Arbitrary Microwave Waveform Generation Based on a Tunable Optoelectronic Oscillator

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***Abstract*—Photonic generation of a phase-coded or frequency-chirped microwave waveform with a tunable microwave carrier frequency using a frequency-tunable optoelectronic oscillator (OEO) is proposed and experimentally demonstrated, for the first time to the best of our knowledge. In the proposed system, the tunable OEO has functions to generate a frequency-tunable microwave signal and to output an optical sideband. The optical sideband and a portion of the light wave from the OEO laser source are sent to a polarization modulator (PolM), with their polarization directions aligned with the two principal axes of the PolM. An electrical signal is applied to the PolM, and two complementary phase-coded or frequency-chirped light waves are generated which are converted to an electrical signal by beating the light waves at a high-speed photodetector. The key significance of the technique is that a phase-coded or frequency-chirped microwave waveform with a tunable microwave carrier frequency and a reconfigurable phase-coding or frequency-chirping pattern can be generated without using a separate microwave source. The technique is experimentally verified. The generation of a binary- and a polyphase-coded microwave waveform with a microwave carrier frequency at 10 and 15 GHz is demonstrated. The generation of a linearly frequency-chirped microwave waveform with a chip rate of 20.98 GHz/ns at a 10-GHz carrier frequency and 22.5 GHz/ns at a 15-GHz carrier frequency is also achieved.**

***Index Terms*—Microwave photonics, microwave signal generation, optoelectronic oscillator (OEO), phase coding, polarization modulator (PolM), radar pulse compression.**

I. Introduction

MICROWAVE pulse compression has been widely employed in modern radar systems to increase the range resolution [1]. To have a large compression ratio, a phase-coded or a frequency-chirped microwave waveform with a large time-bandwidth product is needed. Due to the limited speed and bandwidth of electronic circuits, phase-coded or a frequency-chirped microwave waveforms generated in the electrical domain have low frequency (few GHz) and small bandwidth [2], [3]. In addition, it is also required that the generated microwave waveforms are reconfigurable and frequency tunable. Thanks to the high frequency and broad bandwidth offered by modern photonics, photonic-assisted techniques to generate microwave waveforms have been proposed and developed in the last few years [4]–[14]. For example, an arbitrary phase-coded or frequency-chirped microwave waveform can be generated through optical pulse shaping, which can be implemented based on either space-to-time mapping (STM) [4] or frequency-to-time mapping (FTM) [5], [6]. The approaches based on STM are usually implemented using a spatial light modulator (SLM) with the pulse pattern reconfigurable by updating the SLM in real time. The major limitation of an STM-based system is that the system involves free-space optics. Thus, the system is complicated and bulky. On the other hand, an arbitrary phase-coded or frequency-chirped microwave waveform can be generated based on FTM. The key device in an FTM-based system is an optical spectral shaper, which is designed to shape the spectrum of an ultra-short optical pulse to have a spectral shape that is a scaled version of the generated phase-coded or frequency-chirped waveform. The major limitation of an FTM-based system is that the spectral response of the optical spectral shaper is usually fixed thus the generated waveform is also fixed. To solve this problem, a reconfigurable spectral shaper implemented in a silicon chip that consists of eight cascaded micro-ring resonators [7] has been proposed and demonstrated. Through thermal tuning, the spectral response of the spectral shaper can be changed, which leads to the change of the generated waveforms. To generate sophisticated waveforms, however, a large number of micro-rings should be integrated in the chip, which would increase the footprint and the complexity.

A binary phase-coded microwave waveform with an ultra-wide frequency tunable range can be generated using a Mach–Zehnder modulator (MZM) by switching the bias points of the MZM between the two complementary slopes of the transfer function. A binary phase-coded microwave signal with an ultra-wide frequency turntable range from 10 to 40 GHz was demonstrated [8]. The major limitation of the technique is the phase coding is binary only.

A phase-coded or frequency-chirped microwave waveform can also be generated by phase modulating two phase-correlated wavelengths [9]–[14]. For example, if a phase coding signal is applied to a phase modulator (PM) to modulate the phase of one of the two wavelengths, the beating of the two wavelengths at a photodetector (PD) will generate a phase-coded microwave waveform. If the phase coding signal is changed to a parabolic waveform, then a linearly frequency-chirped waveform can be generated. In the implementation, the two wavelengths must be phase correlated, which can be achieved using two sidebands of an externally modulated light wave [9]–[12] or two modes

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from a mode-locked laser (MLL) [13], [14]. In the first case, the two sidebands can be generated based on external modulation using an MZM that is biased at the minimum transmission point [9] or using two optical filters to select the two desired sidebands [10], [11]. The two sidebands are then either spatially separated using a Sagnac interferometer incorporating a fiber Bragg grating (FBG) [9], a polarization maintaining FBG [10], or a polarization modulator (PolM) [11]. Then, the two sidebands can be arbitrarily and independently phase modulated. By beating the two phase-modulated sidebands at a PD, an arbitrary phase-coded microwave signal is generated. Note that the polarization multiplexing and independent phase modulation can be reversely conducted [12]. However, the frequency tuning range of the microwave carrier and frequency agility are limited due to the use of optical filters with fixed spectral responses to choose the two desired sidebands. In addition, for all the methods discussed in this case, an external microwave source is always required. In the second case, the two modes are selected by two optical filters or an optical filter with two pass bands from the comb lines of the MLL [13], [14], and the phase/amplitude modulation is accomplished in an in-phase/quadrature MZM. The approach has the capability of producing a microwave signal with a wide frequency range due to the large bandwidth of the optical comb. However, optical filtering also causes the frequency agility to be limited.

In this paper, we propose an approach to generating an arbitrary phase-coded or frequency-chirped microwave signal with an ultra-wide frequency tunable range and excellent frequency agility without using an external microwave source and optical filters. The technique is based on the use of a tunable optoelectronic oscillator (OEO) which has two functions: to generate a frequency-tunable microwave signal and to output one optical sideband. The optical sideband is applied to a PolM jointly with part of the light wave from the OEO laser source, with their polarization directions alighted, respectively, with the principal axes of the PolM. An electrical signal is applied to the PolM to generate two complementary phase-coded or frequency-chirped optical signals that are converted to an electrical signal by beating the two signals at a high-speed PD. The OEO is implemented using a PM and a phase-shifted FBG (PS-FBG) in its reflection mode [15]. The joint operation of the PM and the PS-FBG is equivalent to a frequency tunable microwave filter [16]. The fundamental operation of the tunable microwave filter is to perform phase-modulation to intensity-modulation conversion at the PS-FBG, to eliminate one sideband by the notch of the PS-FBG. The tunability is realized by tuning the wavelength of the optical carrier. Note that the eliminated sideband is actually transmitting through the PS-FBG which can be collected from the other end of the PS-FBG. The sideband is combined with part of the optical wave from the OEO laser source and applied to a PolM. In addition, the sideband and the optical wave are orthogonally polarized such that the two waves are traveling along the two principal axes of the PolM. A PolM is a special PM that supports phase modulation with opposite phase modulation indices. By applying a phase-coding or a frequency-chirping signal to the PolM via the RF port, the two waves will experience complementary phase or frequency-chirping modulation. By applying the two phase-modulated or frequency-chirped light waves to a PD through a polarizer, a phase-coded or frequency-chirped microwave signal is generated. The proposed technique is experimentally evaluated. The generation of a binary- and a polyphase-coded microwave waveform with a microwave carrier frequency at 10 and 15 GHz is demonstrated. The generation of a linearly frequency-chirped microwave waveform with a chip rate of 20.98 GHz/ns at a10-GHz carrier frequency and 22.5 GHz/ns at a15-GHz carrier frequency is also achieved.

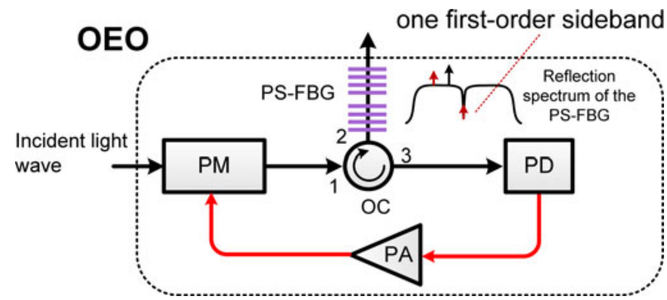

Fig. 1. Configuration of a tunable OEO.

II. Operation Principle

A. Tunable Optoelectronic Oscillator

The key module in the system is a tunable OEO. The schematic of the OEO is shown in Fig. 1. It consists of a PM, a PS-FBG that has an ultra-narrow notch in reflection, an optical circulator, a PD and a power amplifier (PA). Assume that when a microwave frequency is not equal to the frequency difference between the incident light wave and the notch of the PS-FBG, the phase-modulated light wave at the output of the PM would be totally reflected by the PS-FBG and produce only a dc component at the output of the PD, leading to a huge loss of the microwave frequency. When one first-order sideband of the phase-modulated light wave (say the upper sideband) is located at the notch of the PS-FBG, the upper sideband is eliminated and only the optical carrier and the lower first-order sideband are reflected by the PS-FBG. Thus, a single-sideband modulated is obtained and the microwave signal is recovered at the PD. When the PA provides a sufficient gain to compensate for the loss, the OEO will start a self-sustainable oscillation and a microwave signal at this frequency will be generated. Since the oscillation frequency is equal to the difference between the wavelength of the optical carrier and the center wavelength of the notch of the PS-FBG, by tuning the wavelength of the optical carrier, the oscillation microwave frequency is accordingly changed. Therefore, when the OEO starts oscillation, it will generate a microwave signal inside the loop and an upper first-order sideband at the other end of the PS-FBG. Note here that the upper first-order sideband is phase-correlated with the incident light wave due to the phase modulation and its wavelength remains constant when the incident light wave and the oscillation frequency are changed. Further details about the operation of the tunable OEO can be found in [15].

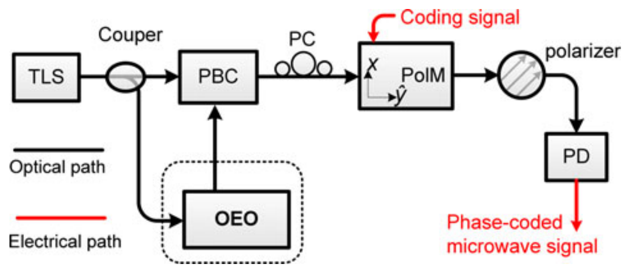

Fig. 2. Schematic of the proposed OEO-based arbitrary phase-coded and frequency-chirped microwave signal generation system.

B. Arbitrary Phase-Coded or Frequency-Modulated Microwave Signal Generation

The schematic of the proposed OEO-based arbitrary phase-coded or frequency-chirped microwave signal generator is shown in Fig. 2. It consists of a tunable laser source (TLS), an optical coupler, a polarization beam combiner (PBC), a tunable OEO, a polarization controller (PC), a PolM, a polarizer, and a PD. The light wave from the TLS is divided into two parts: one is sent to the PBC while the other is send to the OEO as the incident light wave to produce one phase-correlated sideband which is also sent to the PBC. At the output of the PBC, the polarization directions of two wavelengths are orthogonal, namely, the two wavelengths are polarization multiplexed.

Then, the two wavelengths are sent to the PolM with their polarization directions aligned with the two principal axes ($\hat{x}$ and $\hat{y}$) of the PolM. A phase-coding or frequency-chirping signal is applied to the PolM. The PolM is a special PM that supports phase modulation with opposite modulation indices [17]. Mathematically, the light waves along the two principal axes at the output of the PolM can be expressed as

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \begin{bmatrix} E_1 \exp\left[j\left(2\pi f_o t - \dfrac{\pi V}{V_\pi}s(t)\right)\right] \\ E_2 \exp\left[j\left(2\pi(f_o + f_{\rm osc})t + \dfrac{\pi V}{V_\pi}s(t)\right)\right] \end{bmatrix} \tag{1}$$

where E_x and E_y are the electrical fields of the light wave along the $\hat{x}$and $\hat{y}$ axes of the PolM, E_1 and E_2 are the amplitudes of E_x and E_y, respectively, f_o is the frequency of the incident light wave, $f_{\rm osc}$ is the oscillation frequency of the OEO, $s(t)$ is the normalized electrical phase-coding or frequency-chirping signal, V is the amplitude of the electrical signal, and V_π is the half-wave voltage of the PolM.

Then, the phase-coded or frequency-chirped optical signals are sent to the polarizer to make the two polarization multiplexed wavelengths polarized in the same direction. Therefore, by beating the two wavelengths at the PD, a phase-coded or a frequency-chirped microwave signal is generated. The phase-coded or frequency-chirped microwave signal at the output of the PD is given by

$$i(t) \propto ac\left|E_x(t) + E_y(t)\right|^2 = \cos\left[2\pi f_{\rm osc} t + \frac{2\pi V}{V_\pi}s(t)\right] \tag{2}$$

It can be seen from (2) that a microwave signal with a carrier frequency of $f_{\rm osc}$, which is phase-coded or frequency-chirped by the phase coding or frequency-chirping signal $s(t)$ is generated. The phase coding or frequency chirping pattern is determined by the electrical encoding signal $s(t)$. For example, if $s(t)$ is a square wave or a N-step stair wave, and V is equal to $V_\pi/2$ or V_π/N, a binary or a N-level polyphase phase-coded microwave signal with a carrier frequency of $f_{\rm osc}$ is generated; if $s(t)$ is an electrical parabolic waveform, a linearly frequency-chirped microwave signal is generated. Note again that the carrier frequency $f_{\rm osc}$, which is the oscillation frequency of the OEO, can be simply tuned by changing the wavelength of the TLS, which ensures excellent frequency agility. The bandwidth of the PDs, PAs and PMs as well as the reflection bandwidth of the PS-FBG can be 40 GHz or higher, the frequency tuning range of the OEO could be also as large as 40 GHz or greater. Therefore, an arbitrary phase-coded or frequency-chirped microwave signal with an ultra-wide carrier frequency range of tens of GHz and excellent frequency agility can be generated.

III. Experimental Results and Discussion

A. Two-Wavelength Generation

An experiment based on the setup shown in Fig. 1 is performed. A CW light wave at 1550 nm from the TLS (Anritsu, MG9638A) is split into two channels and sent to the PBC and the tunable OEO. Inside the OEO, the CW light wave is sent to a 20-GHz PM (JDS-U). The optical signal at the output of the PM is sent to a PM-PSFBG that has a reflection bandwidth of 0.5 nm and a notch width of about 40 MHz. A 20-GHz PD with a responsivity of about 0.5 A/W (Newport, model 1414) is used to convert the light wave to an electrical signal. The power of the input light wave to the PD is about 0 dBm, and the signal at the output of the PD is amplified by a low-noise amplifier (Nadar, 6–18 GHz, 30 dB gain) followed by a PA(Agilent 83006A, 10 MHz–26.5 GHz, 20 dB gain) and then applied to the PM via the RF port. More details about the setup of the tunable OEO and the properties of the PS-FBG employed in the OEO can be found in [15].

At the other end of the PS-FBG, an optical sideband is obtained which is sent to the PBC with part of the light wave from the TLS. The two light waves are orthogonally polarized at the output of the PBC, and are sent to a 40-GHz PolM (Versawave). The PC between the PBC and the PolM is used to ensure that the polarization directions of the two orthogonally polarized light waves are aligned with the principal axes of the PolM.

Fig. 3 shows the two orthogonally polarized light waves at the output of the PBC. The wavelength spacing between the optical carrier and the sideband is controlled to generate a microwave signal with a frequency at 10 GHz or a 15 GHz. From Fig. 3 we can clearly see that the wavelength of the sideband is not changed, at about 1549.27 nm, while the optical carrier from the TLS is increased from 1549.35 nm to 1549.39 nm, corresponding to an increase in the frequency of the generated microwave of 5 GHz.

The PolM is driven by a phase-coding or frequency-chirping signal generated by an arbitrary waveform generator (AWG, Tektronix, AWG7102). At the output of the PolM, two complementary phase-coded or frequency-chirped optical light waves

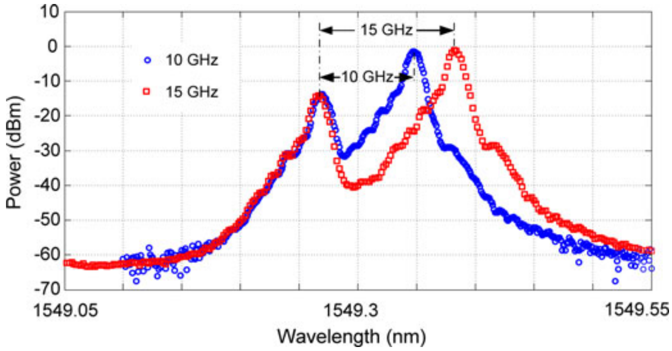

Fig. 3. Measured optical spectra of the two light waves at the output of the PBC when the tunable OEO is configured to generate a microwave carrier at 10 and 15 GHz.

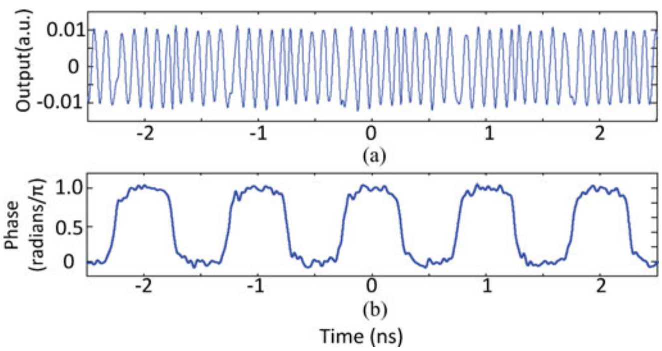

Fig. 4. (a) Generated 10-GHz binary phase-coded microwave waveform. (b) Recovered phase information from the binary phase-coded microwave waveform in (a).

that are orthogonally polarized are generated which are sent to the polarizer to make the two signals projected to the same polarization direction and then beat at another 25-GHz PD with a responsivity of 0.5 A/W (Newport, model 1414). The power of the input light wave is about 0 dBm. A phase-coded or frequency-chirped microwave signal is thus generated. The temporal waveform of the signal is monitored by a real time oscilloscope (Agilent, DSO-X93204A, 80Gsa/s). By programming the phase-coding or frequency-chirping signal from the AWG, an arbitrary phase coded or a frequency-chirped microwave waveform is generated.

B. Binary and Quadratic Phase-Coded Signal Generation

To demonstrate the arbitrary phase-coding capability, the OEO is first configured to generate a 10-GHz microwave carrier. A phase-coding signal generated by the AWG is amplified and applied to the PolM. The half-wave voltage of the PolM is 7 V, and the peak-to-peak voltage of the amplified phase coding signal is 7 V, thus a phase shift of π would be resulted. First, a binary sequence with a peak-to-peak voltage of 7 V is applied to the PolM, a binary phase-coded microwave signal with a phase shift of π is generated. Fig. 4(a) shows the measured temporal waveform of the generated binary phase-coded microwave signal with a carrier frequency of 10 GHz, and Fig. 4(b) shows the phase information recovered from the generated binary phase-coded waveform using the Hilbert transform. As can be seen, the phase shift is π, which confirms the effective generation. Then, the phase coding signal is changed to a stair wave with four voltage levels covering a voltage range of 7 V. A quadratic phase-coded microwave signal is generated. Fig. 5(a) shows a quadratic phase-coded microwave signal and Fig. 5(b) is its phase information recovered from the generated quadratic phase-coded microwave signal. As can be seen, the phase shifts have four levels of 0, $\pi/2$, π and $3\pi/2$, corresponding to the four voltage levels of the phase-coding signal.

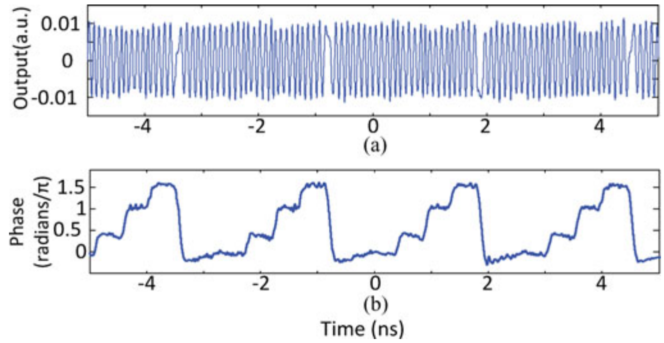

Fig. 5. (a) Generated 10-GHz quadratic phase-coded microwave waveform. (b) Recovered phase information from the quadratic phase-coded microwave waveform in (a).

C. Linearly Frequency-Chirped Signal Generation

To demonstrate the capability of the generation of a linearly frequency-chirped microwave waveform, the OEO is first configured to generate a 10-GHz microwave carrier, and a parabolic pulse train, which is generated again from the AWG, is amplified and applied to the PolM.

A parabolic pulse with a temporal duration of $2T_0$ is given by

$$s(t) = \begin{cases} Kt^2 + 1, & |t| \le T_0 \\ 0, & \text{else} \end{cases} \tag{3}$$

where, K is a coefficient and equal to $-1/T_0^2$, the instantaneous frequency of the generated electrical signal is linearly increasing or decreasing with time. The maximum and the minimum instantaneous frequency of the frequency-chirped waveform are

$$\begin{aligned} f_{\text{ins\_max}} &= f_{\text{osc}} + 2V/(V_\pi T_0) \\ f_{\text{ins\_min}} &= f_{\text{osc}} - 2V/(V_\pi T_0) \end{aligned} \tag{4}$$

and the chirp rate C can be calculated by

$$C = \frac{|f_{\text{ins\_max}} - f_{\text{ins\_min}}|}{2T_0} = \frac{2V}{V_\pi T_0^2}. \tag{5}$$

In the experiment, the peak-to-peak voltage of the parabolic pulse is about 5 V with a temporal duration of 0.5 ns. The calculated chirp rate is about 22.85 GHz/ns. Fig. 6(a) shows the measured temporal waveform of the generated linearly frequency-chirped microwave signal with a carrier frequency of 10 GHz, and Fig. 6(b) shows the instantaneous frequency information recovered from the generated linearly frequency- chirped waveform using the Hilbert transform. As can be seen, a periodic frequency-chirped pulse train is obtained and the measured chirp

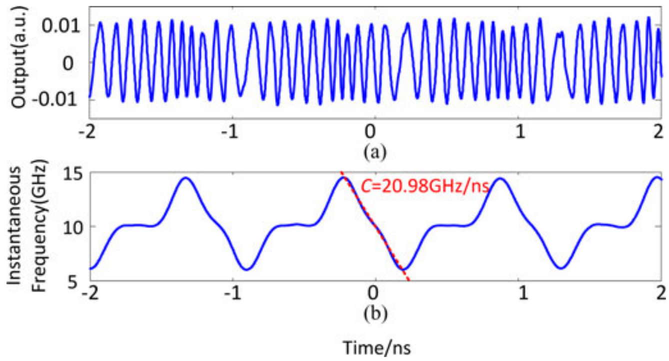

Fig. 6. (a) Generated 10-GHz linearly frequency-chirped microwave waveform. (b) Recovered instantaneous frequency information from the frequency-chirped microwave waveform in (a).

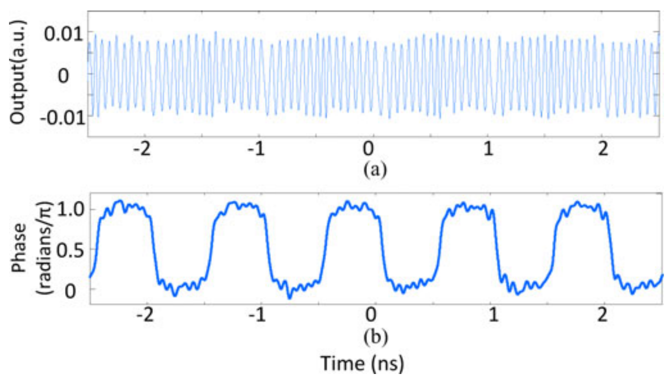

Fig. 7. (a) Generated 15-GHz binary phase-coded microwave waveforms. (b) Recovered phase information from the binary phase-coded microwave waveform in (a).

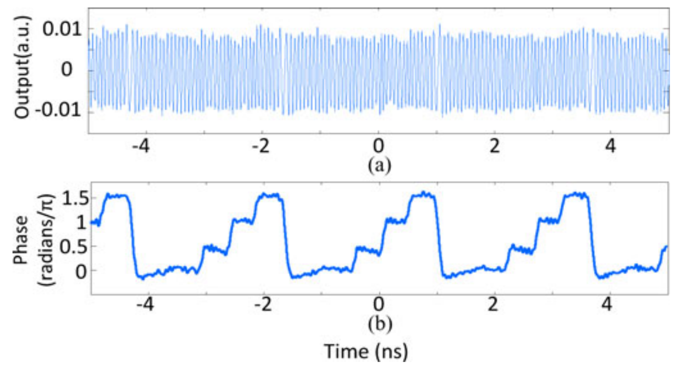

Fig. 8. (a) Generated 15-GHz quadratic phase-coded microwave waveforms. (b) Recovered phase information from the quadratic phase-coded microwave waveform in (a).

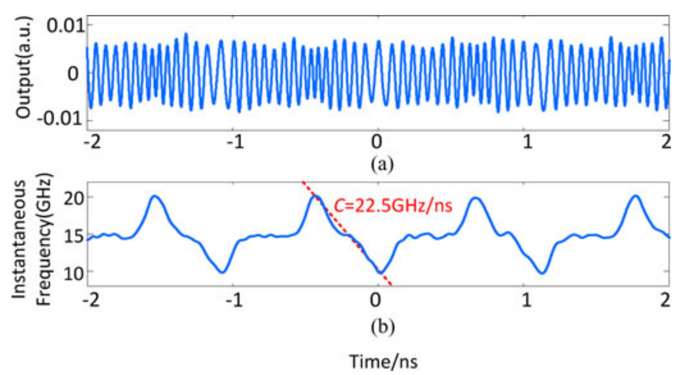

Fig. 9. (a) Generated 15-GHz linearly frequency-chirped microwave waveform. (b) Recovered instantaneous frequency information from the frequency-chirped microwave waveform in (a).

rate is about 20.98 GHz/ns, which is close to the calculated chirp rate of 22.85 GHz/ns.

D. Frequency Agility

Frequency agility is the ability of a waveform generator in a radar to quickly switch its operating frequency from one frequency to another. Such ability is very important for a radar to account for atmospheric effects, jamming, mutual interference with friendly sources, or to make it more difficult to locate through radio direction finding. Therefore, to generate a phase-coded or frequency-chirped microwave waveform with switchable carrier frequency is practically required.

In our proposed approach, changing the microwave carrier frequency can be easily and quickly achieved by changing the wavelength of the TLS. To demonstrate the frequency agility, the carrier frequency of the binary and the quadratic phase-coded, and the linearly frequency-chirped microwave waveform is tuned from 10 to 15 GHz by changing the wavelength of the TLS, and the experimental results are shown in Figs. 7, 8, and 9, respectively.

Fig. 7 and 8 show the generated phase coded signals at a microwave carrier frequency of 15 GHz. The phase coding signals are a binary sequence and a four-level stair wave. Correspondingly, a binary phase-coded and a quadratic phase-coded microwave signal with a carrier frequency of 15 GHz are generated. The measured binary and quadratic phase-coded waveforms are shown in Fig. 7(a) and Fig 8(a), respectively. The recovered phase information from the phase-coded signals is shown in Fig 7(b) and Fig. 8(b).

Fig. 9(a) shows the measured temporal waveform of the generated linearly frequency-chirped microwave signal with a carrier frequency of 15 GHz, and Fig. 9(b) shows the instantaneous frequency information recovered from the generated linearly frequency-modulated waveform using the Hilbert transform. As can be seen, a periodic frequency-chirped pulse train is obtained and the measured chirp rate is about 22.5 GHz/ns, which is close to the calculated chirp rate of 22.85 GHz/ns.

The microwave carrier frequency can be further increased to 28 GHz [15], and the upper limit is determined by the bandwidth of the PDs, PAs and PMs as well as the reflection bandwidth of the PS-FBG. Considering the bandwidths of these devices, a large carrier operation range as large as 40 GHz or wider can be achieved. The switching speed of the carrier frequency is mainly limited by the loop length of the OEO. Given an OEO loop of hundreds of meters, a switching speed in the order of microseconds can be expected.

E. Pulse Compression

To demonstrate the pulse compression capability, a binary phase-coded signal at 10 GHz using a pseudo-random bit

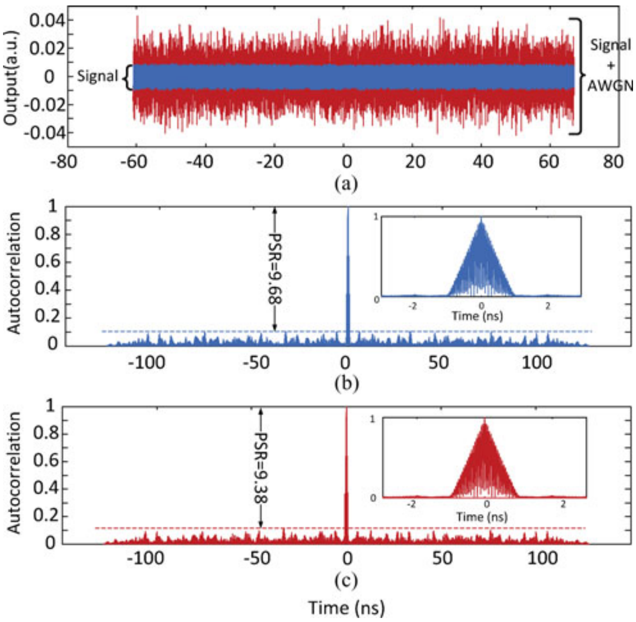

Fig. 10. (a) Generated 10-GHz binary phase-coded microwave waveforms with and without an AWGN. (b) Autocorrelation of the binary phase-coded microwave signal without noise. (c) Autocorrelation of the binary phase-coded microwave signal with noise.

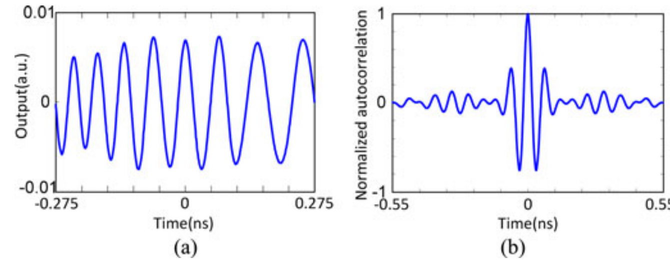

Fig. 11. (a) Measured 15-GHz frequency-chirped microwave pulse. (b) Autocorrelation of the measured frequency-chirped microwave signal.

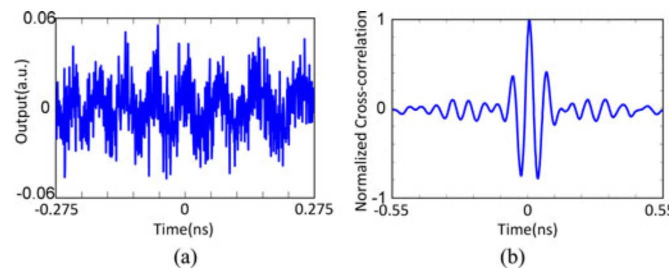

Fig. 12. (a) Measured 15-GHz frequency-chirped microwave pulse with an AWGN. (b) Cross-correlation between the reference frequency-chirped microwave pulse and the pulse with an AWGN.

sequence (PRBS) as the coding signal is generated. The PRBS has a bit rate of 1 Gb/s with a length of 128 bits. Fig. 10(a) shows the generated binary phase-coded signal with a pulse duration of 128 ns. Fig. 10(b) shows the autocorrelation of the binary phase-coded microwave signal. A compressed pulse is obtained. The autocorrelation peak has a full-width at half-maximum (FWHM) of about 0.945 ns, thus the compression ratio is about 132. The peak-to-sidelobe ratio (PSR) in Fig. 10(b) is about 9.68, which is greater than those reported in [8]–[10] thanks to the accurate π phase shift in the phase-coded pulse sequence.

The noise performance of the generated phase-coded signals is also evaluated. To do so, an additive white Gaussian noise (AWGN) is added to the generated binary phase-coded signal, as shown in Fig 10(a), where the signal-to-noise ratio (SNR) is 0 dB. Fig. 10(c) shows the correlation between the original phase-coded signal (as a reference) and the phase-coded signal with an AWGN. The autocorrelation peak has an FWHM of about 0.995 ns, as shown in the inset of Fig. 10(c), leading to a compression ratio of about 129. The PSR in Fig. 10(c) is about 9.38, which is still greater than those reported in [8]–[10].

The pulse compression capability of the generated frequency-chirped microwave waveform is also demonstrated. A frequency-chirped pulse at 15 GHz with a temporal duration of 0.55 nm, shown in Fig. 11(a), is obtained from the measured waveform and its autocorrelation is calculated which is shown in Fig. 11(b). The FWHM of the peak in the compressed pulse is around 24 ps. Therefore, a pulse compression ratio of 23 is achieved.

To evaluate the noise performance of the generated frequency-chirped signal, cross-correlation between the generated frequency-chirped pulse shown in Fig. 11(a) and the pulse with an AWGN shown in Fig 12(a) is calculated. Note that the SNR of the pulse with an AWGN is controlled to be –10 dB. The cross-correlation is shown in Fig. 12(b). The cross-correlation peak has an FWHM of about 24 ps, thus the compression ratio is 23, which is identical to that without the AWGN.

IV. Discussion and Conclusion

For most of the radar applications, a phase-coded or frequency-chirped microwave signal should be pulsed. In the experimental demonstration, however, the phase-coded and frequency-chirped microwave signals are not pulsed. If we look at the generated waveforms in more detail, we will see that a segment of sinusoidal waveform with a constant frequency exists between two adjacent phase-coded or frequency-chirped waveforms, which are not needed for practical applications. To generate a pulsed waveform, a simple solution is to add an intensity modulator as an optical switch before the PD to block the constant-frequency segment. A synchronization signal is needed to control the intensity modulator to perform the blocking operation.

To meet the requirements for various applications such as radar and remote sensing, pulses with different temporal durations are required. Although the temporal duration of the pulse in the experiment is only set to be around 0.5 ns, the pulse duration can be easily increased or decreased by directly changing the length of the phase-coding or frequency-chirping pattern generated from the AWG.

The phase noise of the generated microwave signal is a key limiting factor that affects the detection capability of a radar system using the proposed waveform generator. The phase noise of the generated microwave signal based on the proposed OEO was measured to be –102 dBc/Hz at a 10-kHz offset frequency [15].

The phase noise can be further improved by using a PS-FBG with a narrower notch and a longer fiber. In addition, the use of a well-packaged PS-FBG with precise temperature control would increase the frequency stability of the generated waveforms.

In conclusion, a novel approach to generating phase-coded or frequency-chirped microwave waveforms with a tunable microwave carrier frequency based on a tunable OEO was proposed and experimentally demonstrated. The key significance of the proposed approach is the use of the tunable OEO which functions as a microwave source to generate a frequency-tunable microwave signal, and at the same time, to output one optical sideband. By employing a PolM to phase modulate the sideband and the optical carrier, two complementary phase-coded or frequency-chirped optical signals were generated. By beating the two optical signals at a PD, a phase-coded or frequency-chirped microwave signal with tunable microwave carrier frequency was generated. An experiment was performed. The generation of a binary and a quadratic phase-coded, and a linearly frequency-chirped microwave signals with a carrier frequency at 10 and 15 GHz was demonstrated. Due to the fast frequency tuning, the proposed generator exhibited excellent frequency agility. The generated phase-coded and frequency-chirped microwave signals exhibited a good pulse compression performance.

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