Generation of phase-coded microwave signals using a polarization-modulator-based photonic microwave phase shifter

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Received December 28, 2012; revised January 28, 2013; accepted January 31, 2013;
posted February 1, 2013 (Doc. ID 182541); published February 27, 2013

A scheme for the generation of phase-coded microwave signals using an electrically tunable photonic microwave phase shifter is proposed and demonstrated. The photonic phase shifter is based on a single-sideband polarization modulator (PolM), and the tuning of the phase shifter is implemented by a second PolM. By introducing an RF signal to the first PolM and an electrical coding signal to the second PolM, a phase-coded microwave signal with binary phase codes or polyphase codes is achieved. An experiment is performed. The simple and flexible operation, high coding rate, large frequency range, excellent transmission performance, and high stability of the system is confirmed. © 2013 Optical Society of America

OCIS codes: 070.1170, 050.5080, 350.4010.

Microwave pulse compression is of great importance for increasing the range resolution of the modern radar systems [1]. To perform the pulse compression, a linear frequency-modulated or phase-coded signal should be generated in the transmitter. Since the phase coding allows the radar to operate as a communications terminal and can reduce the radio frequency interference between the adjacent radars, there is growing interest in the generation of the phase-coded signal. Conventionally, the phase-coded signal is achieved in the electrical domain, which would suffer severely from the low operational frequency and small time–bandwidth product (TBWP). To overcome these problems, various approaches were proposed to generate the phase-coded signal in the optical domain, thanks to the inherent features of broad bandwidth, large tunability, and immunity to electromagnetic interference brought by the photonic technologies [2–8]. Previously, a Sagnac interferometer (SI) incorporated with a phase modulator (PM) was employed to produce the phase-coded signal [4]. When the two sidebands of the incoming optical microwave signal is sent to the SI, one sideband selected by a fiber Bragg grating is modulated at the PM. By beating the two sidebands at a photodetector (PD), the generated microwave signal is phase coded. The key limitation associated with this approach is that the interferometer would introduce serious phase variations due to its high sensitivity to the environmental vibrations and temperature variations. The phase-coded signal can also be generated based on a four-tap delay line microwave photonic filter [5]. By carefully adjusting the time delays in each arm, different phase shifts would be introduced to the microwave pulse. However, the maximal time segments of the phase-coded signal are determined by the number of the taps, so the system using this type of pulse generator cannot achieve a large pulse compression ratio. In [6] and [7], the phase-coded signal is generated by making the two sidebands of the incoming optical microwave signal orthogonally polarized followed by polarization modulation, but the method can only generate a phase-coded signal at a specific frequency. Ghelfi *et al.* also proposed two schemes for photonic upconversion of an intermediate frequency phase-coded signal to the high-frequency band based on a mode-locked laser [8,9]. Because the phase-coded signal is actually generated in the electrical domain, the TBWP is small.

In this Letter, a novel scheme for the generation of the phase-coded microwave signals is proposed and demonstrated, which comprises of a laser source, two polarization modulators (PolMs), an optical bandpass filter (OBPF), a polarization controller (PC), a polarizer, and a PD. One PolM together with the OBPF and the polarizer is used to form a photonic microwave phase shifter [10], and the other PolM is used to adjust the polarization direction of the polarizer, which changes the phase shift of the signal according to an electrical coding signal. A microwave signal with binary phase codes or polyphase codes is achieved. As compared with the previously reported methods, the proposed scheme features simple and flexible operation, high coding rate, large frequency range, excellent transmission performance, and high stability.

Figure 1 shows the schematic of the proposed phase-coding system. A linearly polarized optical carrier with its polarization direction oriented to have an angle of 45° to one principal axis of a PolM (PolM1) is emitted from a laser source and then introduced into PolM1, which is driven by an RF source. To perform the single-sideband (SSB) modulation, an OBPF is followed to suppress one

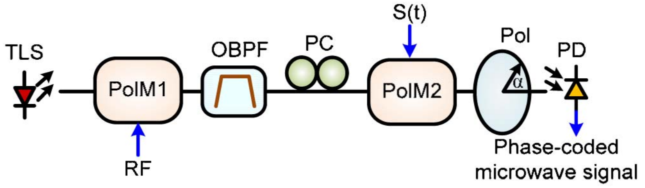

Fig. 1. (Color online) Schematic diagram of the proposed photonic phase coding system. TLS, tunable laser source; PC, polarization controller; PolM, polarization modulator; OBPF, optical bandpass filter; Pol, polarizer; PD, photodetector.

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sideband of the polarization-modulated signal [10]. The optical field of the SSB signal can be written as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \exp(j\omega_o t)\begin{bmatrix} \exp(j\varphi_1)[J_0(\gamma)+jJ_1(\gamma)\exp(j\omega_m t)] \\ J_0(\gamma)-jJ_1(\gamma)\exp(j\omega_m t) \end{bmatrix}, \tag{1}$$

where ω_o is the angular frequency of the optical carrier, ω_m is the angular frequency of the RF signal, γ is the phase modulation index, and φ_1 is the phase difference between E_x and E_y, which can be controlled by the DC bias of the PolM.

A PC and a second PolM (PolM2) driven by an electrical signal $s(t)$ are employed to control the polarization state of the optical microwave signal, which can be then expressed as

$$\begin{aligned} E_x \propto{}& \cos\theta\,\exp(j\omega_o t + j\varphi_1 + j\varphi_2 + j\beta s(t))[J_0(\gamma) \\ &+ jJ_1(\gamma)\exp(j\omega_m t)] \\ &+ \sin\theta\,\exp(j\omega_o t + j\beta s(t))[J_0(\gamma) \\ &- jJ_1(\gamma)\exp(j\omega_m t)], \end{aligned} \tag{2a}$$

$$\begin{aligned} E_y \propto{}& -\sin\theta\,\exp(j\omega_o t + j\varphi_1 - j\beta s(t))[J_0(\gamma) \\ &+ jJ_1(\gamma)\exp(j\omega_m t)] \\ &+ \cos\theta\,\exp(j\omega_o t - j\varphi_2 - j\beta s(t))[J_0(\gamma) \\ &- jJ_1(\gamma)\exp(j\omega_m t)], \end{aligned} \tag{2b}$$

where θ is a parameter of the PC, φ_2 can be controlled by the PC or the DC bias of PolM2, and β is the phase modulation index of PolM2.

A polarizer with its principal axis oriented by an angle of 45° to one principal axis of PolM2 is incorporated to combine E_x and E_y. When $\theta = \pi/4$, $\varphi_1 = \pi/2$, and $\varphi_2 = \pi/2$, we have

$$\begin{aligned} E_{\mathrm{out}}(t) \propto{}& J_1(\gamma)\exp(j\omega_o t + j\omega_m t + j\beta s(t)) \\ &+ J_0(\gamma)\exp(j\omega_o t - j\beta s(t)). \end{aligned} \tag{3}$$

Leading the signal to a PD for square-law detection, the AC term of the output current can be written as

$$I_{\mathrm{AC}}(t) \propto J_0(\gamma)J_1(\gamma)\cos(\omega_m t + 2\beta s(t)). \tag{4}$$

As can be seen from (4), the generated signal has an angular frequency of ω_m, and a phase term of $2\beta s(t)$, so it is a phase-coded microwave signal.

The PC can be removed from the scheme since θ is fixed at $\pi/4$, which can be implemented by introducing a certain rotation angle when splicing the polarization maintaining pigtails of the OBPF and PolM2, and φ_2 can be adjusted by the DC bias of PolM2. The elimination of PC in the system would make the operation of the scheme very simple. The long-term stability can also be improved. If there is a need to transmit the generated phase-coded signal to a remote site, the signal before photodetection can tolerate large fiber dispersion because it is an SSB signal. The operation frequency and the coding rate can be extremely high thanks to the more than 50 GHz bandwidth of the state-of-the-art PolM [11]. In addition, the scheme is based on a straight-forward configuration, so the stability should be high.

A proof-of-concept experiment is carried out based on the configuration shown in Fig. 1. The 3 dB bandwidth and the half-wave voltage of the PolMs (Versawave Inc.) are 40 GHz and 3.5 V, respectively. The tunable OBPF (Yenista XTM-50) has an edge slope of more than 500 dB/nm, which can effectively remove one sideband of the polarization-modulated signal without affecting the other sideband and the optical carrier. The RF signal is generated by an RF signal generator (Agilent E8267D, 43 GHz), and $s(t)$ is generated by a pulse pattern generator (Anritsu MP1763C, 12.5 Gb/s). The peak voltage of the RF signal and the coding signal is 2 V. The PD has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The electrical signals are measured by a 40 GHz oscilloscope (Agilent 86100A).

Figure 2(a) shows the 3.125 Gb/s coding signal with a pulse pattern of "0101," and Figs. 2(b) and 2(c) show the simulated and the experimental results of the phase-coded 12.5 GHz microwave signal. As can be seen, there are phase jumps in the phase-coded signal which are exactly at the rising and falling edges of the coding signal. The experimental result agrees with the simulated result very well. The small difference is mainly because the edges of the coding signal in the experiment are not as steep as those in the simulation, and the resolution of the oscilloscope used in the experiment is not high enough to resolve the fine structures. The generated photonic phase coded signal is transmitted through an 8 km

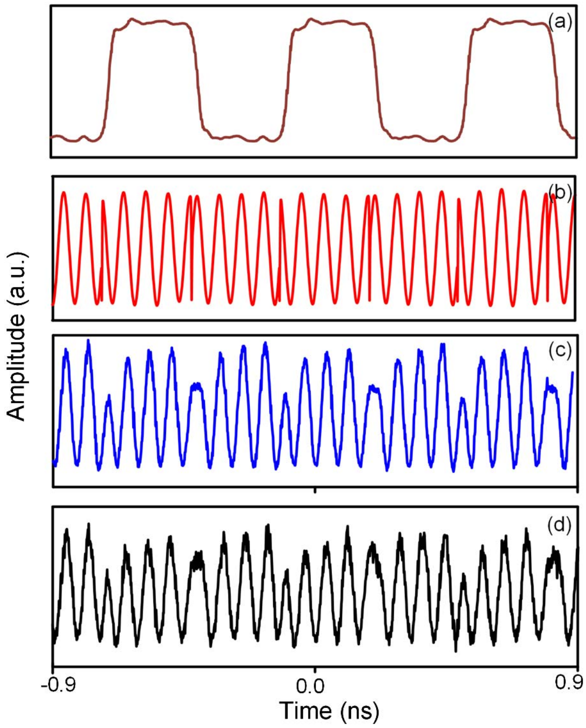

Fig. 2. (Color online) (a) 3.125 Gb/s pulse pattern of "0101", (b) the simulated, and (c) the measured phase-coded microwave signal at 12.5 GHz. (d) The waveform of the phase-coded microwave signal after transmission in an 8 km SSMF.

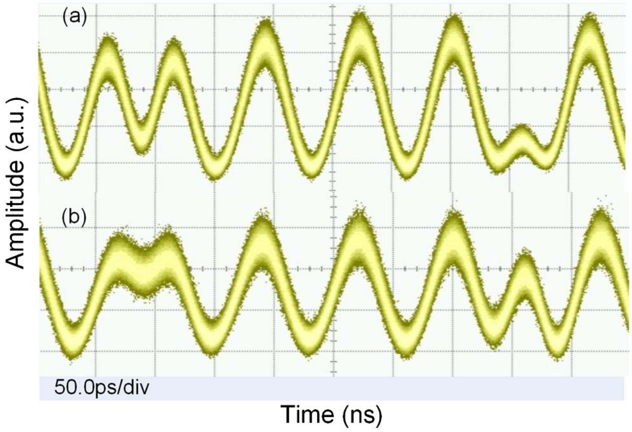

Fig. 3. (Color online) Eye diagrams of the generated phase-coded signals with different phase shifts.

standard single-mode fiber (SSMF). Figure 2(d) shows the waveform after the fiber transmission. As can be seen, no evident degradation in the amplitude and phase can be observed, indicating that the proposed system has a high tolerance to the fiber dispersion. The waveform of the phase-coded 12.5 GHz microwave signals are observed for more than 30 min in the laboratory environment. No significant variation is observed. Good stability of the system is confirmed.

By tuning the power level of the coding signal, which changes β in (4), phase-coded signals with different phase shifts in the adjacent segments can be achieved, as can be seen in Fig. 3, which indicates that a microwave signal with polyphase codes can be achieved if a multilevel amplitude-modulated coding signal is introduced to PolM2.

To investigate the possibility of the scheme to be operated at a high frequency with high coding rate, a 40 GHz microwave signal is introduced to PolM1 and a 10 Gb/s 8 bit coding signal with a pattern of "10101100" is applied to PolM2. Figure 4(a) shows the waveform of the generated phase-coded 40 GHz microwave signal. Because 40 GHz is the upper limit of the oscilloscope, the 40 GHz signal on the oscilloscope has a poor quality. However, the phase jumps can still be clearly observed. Figure 4(b) shows the autocorrelation of the phase-coded 40 GHz microwave signal calculated by Matlab. The autocorrelation peak has a FWHM of ~60 ps, giving a compression ratio of ~13.3.

In conclusion, a novel approach to generate a phase-coded microwave signal using an SSB-PolM-based photonic microwave phase shifter was proposed and experimentally demonstrated. A 40 GHz microwave signal was successfully phase coded by a 10 Gb/s coding signal. The signal could be transmitted in an 8 km SSMF without significant distortion, and the generated waveform kept stable for more than 30 min in the laboratory environment. The system is simple and compact, which can find applications in modern radar systems and wireless communications.

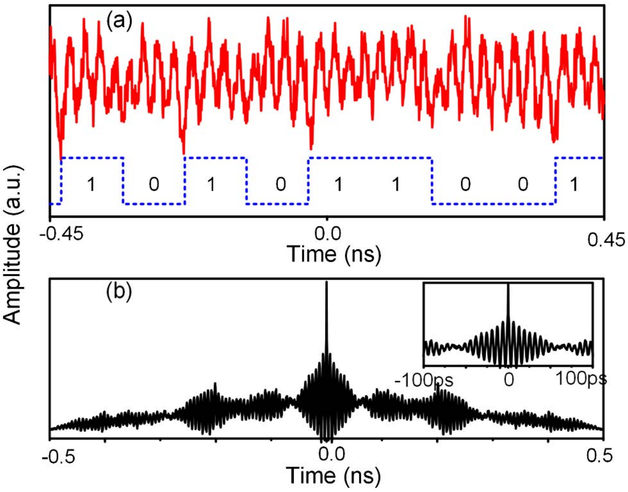

Fig. 4. (Color online) (a) Generated phase-coded 40 GHz signal and (b) calculated autocorrelation of the 40 GHz phase-coded signal.

This work was supported in part by the National Basic Research Program of China (2012CB315705), the National Natural Science Foundation of China (61107063), the Jiangsu Provincial Funds for Distinguished Young Scientists (BK2012031), the Fok Ying Tung Education Foundation, the Fundamental Research Funds for the Central Universities (NE2012002), and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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