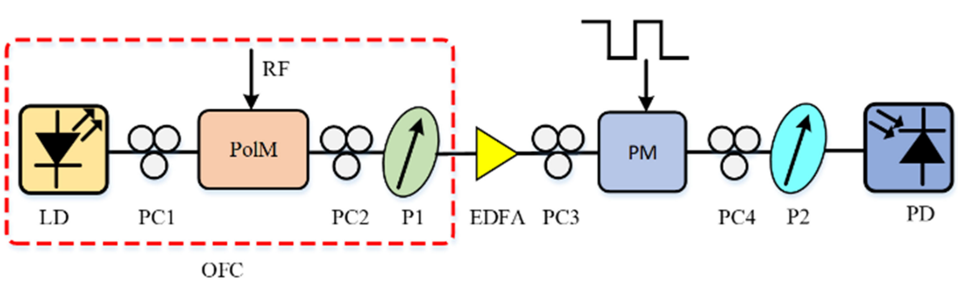
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Photonic Generation of Multicarrier Phase-Coded Microwave Signals Utilizing Polarization Manipulation

Volume 10, Number 5, September 2018

Peng Li
Lianshan Yan
Jia Ye
Yan Pan
Wei Pan
Bin Luo
Xihua Zou
Tao Zhou
Zhiyu Chen
Maowen Wang



DOI: 10.1109/JPHOT.2018.2871179

Photonic Generation of Multicarrier Phase-Coded Microwave Signals Utilizing Polarization Manipulation

Peng Li,[1] **Lianshan Yan**,[1] **Jia Ye**,[1] **Yan Pan**,[1] **Wei Pan**,[1] **Bin Luo**,[1] **Xihua Zou**,[1] **Tao Zhou**,[2] **Zhiyu Chen**,[2] **and Maowen Wang**[2]

[1]Center for Information Photonics and Communications, School of Information Science and Technology, Southwest Jiaotong University, Chengdu 611756, China
[2]Key Laboratory of Electronic Information Control, Southwest China Research Institute of Electronic Equipment, Chengdu 610036, China

DOI:10.1109/JPHOT.2018.2871179

Manuscript received August 22, 2018; revised September 12, 2018; accepted September 14, 2018. Date of publication September 19, 2018; date of current version October 5, 2018. This work was supported in part by the National Basic Research Program of China under Grant 2013CBA01704, in part by the National Natural Science Foundation of China under Grant 61335005, Grant 61771438, and Grant 61860206006, in part by the Ministry of Education United Foundation of Equipment Pre-Research under Grant 6141A020334. Corresponding author: Lianshan Yan (e-mail: lsyan@home.swjtu.edu.cn).

Abstract: A method to generate a multicarrier phase-coded (MCPC) microwave signal is proposed and experimentally demonstrated. By optimizing the angle between the transverse-electric and transverse-magnetic modes in a phase modulator (PM), an MCPC microwave signal can be generated. Compared with the other reported schemes, the proposed one has an extremely simple structure, since only a PM is required. A proof-of-concept experiment is demonstrated to generate radio frequency signals with the carrier frequency of 5 and 10 GHz simultaneously and the coding rate of 1.25 Gb/s.

Index Terms: Microwave photonics, radar, multicarrier phase coding, analog optical signal processing.

1. Introduction

In modern radar systems, pulse compression has been widely used to increase the detection range and range resolution [1], [2]. In general, pulse compression is realized by compressing a frequency-chirped or phase-coded signal with a matched filter. Compared with traditional electrical approaches to generate frequency-chirped or phase-coded signals, photonic ones have attracted great attentions in the past few years, due to their advantages in term of small size, light weight, low insertion loss, immunity to electromagnetic interference and large time-bandwidth products [3].

One method to generate a phase-coded signal is realized by optical pulse shaping with a spatial light modulator (SLM), which always have higher coupling loss and more complicated structure due to the use of free-space optical devices [4]. Another method to generate a phase-coded signal is realized by optical spectral shaping followed by frequency-to-time mapping [5], [6]. The method can be used for arbitrary waveform generation, but the time duration and center frequency of the generated signals are not flexible, which limits its application. The phase-coded signals can also be generated by optical heterodyning with cascaded modulators, such as a dual polarization quadrature phase-keying modulator [7], a dual-parallel polarization modulator [8] or a dual-drive

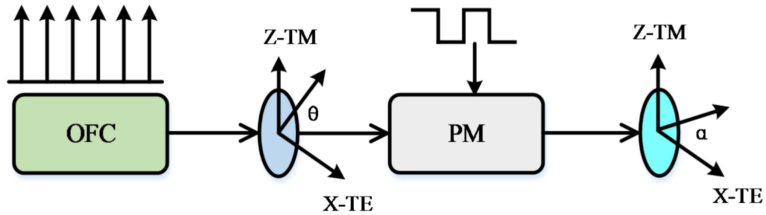


Fig. 1. Schematic diagram of the proposed photonic generation of MCPC microwave signals. OFC, optical frequency comb; PM, phase modulator.

Mach-Zehnder modulator [9]. However, these methods are difficult to control finely and increase the complexity of a transmitter.

The methods mentioned above are mostly designed for single carrier systems. Compared with these methods, multicarrier ones exhibit better performance in target detection and measurement, which can be used in synthetic aperture radar and MIMO radar [10]–[12]. The multicarrier phase-coded (MCPC) waveforms are invented and described by N. Levanon [13], [14]. One way to design an MCPC waveform is based on using an identical coded signal to modulate all carriers [15], [16]. In [17], P. Ghelfi *et al.* proposed a scheme to generate an MCPC microwave signal by modulating a phase-coded radio-frequency (RF) signal to the mode-locked laser modes. However, the time-bandwidth product is limited since the phase-coded signal is generated in the electrical domain. Another method to generate an MCPC microwave signal is realized by utilizing a modulator (polarization modulator or dual-output Mach-Zehnder modulator) together with an electronic balanced detector [18], [19]. However, these two methods suffer from bias drifting problem, which will reduce the stability of the system. Moreover, the coding phase of the generated signal is fixed at π, which will limit the phase coding pattern.

In this paper, a novel photonic approach to generate an MCPC microwave signal is proposed and experimentally demonstrated. Due to the different modulation coefficients in transverse-electric (TE) and transverse-magnetic (TM) modes of the $LiNbO_3$ modulator, by optimizing the angles between the TE and TM modes, an MCPC microwave signal can be generated. According to the theoretical analysis, the proposed scheme has a wide operation frequency range since no optical or electrical filters are used. The only limitation is the bandwidth of the PM and photodetector (PD). In the proof-of-concept experiment, 1.25 Gb/s phase-coded signals with the carrier frequencies of 5 GHz and 10 GHz are obtained.

2. Operation Principle of the Scheme

Fig. 1 shows the schematic diagram of the proposed photonic generation scheme of the MCPC microwave signals. A linearly polarized optical frequency comb (OFC) with the optical field of $E_0(t)$ is sent to a PM which is driven by the electrical coding signal $s(t)$. The polarization of OFC is aligned at an angle of 45° with respect to one principal axis of the PM, which excites two modes (i.e., TE and TM modes) with different modulation coefficients. The optical field at the output of the PM can be expressed as

$$\begin{bmatrix} E_x \\ E_z \end{bmatrix} = \frac{\sqrt{2}}{2} \begin{bmatrix} E_o(t) \exp\left(j\frac{\pi s(t)}{V_\pi^{TE}}\right) \\ E_o(t) \exp\left(j\frac{\pi s(t)}{V_\pi^{TM}}\right) \end{bmatrix} \tag{1}$$

$$E_o(t) = \sum_{k=0}^{n} A_k \exp\left(j\left(\omega_0 + k\Delta\omega\right)t\right) \tag{2}$$

where ω_0 is the angular frequency of the first line of the OFC, $\Delta\omega$ is the angular frequency interval of the OFC. k is the number of the comb lines. A_k is the amplitude of the k-th line. V_π^{TE} and V_π^{TM} are the half-wave voltage of the PM for TE and TM modes respectively. For LiNbO3 modulator, the ratio of V_π^{TE} and V_π^{TM} is approximately 3. Then the output signals are sent to a polarizer with its principal axis oriented at an angle of α to one principal axis of the PM. Consequently, the output of the polarizer can be expressed as

$$E(t) = \frac{\sqrt{2}}{2} E_o(t) \cos\alpha \exp\left(j\frac{\pi s(t)}{3V_\pi^{TM}}\right) + \frac{\sqrt{2}}{2} E_o(t) \sin\alpha \exp\left(j\frac{\pi s(t)}{V_\pi^{TM}}\right) \tag{3}$$

When the output signals are poured into a square-law PD, we can obtain

$$\begin{aligned} I(t) &\approx E(t) \cdot E^*(t) \\ &= \frac{1}{2}\sum_{k=0}^{n} A_k^2 + \cos\alpha \sin a \sum_{k=0}^{n} A_k^2 \cos\left(\frac{2\pi s(t)}{3V_\pi^{TM}}\right) \\ &\quad + \frac{1}{2}\sum_{k=1}^{n} B_k \cos(k\Delta\omega t) \\ &\quad + \cos\alpha \sin a \sum_{k=1}^{n} B_k \cos\left(k\Delta\omega t + \frac{2\pi s(t)}{3V_\pi^{TM}}\right) \end{aligned} \tag{4}$$

where $B_k = \sum_{i=0}^{n-k} A_i A_{i+k}$. When $\alpha = \pi/4$, we have

$$\begin{aligned} I(t) &\approx E(t) \cdot E^*(t) \\ &= \frac{1}{2}\sum_{k=0}^{n} A_k^2 + \frac{1}{2}\sum_{k=0}^{n} A_k^2 \cos\left(\frac{2\pi\phi(t)}{3V_\pi^{TM}}\right) \\ &\quad + \sum_{k=1}^{n} B_k \cos\left(\frac{\pi\phi(t)}{3V_\pi^{TM}}\right) \cos\left(k\Delta\omega t + \frac{\pi\phi(t)}{3V_\pi^{TM}}\right) \end{aligned} \tag{5}$$

It can be seen from Eq. (5), the first and second terms are the direct current and baseband signal respectively, which can be filtered out by employing a suitable digital electronic filter. After the filter, the signal can be expressed as

$$I(t) = \sum_{k=1}^{n} B_k \cos\left(\frac{\pi s(t)}{3V_\pi^{TM}}\right) \cos\left(k\Delta\omega t + \frac{\pi s(t)}{3V_\pi^{TM}}\right) \tag{6}$$

It can be seen that an MCPC microwave signal with the angular frequency of $k\Delta\omega$ and phase shift of $\pi s(t)/3V_\pi^{TM}$ is generated and the phase shift is proportional to the amplitude of the electrical coding signal *s(t)*. For example, if *s(t)* is a square or a N-step stair wave, a binary or a N-level polyphase phase-coded microwave signal with multi carrier frequencies can be obtained.

3. Experiment Results and Analysis

To verify the feasibility of the proposed approach, an experimental setup is built as shown in Fig. 2. For simplicity, the OFC with three spectral lines is generated through optical amplitude modulation. A laser source with the center wavelength of 1550.1 nm and power of 16 dBm is sent into a polarization modulator (PolM, Versawave, 40 Gb/s). The PolM is driven by a microwave signal with the frequency of 5 GHz and power of 10 dBm from a microwave signal generator (Anritsu, MS2840A). By adjusting the two polarization controllers (PC1 and PC2), three equal-amplitude spectral lines can be generated. The generated spectral lines are amplified by an erbium-doped fiber amplifier (EDFA, Amonics) and then injected into a PM (Pholine, MPZ-LN-10) driven by an

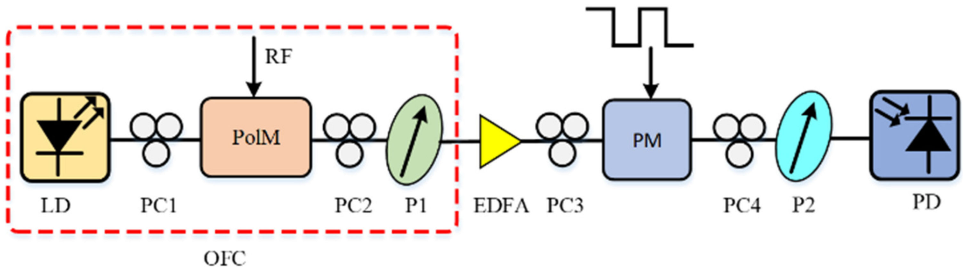


Fig. 2. Experimental setup of the proposed approach. LD, laser diode; PC, polarization controller; PolM, polarization modulator; RF, radio frequency; P, polarizer; OFC, optical frequency comb; EDFA, erbium-doped fiber amplifier; PM, phase modulator; PD, photodetector.

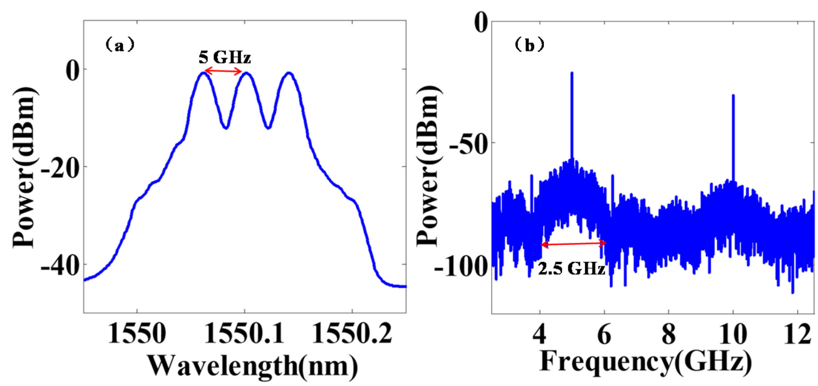


Fig. 3. (a) The optical spectrum at the output of the PolM. (b) The electrical spectrum of the simultaneously generated 5 GHz and 10 GHz phase-coded signal.

electrical coding signal generated by a pulse pattern generator (PPG, Anritsu, MT1810A). The PM has a bandwidth of 10 GHz and half-wave voltage of 4 V. The PC3 is used to adjust the polarization angle of the input lightwave before the PM. The PC4 followed by a polarizer is used to adjust the angle of the output signal and combine the TE and TM modes. Afterward the output optical signal is detected by a PD (Agilent 11982A) with the 3-dB bandwidth of 15 GHz. The optical spectra are captured by an optical spectrum analyzer (OSA, Yokogawa, AQ6370D) with the resolution of 0.02 nm, and the generated photocurrents are measured by an electrical spectrum analyzer (ESA) and a digital storage oscilloscope (LeCroy, WaveMaster 813Zi) with the bandwidth of 13 GHz and sampling rate of 40 GSa/s.

Fig. 3(a) shows the optical spectrum at the output of the PolM captured by an OSA. It can be seen that the generated three spectral lines have the same amplitude with the frequency interval of 5 GHz. After the PD, a phase-coded signal can be obtained. The electrical spectrum of the generated signal is shown in Fig. 3(b). Two microwave signals with the same bandwidth of 1.25 GHz at 5 GHz and 10 GHz can be observed respectively.

A 1.25 Gbit/s 16-bit binary coding signal with a fixed pattern of “1 1 1 0 1 0 0 0 1 0 0 1 1 1 1 0” generated by the PPG is applied to the PM. The peak to peak voltage of the binary coding signal *s(t)* is set to be 4 V. As the half-wave voltage of the PM for TM mode is 4 V, the phase shifts are calculated to be 60° according to Eq. (5). Fig. 4 shows the waveform of the measured MCPC microwave signal in the duration of 15.8 ns. The measured signals are filtered by digital bandpass filters with the bandwidth of 2.5 GHz centered at 5 GHz and 10 GHz respectively. Fig. 4(a) and (c) show the waveforms of the 5 GHz and 10 GHz phase-coded signal. Fig. 4(b) and (d) show the waveform of the extracted phase shift information based on coherent demodulation corresponding to Fig. 4(a) and (c). It can be seen that a phase shift (∼60°) is observed between bit “1” and bit “0”, which agrees well with the theoretical value. In order to investigate the pulse-compression capacity

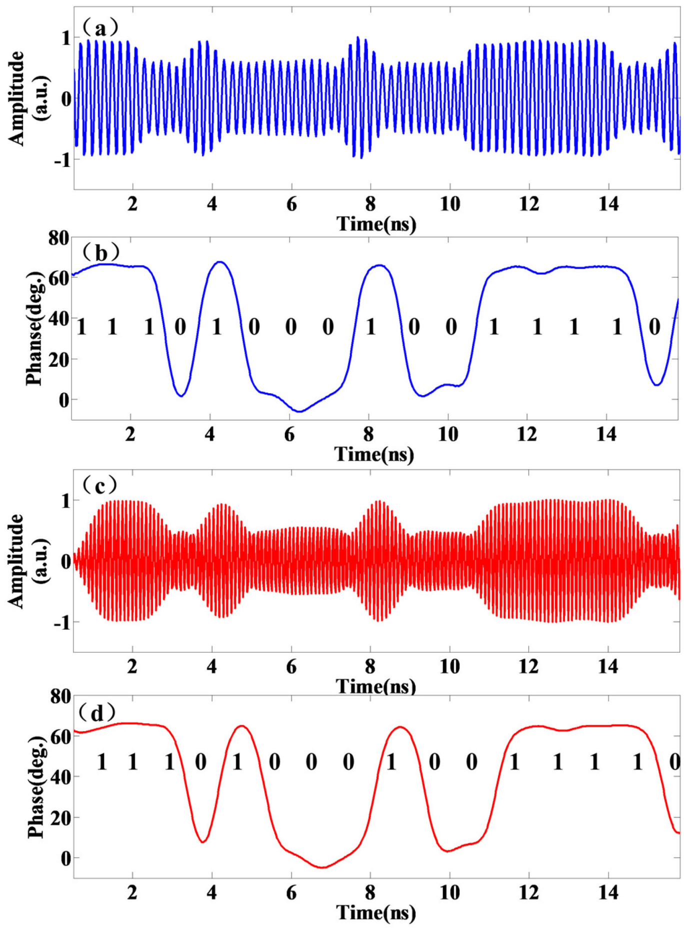


Fig. 4. (a) Waveform of the generated 5 GHz phase-coded signal, and (b) Extracted phase shift information from (a). (c) Waveform of the generated 10 GHz phase-coded signal, and (d) Extracted phase shift information from (c).

of the generated phase-coded signal, a matched filter whose frequency response is the complex conjugate of the received signal is designed. Through the filter, an autocorrelation is implemented to the received signal and the output is the inverse Fourier transform of the product of the signal spectrum $H(\omega)$ and the matched filter response $H^*(\omega)$, as shown in Fig. 5. The full width at half-maximum (FWHM) of the compressed pulse is 3.86 ns, and the time duration of the phase-coded signal is 15.8 ns. Thus a compression ratio of 4 is achieved after pulse compression.

Then, we increase the peak to peak voltage of the binary phase-coded signal up to 8 V, and the waveforms of the generated phase-coded signals and corresponding extracted phase shift information are shown in Fig. 6. By comparing the results with those in Fig. 4, it can be seen that the extracted phase shift between bit “1” and bit “0” are fluctuated near to 120°, which agrees well with the theoretical analyses. The pulse compression capacity is also investigated as shown in Fig. 7. The FWHM of the compression pulse is 0.66 ns, corresponding to a compression ratio of 24 which is 6 times than those in Fig. 5.

Finally, the phase shift of the generated MCPC microwave signal as a function of the peak to peak voltage of the binary phase-coded signal is shown in Fig. 8. It can be seen that the phase shift of the generated signal is directly proportional to the voltage of the modulated signal, which agrees well with the theoretical values.

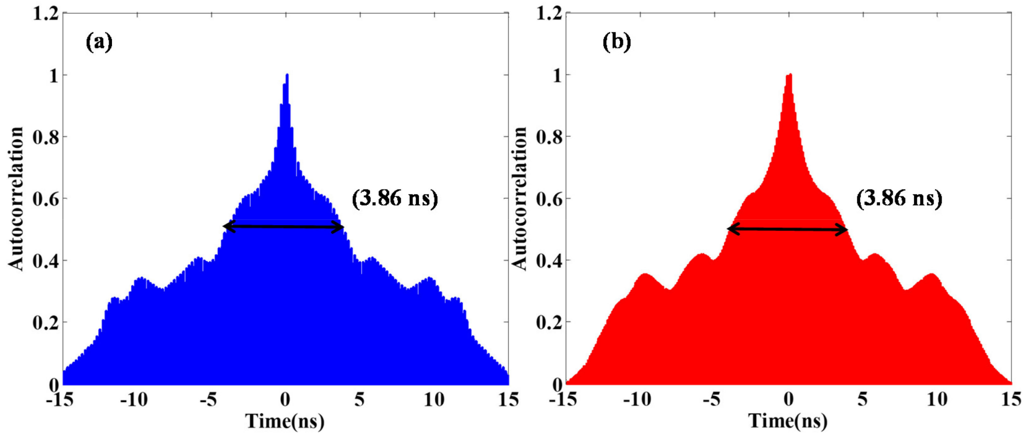


Fig. 5. Autocorrelation of the generated (a) 5 GHz phase-coded signal and (b) 10 GHz phase-coded signal.

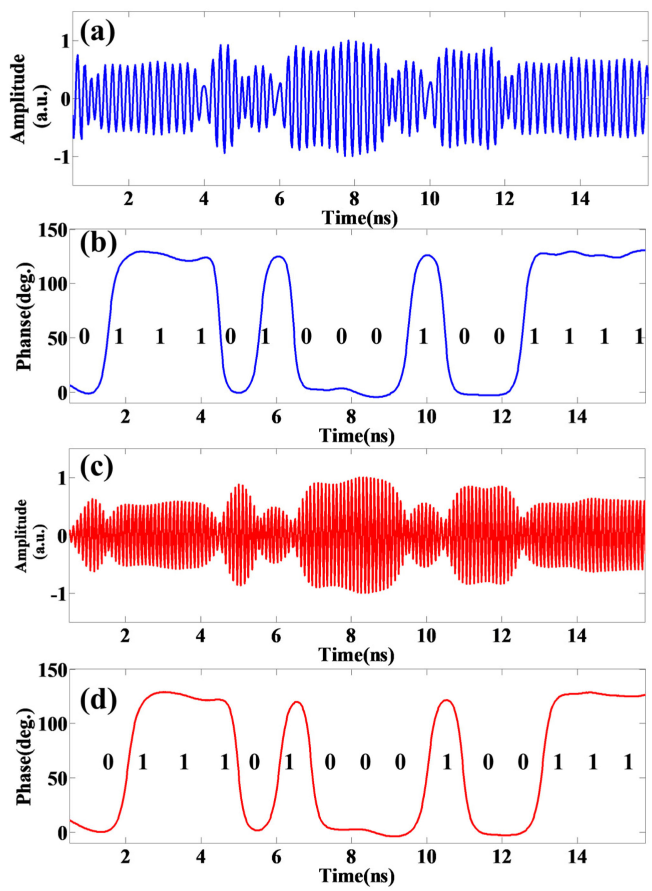


Fig. 6. (a) Waveform of the generated 5 GHz phase-coded signal, and (b) Extracted phase shift information from (a). (c) Waveform of the generated 10 GHz phase-coded signal, and (d) Extracted phase shift information from (c).

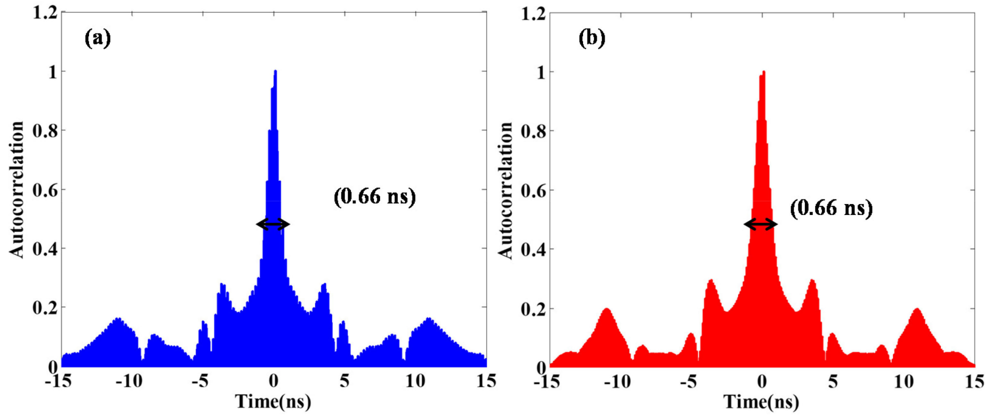


Fig. 7. Autocorrelation of the generated (a) 5 GHz phase-coded signal and (b) 10 GHz phase-coded signal.

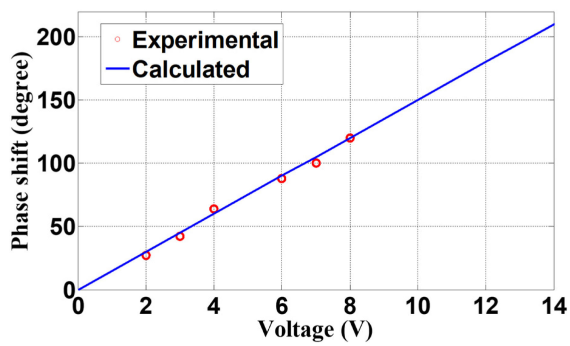


Fig. 8. Measured phase shift of the generated MCPC microwave signal.

4. Conclusion

In this paper, a method to generate an MCPC signal is theoretically analyzed and experimentally demonstrated. Theoretical analysis shows that the proposed scheme has a wide operation frequency range since no optical or electrical filters are used. The only limitation is the bandwidth of the PM and PD. Experimental results show that phase-coded signals at 5 GHz and 10 GHz with the coding rate of 1.25 Gb/s are generated. The system has a simple structure, which can be used in synthetic aperture radar and MIMO radar.

References

[1] M. I. Skolnik, *Introduction to radar*. New York, NY, USA: McGraw-Hill, 1962.
[2] M. Skolnik, "Role of radar in microwave," *IEEE Trans. Microw. Theory Techn.*, vol. 50, no. 3, pp. 625–632, Mar. 2002.
[3] J. P. Yao, "Microwave photonics," *J. Ligthw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.
[4] J. D. McKinney, D. E. Leaird, and A. M. Weineer, "Millimeter-wave arbitrary waveform generation with a direct space-to-time pulse shaper," *Opt. Lett.*, vol. 27, no. 15, pp. 1345–1347, Aug. 2002.
[5] J. Ye *et al.*, "Photonic generation of microwave phase-coded signals based on frequency-to-time conversion," *IEEE Photon. Technol. Lett.*, vol. 24, no. 17, pp. 1527–1529, Sep. 2012.
[6] F. Z. Zhang, X. Z. Ge, S. L. Pan, and J. P. Yao, "Photonic generation of pulsed microwave signals with tunable frequency and phase based on spectral-shaping and frequency-to-time mapping," *Opt. Lett.*, vol. 38, no. 20, pp. 4256–4259, Oct. 2013.
[7] Y. Chen, A. J. Wen, and W. Zhang, "Generation of phase-coded microwave signals through equivalent phase modulator," *Photon. Technol. Lett.*, vol. 29, no. 16, pp. 1371–1374, Aug. 2017.
[8] S. F. Liu, D. Zhu, Z. W. Wei, and S. L. Pan, "Photonic generation of widely tunable phase-coded microwave signals based on a dual-parallel polarization modulator," *Opt. Lett.*, vol. 39, no. 13, pp. 3958–3961, Jul. 2014.

[9] Z. Z. Tang, T. T. Tang, F. Z. Zhang, and S. L. Pan, "Photonic generation of a phase-coded microwave signal based on a single dual-drive Mach-Zehnder modulator," *Opt. Lett.*, vol. 38, no. 24, pp. 5365–5368, Dec. 2013.
[10] N. Prasad, V. Shameem, U. Desai, and S. Merchant, "Improvement in target detection performance of pulse coded Doppler radar based on multicarrier modulation with fast fourier transform (fft)," *IEE Proc. Radar, Sonar Navigation*, vol. 151, no. 1, pp. 11–17, Feb. 2004.
[11] M. Mahmood and M. Bell, "Non-linear processing for multicarrier mimo radar for improved target resolution," in *Conf. Rec. 46th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2012, pp. 1317–1322.
[12] G. Qin, B. Chen, and D. Chen, "A new method for velocity estimation in multicarrier frequency MIMO radar," in *Proc. IET Int. Radar Conf.*, Apr. 2009, pp. 1–4.
[13] N. Levanon, "Multifrequency radar signals," in *Proc. IEEE Int. Radar Conf.*, May 2000, pp. 683–688.
[14] N. Levanon, "Multifrequency complementary phase-coded radar signal," *IEE Proc., Radar, Sonar Navigation*, vol. 147, no. 6, pp. 276–284, 2000.
[15] E. Mozeson and N. Levanon, "Multicarrier radar signals with low peak-to-mean envelope power ratio," *IEE Proc., Radar, Sonar Navigation*, vol. 150, no. 2, pp. 71–77, 2003.
[16] Q. C. Xu, Z. J. Yang, and X. Hu, "Phase coded interrupted CW signals and processors," *IEEE Trans. Aerospace Electrical Syst.*, vol. 45, no. 1, pp. 209–220, 2009.
[17] P. Ghelfi, F. Scotti, F. Laghezza, and A. Bogoni, "Phase coding of RF pulses in photonic-aided frequency-agile coherent radar systems," *IEEE J. Quantum Electron.*, vol. 48, no. 9, pp. 1151–1156, Sep. 2012.
[18] D. Zhu, W. Y. Xu, Z. W. Wei, and S. L. Pan, "Multi-frequency phase-coded microwave signal generation based on polarization modulation and balanced detection," *Opt. Lett.*, vol. 41, no. 1, pp. 107–110, Jan. 2016.
[19] D. Wu *et al.*, "Photonic generation of multi-frequency phase-coded microwave signal based on a dual-output Mach-Zehnder modulator and balanced detection," *Opt. Exp.*, vol. 25, no. 13, pp. 14516–14523. Jun. 2017.