Photonic Generation of a Phase-Coded Chirp Microwave Waveform With Increased TBWP

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***Abstract*— Photonic generation of a phase-coded chirped microwave waveform with an increased time bandwidth product (TBWP) using a frequency-tunable optoelectronic oscillator (OEO) is proposed and experimentally demonstrated. The frequency-tunable OEO is implemented using a tunable laser source (TLS), a phase modulator (PM), a phase-shifted fiber Bragg grating, and a photodetector (PD), with the frequency tuning realized by tuning the wavelength of the TLS. A frequency-tunable optical sideband with a frequency that is equal to that of the optical carrier plus the OEO oscillation frequency is generated by the OEO, which is then orthogonally polarization multiplexed with the optical carrier from the TLS at a polarization beam combiner, and applied to a polarization modulator, to which a binary phase-coded parabolic electrical signal is applied. By beating the two orthogonally polarized optical signals at a PD, a phase-coded chirped microwave waveform is generated. The TBWP is significantly increased due to the increase of the temporal duration of the microwave waveform. The proposed approach is experimentally demonstrated. Two phase-coded chirped microwave waveforms with TBWPs of 58.5 and 80 000 using two phase coding signals corresponding to a 13 Barker code and a 20480-bit pseudorandom sequence are generated.**

***Index Terms*— Linear frequency modulation, phase modulation, microwave photonics, microwave signal generation, optoelectronic oscillator, radar pulse compression, time bandwidth product (TBWP).**

I. Introduction

SPREAD spectrum microwave waveforms have widely been utilized in modern radar systems to increase detection range while maintaining a high range resolution [1], [2]. The range resolution is maintained based on pulse compression at a receiver by matched filtering [3], [4]. The pulse compression factor is proportional to the time bandwidth product (TBWP) of the microwave waveform. A chirped or a phase-coded microwave waveform can have a large TBWP and has been used in radar systems. In general, a chirped microwave waveform can be generated using an analog [5], [6] or digital circuit [7]. For a chirped microwave waveform with a high center frequency and large bandwidth, an electronic circuit may not be able to accomplish the work. The same limitation also applies to the generation of a high frequency and large bandwidth phase-coded microwave waveform.

Thanks to the high frequency and large bandwidth provided by modern photonics, photonic generation of spread-spectrum microwave waveforms has been considered a solution and numerous approaches have been proposed. For example, a chirped or a phase-coded microwave waveform can be generated based on space-to-time mapping (STM) [8], [9] or spectral-shaping and wavelength-to-time (SS-WTT) mapping [10]–[12]. In an STM-based system, a spatial light modulator (SLM) is usually used. The advantage of using an SLM is that the microwave waveform can be updated in real time, but due to the two-dimensional nature of an SLM, the system is relatively bulky and complicated [8], [9]. On the other hand, microwave waveform generation based on SS-WTT mapping can be implemented based on pure fiber or waveguide optics, the systems are simpler. The tuning of a generated microwave waveform can be done by changing either the spectral response of the optical spectral shaper [10], [11] or the dispersion of the dispersive element [12], which is hard to implement since the spectral shaper or the dispersive element, once fabricated, has a fixed spectral response. Another method to generate a chirped microwave waveform is to beat two optical wavelengths that are complementarily phase modulated by a parabolic electrical waveform. For example, in [13] we proposed to use an optoelectronic oscillator (OEO) to generate an optical single sideband, which is orthogonally polarization multiplexed with the light wave from the laser source used in the OEO, and then applied to a polarization modulator (PolM), where the two light waves are complementarily phase modulated. By beating the two complementarily phase-modulated optical signals at a photodetector (PD), a linearly chirped microwave waveform is generated. The key limitation of the approach is the small chirp due to the low parabolic voltage applied to the PolM. By allowing the optical wave to be phase modulated multiple times, the chirp rate can be increased by the same number of times [14]. But the temporal duration of the microwave waveform is still short, leading to a limited TBWP. In [15], a chirped microwave waveform based on SS-WTT mapping was demonstrated, in which the temporal duration of the waveform is increased by phase coding the chirped waveform, which was done by switching the polarity of the chirped waveforms using a pseudorandom (PN) sequence. Thus, the TBWP was increased. The major difficulty in implementing this technique is the synchronization of the phase-coded chirped waveforms with the pseudo-noise (PN) sequence. In addition, the center frequency of the chirped waveform is not tunable. Furthermore, since a mode locked laser source is used, the system is rather complicated and costly.

In this letter, we propose an approach to photonic generation of a frequency-tunable phase-coded chirped microwave waveform with an increased TBWP using a

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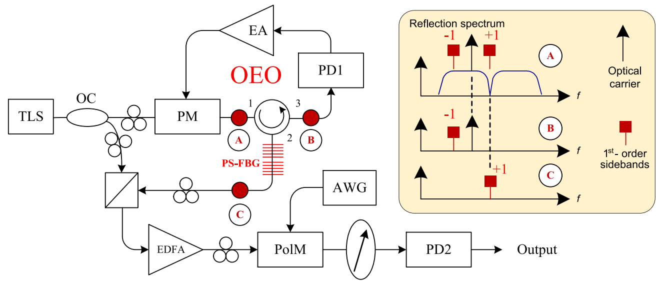

Fig. 1. Schematic of the proposed OEO-based phase coded chirp microwave waveform generation system. TLS: tunable laser source; PC: polarization controller; PM: phase modulator; PS-FBG: phase-shifted fiber Bragg grating; EA: electronic amplifier; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier; PolM: polarization modulator; AWG: Arbitrary waveform generator; PD: photo detector.

frequency-tunable OEO. Since no mode locked laser source is used, the system is simpler and less costly. In the proposed system, the OEO is used to generate a frequency-tunable optical sideband which has a frequency that is equal to that of the optical carrier plus the OEO oscillation frequency. The single sideband is then orthogonally polarization multiplexed with the optical carrier from the tunable laser source (TLS) in the OEO, and applied to a PolM, to which a binary phase-coded electrical parabolic signal is applied. By beating the two orthogonally polarized optical signals at a PD, a phase-coded chirped microwave waveform is generated. The key significance of the technique is that the TBWP is significantly increased due to the increase in the temporal duration of the microwave waveform. The proposed approach is experimentally demonstrated. A seed chirped waveform with a center frequency tunable from 6 to 15 GHz and a TBWP of 4.51 is first generated. By phase coding the seed chirped waveform by a 13 Barker parabolic electrical code and a 20480-bit PN parabolic electrical sequence, phase-coded chirped microwave waveforms with increased TBWPs of 58.5 and 80000 are generated.

II. Principle

The schematic of the proposed phase-coded chirp waveform generation system based on a tunable OEO is shown in Fig. 1. A light wave with a frequency at f_0 is generated by a TLS, which is divided into two channels by an optical coupler (OC), with one channel connected to the input of a phase modulator (PM), as a light source for the OEO. The OEO consists of a TLS, a PM, a PS-FBG, an optical circulator, a PD, and an electronic amplifier (EA). The joint operation of a PM, a PS-FBG and a PD (PD1) corresponds to a microwave filter with the center frequency equal to the wavelength difference between those of the optical carrier and the notch of the PS-FBG [16]. When the OEO loop is closed and the loop gain is sufficiently high to compensate for the loop loss, oscillation will start and a microwave signal will be generated. As shown in the inset in Fig. 1, at point A, a phase-modulated double-sideband with carrier (DSB+C) signal is generated. When one of the first sidebands (+1 order) is removed by the notch of the PS-FBG, a single sideband with carrier (SSB+C) signal is obtained (at point B), and the phase modulation is converted to intensity modulation. At point C, the removed sideband (+1 order) is transmitted through the PS-FBG, which has a frequency that is equal to that of the optical carrier plus the frequency of the generated microwave signal, $f_0 + f_{\mathrm{osc}}$. The single sideband and the light wave from the second channel of the OC are polarization multiplexed at a polarization beam combiner (PBC), and applied a PolM, with the polarization directions aligned with the two principle axes of the PolM. Note that a PolM is a special PM that supports phase modulation along the two principal axes with opposite modulation indices [17]. To generate a chirped microwave waveform, a parabolic modulation signal $s(t)$ generated by an arbitrary waveform generator (AWG) is applied to the PolM. At the output of the PolM, two complementarily frequency-chirped optical signals are generated. By using a polarizer to project the two orthogonally polarized optical signals to one polarization direction, and beating the two signals at a PD (PD2), a chirped microwave waveform with a central frequency at f_{osc} is generated. The photocurrent at the output of PD2 is given by

$$i(t) \propto \cos\left[2\pi f_{osc}t + \frac{2\pi}{V_\pi}s(t)\right] \tag{1}$$

where V_π is the half-wave voltage of the PolM.

Mathematically, a parabolic electrical modulation signal can be expressed as

$$s(t) = V_e \frac{4(t - T_0/2)^2}{T_0^2}, \quad t \in [0, T_0] \tag{2}$$

where V_e is the amplitude of the modulation signal, and T_0 is the temporal duration. Thus, the instantaneous frequency of the generated chirped signal is given by

$$f_i = f_{osc} + \frac{8V_e}{V_\pi T_0^2}\left(t - \frac{T_0}{2}\right), \quad t \in [0, T_0] \tag{3}$$

with its chirp rate C and the TBWP given by

$$C = \frac{8V_e}{V_\pi T_0^2} \tag{4}$$

$$TBWP = \frac{8V_e}{V_\pi} \tag{5}$$

Since the amplitude of the signal V_e should be smaller or equal to the half-wave voltage of the PolM, the TBWP of the generated waveform is equal or less than 8, which is very small.

One solution to increase the TBWP is to increase the temporal duration of the microwave waveform, which can be realized via phase encoding.

For a chirped microwave waveform with a temporal duration of T_0, a chirped rate of C and a center frequency of f_{osc}, we have

$$u_{LCMW}(t) = \frac{1}{\sqrt{T_0}} rect\left(\frac{t}{T_0}\right) e^{j2\pi f_{osc}t} e^{j\pi Ct^2} \tag{6}$$

A binary PN pulse sequence can be expressed as

$$u_B(t) = \begin{cases} \sum_{n=0}^{p-1} c_n \delta(t - nT_0) & 0 < t < PT_0 \\ 0 & otherwise \end{cases} \tag{7}$$

where P is the bit length of the binary pulse sequence, and c_n is the value of one bit, which can be +1 or -1.

A phase-coded chirped waveform with an increased length can be obtained by convolving the two functions, which is given by

$$u_{B-LCMW}(t) = u_{LCMW}(t) * u_B(t) \tag{8}$$

The spectrum of the phase-coded chirp waveform can be calculated by

$$U_{B-LCMW}(f) = U_{LCMW}(f)\, U_B(f) \tag{9}$$

where $U_{LCMW}(f)$ and $U_B(f)$ are the Fourier transforms of $u_{LCMW}(t)$ and $u_B(t)$, and the $U_B(f)$ is given by

$$U_B(f) = FT[u_B(t)] = \frac{1}{T_0}\sum_{n=0}^{P-1} c_n e^{-j2\pi n T_0 f} \tag{10}$$

Then, the spectrum of the phase-coded chirp microwave waveform is given by

$$U_{B-LCMW}(f) = \frac{1}{T_0} U_{LCMW}(f) \sum_{n=0}^{P-1} c_n e^{-j2\pi n T_0 f} \tag{11}$$

As can be seen, the spectrum of the PN phase-coded microwave waveform, $U_{B-LCMW}(f)$, has the same bandwidth as U_{LCMW}. Thus, the TBWP of the phase-coded chirp microwave waveform is increased to $8PV_e/V_\pi$. If a chirped microwave waveform is phase coded by a 13 Barker code or a 20480-bit PN sequence, the TBWP will be increased by 13 or 20480 times.

III. Experiment

An experiment based on the setup shown in Fig. 1 is performed. A CW light from the TLS (Anritsu, MG9638A) is divided into two channels by the OC with one sent to the PM (Thorlabs, 40 GHz) in the OEO loop. The phase modulated optical signal is sent to the PS-FBG, which has a reflection bandwidth of 0.4 nm and a notch width of about 40 MHz centered at 1549.3 nm. One of the two sidebands of the phase-modulated signal is transmitted through the notch of the PS-FBG. Thus, the phase-modulated DSB+C signal is converted to a SSB+C intensity-modulated signal. A PD (PD1, Newport, model 1014, 45 GHz) is utilized to convert the SSB+C signal to an electrical signal. The electrical signal at the output of PD1 is amplified by a low-noise EA (Nadar, 6–18 GHz, 30 dB gain) and a power EA (Agilent 83006A, 10 MHz–26.5 GHz, 20 dB gain) to compensate the insertion loss of the loop, and then applied to the PM via the RF port to close the loop. The transmitted sideband is orthogonally polarization multiplexed with the light wave from the other channel of the OC at the PBC, and fed to the PolM (Versawave, 40 GHz). A phase-coded parabolic electrical signal generated by an AWG (Keysight M8195A) is sent to the PolM, to generate two complementarily chirped optical waveforms. By beating the two optical waveforms at a second PD (PD2, Newport, model 1014, 45 GHz), a phase-coded chirped microwave waveform is generated, which is monitored by a real-time oscilloscope (Agilent, DSO-X93204A, 80G Sa/s).

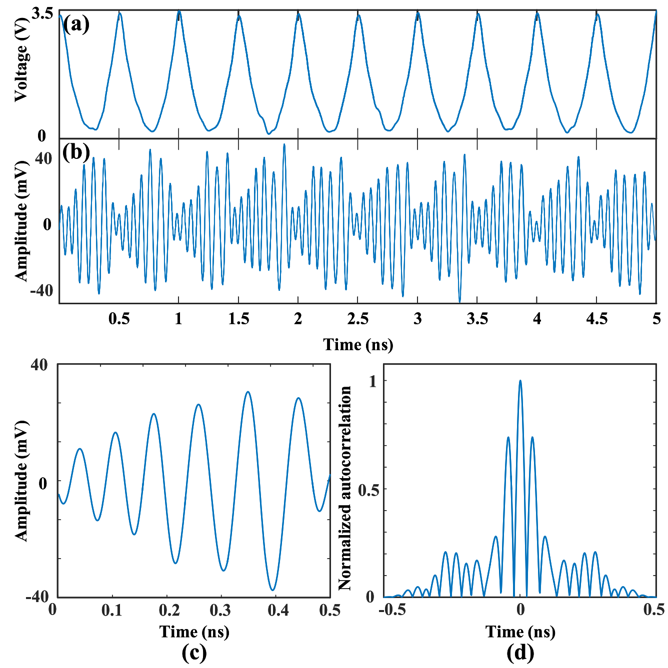

Fig. 2. (a) Measured parabolic waveform as a modulation signal. (b) Generated chirped microwave waveform. (c) Measured 1 bit chirped microwave waveform. (d) Normalized autocorrelation of 1 bit chirped microwave waveform.

Fig. 2(a) shows a 10-bit binary parabolic electrical signal with all bits 1, which is generated by the AWG with a peak to peak voltage of 3.2 V. The half-wave voltage of the PolM is 5.5 V, based on (5) the TBWP of the generated chirp waveform is calculated to be 4.65. Fig. 2(b) shows that a generated chirped microwave waveform. For a 1-bit chirped microwave waveform, shown in Fig. 2(c), the central frequency is 13.18 GHz and the instantaneous frequency is varying from 9.39 to 18.41 GHz. The chirp rate is about 18.04 GHz/ns and the TBWP is about 4.51, which is close to the theoretically calculated value of 4.65. Fig. 2(d) shows the normalized autocorrelation of a 1-bit chirped microwave waveform. The width of the autocorrelation peak is about 0.099 ns. Considering the chirped pulse width is 0.42 ns, the pulse compression ratio is 4.24, which is low due to the small TBWP. The peak-to-sidelobe ratio (PSR) is 15.61 dB. The center frequency of the generated chirped microwave waveform can be tuned. To do so, we tune the wavelength of the TLS. In the experiment, by tuning the wavelength of the TLS from 1549.18 to 1549.25 nm, the center frequency of the generated chirped microwave waveform is from 6.7 to 15.3 GHz.

Based on (1), the generated chirped microwave waveform will experience a π phase shift if the offset voltage of $s(t)$ is increased by half V_π. Based on this concept, a 13-bit binary phase-coded parabolic electrical signal corresponding to a 13-bit Barker code is generated by the AWG, as shown in Fig. 3(a). The voltage difference between the higher and the lower parabolic waveforms is 2.75V, which is half V_π, to introduce a π phase shift to the generated waveform. By applying the phase-coded parabolic electrical signal to the PolM, a phase coded chirp microwave waveform with

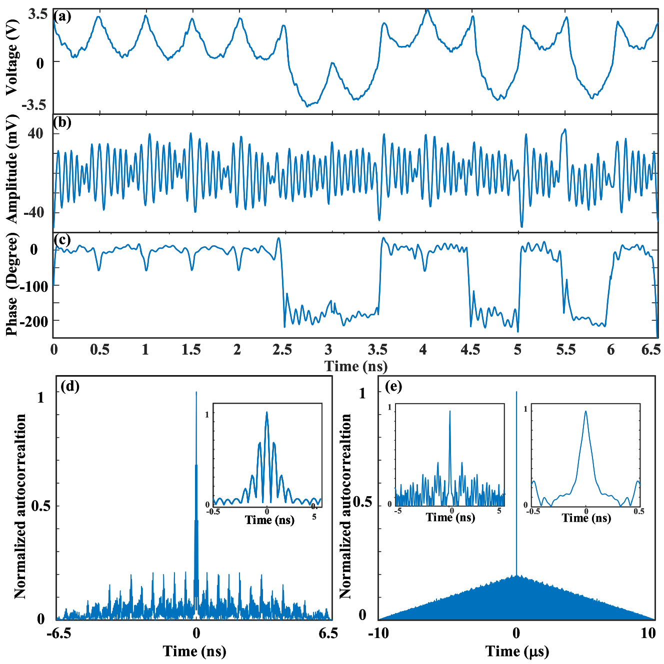

Fig. 3. (a) Measured phase coded parabolic waveform as a modulation signal. (b) Generated 13-bit Barker phase-coded chirped microwave waveform. (c) Recovered phase information from the microwave waveform in (b). (d) Normalized autocorrelation of the 13-bit Barker phase-coded chirped microwave waveform. (e) Normalized autocorrelation of a 20480-bit PN phase-coded chirped microwave waveform.

an increased temporal duration is generated. Fig. 3(b) shows the generated microwave waveform and Fig. 3(c) shows the phase information recovered from the generated waveform by Hilbert transform. The TBWP of the generated chirp waveform is calculated to be 58.5. Fig. 3(d) shows the normalized autocorrelation. The width of the compressed pulse is 0.090 ns. Considering the temporal width of the microwave waveform is increased by 13 times, the pulse compression ratio is also increased by 13 times, which is 55.12. This value is close to the theoretical value of 58.5.

To generate a chirped microwave waveform with a higher TBWP, a 20480-bit PN sequence is used for phase coding and a phase-coded chirped waveform with a temporal duration of 10 μs is generated. Fig. 3(e) shows the normalized autocorrelation. The width of the compressed pulse is about 0.100 ns. Since the temporal width of the microwave waveform is increased by 20480 times, the pulse compression ratio is also increased by 20480 times, which is 86835. The TBWP of the generated waveform exceeds 80,000. The PSR is 8.9 dB, which is significantly reduced. In the experiment, because of the misalignment of the axes of the orthogonally polarized light waves from the OEO with the principle axes of the PolM, a chirp-free microwave waveform is generated. The auto-correlation of a chirp-free microwave waveform generates a triangle pulse, as can be seen from Fig. 3(e), which leads to a reduced PSR.

IV. Conclusion

A novel approach to generating a phase-coded chirp microwave waveform with an increased TBWP was proposed and experimentally demonstrated. The key to increase the TBWP was to use phase coding, to increase the temporal duration of the microwave waveform, which was done by phase coding a seed chirped microwave waveform generated by an OEO. The proposed approach was demonstrated by an experiment in which two phase-coded chirped microwave waveforms with the phase coding signals being a 13 Barker code and a 20840 bit PN sequence were generated, with TBWPs of 58.5 and 80000, respectively.

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