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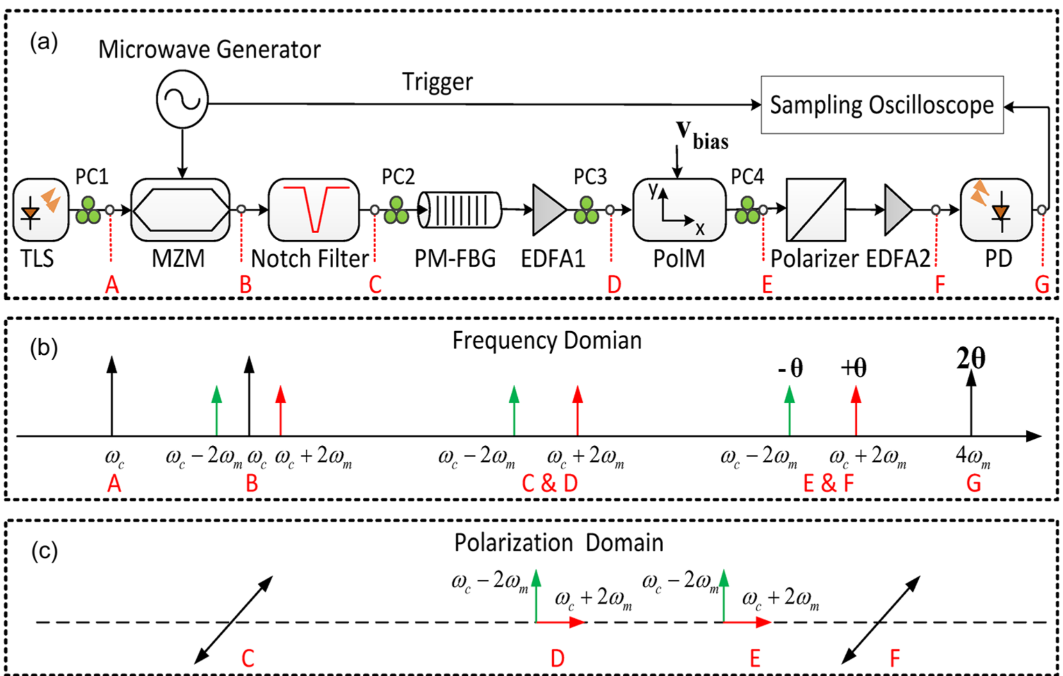

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Photonic Generation of Millimeter-Wave Signals With Tunable Phase Shift

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Abstract: A novel photonic approach to generating a frequency-quadrupled millimeter-wave (mm-wave) signal with a tunable phase shift is proposed and demonstrated. Two second-order optical sidebands are generated by using a Mach–Zehnder modulator (MZM) that is biased at the maximum transmission point and an optical notch filter. A polarization-maintaining fiber Bragg grating (PM-FBG) is then utilized to make the two sidebands orthogonally polarized, which are then sent to a polarization modulator (PolM). By aligning the two orthogonally polarized sidebands with the two principal axes of the PolM, complementary phase modulation is thus achieved. By beating the two phase-modulated sidebands at a photodetector, an mm-wave signal is generated and its phase is continuously tunable by tuning the bias voltage to the PolM. An experiment is performed. An mm-wave signal with a frequency tunable from 36 to 52 GHz is generated and its phase is tunable over 360° by tuning the bias voltage.

Index Terms: Microwave photonics, mm-wave signal generation, phase-array beamforming, tunable phase shift.

1. Introduction

Photonic generation of microwave, millimeter-wave (mm-wave), and terahertz waves has been a topic of interest in the last few years which can find numerous applications, such as wireless communications, radar, medical imaging, sensing, and modern instrumentation. The key advantages of using photonics to generate a high-frequency electrical signal are the broad bandwidth and large tunability, which is difficult to realize using pure electronics [1]. In [2], [3], a frequency-quadrupled microwave signal was generated using a Mach–Zehnder modulator (MZM) and an optical notch filter. The MZM was biased at the maximum transmission point (MATP) to suppress the odd-order sidebands, and the optical carrier was suppressed by the optical notch filter. A frequency-quadrupled microwave signal was generated by beating the two 2nd-order sidebands at a photodetector (PD). The frequency can be continuously tuned by tuning the frequency of the input microwave signal, but the phase term of the generated microwave signal is not controllable. For many applications, such as phased array beamforming and array signal processing [4], the phase of a signal should be arbitrarily controlled. Conventional electronic phase shifters may be used to fulfill this task, but purely electronic phase shifters have the limitations such as small bandwidth and limited phase-shift range. This has prompted the development of photonically assisted phase shifters, such as homodyne mixing [5], [6] and vector sum techniques [7], [8], but these techniques are complicated and costly.

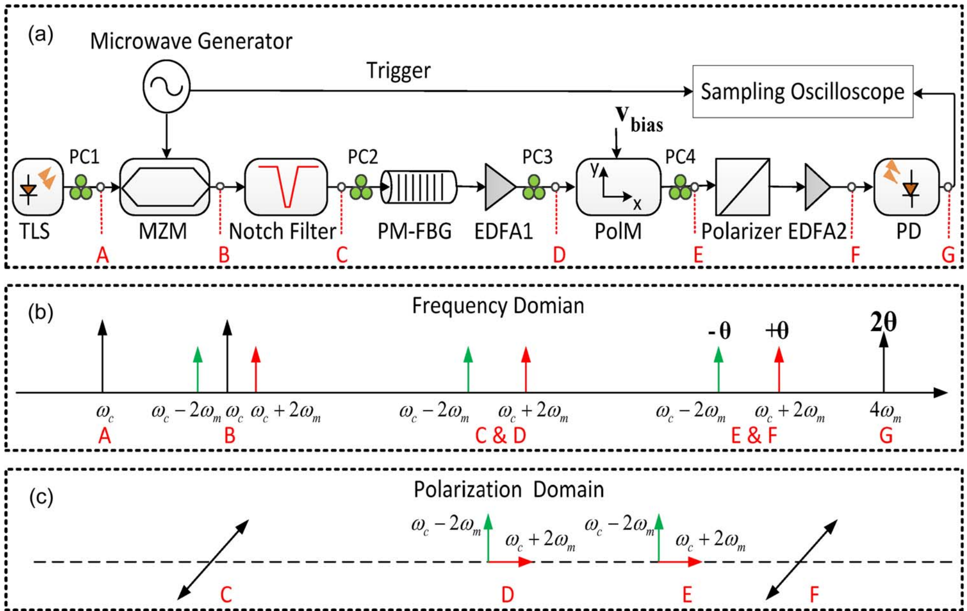

Fig. 1. (a) Schematic of the proposed system for mm-wave signal generation with tunable phase shift. (b) Illustration of the operation principle in the frequency domain, and (c) evolution of the polarization states.

In this paper, we propose and demonstrate a simple approach to generating a frequency-tunable mm-wave signal with a largely tunable phase shift. In the proposed approach, two second-order optical sidebands are generated by using a MZM and an optical notch filter. The MZM is biased at the MATP to suppress the odd-order sidebands, and the optical carrier is removed by the optical notch filter. The two 2nd-order sidebands are then sent to a polarization-maintaining fiber Bragg grating (PM-FBG) to make the two sidebands orthogonally polarized. By aligning the polarization directions of the two sidebands with the two principal axes of a polarization modulator (PolM), the two orthogonally polarized sidebands are complementarily phase modulated, with the modulation depth depending on the bias voltage applied to the PolM. By beating two sidebands at a PD, an mm-wave signal is generated and its phase-shift is tunable by adjusting the bias voltage to the PolM.

The use of a PolM to generate a phase-coded microwave signal was recently proposed by us to generate a phase-coded microwave signal [9]. Although the system here is similar, the concept is different. In [9], the PolM was used to introduce two phase values to generate a binary phase-coded microwave signal. Here, in this paper, the PolM is used to introduce a tunable phase shift to a microwave signal. By adjusting the bias voltage to the PolM, a continuously tunable phase shift is produced.

2. Principle

The schematic of the proposed system for the generation of a frequency-quadrupled mm-wave signal with tunable phase shift is shown in Fig. 1. A continuous-wave (CW) light wave from a tunable laser source (TLS) is sent to an MZM through a polarization controller (PC1). A microwave signal is applied to the MZM, which is biased at the MATP to generate two second-order sidebands plus the optical carrier. The optical carrier is then suppressed by an optical notch filter. The two second-order sidebands at the output of the notch filter are then sent to a specially designed PM-FBG through a second PC (PC2). The polarization directions of the two-sidebands are adjusted by PC2 to have an incident angle of 45° relative to one principal axis of the polarization-maintaining fiber (PMF), in which an FBG is written. Due to the birefringence in the PMF, the PM-FBG has two spectrally separated and orthogonally polarized transmission bands [9], [10]. The wavelength spacing between the two transmission bands is given by

$$\Delta\lambda = 2\Delta n_{eff}\Lambda \tag{1}$$

where Δn_{eff} is the effective refractive index difference between the two orthogonal polarization states of the fundamental mode and Λ is the period of the FBG.

By aligning the two sidebands with the two transmission bands, two orthogonally polarized optical sidebands are obtained at the output of the PM-FBG. The two optical sidebands are amplified by an erbium-doped fiber amplifier (EDFA) and then are sent to the PolM through a third PC (PC3), with their polarization directions aligned with the two principal axes of the PolM. The PolM is a special phase modulator that has opposite modulation indices along the two principal axes [11]. The two optical sidebands are complementarily phase modulated at the PolM by the bias voltage. By passing the two phase-modulated optical sidebands through a polarizer with its principal axis aligned at 45° relative to one principal axis of the PolM, the polarizations directions of the two sidebands are aligned with the principal axis of the polarizer. By beating the two sidebands at the PD, a microwave signal with its frequency that is four times the frequency of the microwave drive signal is generated. The phase of the generated microwave signal can be tuned by adjusting the bias voltage to the PolM. To compensate for the loss, a second EDFA is placed at the output of the polarizer.

Mathematically, the optical signal at the output of the optical notch filter can be expressed as

$$E_C(t) = A_{-2}e^{j(\omega_c-2\omega_m)t} + A_2e^{j(\omega_c+2\omega_m)t} \tag{2}$$

where ω_c and ω_m are, respectively, the angular frequencies of the optical carrier and the microwave signal applied to the MZM, and A_{-2} and A_2 are the amplitudes of the two second-order sidebands. The optical signal at the output of the PM-FBG is

$$\vec{E}_D(t) = \hat{x}A_{-2}e^{j(\omega_c-2\omega_m)t} + \hat{y}A_2e^{j(\omega_c+2\omega_m)t} \tag{3}$$

where $\hat{x}$ and $\hat{y}$ are the polarization directions corresponding to the principal axes of the PolM. If a direct-current voltage V_{bias} is applied to the PolM, the two sidebands at the output of the PolM is given by

$$\vec{E}_E(t) = \hat{x}A_{-2}e^{j\left[(\omega_c-2\omega_m)t-\pi\frac{V_{bias}}{V_\pi}\right]} + \hat{y}A_2e^{j\left[(\omega_c+2\omega_m)t+\pi\frac{V_{bias}}{V_\pi}\right]} \tag{4}$$

where V_π is the half-wave voltage of the PolM.

The two sidebands are then sent to the polarizer. The signal at the output of the polarizer is given by

$$E_F(t) = \frac{\sqrt{2}}{2}A_{-2}e^{j\left[(\omega_c-2\omega_m)t-\pi\frac{V_{bias}}{V_\pi}\right]} + \frac{\sqrt{2}}{2}A_2e^{j\left[(\omega_c+2\omega_m)t+\pi\frac{V_{bias}}{V_\pi}\right]}. \tag{5}$$

By beating the two sidebands at the PD, an mm-wave signal with a tunable phase is generated. The photocurrent at the output of the PD is

$$i(t) = \frac{1}{2}RA_{-2}A_2\cos\left(4\omega_m t + 2\pi\frac{V_{bias}}{V_\pi}\right) \tag{6}$$

where R is the responsivity of the PD. As can be seen from (6), a frequency-quadrupled mm-wave signal is generated. The frequency can be continuously tuned by tuning the frequency of the input microwave signal. The phase term is a function of the bias voltage. As the voltage V_{bias} changes from 0 to V_π, the phase of the generated microwave signal is tuned from 0° to 360°.

3. Experiment

An experiment based on the setup shown in Fig. 1 is performed. The key component in the system is the PM-FBG, which is fabricated using a frequency-doubled argon-ion laser source operating at 244 nm and a phase mask. Fig. 2 shows the transmission spectra of the PM-FBG measured using a

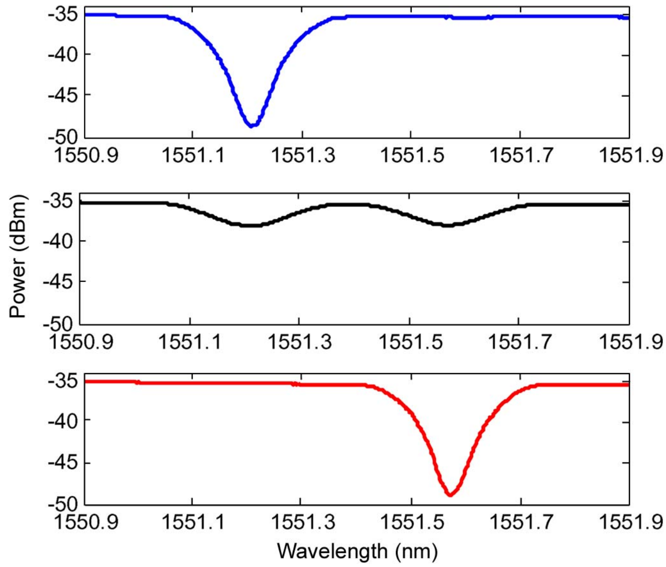

Fig. 2. Transmission spectra of the PM-FBG measured using a broadband light source with its polarization direction oriented at an angle of 0°, 45°, and 90° to the fast axis of the PM-FBG.

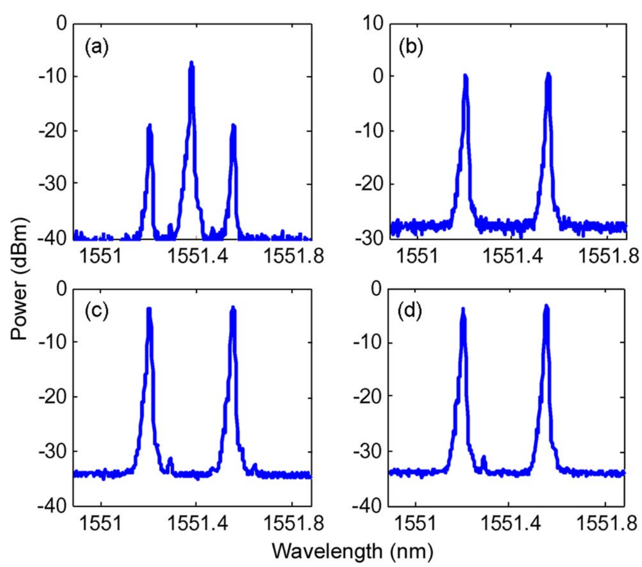

Fig. 3. Measured spectra using an optical spectrum analyzer at the output of the (a) MZM; (b) PM-FBG; (c) PolM; and (d) Polarizer.

broadband light source, an optical linear polarizer and an optical spectrum analyzer (OSA). The polarizer is used to control the polarization state of the input light to the PM-FBG. When the polarization direction of the broadband light source is aligned at an angle of 0°, 45°, and 90° with respect to the fast axis of the PM-FBG, we have the transmission spectral shown in Fig. 2. The center wavelength spacing between the two transmission bands is about 0.36 nm. The minimum wavelength spacing between the two transmission bands is 0.28 nm which corresponds to a minimum frequency of 35 GHz for the generated mm-wave signal. The maximum wavelength spacing is 0.44 nm, which corresponds to maximum frequency of 55 GHz. To increase the frequency-tunable range, the PM-FBG should be designed to have smaller wavelength spacing and wider transmission bands, which

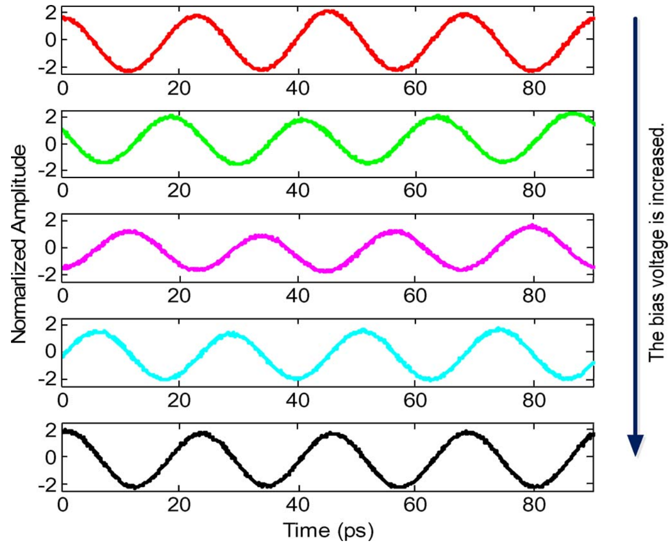

Fig. 4. Temporal waveforms of the generated 44-GHz mm-wave signal at different bias voltages measured using a sampling oscilloscope. When the voltage is tuned, the 44-GHz waveform is laterally shifted corresponding a shift in phase.

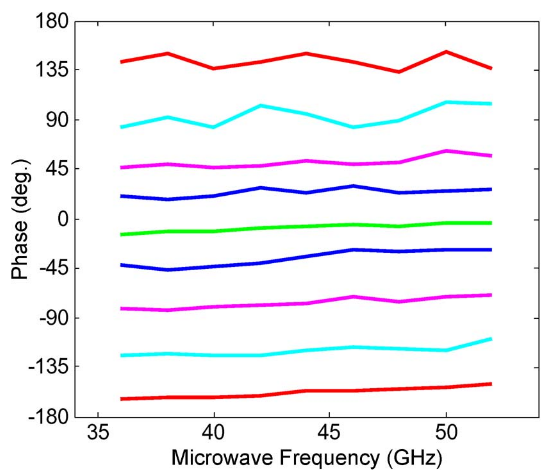

Fig. 5. Measured phase shifts at different bias voltages over a microwave frequency band from 36 to 52 GHz. The phase shifts are independent of the microwave frequency.

can be achieved using a chirped phase mask to fabricate the PM-FBG, leading to smaller wavelength spacing and wider transmission bands.

The wavelength of the TLS is tuned to match the center wavelengths of the two transmission bands of the PM-FBG. The frequency of the microwave signal from a signal generator (Agilent E8254A) is tuned such that the two $\pm$2nd-order sidebands lie in the two transmission bands. Fig. 3(a) shows the spectrum at the output of the MZM. Since the MZM is biased at the MATP, the odd-order sidebands are suppressed and only the $\pm$2nd-order sidebands and the optical carrier are observed. Fig. 3(b) shows the spectrum of the two $\pm$2nd-order sidebands amplified by the first EDFA at the output of the PM-FBG. When aligned at an angle of 45° relative to one principal axis of the PM-FBG, the two $\pm$2nd-order sidebands have the same amplitude. Fig. 3(c) shows the spectrum at the output of the PolM, and Fig. 3(d) shows the spectrum of the two $\pm$2nd-order sidebands amplified by the second

EDFA at the output of the polarizer. When a microwave signal at 11 GHz is applied to the MZM, a frequency-quadrupled mm-wave signal at 44 GHz is generated, as shown in Fig. 4.

To demonstrate the phase-shift tuning capability, the bias voltage to the PolM is tuned. As can be seen from Fig. 4, the 44-GHz waveform is laterally shifted with the amount of shift corresponding to the phase change when the bias voltage is tuned. The phase shift over a bandwidth of 36 to 52 GHz is measured. Fig. 5 shows the phase shift when the generated microwave signal is tuned from 36 to 52 GHz, corresponding to the input microwave drive signal tuned from 9 to 13 GHz. Over the bandwidth, a constant phase shift for a given bias voltage is achieved. Some variations are observed which are caused mainly by the measurement errors.

4. Discussion and Conclusion

In the experiment, the minimum and maximum frequencies of the generated mm-wave signal are limited by the spacing and the bandwidths of the two transmission bands of PM-FBG, which can be increased if a PM-FBG with a broader bandwidth is used. In the experiment, a stable operation is observed. This is because the two sidebands are traveling in the same optical path, the optical phase variations due to the environmental changes are canceled out. In addition, since the polarization orthogonality of the two light waves to the PolM is independent of the wavelength spacing, the frequency of the generated mm-wave signal is continuously tunable with a wide tunable range.

In conclusion, we have proposed and demonstrated a novel approach to generating a frequency-quadrupled mm-wave signal with a largely tunable phase shift. The key component in the system is the PM-FBG, which was employed to ensure the generation of two orthogonally polarized optical sidebands with tunable wavelength spacing. The tunable phase shift was realized by complementary phase modulation of the two sidebands at the PolM. The generation of an mm-wave signal tunable from 36 to 52 GHz with a tunable phase shift of 360° was experimentally demonstrated. The proposed system has a unique feature that combines frequency quadrupling and phase tuning, which can find applications in broadband and high frequency beamforming systems and array signal processing systems.

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