE Photon. Technol. Lett.*, vol. 21, no. 14, pp. 969–971, Jul. 2009.

[20] M. Bolea, J. Mora, L. R. Chen, and J. Capmany, "Highly chirped reconfigurable microwave photonic filter," *IEEE Photon. Technol. Lett.*, vol. 23, no. 17, pp. 1192–1194, Sep. 2011.

[21] X. Xue, X. Zheng, H. Zhang, and B. Zhou, "Tunable chirped microwave photonic filter employing a dispersive Mach–Zehnder structure," *Opt. Lett.*, vol. 36, no. 17, pp. 3518–3520, Sep. 2011.

[22] J. Zhang and J. P. Yao, "Broadband and precise microwave time reversal using a single linearly chirped fiber Bragg grating," *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 7, pp. 2166–2172, Jul. 2015.

Jiejun Zhang (S'12) received the B.Eng. degree in electronic science and technology from the Harbin Institute of Technology, Harbin, China, in 2010, and the M.Sc. degree in optical engineering from Huazhong University of Science and Technology, Wuhan, China. He is currently working toward the Ph.D. degree in electrical engineering in the Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, Canada.

His research interests include photonic generation of microwave waveforms, photonic processing of microwave signals, and fiber optic sensors.

Jianping Yao (M'99–SM'01–F'12) received the Ph.D. degree in electrical engineering from the Université de Toulon et du Var, Toulon, France, in December 1997.

From 1998 to 2001, he was an Assistant Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. In December 2001, he was an Assistant Professor in the School of Electrical Engineering and Computer Science, University of Ottawa, where he was promoted as an Associate Professor in 2003 and a Full Professor in 2006. In 2007, he was appointed as a University Research Chair in Microwave Photonics. From July 2007 to June 2010 and from July 2013 to June 2016, he was the Director of the Ottawa-Carleton Institute for Electrical and Computer Engineering. He is currently a Professor and the University Research Chair in the School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada. He has authored or co-authored more than 520 research papers, including more than 310 papers in peer-reviewed journals and 210 papers in conference proceedings

Dr. Yao is a Topical Editor of *Optics Letters*, and serves on the Editorial Boards of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, *Optics Communications*, *Frontiers of Optoelectronics*, and *Science Bulletin*. He was as a Guest Co-Editor for a focus issue on microwave photonics in *Optics Express* in 2013 and a Lead-Editor for a feature issue on microwave photonics in *Photonics Research* in 2014. He is a Chair of numrous international conferences, symposia, and workshops, including the Vice Technical Program Committee (TPC) Chair of the IEEE Microwave Photonics Conference in 2007, TPC Cochair of the Asia-Pacific Microwave Photonics Conference in 2009 and 2010, TPC Chair of the high-speed and broadband wireless technologies subcommittee of the IEEE Radio Wireless Symposium in 2009–2012, TPC Chair of the microwave photonics subcommittee of the IEEE Photonics Society Annual Meeting in 2009, TPC Chair of the IEEE Microwave Photonics Conference in 2010, General Co-Chair of the IEEE Microwave Photonics Conference in 2011, TPC Co-Chair of the IEEE Microwave Photonics Conference in 2014, and General Co-Chair of the IEEE Microwave Photonics Conference in 2015. He is also a committee member of numerous international conferences, such as IPC, OFC, BGPP, and MWP. He received the 2005 International Creative Research Award of the University of Ottawa, the 2007 George S. Glinski Award for Excellence in Research, and a Natural Sciences and Engineering Research Council of Canada Discovery Accelerator Supplements Award in 2008. He was selected to receive an inaugural OSA Outstanding Reviewer Award in 2012. He was an IEEE MTT-S Distinguished Microwave Lecturer for 2013–2015. He is a registered Professional Engineer of Ontario. He is a Fellow of the OSA, and the Canadian Academy of Engineering CAE. In June 2016, he was conferred the title of Distinguished University Professor of the University of Ottawa.