Generation of a Frequency-Quadrupled Phase-Coded Signal With Large Tunability

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***Abstract*— A photonic approach for frequency-quadrupled phase-coded signal generation with large tunability is proposed and demonstrated. In the proposed scheme, a dual-parallel Mach–Zehnder modulator is used to generate two second-order optical sidebands, which are made orthogonally polarized in a Sagnac loop incorporating a fiber Bragg grating. Then, a polarization modulator is employed to perform phase coding with high coding rate. A distinct advantage of this approach is the capability to generate a phase-coded signal with a large frequency tuning range, from several megahertz to more than 100 GHz. A proof-of-concept experiment is carried out. The generation of a 2.5-Gb/s phase-coded signal with a frequency tuning from 13 to 30 GHz is experimentally verified.**

***Index Terms*— Microwave signal generation, phase coding, radar pulse compression, microwave photonics.**

I. INTRODUCTION

THE generation of phase-coded microwave or millimeter-wave (mm-wave) signals is of great importance for modern radar systems with high resolution. Conventionally, the phase-coded signals are generated in the electrical domain, which has the limitations of low central frequency and small time-bandwidth product (TBWP). In some radar systems, however, the central frequency can reach tens or even hundreds of GHz [1]. Compared with the electrical approaches, photonic methods can possibly generate high frequency, wide tuning range and large TBWP phase-coded signals.

Various schemes for photonic generation of phase-coded signals have been demonstrated. One typical method is based on optical spectral shaping followed by frequency-to-time mapping [2], [3]. The spectral shaping can be realized based on a spatial light modulator (SLM) or a specially designed fiber Bragg grating (FBG). However, the SLM-based approach is bulky and lossy, while the FBG-based approach has poor tunability. The phase-coded signal can also be generated by heterodyning two phase-correlated optical wavelengths. In this kind of method, a phase modulator is usually incorporated in a Michelson, Mach-Zehnder or Sagnac interferometer to perform the phase coding [4]–[6]. One key problem associated with these schemes is their poor stability due to the physical separation and independent modulation of the two wavelengths. To overcome this problem, polarization modulation based approaches were proposed [7]–[12], in which two orthogonally-polarized wavelengths are first generated and then complementarily phase modulated in a polarization modulator (PolM). One of the key steps in these approaches is the generation of the orthogonally-polarized wavelength pair, which can be realized by employing a differential group delay (DGD) element [7], a polarization-maintaining FBG (PM-FBG) [8], a PolM followed by an optical filter (OF) [9]–[11], or a dual-parallel polarization modulator [12]. However, all these approaches can only generate a phase-coded signal in a relatively small frequency range which is limited by the frequency dependence of the optical components or the bandwidth of the modulators and electrical devices. To increase the frequency range of the photonic microwave phase-coded signal, frequency multiplication with high multiplication factor is highly desired. Previously, schemes for frequency-doubled phase-coded signal generation were reported [7], [11], [12], but the frequency multiplication factors are small, which can hardly support high frequency applications. Generation of a frequency-quadrupled phase-coded signal was also demonstrated [8], but its frequency tuning range is dependent on the polarization response of a PM-FBG. In addition, some of the reported frequency-multiplied phase-coded signal generators rely on 90° electrical hybrids for undesired sidebands suppression, which would restrict the frequency tuning range and the spectral purity since electrical hybrids always have a limited bandwidth and poor phase accuracy.

In this letter, we propose an approach to generate a frequency-quadrupled phase-coded signal with large frequency tunability. A dual-parallel Mach-Zehnder modulator (DPMZM) is used to generate two second-order optical sidebands. Then the two sidebands are made orthogonally polarized in a FBG-based Sagnac loop and phase modulated in a PolM. After beating the two modulated

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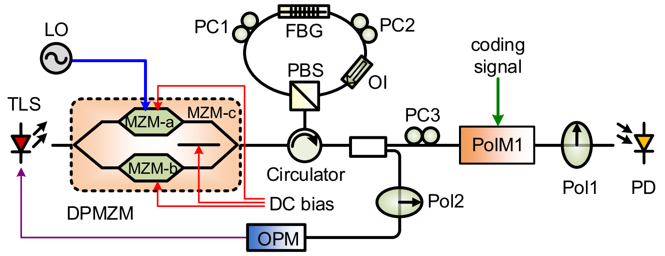

Fig. 1. Schematic diagram of the proposed frequency-quadrupled phase-coded signal generator. LO, local oscillator; TLS, tunable laser source; DPMZM, dual-parallel Mach-Zehnder modulator; PBS, polarization beam splitter; PC, polarization controller; FBG, fiber Bragg grating; OI, optical isolator; PolM, polarization modulator; Pol, polarizer; PD, photodiode; OPM, optical power monitor.

sidebands in a photodiode (PD), a frequency-quadrupled phase-coded signal is generated. The lowest frequency of the generated signal is half of the notch bandwidth of the FBG, which can be as low as several MHz [13], while the upper bound of the frequency range is four times the bandwidth of the DPMZM. As a result, a phase-coded signal from several MHz to more than 100 GHz can be possibly generated. In addition, no 90° electrical hybrid is used, guaranteeing again the large frequency tuning range.

II. PRINCIPLE

Fig. 1 shows the schematic diagram of the proposed frequency-quadrupled phase-coded signal generator. A linearly polarized light wave from a tunable laser source (TLS) is sent to a DPMZM. The DPMZM consists of two sub-MZMs (MZM-a and MZM-b) and a main MZM (MZM-c). A radio-frequency (RF) signal from a local oscillator (LO) is applied to MZM-a, which is biased at the maximum transmission point to generate an optical carrier and two second-order sidebands. MZM-b is not driven by the RF signal, but biased to generate an optical carrier which has identical power as the optical carrier from MZM-a. MZM-c is biased to let the two optical carriers from the two sub-MZMs out of phase. As a result, two second-order sidebands with carrier suppressed are obtained without the use of a 90° electrical hybrid. The two sidebands are then sent to a Sagnac loop through an optical circulator and a PBS. In the loop, the counter-clockwise transmitted signal is blocked by an optical isolator (OI), while the clockwise transmitted two wavelengths are separated by a FBG, i.e. the −2nd-order sideband is reflected back and the +2nd-order sideband is passed through the FBG. By adjusting the polarization controllers (PC1 and PC2) in the loop, the two separated wavelengths are polarization multiplexed at the polarization beam splitter (PBS). Therefore, a pair of orthogonally-polarized wavelengths are generated. The two polarization-multiplexed sidebands are then complementarily phase modulated in a PolM by a coding signal $s(t)$ with an amplitude of V. The optical signal at the output of the PolM is given by

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} \propto E_{in}(t)\, J_2(m) \begin{bmatrix} \exp[-j2\omega t - j\beta s(t)] \\ \exp[j2\omega t + j\beta s(t)] \end{bmatrix} \quad (1)$$

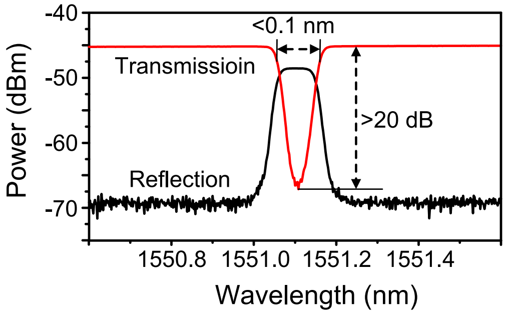

Fig. 2. Transmission and reflection responses of the FBG.

where $E_{in}(t)$ is the field of the optical carrier from the TLS, m is the modulation index of the DPMZM, ω is the angular frequency of the RF signal, J_n is the nth-order Bessel function of the first kind, $\beta = \pi V/V_\pi$ is the phase modulation index of the PolM, V_π is the half-wave voltage of the PolM, x and y represent the two principal axes of the PolM. The modulated optical signal output from the PolM is sent to a polarizer (Pol1) to project the two orthogonally-polarized sidebands in the same direction. After square-law detection in a PD, the generated electrical signal can be expressed as

$$i(t) \propto E_{in}^2(t) J_2^2(m) \cos[4\omega t + 2\beta s(t)] \quad (2)$$

As can be seen, a frequency-quadrupled signal phase modulated by $s(t)$ is generated.

To adjust the frequency of the generated phase-coded signal, the frequency of the RF signal should be changed. Then, the wavelength of the optical signal from the TLS is tuned accordingly to make the −2nd-order sideband located in the notch of the FBG. To do this, a feedback circuit can be utilized, as shown in Fig. 1. The optical signal is tapped out after the circulator, which is sent to a polarizer (Pol2). The direction of the polarizer is adjusted to select the sideband reflected by the FBG. An optical power monitor (OPM) is inserted to obtain the error signal to control the wavelength of the TLS.

The lowest frequency of the generated signal is limited by the notch bandwidth of the FBG. The smaller the notch bandwidth of the FBG is, the lower the frequency of the phase-coded signal can be reached. Recently, an ultra-narrow FBG with a notch bandwidth of 9 MHz was reported [13], indicating that the proposed approach can achieve a phase-coded signal with a frequency as low as several MHz. The upper bound of the frequency tuning range is four times the maximum frequency of the drive signal source and the bandwidth of the DPMZM, which can reach 40 GHz in laboratory environment. As a result, a phase-coded signal from several MHz to more than 100 GHz can possibly be generated with the proposed scheme.

III. EXPERIMENT RESULTS AND DISCUSSION

A proof-of-concept experiment based on the setup shown in Fig. 1 is performed. First, the transmission and reflection spectra of the FBG are measured by using a broadband optical source and an optical spectrum analyzer (Yokogawa AQ6370C) with a resolution of 0.02 nm. As shown in Fig. 2,

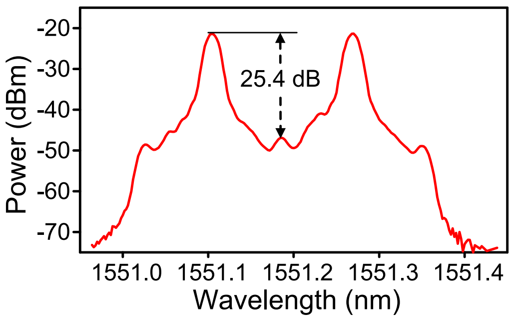

Fig. 3. The optical spectrum at the output of the DPMZM.

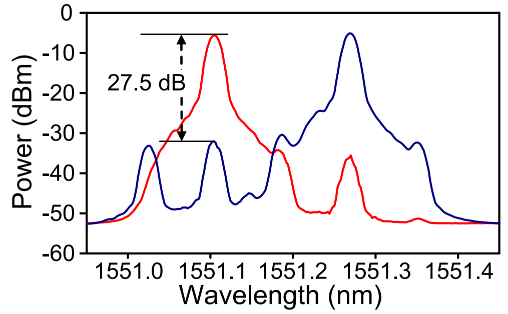

Fig. 4. The optical spectra of the orthogonally polarized signals split by a PBS.

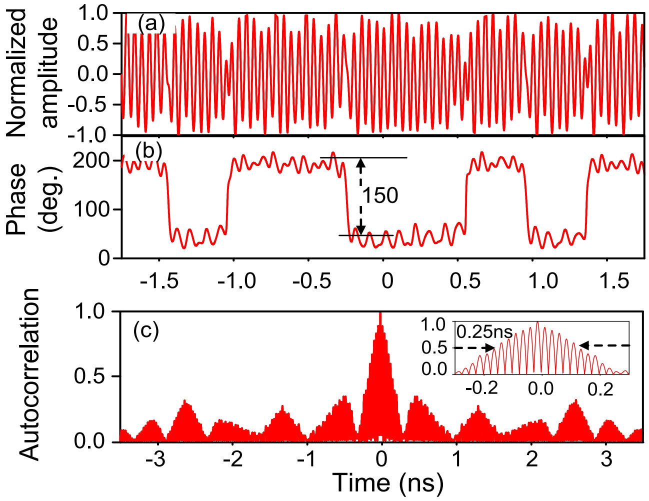

Fig. 5. (a) The waveform of the 2.5-Gbit/s phase-coded 20-GHz signal, (b) the recovered phase profile, and (c) the autocorrelation. Inset: zoom-in view of the peak of the autocorrelation.

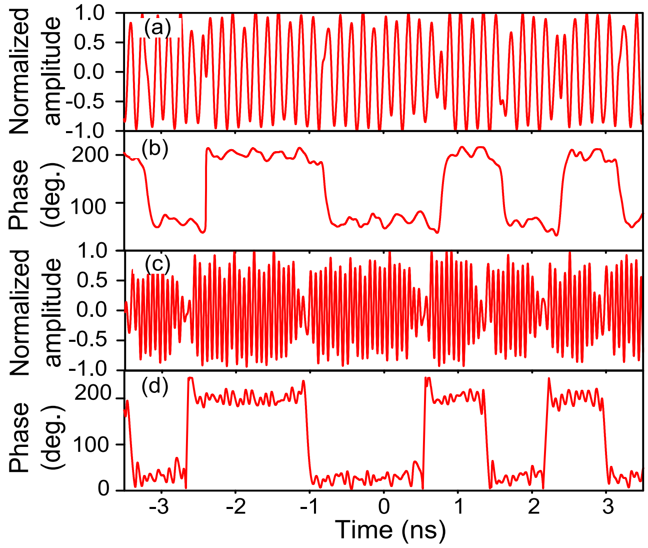

Fig. 6. (a) The waveform and (b) the recovered phase profile of the 2.5-Gbit/s phase-coded 13-GHz signal, and (c) the waveform and (d) the recovered phase profile of the 2.5-Gbit/s phase-coded 30-GHz signal.

the central wavelength of the FBG is 1551.104 nm, and the 3-dB bandwidth is less than 0.1 nm.

Then, a RF signal from a signal generator (Agilent E8257D) with a frequency of 5 GHz and a power of 20.3 dBm is applied to the DPMZM (Fujitsu FTM7962EP). The bandwidth of the DPMZM is about 28 GHz. A light wave from a TLS (Agilent N7714A) with a power of 16 dBm is tuned to have a wavelength of 1551.185nm. A modulator bias controller (YY LABS Inc. D0156) is used to control the DC bias of the DPMZM. Fig. 3 shows the optical spectrum at the output of the DPMZM. The two second-order sidebands are 25.4-dB higher than the optical carrier and other sidebands. In addition, the −2nd-order sideband is located at the center of the notch of the FBG.

To verify the polarization isolation of the polarization-multiplexed wavelengths after the Sagnac loop, another PBS is temporarily connected to the output of PC3. Fig. 4 shows the optical spectra of the two orthogonally polarized wavelengths at the two output ports of the PBS. As can be seen, the polarization distinction ratio between the two wavelengths is 27.5 dB.

The orthogonally-polarized wavelengths are sent to a PolM (Versawave Technologies) with a bandwidth of 40 GHz, to be modulated by a 2.5-Gbit/s 8-bit coding signal with a pattern of "10101100". A PD (u2t Photonics, XPDV2150R) with a bandwidth of 50 GHz is used for the optical to electrical conversion. The generated phase-coded signal is monitored by a 32-GHz digital storage oscilloscope (Agilent DSO-X 92504A). Fig. 5(a) shows the normalized waveform of the 20-GHz frequency-quadrupled phase-coded signal and Fig. 5(b) shows the corresponding recovered phase profile. As can be seen, the 20-GHz frequency-quadrupled signal is successfully phase coded, the phase shift between the bits "0" and "1" is about 150°. The pulse-compression capability of the generated signal is also investigated, with the autocorrelation curve shown in Fig. 5(c). The full width at half-maximum (FWHM) of the autocorrelation is 0.25 ns, and the time duration of phase-coded signal is 3.2 ns, corresponding to a compression ratio of about 12.8. The compression ratio can be improved by employing a longer code length.

To investigate the frequency tunability, the LO is tuned to 3.25 GHz while the TLS is tuned to 1551.156 nm. The two optical sidebands output from the DPMZM have a wavelength spacing larger than the half of the notch bandwidth of the FBG, as a result, they can still be sufficiently separated by the FBG. Figs. 6(a) and 6(b) show the waveform of the 2.5-Gbit/s phase-coded signal with a frequency of 13 GHz and the corresponding recovered phase profile. In another study, the LO is adjusted to 7.5 GHz and the TLS is tuned to 1551.224 nm. The generated mm-wave phase-coded signal and the corresponding recovered phase profile are shown in Figs. 6(c) and 6(d), respectively. Thanks to the frequency quadrupling operation, a phased-coded signal with a higher frequency can also be generated, but cannot be observed in the experiment because the maximum frequency of the oscilloscope is only 32 GHz.

In the experiment, a good short-term stability (about 10 minutes) is observed, but the long-term stability (more than 1 hour) is relatively poor, due to the variation of the FBG used in the setup. This problem can be solved by packaging the FBG and the Sagnac loop.

IV. CONCLUSION

In conclusion, we have proposed and demonstrated a photonic approach for the generation of a frequency-quadrupled phase-coded signal. The system has large frequency tunability. The minimum frequency of the generated phase-coded signal is restricted by the half of the notch bandwidth of the FBG, while the maximum frequency is four times the bandwidth of the DPMZM, so the frequency can be continuously tuned from several MHz to more than 100 GHz. A 2.5-Gbit/s phase-coded signal with a frequency tuning from 13 to 30 GHz is experimentally generated. The proposed approach can find applications in frequency-agile radar systems and wireless communication systems.

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