Photonic generation of a phase-coded microwave signal based on a single dual-drive Mach–Zehnder modulator

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A compact scheme for photonic generation of a phase-coded microwave signal using a dual-drive Mach–Zehnder modulator (DMZM) is proposed and experimentally demonstrated. In the proposed scheme, the radio frequency (RF) carrier and the coding signal are sent to the two RF ports of the DMZM, respectively. By properly setting the amplitude of the coding signal and the bias voltage of the DMZM, an exact π-phase-shift phase-coded microwave signal is generated. The proposed scheme has a simple structure since only a single DMZM is required. In addition, good frequency tunability is achieved because no frequency-dependent electrical devices or wavelength-dependent optical devices are applied. The feasibility of the proposed scheme is verified by experiment. 2 or 2.5 Gb/s phase-coded 10 and 20 GHz microwave signals are successfully generated.   © 2013 Optical Society of America

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To increase the spatial resolution and sensitivity in radar systems, a phase-coded pulse-compression technique is widely adopted [1]. Conventionally, a phase-coded microwave signal is generated in the electrical domain exploiting direct digital synthesizers (DDS). Since the DDS has a limited operation frequency (usually less than a few GHz), to achieve a phase-coded microwave signal in the high-frequency regime, a frequency up-conversion scheme is needed, which may introduce significant amplitude and phase distortions to the generated signal. In order to overcome these problems, generation of the phase-coded microwave signals in the optical domain was proposed and demonstrated [2–9], which features a large bandwidth, low loss, small size, and immunity to electro-magnetic interference. Previously, a phase-coded microwave-signal-generation scheme was realized by a spatial light modulator (SLM) based spectral shaping followed by frequency-to-time mapping [2]. The system is flexible because the spectral response of the SLM can be updated in real time. However, the inefficient coupling between the optical fibers and the free space leads to huge insertion loss and high complexity. On the other hand, schemes based on pure fiber optics are attractive due to the relatively low loss and compact structure [3–14]. For example, a phase-coded microwave signal can be generated based on a four-tap photonic microwave delay-line filter [3]. The main limitation of this approach is that the length of the pattern of the coding signal is equal to the number of the taps; thus it is difficult to achieve a high-pulse-compression ratio. Another way to generate the phase-coded microwave signal relies on carrier-suppressed modulation and phase modulation [4–6]. In this approach, the two sidebands generated by carrier-suppressed modulation are first split by a wavelength-dependent device, so that phase modulation is performed to one sideband. The two sidebands are then recombined and heterodyned at a photodetector (PD) to generate the phase-coded microwave signal. The key problem associated with this approach is that a high-Q optical filter is required to effectively split the two sidebands, which is typically unstable and has a small operation bandwidth. Phase-coded microwave signals also can be generated by mapping the two sidebands of the carrier-suppressed modulation signal into two orthogonal polarization directions followed by polarization modulation [7,8]. However, these systems usually operate at a fixed microwave frequency because the methods to make the two sidebands orthogonally polarized are based on a certain length of polarization maintaining fiber [7] or a specific polarization-maintaining fiber Bragg grating (FBG) [8]. Ghelfi *et al.* also proposed schemes for photonic generation of a phase-coded signal using a mode-locked laser and optical filter [9,10]. Because the phase-coded signal is actually generated in the electrical domain by DDS, the time-bandwidth product is small. In addition, phase coding of a microwave signal can be realized by a photonic microwave phase shifter with a fast phase-tuning speed [11], but schemes in this category are always complex. Recently, a scheme to generate a phase-coded signal employing a polarization modulator followed by a phase modulator was proposed [12]. It should be noted that most of the above approaches require two or more electro-optics modulators. To achieve low cost and reduce the system complexity, it is highly desirable to generate the phase-coded microwave signals using a single modulator [13,14]. In [13], a phase-coded signal based on the asymmetric phase-modulation indexes of a phase modulator in the TE and TM polarization states is obtained. But the radio frequency (RF) carrier and the coding signal should be applied to the modulator using a wideband microwave coupler. Thanks to the high integration of the dual-parallel Mach–Zehnder modulator (DPMZM), a phase-coded signal can be generated only using a single DPMZM [14]. However, it needs three bias voltages to maintain the phase shift, which makes this method unstable and hard to control.

In this Letter, we propose and experimentally demonstrate a compact and cost-effective scheme for photonic generation of phase-coded microwave signals using a single dual-drive Mach–Zehnder modulator (DMZM). The microwave carrier signal and the coding signal are sent to the two RF ports of the modulator, respectively. By properly setting the amplitude of the coding signal and the bias-voltage applied to the modulator, a phase-coded microwave signal with an exact π phase shift is generated. Compared with most of the previously reported methods, the proposed scheme has a simple structure and good frequency tunability because only one modulator is adopted and no frequency-dependent electrical devices or wavelength-dependent optical devices are used.

Figure 1 shows the schematic diagram of the proposed scheme for phase-coded microwave-signal generation. Continuous-wave (CW) light from a tunable laser source (TLS) is sent to a DMZM. When the microwave carrier signal and the binary coding signal $s(t)$ are applied to the two RF ports of the DMZM, respectively, the optical field at the output of the DMZM can be written as

$$E_1 = e^{j\omega_c t}[e^{j\beta \cos \omega_{RF} t} \cdot e^{j\phi_0} + e^{j\gamma s(t)}], \qquad (1)$$

where ω_c is the angular frequency of the optical carrier, ω_{RF} is the angular frequency of the microwave signal, $\beta = \pi V_{RF}/V_\pi$ and γ are the modulation indices in the two arms of the DMZM, V_{RF} is the amplitude of the microwave signal, V_π is the half-wave voltage of the DMZM, and ϕ_0 is the phase difference between the two arms, which can be tuned by changing the bias voltage applied to the DMZM.

Based on the Jacobi–Anger expansions, and considering small-signal modulation, Eq. (1) can be expanded to be

$$E_1 = [J_0(\beta)e^{j\omega_c t}e^{j\phi_0} + jJ_1(\beta)e^{j\phi_0}e^{j(\omega_c - \omega_{RF})t}$$
$$+ jJ_1(\beta)e^{j\phi_0}e^{j(\omega_c + \omega_{RF})t} + e^{j\omega_c t}e^{j\gamma s(t)}], \qquad (2)$$

where J_n is the nth order Bessel function of the first kind. When the signal in Eq. (2) is directed to a PD, the AC term of the detected signal is given by
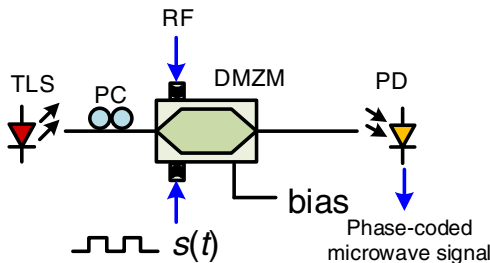

Fig. 1.   Schematic diagram of the proposed photonic phase-coded microwave signal generator. TLS, tunable laser source; PC, polarization controller; DMZM, dual-drive Mach–Zehnder modulator; PD, photodetector.

$$i_{AC} \propto J_1(\beta) \sin(\omega_{RF} t + \gamma s(t) - \phi_0)$$
$$- J_1(\beta) \sin(\omega_{RF} t - \gamma s(t) + \phi_0)$$
$$+ J_0(\beta) \cos(\gamma s(t) - \phi_0)$$
$$= 2J_1(\beta) \cos(\omega_{RF} t) \sin(\gamma s(t) - \phi_0)$$
$$+ J_0(\beta) \cos(\gamma s(t) - \phi_0). \qquad (3)$$

By tuning the bias voltage to let $\phi_0 = \pi/2$, Eq. (3) can be simplified as

$$i_{AC} = -2J_1(\beta) \cos(\omega_{RF} t) \cos(\gamma s(t)) + J_0(\beta) \sin(\gamma s(t)). \qquad (4)$$

As can be seen from Eq. (4), $J_0(\beta) \sin(\gamma s(t))$ is located at the baseband, which can be easily eliminated by an electrical filter or an antenna. If $\gamma = \pi$, which can be realized by setting the amplitude of $s(t)$ to be V_π, the obtained signal is

$$i = \begin{cases} 2J_1(\beta) \cos(\omega_{RF} t) & \text{for } s(t) = 1 \\ 2J_1(\beta) \cos(\omega_{RF} t + \pi) & \text{for } s(t) = 0 \end{cases}. \qquad (5)$$

As can be seen from Eq. (5), an exact π phase shift is obtained between bit "1" and bit "0" while the magnitudes maintain the same. Thus a phase-coded microwave signal at an angular frequency of ω_{RF} is generated.

A proof-of-concept experiment is carried out based on the configuration shown in Fig. 1. CW light from a TLS (Agilent N7714A) is sent to a 40 GHz DMZM (Fujitsu FTM7937EZ). The half-wave voltage of the DMZM is 1.8 V. The microwave carrier signal is generated by an analog signal generator (Agilent E8267D), and the binary coding signal is generated by a pulse-pattern generator (Anritsu MP1763C). The output signal from the DMZM is observed by a 40 GHz oscilloscope (Agilent 86100A).

First, the microwave carrier frequency is set to be 10 GHz. The coding signal is a 2 Gb/s signal with a fixed pattern of "1010 1100," as shown in Fig. 2(a). Figure 2(b) shows the waveform of the generated phase-coded 10 GHz microwave signal. As can been seen, a clear phase shift is observed at each bit transition in the coding signal. The phase shift extracted from the generated signal is shown in Fig. 2(c). A π shift can be observed.
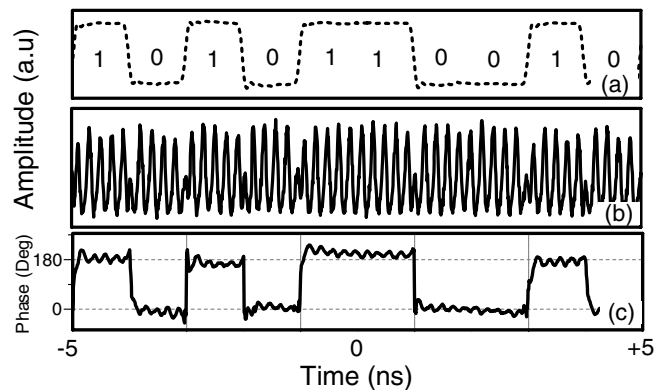

Fig. 2.   Waveforms of (a) the 2 Gb/s coding signal with a pattern of "1010 1100." (b) Phase-coded 10 GHz microwave signal. (c) Extracted phase shift of the generated signal.
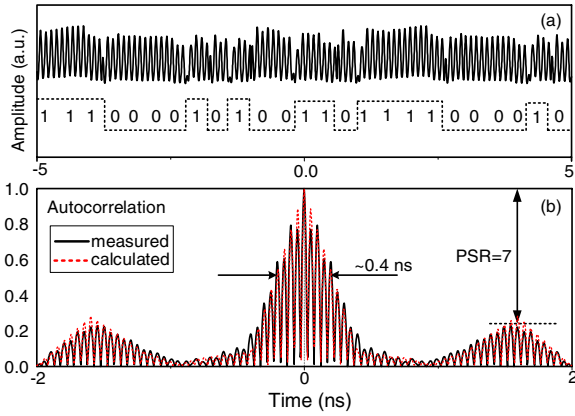
Fig. 3. (a) Waveform of the 2.5 Gb/s phase-coded 10 GHz microwave signal. (b) Autocorrelations of the measured (solid line) and calculated (dashed line) signals.

Then the pulse-compression capability of the generated phase-coded microwave signal is investigated. A 10 GHz microwave signal is modulated by a 2.5 Gb/s 16 bit coding signal with a pattern of "1111 0000 1010 0110." Figure 3(a) shows the waveform of the generated phase-coded microwave signal, in which the time duration is 6.4 ns. When this signal is compressed through autocorrelation, the resulting waveform is shown in Fig. 3(b). The FWHM of the autocorrelation peak is about 0.4 ns. The compression ratio is 16, and the peak-to-side-lobe ratio (PSR) is about 7.0. The autocorrelation of the calculated signal is also shown as the dashed line in Fig. 3(b). As can be seen, the measured result agrees well with the calculated one.

A distinctive advantage of the proposed scheme is the wideband operation-frequency range since no frequency-dependent electrical devices or wavelength-dependent optical devices are used. The only limitation is the bandwidth of the DMZM and the PD. To show the frequency tunability of the propose scheme, the frequency of the microwave signal is tuned to 20 GHz. When the coding signal is a 2 Gb/s signal with an 8 bit pattern of "0101 0101" as shown in Fig. 4(a), a phase-coded 20 GHz microwave signal is successfully generated, as shown in Fig. 4(b). The phase shift of the generated signal is shown in Fig. 4(c). Again, a π-shift phase-coded signal is achieved. To investigate the pulse-compression
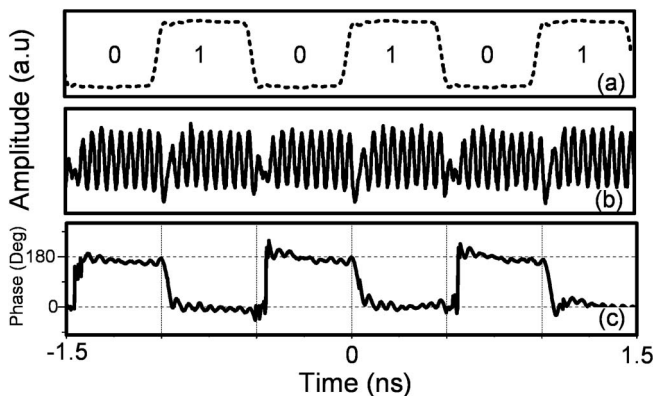

Fig. 4. (a) 2 Gb/s coding signal. (b) Measured phase-coded signal at 20 GHz with a pulse pattern of "0101 0101." (c) Phase shift of the generated phase-coded signal.
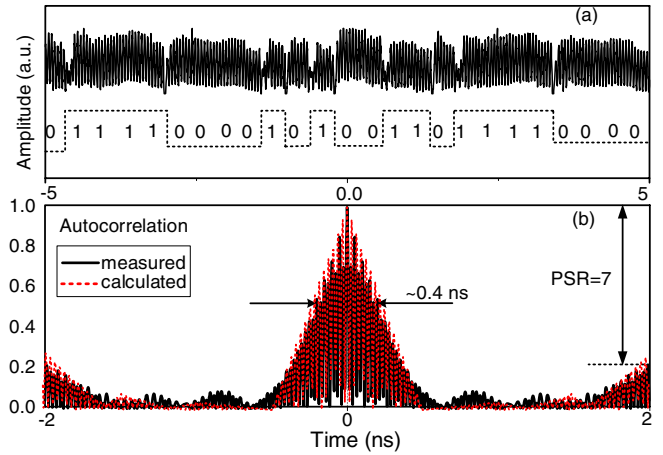

Fig. 5. (a) Waveform of the 2.5 Gb/s phase-coded 20 GHz microwave signal. (b) Autocorrelations of the measured (solid line) and calculated (dashed line) signals.

capability, a 2.5 Gb/s 16 bit coding signal with the pattern of "1111 0000 1010 0110" is applied to the DMZM. Figure 5(a) shows the waveform of the generated 20 GHz phase-coded signal with a time duration of 6.4 ns. The autocorrelation result is shown in Fig. 5(b). The FWHM of the peak pulse is about 0.4 ns. The pulse compression ratio is about 16, and the PSR is about 7. The calculated result also is given in Fig. 5(b). As can be seen, two nearly identical main-lobes are observed.

In conclusion, a novel photonic approach to generate a phase-coded microwave signal was proposed and demonstrated. The proposed scheme was constructed based on only a single modulator, which did not require assistance from the frequency-dependent electrical devices or wavelength-dependent optical devices, such as the optical filters, electrical combiners, or differential group delays. The feasibility of the proposed scheme and the pulse-compression capability were experimentally verified. 2 or 2.5 Gb/s phase-coded 10 and 20 GHz microwave signals were successfully generated. A pulse-compression ratio of 16 was achieved for a 16 bit coding pattern. Note that the pulse-compression performance is not as good as the reported results in [12–14], and it should be owed to the data rate and code length of the coding signal we used, which is much slower and shorter and is restricted by the sampling ability of our oscilloscope. The system features simple structure, wide tunability, and low cost, which can find applications in radar systems.

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