**Frequency-Doubled and Phase-Coded RF Signal Generation Based on Orthogonally Polarized Carrier-suppressed Double Sideband Modulation**

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**Abstract:** A novel approach to generating wideband frequency-doubled and phase-coded RF signals is proposed based on orthogonally polarized carrier-suppressed double sideband modulation. Phase-coded RF signals at 18 and 30 GHz are experimentally generated and evaluated.

**OCIS codes:** 060.5625 (Radio frequency photonics), 060.4080 (Modulation), 320.5520 (Pulse compression)

1. **Introduction**

Pulse compression is an important technology in radar systems to improve the range resolution [1]. Phase coding of the launched radio frequency (RF) signal is one of the most popular techniques to achieve RF pulse compression, which has drawn a lot of attentions in the past decades. Conventionally, phase-coded RF signals are generated in the electrical domain, but it is usually complicated and suffers from limited operation bandwidth. To deal with these problems, phase-coded RF signal generation in the optical domain has been proposed with the advantages in terms of large bandwidth, low cost and low loss, etc. Many methods for photonic generation of phase-coded RF signals have been reported [2-9]. In [2], phase-coded RF signals are realized based on optical spectral shaping followed by frequency-to-time mapping using a spatial light modulator (SLM). This approach is flexible, but complicated and lossy. Phase-coded RF signals can also be generated by introducing a phase difference to the two sidebands in the optical signal [4, 5]. In this method, the two optical sidebands are firstly separated by a fiber Bragg grating (FBG) [4] or a Sagnac loop [5], and then one of the sidebands is phase modulated by an electrical coding signal before beating with the other sideband at a photodetector (PD). However, the independent operation of the two separated sidebands in [4] and [5] would suffer severely from instability caused by optical interference. To cope with this problem, a polarization modulator (PolM) can be employed to complementarily phase modulate two orthogonally polarized sidebands. The key challenge of this method is the generation of two phase correlated sidebands with orthogonal polarization states, which was previously implemented by a differential group delay (DGD) element [6], a polarization maintaining FBG [7] and the simulated Brillouin scattering (SBS) in optical fibers [8]. The main drawbacks of these systems are the frequency-dependent (i.e. narrow band) operation [6, 7], or the complicated configuration [8]. On the other hand, to obtain high frequency phase-coded signal with low frequency devices, frequency multiplication is highly desirable when performing phase coding. Ref. [9] proposed a method to generate a frequency-doubled and phase-coded RF signal based on a dual-parallel PolM. However, the system stability is a serious problem since there is no integrated dual-parallel PolM.

![Fig. 1. The schematic diagram of the proposed frequency-doubled and phase-coded signal generator. OSC: oscilloscope.](image)

In this paper, we propose a novel scheme for generating a frequency-doubled and phase-coded RF signal based on orthogonally polarized carrier-suppressed double sideband (CS-DSB) modulation. The orthogonally polarized CS-DSB modulation, which can suppress the optical carrier and generate ±1-st order sidebands in orthogonal polarizations, is realized by a Mach-Zehnder modulator (MZM), a polarization modulator (PolM) and a wavelength fixed FBG. The two sidebands are sent to another PolM to introduce a phase difference to each other according to the coding information. A frequency-doubled and phase-coded RF signal can be generated after optical-to-electrical conversion. The performance of the system is experimentally investigated.
2. Principle

Figure 1 shows the schematic diagram of the proposed frequency-doubled and phase-coded RF signal generator. The system consists of a laser diode (LD), an MZM, two PolMs, three polarization controllers (PCs), a wavelength fixed FBG, a polarizer, a PD, and an electrical 90-degree hybrid. The MZM and PolM1 are driven by two orthogonal RF signals with a frequency of $f$, so optical single sideband (OSSB) modulation is implemented for both the TE and TM modes [10]. Due to the complementary phase modulations in the PolM, if the TE mode contains the optical carrier and the +1st-order sideband, the TM mode will consist of the optical carrier and the -1st-order sideband. By using the FBG to remove the optical carrier, two orthogonally polarized sidebands are obtained, i.e., an orthogonally polarized CS-DSB modulated signal is obtained. The two optical sidebands are then sent into PolM2 which is driven by an electrical coding signal, to experience complementary phase modulations before combined at a polarizer. After photodetection at the PD, a phase-coded signal at the frequency of $2f$ is generated. Thanks to the frequency doubling operation, the system can work at a frequency beyond the operation bandwidth of the devices and has good frequency tunability.

3. Experiment and Results

An experiment is carried out based on the setup shown in Fig. 1. The wavelength and output power of the LD are 1551.392 nm and 16 dBm, respectively. The 3-dB bandwidths and the half-wave voltages of the three modulators are 40 GHz and 3.5 V, respectively. The microwave signal is generated by a signal generator (Agilent, 8257D) with a power of 15 dBm, which is split into two paths by a 90-degree hybrid (1.7-36 GHz). The two signals are then sent to the RF ports of the MZM and PolM1. The FBG connected to PolM1 is used to remove the optical carrier, which has a 3-dB bandwidth of ~10 GHz centered at 1551.392 nm. After the FBG, orthogonally polarized CS-DSB modulation is realized. The two sidebands are then sent to PolM2 driven by an electrical coding signal generated by a pulse pattern generator (PPG). The polarization states of the orthogonally polarized sidebands are aligned to the two principal axes of PolM2, respectively, by adjusting PC3. The PD used for optical-to-electrical conversion has a 3-dB bandwidth of 50 GHz and a responsivity of 0.65 A/W. The optical spectra are measured by an optical spectrum analyzer (OSA, AQ6370C), and the waveforms of the generated phase-coded signal are observed by a 32-GHz real-time oscilloscope (Agilent, DSO-X 92504A).

![Fig. 2. (a) The optical spectrum of the signal after the notch filter and (b) the optical spectra of the signals along different polarization axes.](image)

Figure 2(a) shows the optical spectrum of the signal after the notch filter, from which we can see that, the optical carrier is about 25-dB lower than the ±1st-order sidebands. Figure 2(b) shows the optical spectra of the signals along different polarization axes measured by connecting a polarization beam splitter (PBS) to the notch filter. As can be seen, the signal along one polarization axis contains only the +1st-order sideband, while the signal along the other polarization axis is the -1st-order sideband, i.e. the two sidebands are well separated in the two orthogonal polarization directions.

![Fig. 3. The waveforms (upper), recovered phase shifts (middle) and auto-correlations (lower) of the generated 18-GHz phase-coded signals with 8-bit (a), 16-bit (b) and 32-bit (c) coding signals.](image)
Figure 3 (a), (b) and (c) show the waveforms, the recovered phase shifts and the auto-correlations of the generated 18-GHz phase-coded signals with 4.5 Gb/s 8-bit, 16-bit and 32-bit coding signals, respectively. In the three phase-coded waveforms, the phase jumps can be obviously observed. When the phase information is recovered, a phase jump of 220°, 230° and 200° are observed. To evaluate the pulse compression capability of the generated RF signals, the auto-correlations are calculated. The full widths at half maximum (FWHM) of the three compressed pulses are about 0.16 ns, corresponding to a pulse compression ratio of 11.1, 22.2 and 44.4 for the three RF signals. The peak-to-sideband suppression ratios are about 6 dB, 5.69 dB and 6.58 dB, respectively.

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Fig. 4. The waveform (a), the recovered phase shift (b) and the auto-correlation (c) of the generated 30-GHz phase-coded signal.

To demonstrate the ability of the proposed system to generate high frequency signals, a 30-GHz phase-coded signal is generated based on the scheme. The electrical coding signal is a 3.75 Gb/s 32-bit signal, with a peak-to-peak voltage of about 1.12 V. The measured waveform of the generated signal is shown in Fig. 4(a) and the recovered phase shift is shown in Fig. 4(b). The pulse compression capability is also evaluated, as shown in Fig. 4(c). The FWHM of the compressed pulse is about 0.34 ns, corresponding to a pulse compression ratio of about 25.1 dB. The peak-to-sideband suppression ratio is about 4.8 dB. It should be noted that the maximum frequency of the scheme can be as high as 72 GHz (limited by the bandwidth of the electrical 90-degree hybrid), which is not observable due to the 32-GHz bandwidth of the oscilloscope.

4. Conclusion

A frequency-doubled and phase-coded RF signal generator is proposed and demonstrated. 18- and 30-GHz phase-coded signals are generated with different coding sequences. The pulse compression capabilities are evaluated. The frequency doubling operation makes the system be able to work at a frequency range over the operation bandwidth of the devices used in the system. The proposed frequency-doubled and phase-coded RF signal generator may find applications in radars and communication systems.

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6. References