Abstract—A novel phase-coded microwave signal generator based on two cascaded polarization modulators (PolMs) is proposed and demonstrated. One of the cascaded PolM together with an optical bandpass filter (OBPF) is used to convert a RF signal to a single-sideband (SSB) polarization-modulated optical signal, and the other PolM is used to control the phase of the RF signal according to an electrical coding signal. A phase-coded microwave signal with binary phase codes or polyphase codes is thus generated. An experiment is performed. The simple and flexible operation, high coding speed, large frequency range, excellent transmission performance and high stability of the system is confirmed.

Keywords—Microwave photonic filter, microwave photonic phase shifter, analog optical signal processing, microwave photonics.

I. Introduction

Because of the capability for improving the range resolution of modern radar systems, microwave pulse compression has drawn great attentions in the past few decades [1]. To perform the pulse compression, the generation of phase-coded signals in the transmitter is of great interests. Thanks to the inherent features of broad bandwidth, large tunability and immunity to electromagnetic interference brought by the photonic technologies, various approaches were proposed recently to generate the phase-coded signals in the optical domain [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 (FBG) 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 (IF) 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 time-bandwidth product is small.

Figure 1 shows the schematic diagram of the proposed photonic phase coded system.

In this paper, a novel phase-coded microwave signal generator based on two cascaded polarization modulators (PolMs) is proposed and demonstrated. The first PolM is used to convert a RF signal to a double sideband polarization-modulated signal. An optical bandpass filter (OBPF) is followed to remove one sideband of the optical RF signal, converting it to a single-sideband (SSB) optical signal. By inserting a polarizer, a photonic microwave phase shifter is formed [10]. The other PolM is inserted between the OBPF and the polarizer to adjust the polarization state of the optical signal, which can change the phase of the RF signal according to an electrical coding signal. A phase-coded microwave signal with binary phase codes or polyphase codes is thus generated. 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.

II. Principle

Figure 1 shows the schematic diagram of the proposed phase-coded microwave signal generator. 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 a RF source. To perform the SSB modulation, an OBPF is followed to suppress one sideband of the polarization-modulated signal [10]. The optical field of the SSB signal can be written as

\[
E_o(t) = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \begin{bmatrix} \exp(j\omega_0 t) [I_x(\gamma) + jI_y(\gamma) \exp(j\phi^M)] \\ j\omega_0 t - jI_y(\gamma) \exp(-j\omega_0 t) \end{bmatrix}
\]  

(1)

where \( \omega_0 \) is the angular frequency of the optical carrier, \( \omega_{RF} \) is the angular frequency of the RF signal, \( \gamma \) is the phase modulation index and \( \phi^M \) 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 \( s(t) \) is employed to control the polarization state of the optical microwave signal, which can be then expressed as

\[
E_x(t) = \cos \theta \exp(j\omega_{RF} t + j\phi^P \beta s(t)) [I_x(\gamma) + jI_y(\gamma) \exp(j\phi^M)] + \sin \theta \exp(j\omega_{RF} t + j\phi^P \beta s(t)) [I_y(\gamma) - jI_x(\gamma) \exp(j\phi^M)]
\]

\[
E_y(t) = -\sin \theta \exp(j\omega_{RF} t + j\phi^P \beta s(t)) [I_x(\gamma) + jI_y(\gamma) \exp(j\phi^M)] + \cos \theta \exp(j\omega_{RF} t + j\phi^P \beta s(t)) [I_y(\gamma) - jI_x(\gamma) \exp(j\phi^M)]
\]

(2a)

(2b)

where \( \theta \) is a parameter of the PC, \( \phi^P \) can be controlled by the PC or the DC bias of PolM2, and \( \beta \) 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 \( \theta = \pi/4 \), \( \phi^P = \pi/2 \), and \( \beta = \pi/2 \), we have

\[
E_{out}(t) = 2I_x(\gamma) \exp(j\omega_{RF} t + j\phi^M) + 2jI_y(\gamma) \exp(j\omega_{RF} t + j\phi^P \beta s(t))
\]

(3)

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

\[
I(t) = E_{out}(t)E^*_{out}(t) = 4J_x(\gamma)J_y(\gamma) \cos(\omega_{RF} t + 2\phi^P \beta s(t))
\]

(4)

As can be seen from (4), the generated signal has an angular frequency of \( \omega_{RF} \), and a phase term of \( 2\phi^P \beta s(t) \), so it is a phase-coded microwave signal.

Since \( \theta \) is fixed at \( \pi/4 \) and \( \phi^P \) can be adjusted by the DC bias of PolM2, the PC can be removed from the scheme, which would make the operation of the scheme very simple. 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 a 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 straightforward configuration, so the stability should be high.

### III. Experimental Demonstration

An 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 a RF signal generator (Agilent E8267D, 43 GHz), and \( s(t) \) is generated by a pulse pattern generator (Agilent 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](image316x443 to 323x538)

Figure 2. (a) The 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 standard single-mode fiber (SSMF).

Figure 2(a) shows the 3.125-Gb/s coding signal with a pulse pattern of “0101”, and Fig. 2(b) and (c) shows 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 experiment result agrees with the simulated result very well. The small difference is mainly because that 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 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
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 minutes in the laboratory environment. The system is simple and compact, which can find applications in modern radar systems and wireless communications.

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