Photonic Generation of Frequency Tunable Binary Phase-Coded Microwave Waveforms

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***Abstract*— A novel photonic approach to generating a precisely π phase-shifted binary phase-coded microwave waveform with ultra-wide frequency tunable range is proposed and experimentally demonstrated. In the proposed system, a polarization modulator (PolM) functions in conjunction with a polarization controller (PC) and an optical polarizer (Pol) as an equivalent Mach–Zehnder modulator (MZM) with the bias point switchable by applying a binary-coding signal to the PolM. To generate a phase-coded microwave signal at a specific microwave frequency, the binary-coding signal is combined with a microwave signal at that frequency and applied to the PolM. By switching between the two quadrature transmission points or the maximum and the minimum transmission points, a phase-coded microwave waveform at the fundamental or doubled frequency is generated. The proposed technique is experimentally evaluated. A phase-coded microwave waveform at the fundamental and doubled frequency is generated. The tunability of the approach is also experimentally demonstrated.**

***Index Terms*— Microwave phase coding, frequency doubling, microwave photonics, radar pulse compression.**

I. Introduction

IN MODERN radar systems, pulse compression has been widely employed to increase the range resolution and improve the signal-to-noise ratio (SNR) [1]. Usually, microwave pulse compression is implemented in a radar receiver by sending a large time-bandwidth product (TBWP) microwave waveform, such as a frequency-chirped or a phase-coded microwave waveform, to a matched filter. Conventionally, a frequency-chirped or a phase-coded microwave waveform is generated in the electrical domain using an electronic circuit. However, the limited speed makes the generated waveform have a small TBWP, leading to pulse compression with a small compression ratio. Thanks to the large bandwidth and high speed offered by modern photonics, the generation of a frequency-chirped [2]–[5] or phase-coded [6]–[11] microwave waveform in the optical domain has been a topic of interest, and numerous techniques have been proposed and demonstrated. A phase-coded microwave waveform can be generated based on optical pulse shaping using a spatial light modulator (SLM) [6]. The key advantage of employing an SLM is its high flexibility, which enables the generation of real-time updatable arbitrary microwave waveforms. Since free-space optics is involved, however, the system is usually bulky and with a high loss. A phase-coded microwave waveform can also be generated based on pure fiber optics [7]–[11]. For example, in [7] a phase-coded microwave waveform is generated using all-fiber components. In the system, an ultrashort pulse is broadened and chirped by passing it through a dispersive element, which is then sent to a Mach-Zehnder interferometer (MZI) to get two time-delayed chirped pulses. By beating the time-delayed chirped pulses at a photodetector (PD), a microwave waveform with its frequency determined by the time delay difference is generated. The generated microwave pulse is then phase coded by an encoding signal applied to a phase modulator (PM) that is incorporated in one arm of the MZI. The MZI in [7] could be replaced by a Sagnac interferometer (SI) to make the system have better stability. A phase-coded microwave waveform can also be generated using a polarization modulator (PolM) without using an MZI or an SI [8]. By applying the two sidebands from a carrier-suppressed double-sideband-modulated signal to the PolM through a length of polarization maintaining fiber (PMF) to make the two sidebands orthogonally polarized, two complementarily phase-modulated optical signals are generated. The beating of the two signals at a PD will generate a phase-coded microwave signal. The major limitation of the technique in [8] is that the orthogonal polarization of the two sidebands by the PMF is frequency dependent, thus the microwave carrier frequency is not tunable. To generate a frequency tunable phase-coded microwave waveform, the PMF in [8] was replaced by a polarization-maintaining fiber Bragg grating (PM-FBG) [9]. A frequency-tunable signal from 40 to 50 GHz was generated. A similar technique to generate a phase-coded microwave signal using a PM-FBG with a precise π phase shift was also demonstrated [10]. Note that the frequency tunable range in [9]–[10] was limited by the bandwidths of the two orthogonal passbands of the PM-FBG. To further increase the tunable range, a phase coding system based on two PolMs without using any optical filters was recently proposed [11]. A phase-coded microwave waveform with a frequency tunable range as large as 30 GHz was generated. Since two PolMs are needed, the system is relatively more costly.

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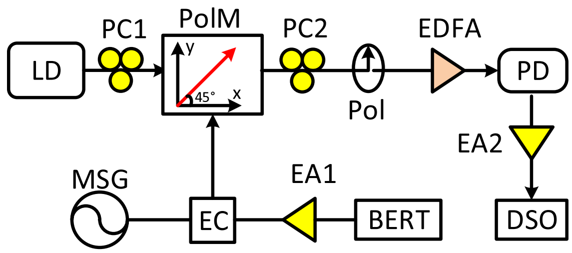

Fig. 1. Schematic of the proposed phase-coded microwave waveform generation system. LD, laser diode; PC, polarization controller; PolM, polarization modulator; Pol, polarizer; PD, photodetector; EDFA, erbium-doped fiber amplifier; MSG, microwave signal generator; EA, electrical amplifier; DSO, digital sampling oscilloscope; BERT, bit error rate tester; EC, electrical coupler.

In this letter, we propose and experimentally demonstrate a photonic technique to generate a precisely π phase-shifted binary phase-coded microwave waveform with ultra-wide frequency tunable range using only a single PolM, thus the overall system is simplified and less costly as compared with the generator in [11]. The key component in the system is the PolM, which functions in conjunction with a polarization controller (PC) and an optical polarizer (Pol) as an equivalent Mach-Zehnder modulator (MZM) with the bias point switchable by applying a binary-coding signal to the PolM. By switching between the two quadrature transmission points in the complementary slopes or the maximum and the minimum transmission points, a phase-coded microwave waveform at the fundamental or doubled frequency is generated. The proposed technique is experimentally evaluated. A phase-coded microwave waveform at the fundamental and doubled frequency with a frequency tunable range from 4 to 24 GHz is generated.

II. Principle of Operation

The schematic diagram of the proposed phase-coded microwave waveform generation system is shown in Fig. 1. A light wave generated from a laser diode (LD) is sent to a PolM. The polarization direction of the light wave is adjusted by PC1 to have an angle of 45° relative to one principal axis of the PolM. A binary-coding signal from a bit error tester (BERT) is amplified by an electrical amplifier (EA1) and then combined with a microwave signal from a microwave signal generator (MSG) using an electrical coupler (EC). The signal at the output of the EC is sent to the PolM via the RF port. The PolM is operating with a second PC (PC2) and a Pol as an equivalent MZM. The optical signal at the output of the equivalent MZM is amplified by an erbium-doped fiber amplifier (EDFA) before being detected by a PD.

The normalized optical field at the output of the PolM along the principal axes (x and y) can be expressed as

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \frac{\sqrt{2}}{2} E_0 \begin{bmatrix} \exp\left(j\omega_c t + j\pi V(t)/V_\pi\right) \\ \exp\left(j\omega_c t - j\pi V(t)/V_\pi\right) \end{bmatrix} \quad (1)$$

where E_0 and ω_c are the amplitude and the angular frequency of the optical carrier, V_π is the half-wave voltage of the PolM, and $V(t)$ is the electrical signal applied to the PolM. Applying the two signals to the Pol with its principal axis oriented at an angle of 45° to one principal axis of the PolM, we have

$$E(t) = \frac{\sqrt{2}}{2}\left[E_x(t) + E_y(t)\, e^{-j\theta_0}\right] \quad (2)$$

where θ_0 is the static phase term introduced by PC2. As can be seen, the expression in (2) is equivalent to that of an optical signal at the output of an MZM [12]. Applying the optical signal to the PD, we have the photocurrent at the output of the PD, given by

$$i(t) = R\,|E(t)|^2 = 0.5RE_0^2\left\{1 + \cos\left[2\pi V(t)/V_\pi + \theta_0\right]\right\} \quad (3)$$

where R is the responsivity of the PD.

Assume that the static phase term θ_0 introduced by PC2 is 0, and the electrical signal applied to the PolM consists of a microwave carrier and a phase-coding signal, given by $V(t) = V_0 \sin(\omega_s t) + V_1 s(t)$, where ω_s and V_0 are the angular frequency and the amplitude of the microwave carrier, and V_1 is the amplitude of the binary-coding signal $s(t)$, the photocurrent at the output of the PD can be further written as

$$i(t) = 0.5RE_0^2\left\{1 + \cos\left[2m_0 \sin(\omega_s t) + 2\pi V_1 s(t)/V_\pi\right]\right\} \quad (4)$$

where $m_0 = \pi V_0/V_\pi$ is the modulation index.

First, we assume that the binary-coding signal $s(t)$ has two levels of -1 and $+1$. V_1 should be $V_\pi/4$ to switch the bias points between the two quadrature transmission points in the two complementary slopes. Under small signal modulation condition, the signal at the output of the PD can be written as

$$i(t) = \begin{cases} 0.5RE_0^2\left[1 - 2J_1(2m_0)\sin(\omega_s t)\right] & s(t) = 1 \\ 0.5\,RE_0^2\left[1 + 2J_1(2m_0)\sin(\omega_s t)\right] & s(t) = -1 \end{cases} \quad (5)$$

where $J(\cdot)$ is the n-th order Bessel function of the first kind. Note that for small signal modulation, $m_0 \ll 1$, the sidebands higher than first order are very small and are ignored. It is clearly seen that a microwave signal at ω_s is generated with a precise π phase difference for the binary-coding signal at the levels of $+1$ and -1. A phase-coded microwave waveform at the fundamental frequency is thus generated.

Then, we assume that the binary-coding signal $s(t)$ has two levels of 0 and $+1$. V_1 should be $V_\pi/2$, to switch the bias points between the maximum and the minimum transmission points. The signal at the output of the PD is given by

$$i = \begin{cases} 0.5RE_0^2\left[1 + J_0(2m_0) + 2J_2(2m_0)\cos(2\omega_s t)\right] & s(t)=0 \\ 0.5RE_0^2\left[1 - J_0(2m_0) - 2J_2(2m_0)\cos(2\omega_s t)\right] & s(t)=1. \end{cases} \quad (6)$$

Again, small signal modulation is considered in the derivation. It is seen that a frequency-doubled microwave signal at $2\omega_s$ is generated with a precise π phase difference for binary-coding signal at the levels of 0 and 1. Thus, a phase-coded microwave waveform at a doubled frequency is generated. It is also noticed that the DC components are different for the binary-coding signal at the levels of 0 and 1, which leads to a baseband modulation. Considering that the baseband component cannot be radiated to free space due to the bandpass nature of the transmitting antenna, the baseband modulation has no impact on the phase-coded microwave signal.

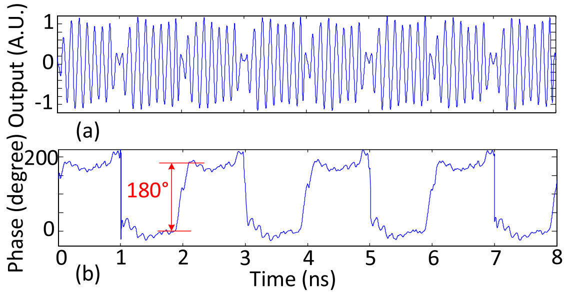

Fig. 2. (a) Generated 8-GHz phase-coded microwave waveform from an 8-GHz microwave signal. (b) The recovered phase information from (a).

III. Experiment and Discussion

An experiment based on the configuration shown in Fig. 1 is carried out. A light wave at 1550 nm from the LD (Anritsu MG9638A) is sent to the PolM via PC1. The PolM (Versawave) have a 3-dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. The optical signal at the output of the PolM is sent to the Pol through PC2. The optical signal at the output of the Pol is amplified by the EDFA before it is injected into the PD (New Focus, 25 GHz) for optical-to-electrical conversion. An electrical amplifier, EA2, is used to amplify the electrical signal at the output of the PD, and the waveform at the output of EA2 is monitored by the DSO (Agilent DSO-X 93204A). To perform phase coding, a binary phase-coding signal is generated by the BERT (Agilent N4901B), and amplified by EA1 before sending to the EC to combine with a sinusoidal microwave signal generated by the MSG (Agilent E8254A) as the microwave carrier. The signal at the output of the EC is applied to the PolM via the RF port.

First, a phase-coded microwave signal at 8 GHz generated from an 8-GHz microwave source to demonstrate the generation of a fundamental microwave phase-coded signal is performed. Fig. 2(a) shows the generated 8-GHz phase-coded microwave waveform. The phase-coding signal is a "0101" digital sequence at a data rate of 1 Gb/s generated by the BERT. Fig. 2(b) shows the phase information recovered from the phase-coded waveform using Hilbert transform. As can be seen, the phase shift is very close to the theoretical value of 180°. Then, a pseudo-random bit sequence (PRBS) phase-coding signal at 1 Gb/s with a length of 128 bits generated by the BERT is applied to the PolM. A waveform with a time-duration of 128 ns is generated. Fig. 3(a) shows a section of the generated 8 GHz phase-coded microwave waveform. To show the pulse compression capability, an autocorrelation of the original phase-coded microwave waveform is calculated and the result is shown in Fig. 3(b). A pulse compression ratio (PCR) of about 113.58 is obtained. Here the PCR is defined as the ratio of the 3-dB temporal width of the transmitted pulse to that of the compressed pulse. The peak-to-sidelobe ratio (PSR) is calculated to be about 6.93 dB. Here the PSR is defined as the ratio of the power of the mainlobe to that of the highest sidelobe. To study the robustness of the generated waveform to noise, a waveform with an additive white Gaussian noise (AWGN) is generated, as shown in Fig. 3(c), where the SNR is controlled to be as small as 0 dB. A correlation between

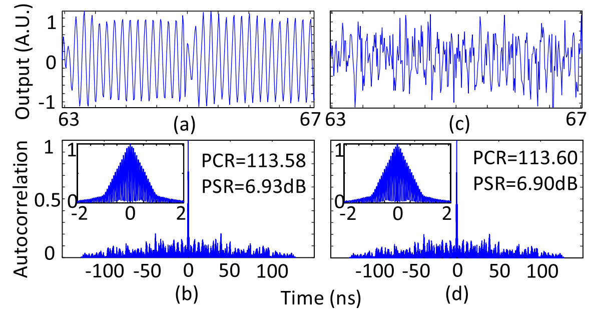

Fig. 3. (a) An 8-GHz phase-coded microwave waveform. (b) Autocorrelation of the original phase-coded microwave waveform. (c) Phase-coded microwave waveform with an AWGN. (d) Correlation between the original phase-coded microwave waveform and the phase-coded microwave waveform with an AWGN. Insets in (b) and (d): zoom-in views of the correlation peaks.

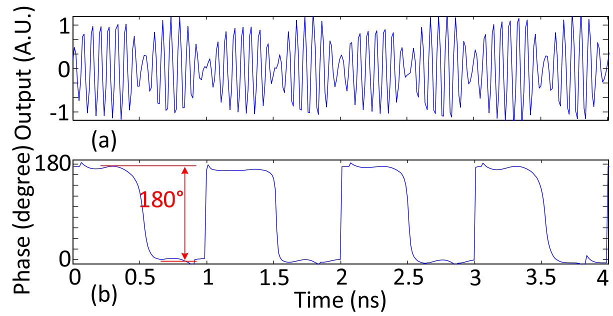

Fig. 4. (a) Generated 16-GHz phase-coded microwave waveform from an 8-GHz microwave signal. (b) The recovered phase information from (a).

the original phase-coded microwave waveform and the phase-coded microwave waveform with an AWGN is then calculated and the result is shown in Fig. 3(d). The PCR is about 113.60, and the PSR is about 6.90 dB. The PCRs and PSRs are nearly the same with and without an AWGN, which confirms the robustness of the pulse compression process.

Then, the generation of a 16-GHz phase-coded microwave signal from an 8-GHz microwave source to demonstrate the generation of a frequency-doubled microwave phase-coded signal is performed. The phase-coding signal is again a "0101" digital sequence but at a data rate of 2 Gb/s. Fig. 4(a) shows the generated 16-GHz phase-coded microwave waveform, and Fig. 4(b) shows the phase information recovered from the phase-coded waveform using again the Hilbert transform. As can be seen, the phase shift is again very close to the theoretical value of 180°. A PRBS phase-coding signal at 2 Gb/s with a length of 128 bits is applied to the PolM. A waveform with a time-duration of 64 ns is generated. Fig. 5(a) shows the generated 16-GHz phase-coded microwave waveform. An autocorrelation is calculated which is shown in Fig. 5(b). Then, an AWGN is added to the waveform to make the SNR to be 0 dB, as shown in Fig. 5(c). A correlation between the original waveform and the waveform with an AWGN as discussed in Fig. 3 is also calculated, which is shown in Fig. 5(d). Again, a highly compressed pulse is observed. The PCRs and PSRs are again nearly the same with and without an AWGN.

In our experiment, the PCRs are in accordance with the theoretical value of 128, and the PSRs are close to those

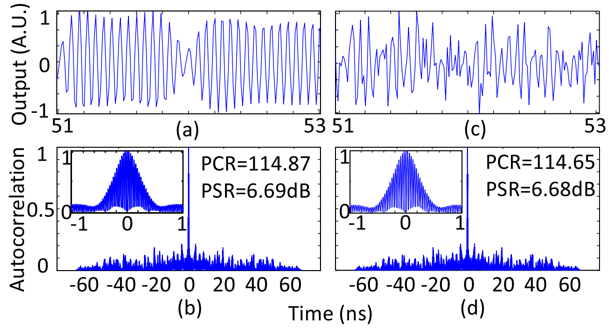

Fig. 5. (a) A 16-GHz phase-coded microwave waveform. (b) Autocorrelation of the original phase-coded microwave waveform. (c) Phase-coded microwave waveform with an AWGN. (d) Correlation between the original phase-coded microwave waveform and the phase-coded microwave waveform with an AWGN. Insets in (b) and (d): zoom-in views of the correlation peaks.

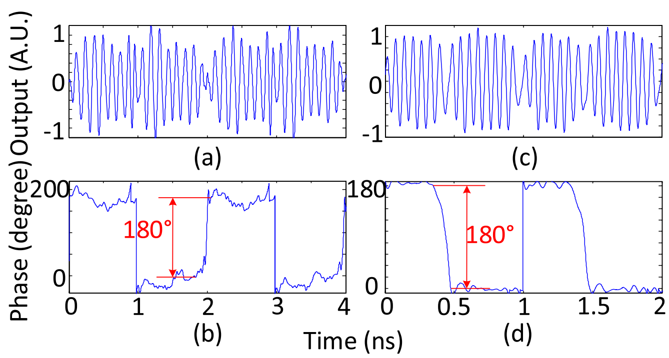

Fig. 6. (a) Generated 8-GHz phase-coded microwave waveform from a 4-GHz microwave signal. (b) The recovered phase information from (a). (c) Generated 16-GHz phase-coded microwave waveform from a 16-GHz microwave signal. (d) The recovered phase information from (c).

reported in [9]–[10]. However, the PCRs and PSRs are not as good as those reported recently in [11]. The reason is that we a 5-dB attenuator between the MSG and the EC to reduce the crosstalk and reflection between the two input ports of the EC, because the impedance match between the MSG and the EC is not optimized, which greatly reduces the power of the microwave signal applied to the PolM. The use of the EC also reduces the microwave signal power by an additional 3 dB. A total insertion loss of 8 dB is introduced to the microwave signal, so the SNR of the generated waveform is poorer than that in [11], which leads to the poorer PCRs and PSRs. If a high power microwave source or a better EC is used, the PCRs and PSRs can be improved.

One important feature of the proposed technique is its wide frequency tunable range, which is also investigated in the experiment. When an input microwave source with its frequency tuned from 4 to 12 GHz is applied, a phase-coded microwave signals from 4 to 12 GHz, or from 8 to 24 GHz is generated. Fig. 6 shows of the generation of an 8-GHz and 16-GHz phase-coded microwave signal from a 4-GHz and 16-GHz microwave source. As can be seen, the phase information is successfully recovered from the waveforms. In our experiment, the PCRs and the PSRs are maintained identical during the entire tunable range. Note that the EC used in our experiment can only operate up to 12 GHz, so the frequency tunable range is up to 24 GHz. Theoretically, the tunable range is only limited by the bandwidths of the PolM, the EC and the PD. If the devices with wider bandwidths are used, the tunable range can be further increased.

IV. Conclusion

A novel and simple photonic approach to generating a precisely π phase-shifted binary phase-coded microwave waveform with ultra-wide frequency tunable range was proposed and experimentally demonstrated. The key contribution of the work was the use of the PolM which was functioning with PC2 and the Pol as an equivalent MZM with its bias points switchable between the two quadrature transmission points for fundamental phase-coded microwave waveform generation and the maximum and minimum transmission points for frequency-doubled phase-coded microwave waveform generation. The proposed technique was investigated experimentally. The generation of a phase-coded microwave signals at the fundamental and the doubled frequency of 8 and 16 GHz was demonstrated. The tunability of the system was also investigated. A phase-coded microwave signal from 4 to 12 GHz or 8 to 24 GHz was generated. The pulse compression performance was also evaluated. Over the entire tunable range, the PCRs and the PSRs were maintained identical.

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