Photonic Generation of Phase-Coded Millimeter-Wave Signal Using a Polarization Modulator

Hao Chi and Jianping Yao, *Senior Member, IEEE*

***Abstract*—A novel approach to generating phase-coded millimeter-wave (mm-wave) signal in the optical domain is proposed. In the proposed system, a radio frequency signal is applied to a Mach–Zehnder modulator that is biased at the minimum transmission point to generate two optical sidebands with suppressed carrier. A differential group delay device is utilized to rotate the polarization states of the optical sidebands to ensure they are orthogonally polarized. The two sidebands are then sent to a polarization modulator (PolM), with their polarization directions aligned with the two principal axes of the PolM, to achieve phase coding. A 33-GHz mm-wave signal that is phase coded by an 8.28 Gb/s digital sequence is experimentally demonstrated. The approach has potential applications in mm-wave pulse compression radar and wireless communications.**

***Index Terms*—Millimeter-wave (mm-wave) signal generation, phase coding, phase modulation, pulse compressed radar.**

I. Introduction

THE generation of microwave and millimeter-wave (mm-wave) signals in the optical domain has attracted intensive research interest in the last few years [1], thanks to the advantages such as wide bandwidth, low loss, and immunity to magnetic interference offered by optics. In addition, microwave and mm-wave signals generated in the optical domain are ready to be distributed to a remote site using the state-of-the-art radio over fiber technology without the need of additional electrical to optical conversion. On the other hand, it is also desirable to generate microwave and mm-wave signals that are frequency chirped or phase-coded for applications such as in modern radar systems, to achieve pulse compression with an increased range resolution [2]. Chirped or phase-coded signals can be generated in the electrical domain using either analog or digital electronics, but the operating frequency is usually limited to several GHz. An effective alternative to this problem is to generate high-frequency pulsed electrical signals in the optical domain. Recently, techniques to generate chirped or phase-coded microwave and mm-wave signals have been demonstrated based on optical pulse shaping using a spatial light modulator (SLM) [3], [4]. High-frequency chirped or phase-coded electrical signals can also be generated using pure fiber-optic components [5]–[7]. We have demonstrated recently the generation of chirped microwave pulses based on nonlinear frequency-to-time mapping in a nonlinearly chirped dispersion medium [5]. Zeitouny *et al.* has demonstrated a technique to generate linearly chirped electrical pulses by beating two chirped optical pulses, in which the two chirped optical pulses were obtained by passing an ultra-short pulse through two chirped fiber gratings that were located in the two arms of a Mach–Zehnder interferometer (MZI) [6]. Very recently, we have also demonstrated a technique to generate phase-coded pulses by incorporating an optical phase modulator in one arm of an MZI [7]. In the approaches in [6], [7], the systems are sensitive to environmental variations since they are based on a fiber-optic MZI.

In this letter, we propose a novel approach to generating phase-coded mm-wave signals using a system without using a fiber-optic MZI. In the proposed approach, two optical wavelengths generated by a Mach–Zehnder modulator (MZM) that is biased at the minimum transmission point is sent to a polarization modulator (PolM) via a differential group delay (DGD) device to make the two wavelengths orthogonally polarized. Phase coding is implemented at the PolM with an encoding signal applied to the PolM via its radio frequency (RF) port. Since the PolM is an integrated waveguide device, a stable operation is ensured. A 33-GHz mm-wave signal that is phase coded by an 8.28 Gb/s data sequence is experimentally demonstrated.

II. System Configuration

The schematic diagram of the proposed system is shown in Fig. 1. The lightwave from a laser diode (LD) is fed into the first MZM (MZM1), which is biased at the minimum transmission point to suppress the optical carrier. A polarization controller (PC1) is used to ensure the incident light is well aligned with the principal axis of MZM1. The two optical sidebands ω_1 and ω_2 at the output of MZM1 has the same polarization states, which are rotated to have an angle of 45° with respect to the principal axis of the differential group delay (DGD) module by adjusting PC2. The DGD module is utilized to rotate the polarization states of the two optical sidebands to ensure they are orthogonally polarized. The principle of the polarization state rotation filter is explained schematically in Fig. 2 [8], [9]. If the angular frequencies of the optical carrier ω_0 and the modulating microwave signal ω_m satisfy $\omega_0\tau = 2n\pi \pm \pi/2$ and

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H. Chi is with the Department of Information and Electronic Engineering, Zhejiang University, Hangzhou 310027 China. He is also with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada.

J. P. Yao is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

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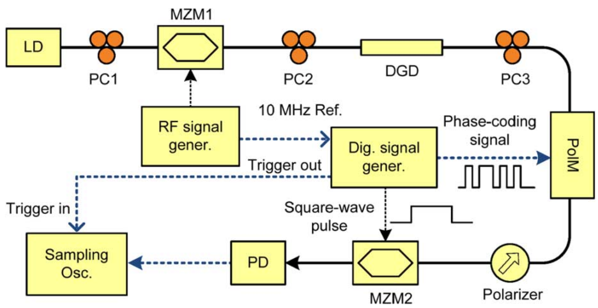

Fig. 1. Schematic diagram of the proposed phase-coding system. LD: laser diode; PC: polarization controller; PMF: polarization maintaining fiber; PolM: polarization modulator; PD: photodetector.

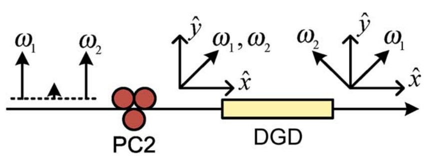

Fig. 2. Illustration of the polarization state rotation of the two optical sidebands through a length of PMF.

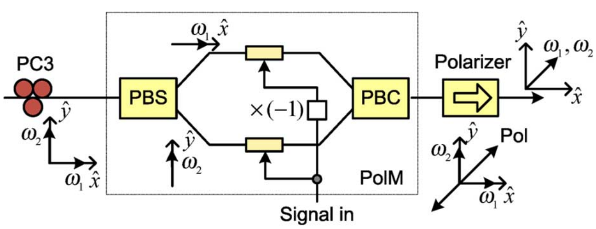

Fig. 3. Illustration of the phase-coding process using a PolM. PBS/PBC: polarization beam splitter/combiner.

$\omega_m = \pi/(2\tau)$, where τ is the differential group delay, the two optical sidebands at the output of the DGD device would be orthogonally polarized (see Fig. 3).

The two optical sidebands are then coupled to the PolM with their polarization directions aligned with the two principal axes, realized by PC3. The PolM is a special phase modulator that has opposite modulation indices along the two principal axes [10]. When the two optical sidebands propagate within the PolM, they are phase-modulated, but with opposite phase shifts. At the output of the PolM, the phase-modulated optical sidebands are applied to a PD through a polarizer. The beating between the two phase modulated sidebands generates a phase-modulated electrical signal. A second MZM (MZM2) that is driven by a square-wave signal is used to generate a pulsed signal.

In principle, the electrical fields of the lower and upper sidebands can be expressed as

$$E_1(t) = \exp\{j[(\omega_0 - \omega_m)t - (V_s/V_\pi)\pi \cdot s(t)]\} \quad (1)$$

and

$$E_2(t) = \exp\{j[(\omega_0 + \omega_m)t + (V_s/V_\pi)\pi \cdot s(t)]\} \quad (2)$$

where $s(t)$ denotes the input phase encoding signal applied to the PolM with its amplitude of V_s, and V_π is the half-wave voltage of the PolM. The electrical signal at the output of the PD is

$$i(t) = \mathrm{R}E_1E_2^* = \mathrm{R}\exp\{j[2\omega_m t + 2(V_s/V_\pi)\pi \cdot s(t)]\} \quad (3)$$

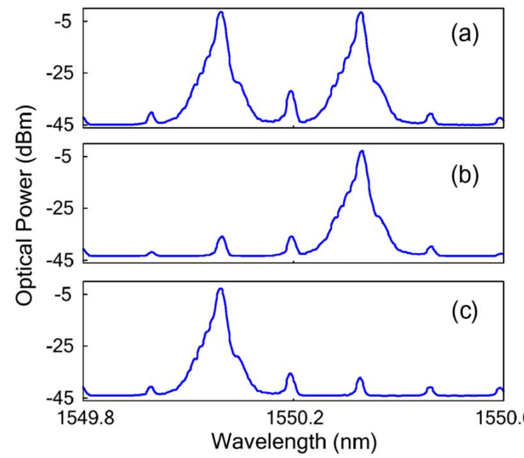

Fig. 4. Optical spectra of the carrier-suppressed optical signal (resolution: 0.01 nm). (a) Before the PMF; (b) and (c) at the two outputs of a PBS after the PMF.

where R is the responsivity of the PD. It is shown in (3) that the generated electrical signal is frequency-doubled and the signal $s(t)$ applied to the PolM is transferred to the phase of the generated electrical signal. Thus, a phase-coded signal is generated.

III. Experiment and Discussion

The experimental setup shown in Fig. 1 is built. In the experiment, a 16.56-GHz microwave signal from a signal generator is applied to MZM1 via its RF port. An 8.28 Gb/s return-to-zero digital signal from a bit error rate tester (BERT) is applied to the PolM to achieve phase coding. A PD with 40 GHz bandwidth is used to recover the phase-coded mm-wave signal, which is monitored by a sampling oscilloscope. To synchronize the digital data with the microwave drive signal, a 10-MHz external reference source from the signal generator is sent to the BERT; and the oscilloscope operates in the trigger mode with the trigger signal from the BERT. A length of polarization maintaining fiber (PMF) with a differential time delay $\tau = 150.9$ ps is utilized as the DGD module to rotate the polarization directions of the optical sidebands. Note that the differential time delay is determined by the length of the PMF, which is selected to match the modulation frequency.

Fig. 4(a) shows the optical spectrum at the output of MZM1; the optical carrier is suppressed by about 30 dB. At the output of the PMF, we use a polarization splitter to monitor the polarization state rotation of the two sidebands. Fig. 4(b) and (c) shows the spectra at the two outputs of the polarization splitter. It can be seen that the polarization isolation between the two optical sidebands is around 35 dB. The two orthogonally polarized optical sidebands are then sent to the PolM via PC3 to align the polarization directions of the two optical sidebands with the principal axes of the PolM. Phase coding is realized at the PolM. The output at the PolM is then sent to a PD via a polarizer, to project equally the two phase-coded optical sidebands to the principal axis of the polarizer.

Fig. 5(a) shows the generated 33.12 GHz mm-wave signal without phase coding. The power P of the phase coding signal from the BERT is 25 dBm (316 mW). The signal voltage V_s is calculated to be 3.97 V based on $V_s = \sqrt{PZ_m}$, where the

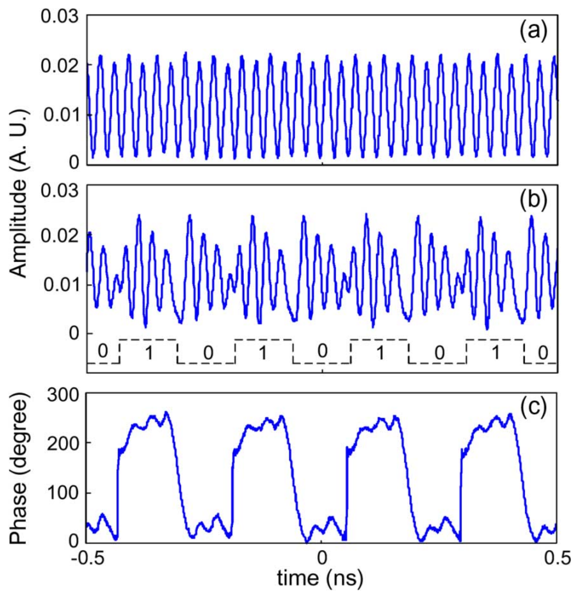

Fig. 5. (a) Generated mm-wave signal without phase coding; (b) the mm-wave signal with phase coding; and (c) the recovered phase shift.

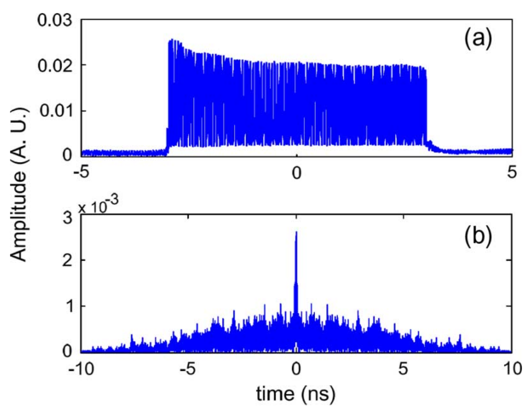

Fig. 6. (a) Measured phase-coded 33 GHz pulse and (b) the autocorrelation.

input impedance Z_m of the PolM is 50 Ω. The half-wave voltage V_π of the PolM is 5.3 V. The phase shift corresponding to bit "1" is calculated to be around 270° according to (3). The generated mm-wave signal with 8.28 Gb/s phase coding is shown in Fig. 5(b). The phase information recovered from the phase-coded signal using the Hilbert transform is shown in Fig. 5(c). It can be seen that the maximum phase shift is around 280°, which agrees well with the theoretical value. The phase shift value can be adjusted by controlling the power of the digital signal applied to the PolM. To demonstrate the pulse compression capability, we also calculate the autocorrelation of the pseudo-random bit sequence (PRBS) phase-coded signal. Fig. 6(a) and (b) shows the phase-coded signal with 6-ns time duration and its autocorrelation, respectively. A compression ratio of about 60 is achieved.

In the experiment, the length of the PMF is controlled to match the carrier frequency. If a variable DGD device is employed in the system to replace the PMF, the carrier frequency of the signal can be tunable [8], [9]. In the experimental demonstration, no polarization maintaining components (such as standard single mode fiber) are used. Therefore, several PCs have to be used to control the polarization states, which may affect the long-term stability. In the experiment, a good short-term stability (within 10 minutes) is observed if the system is placed on a floating optical table to isolate the environmental variations. The long-term stability is affected due to the use of several PCs. For practical applications, however, polarization maintaining components should be used, which would ensure a long-term stability. There are two major advantages of our approach. First, the mm-wave carrier is generated in the optical domain based on frequency doubling, which alleviates the requirement for a very high-frequency local oscillator. Second, instead of using a fiber-optic MZI which is extremely sensitive to environmental variations due to optical interference, in our approach a PolM is employed. Since the PolM is an integrated waveguide device, the two orthogonally polarized lightwaves are traveling in the same optical path; optical interference due to environmental changes is minimized.

IV. Conclusion

In conclusion, we have demonstrated a novel approach for the generation of phase-coded mm-wave signals in the optical domain. Since the phase-coding process was implemented in an integrated PolM, the stable operation can be achieved compared to the previous approaches using a fiber-optic interferometric structure. An mm-wave signal at 33.12 GHz with 8 Gb/s phase coding was experimentally demonstrated. The approach provides a simple and effective solution for the generation of high-frequency phase-coded electrical signals, which could find applications in pulse compression radar, fiber radio and spread-spectrum communication systems.

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