Photonic Generation of Tunable Frequency-Multiplied Phase-Coded Microwave Waveforms

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***Abstract*— A novel photonic approach to generate frequency-multiplied phase-coded microwave waveforms with large frequency tunability is proposed and experimentally demonstrated. By using a dual-drive Mach–Zehnder modulator, biased at specially designed bias point, and a single-port photodetector, phase-coded microwave waveforms at the doubled or tripled frequency of the applied microwave reference signal are generated, with a large frequency tunable range limited by the bandwidth of the dual-drive Mach–Zehnder modulator. The proposed technique is experimentally verified. Phase-coded microwave waveforms at the doubled frequency from 16 to 30 GHz and the tripled frequency from 21 to 30 GHz are generated. The pulse compression performance of the generated phase-coded microwave waveforms is also studied.**

***Index Terms*— Microwave photonics, phase coding, frequency multiplication, pulse compression.**

I. INTRODUCTION

PHOTONIC generation of microwave arbitrary waveforms has been a topic of interest in the past few years [1], [2]. Numerous photonic approaches [3]–[6] have been proposed to generate microwave signals, radar pulse compression signals, microwave triangular or square waveforms, etc., to overcome the limited frequency and bandwidth of the generated waveforms associated with the well-known electronic bottleneck in electrical generation methods, taking the unique advantages, such as low loss, high frequency, large bandwidth, immunity to electromagnetic interferences, offered by photonics.

Among these different kinds of microwave waveforms, phase-coded microwave waveform is widely used in pulse compression radar system due to its easy generation and good pulse compression capability [7]. Phase-coded microwave waveforms can be generated using free-space optics, which has great reconfigurability but is lossy and bulky [8]. Pure fiber based approaches are proposed to avoid the transmission of signals in free space. One method is based on optical spectral shaping and frequency-to-time mapping [9]. However, the limited time duration of the generated waveform limits its application. Optical external modulation is an effective solution to generate phase-coded microwave waveforms with long time duration and easy implementation [4], [10]–[12]. With the rapid development of radar system, phase-coded microwave waveforms are desired to be generated in even higher frequency band to fulfill the latest applications, so photonic frequency-multiplied phase-coded microwave waveform generation methods are researched and demonstrated [13]–[15]. However, the method in [13] can only generate frequency-doubled phase-coded microwave waveforms, although the structure is mainly based on a simple polarization modulator. Moreover, the small frequency multiplication factor limits its applications. The methods in [14] and [15] can achieve relatively larger frequency multiplication factors up to 4 or 8, but the structures of the systems are relatively complicated, both employing a dual-polarization quadrature phase-shift-keying (DP-QPSK) modulator, or even more electrical and optical devices. To simplify the structure and reduce the cost of the frequency-multiplied phase-coded microwave waveform generation system, novel methods are urgently needed.

In this letter, a novel photonic approach to generate frequency-multiplied phase-coded microwave waveforms with large frequency tunability is proposed and experimentally demonstrated mainly based on a simple dual-drive Mach-Zehnder modulator (DD-MZM), thus the overall system is simplified and less costly as compared with the generator in [14] and [15]. In addition, the frequency multiplication factor of the proposed system can be 2 to 4 in theory, which is the same as that of the generator in [15] and larger than that of the generator in [13]. The proposed technique is experimentally evaluated. Frequency-doubled phase-coded microwave waveforms at 16 or 30 GHz, and frequency-tripled phase-coded microwave waveforms at 21 or 30 GHz are generated and demonstrated.

II. PRINCIPLE OF OPERATION

Fig. 1 shows the schematic diagram of the proposed frequency-multiplied phase-coded microwave signal generation scheme. A continuous-wave (CW) light wave from a laser diode (LD) is sent to a DD-MZM, in which the light wave is split into two paths, modulated by a microwave signal from

Manuscript received January 11, 2018; revised May 17, 2018; accepted May 21, 2018. Date of publication May 25, 2018; date of current version June 12, 2018. This work was supported in part by the National Natural Science Foundation of China under Grant 61601297 and Grant 61422108, in part by the Open Fund of IPOC, BUPT, and in part by the Fundamental Research Funds for Central Universities. *(Corresponding author: Yang Chen.)*

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Digital Object Identifier 10.1109/LPT.2018.2840479

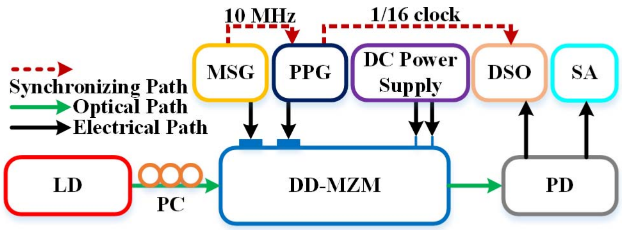

Fig. 1. Schematic diagram of the proposed frequency-multiplied phase-coded microwave signal generation scheme. LD, laser diode; DD-MZM, dual-drive Mach-Zehnder modulator; MSG, microwave signal generator; PPG, pulse patter generator; PD, photodetector; DSO, digital sampling oscilloscope; SA, signal analyzer.

a microwave signal generator (MSG) and a binary coding signal from a pulse pattern generator (PPG), respectively, and then combined again via a 3-dB coupler. The MSG and the PPG are synchronized together using a 10-MHz signal. The optical signal at the output DD-MZM is converted to a photocurrent at a photodetector (PD). The spectra of the photocurrent are measured by a signal analyzer (SA), and corresponding waveforms are recorded by a digital sampling oscilloscope (DSO). The DSO is triggered by a clock from the PPG to be synchronized with the MSG and the PPG.

The optical signal at the output of DD-MZM is

$$E(t) = E_{in}(t)\cos(\delta\cos(\omega_{RF}t) - \kappa S(t) - \varphi)\exp(j\phi(t)), \quad (1)$$

where $E_{in}(t)$ represents the input optical signal, $\delta = \pi V_{RF}/2V_\pi$ is the modulation index, $\kappa = \pi V_{Code}/2V_\pi$, $\varphi = \pi V_{DC}/2V_\pi$, V_π is the half-wave voltage of the DD-MZM, V_{RF} and ω_{RF} are the amplitude and angular frequency of the applied microwave signal, V_{Code} is the amplitude of the binary coding signal $S(t)$, V_{DC} is the DC bias voltage, and $\phi(t)$ is the phase modulation term introduced in the DD-MZM. When the optical signal is beaten at the PD, a photocurrent is generated, which can be expressed as

$$\begin{aligned} i(t) &\propto \cos^2(\delta\cos(\omega_{RF}t) - \kappa S(t) - \varphi) \\ &= \frac{1}{2} + \frac{1}{2}\cos(2\delta\cos(\omega_{RF}t) - 2\kappa S(t) - 2\varphi). \end{aligned} \quad (2)$$

When $\kappa = \pi/4$, $S(t)$ is a bipolar $(-1, 1)$ binary sequence, and the DD-MZM is biased at the maximum transmission point, i.e., $\varphi = 0$, the second term in (2) can be simplified as

$$\begin{aligned} i_1(t) &\propto \cos(2\delta\cos(\omega_{RF}t) - 2\kappa S(t)) \\ &= S(t)\sin(2\delta\cos(\omega_{RF}t)) \\ &\approx 2S(t)J_1(\delta)\cos(\omega_{RF}t) - 2S(t)J_3(\delta)\cos(3\omega_{RF}t). \end{aligned} \quad (3)$$

Phase-code microwave waveforms at the fundamental and tripled frequencies are generated. If the modulation index δ is selected to make $J_1(\delta) = 0$ establish, i.e., $\delta = 3.83$, the first term in (3) is completely suppressed, so that a frequency-tripled phase-coded microwave waveform at $3\omega_{RF}$ is generated.

When $\kappa = \pi/4$, $S(t)$ is a bipolar $(-1, 1)$ binary sequence, and the DD-MZM is biased at the quadrature transmission point, i.e., $\varphi = \pi/4$, the second term in (2) can be simplified as

$$\begin{aligned} i_2(t) &\propto \sin(2\delta\cos(\omega_{RF}t) - 2\kappa S(t)) \\ &= -S(t)\cos(2\delta\cos(\omega_{RF}t)) \\ &\approx -S(t)J_0(\delta) + 2S(t)J_2(\delta)\cos(2\omega_{RF}t) \\ &\quad - 2S(t)J_4(\delta)\cos(4\omega_{RF}t) \end{aligned} \quad (4)$$

Phase-code microwave waveforms at the doubled and quadrupled frequencies besides a baseband modulation component are generated. If small signal modulation condition ($\delta \ll 1$) is used, the frequency-quadrupled component can be ignored due to the characteristics of Bessel functions, so a frequency-doubled phase-coded microwave waveform is generated. If the modulation index δ is selected to make $J_2(\delta) = 0$ establish, i.e., $\delta = 5.13$, the second term in (4) is completely suppressed, thus a frequency-quadrupled phase-coded microwave waveform at $4\omega_{RF}$ is generated.

III. Experimental Results

An experiment is performed based on the setup shown in Fig.1. A 16-dBm CW light wave from the LD (Teraxion NLL) is sent to a DD-MZM (Fujitsu FTM 7937EZ) with a bandwidth of about 35 GHz via a PC. The microwave signal from the MSG (Agilent E8257D) is injected to one RF port of the DD-MZM, whereas the bipolar binary coding signal from the PPG (Anritsu MP1763C) is sent to the other RF port of the DD-MZM after being amplified by an electrical amplifier. The modulated optical signal from the DD-MZM is beaten at the PD (u2t) with a bandwidth of 40 GHz.

First, the generation of a 16-GHz frequency-doubled phase-coded microwave waveform from an 8-GHz microwave signal is demonstrated. The binary coding signal is a 1.6-Gbps 64-bit binary sequence with the pattern of "11011001110110100111 101111101010000110100011000111011000101011".

Fig. 2 (a) shows the electrical spectrum of the generated 16-GHz frequency-doubled phase-coded microwave waveform

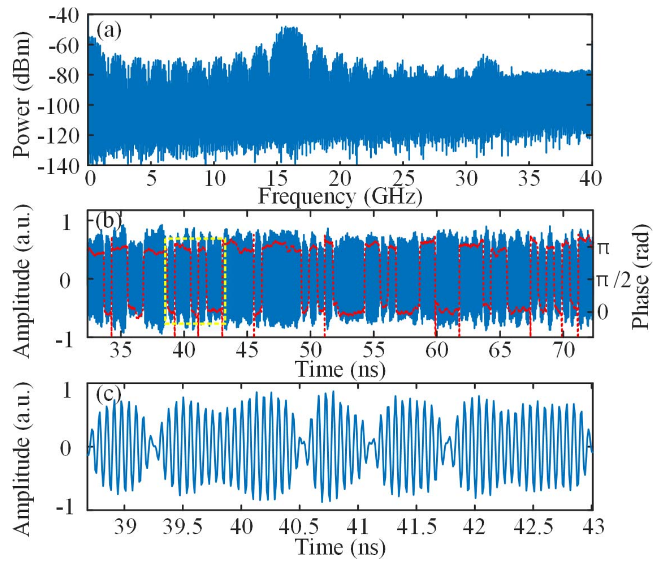

Fig. 2. (a) Electrical spectrum, and (b) temporal waveform (in blue solid line) and recovery phase information (in red dotted line) of the generated 16-GHz frequency-doubled phase-coded microwave waveform. (c) A section of the generated waveform outlined in yellow dotted line in (b).

measured by an SA (Keysight N9010A). The spectrum shows good consistency with the analysis in (4). A baseband modulation product, a frequency-doubled component and a frequency-quadrupled component are generated. Since the baseband modulation product cannot be radiated due to the band-pass characteristic of the radar transmit antenna, it can be ignored. We also find some sidelobes of the baseband signal, which have much lower power compared with the mainlobe. Therefore, the influence from the sidelobes is very small. In addition, the sidelobes can be further suppressed using electrical low-pass filter to reshape the spectrum of the binary baseband data. The frequency-quadrupled component is 20 dB lower than the desired frequency-doubled component because we use a low modulation index, so the desired frequency-doubled component is in dominant. Fig. 2 (b) shows a period of the generated 64-bit 16-GHz phase-coded microwave waveform captured by the DSO (Agilent DCA-J 86100C), which has an electrical bandwidth of more than 80 GHz. The red dotted line shows the recovered phase information from the waveform using Hilbert transform, which is in consistent with the binary sequence. Fig. 2 (c) shows a section of the generated waveform outlined in yellow dotted line in Fig. 2 (b), where approximate π phase jumps between adjacent “0” and “1” can be clearly observed.

To show the frequency tunability, the generation of 30-GHz phase-coded microwave waveform using a 15-GHz microwave signal is studied. The data rate of the binary coding signal is 3 Gbps. Fig. 3 (a) shows the spectrum of the generated 30-GHz microwave waveform. The fundamental frequency component at 15 GHz is suppressed. A period of the generated 30-GHz phase-coded microwave waveform and the recovery phase information are shown in Fig. 3 (b). The recovered phase information is also in consistent with the binary sequence. The waveform outlined in yellow dotted line is shown in Fig. 3 (c), where approximate π phase jumps are observed.

Pulse compression capability of the generated waveforms is also studied, which is shown in Fig. 4, where compressed pulses are obtained. For the 16-GHz waveform, the peak-to-sidelobe ratio (PSR) is about 7.58 dB, and the full width at half-maximum (FWHM) of the autocorrelation peak is about 0.65 ns, which corresponds to a pulse compression ratio (PCR) of about 61.5. The PSR and PCR of the 30-GHz waveform are 7.91 dB and 61.0, respectively.

Then, frequency-tripled phase-coded microwave waveform generation is demonstrated. Fig. 5 (a) shows the spectrum of the generated 21-GHz frequency-tripled phase-coded microwave waveform with a data rate of 2.1 Gbps. As predicted in the theory, only a frequency-tripled component is generated, and the baseband, fundamental, frequency-doubled and higher frequency components are well suppressed. Fig. 5 (b) shows a section of the generated waveform and the corresponding recovered phase information, where π phase jumps between adjacent “0” and “1” can be clearly observed.

The frequency of the microwave signal is increased to 10 GHz to verify the frequency tunability of the frequency-tripled phase-coded microwave waveform generation. Fig. 6(a) shows the spectrum of the 30-GHz phase-coded microwave waveform. Different from the spectrum in Fig. 3 (a), no

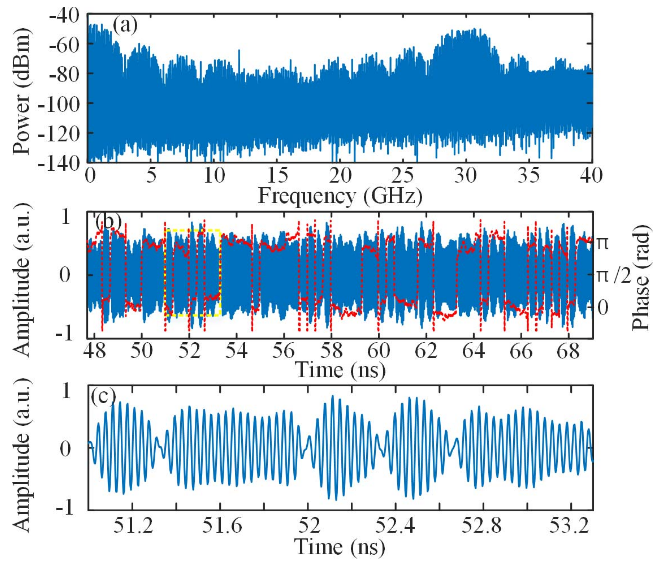

Fig. 3. (a) Electrical spectrum, and (b) temporal waveform (in blue solid line) and recovery phase information (in red dotted line) of the generated 30-GHz frequency-doubled phase-coded microwave waveform. (c) A section of the generated waveform outlined in yellow dotted line in (b).

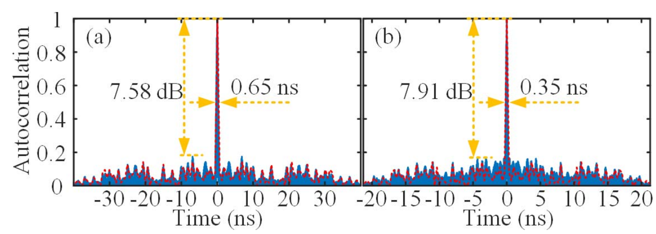

Fig. 4. Pulse compression performance of the generated frequency-doubled phase-coded microwave waveform at (a) 16 GHz, (b) 30 GHz. The red dotted lines show the autocorrelation of the binary coding signal.

baseband modulation product is observed, which is consistent with the theory. Fig. 6(b) shows a section of the generated waveform and the corresponding recovered phase information. Approximate π phase shift has been restored from the waveform.

Pulse compression capability of the generated 21 and 30-GHz phase-coded microwave waveforms are also demonstrated, which is shown in Fig. 7. Compressed narrow pulses are obtained. The PSR for the 21-GHz phase-coded microwave waveform is about 8.38 dB, and the PCR is about 60.1. The PSR and PCR for the 30-GHz phase-coded microwave waveform are about 8.01 dB and 62.7, respectively.

IV. Discussion

In the theoretical analysis, it is shown that high modulation indices are needed for the generation of frequency-tripled and frequency-quadrupled phase-coded microwave signal. The Fujitsu FTM 7937EZ has a half-wave voltage of 1.8 V, which means the required voltages of the microwave signal are 4.01 V and 5.88 V for the frequency-tripled and frequency-quadrupled phase-coded microwave signal generation, respectively. The allowable microwave amplitude to the DD-MZM is 5 V, so frequency-quadrupled phase-coded microwave waveform generation is not experimentally demonstrated to avoid damaging the modulator. DD-MZM with lower half-wave voltage is expected to be fabricated, or integrated by integrated

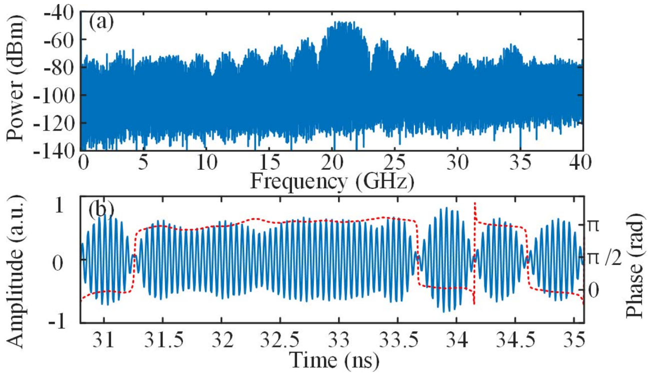

Fig. 5. (a) Electrical spectrum, and (b) a section of the temporal waveform (in blue solid line) and the corresponding recovery phase information (in red dotted line) of the generated 21-GHz frequency-tripled phase-coded microwave waveform.

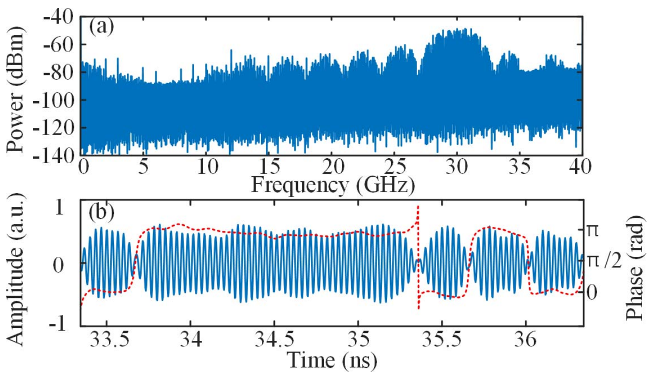

Fig. 6. (a) Electrical spectrum, and (b) a section of the temporal waveform (in blue solid line) and the corresponding recovery phase information (in red dotted line) of the generated 30-GHz frequency-tripled phase-coded microwave waveform.

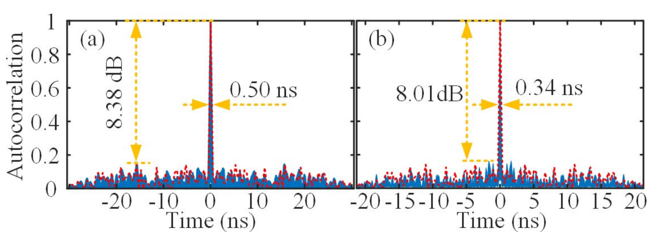

Fig. 7. Pulse compression performance of the generated frequency-tripled phase-coded microwave waveform at (a) 21 GHz, (b) 30 GHz. The red dotted lines show the autocorrelation of the binary coding signal.

photonics, so that not only high frequency multiplication factor can be achieved, but also the power consumption of the system can be reduced.

The frequency tunable range of the proposed technique is only limited by the bandwidths of the DD-MZM and the PD. By employing a DD-MZM with 35-GHz bandwidth and a PD with enough corresponding bandwidth, the frequency of the generated phase-coded microwave waveform can be as high as 105 GHz by frequency tripling. The frequency tunability of the system is demonstrated in the experiment using four specific cases. Over the entire tunable range, the performance of the waveforms does not have obvious changes. Although electronic techniques can also realize radar signal generation up to 100 GHz, the operating bandwidth is still limited to several GHz. The large frequency tunable range provided in this letter is the key advantage of the photonic method compared with the traditional electronic method, which will promote the development of multi-function and multi-band radar systems.

The proposed system employs a simple DD-MZM, which has much simpler system structure compared with the DP-QPSK modulator based frequency-multiplied phase-coded microwave waveform generator in [15], but also realize high frequency multiplication factor. Since only one DC bias voltage is needed in a DD-MZM, the bias control of the system is simplified, and the stability of the system is high.

V. Conclusion

In conclusion, a photonic approach to generate frequency-multiplied phase-coded microwave waveform with π phase shift is proposed and experimentally demonstrated. The key contribution of the work is that high frequency phase-coded microwave waveforms can be generated by employing frequency multiplication factors from 2 to 4. An experiment is performed to verify the frequency-doubled and frequency-tripled phase-coded microwave waveform generation. A 16 or 30-GHz waveform is generated based on frequency doubling, and a 21 or 30-GHz waveform is generated based on frequency tripling. The phase recovery and pulse compression capability of the generated waveforms are also studied.

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