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Photonic generation of frequency-sextupled microwave signal based on dual-polarization modulation without an optical filter

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ABSTRACT

Frequency-sextupled microwave signal generation based on dual-polarization modulation using an electro-optic dual-parallel polarization modulator (DPPolM) without an optical filter is proposed. From a theoretical analysis, the frequency-sextupled microwave signal can be obtained by properly adjusting the polarization directions of the modulated optical signals, the powers and the phases of the microwave drive signals applied to the DPPolM. Simulation results show that a 24 GHz microwave signal with an optical sideband suppression ratio (OSSR) exceeding 31 dB and a radio frequency spurious suppression ratio (RFSSR) higher than 25 dB is generated from a 4 GHz microwave drive signal, which match well with the theoretical analysis. Furthermore, it is also proved to be valid that even if the microwave drive voltage, the phase difference, and the polarization direction of light wave deviate from the ideal values to a certain degree, the performance of the generated frequency-sextupled microwave signal is still acceptable.

1. Introduction

Photonic generation of microwave signals has attracted much attention in radio-over-fiber (RoF) link, satellite communication system, and Radar due to its advantages of ultrahigh bandwidth, large tunable range, and immunity to electromagnetic interference [1,2]. Many approaches have been developed to generate microwave signal in the optical domain, such as direct modulation [3], remote heterodyne detection [4], optoelectronic oscillator [5,6], external optical modulation [7–14], and so on. Among them, the external optical modulation has shown great potential for high frequency microwave signal generation because of low phase noise, excellent frequency tunable ability, and easy implementation.

The method of external optical modulation to generate microwave signal is based on beating the two high-order optical sidebands with good coherence in the photodiode, which can be divided into intensity modulation [7–11], phase modulation [12], and polarization modulation [13–15]. In [7], optical microwave generation configuration by frequency quadrupling using two cascaded Mach-Zehnder modulators was proposed. In [8], a dual-parallel MZM (DP-MZM) was used to generate frequency-quadrupled microwave signal without optical filter. In order to improve the frequency multiplication factor, a DP-QPSK was used to generate frequency-octupled microwave signal [9]. Two cascaded DP-MZM [10] or a DP-MZM [11] was presented to generate frequency-twelvetupled microwave signal. However, the above schemes using MZM would suffer from the bias drift problem and has limited extinction ratio, which influences the spectral purity of the generated microwave signal. Compared with the intensity modulation approach using MZM, the PolM based microwave signal generation methods could achieve better performance due to their bias free operation and high extinction ratio [13–15]. Since the PolM is unnecessary to be direct current biased, there is no bias drift problem, which ensures the good stability. In addition, the residual chirp can be adjusted to zero by tuning a polarization controller (PC) placed before the PolM, which realizes high extinction ratio to improve the spectral purity of the generated microwave signal.

Several schemes to generate microwave signal based on polarization modulation have been proposed. A frequency-sextupled scheme using a polarization modulator (PolM) and a wavelength-fixed notch filter was proposed in [13]. The joint operation of the PolM and 135° polarizer formed an equivalent MZM that was biased at the minimum transmission point (MITP) to suppress the even-order optical sidebands. By using a fiber Bragg grating (FBG) to remove the optical first-order sidebands, a microwave signal with a frequency that is six times the frequency of the microwave drive signal was generated. To further increase the frequency multiplication factor (FMF), a frequency-twelvetupled signal generation scheme by a joint use of a PolM for frequency quadrupling and a semiconductor optical amplifier (SOA) for frequency tripling was proposed [14]. In all these approaches, an optical filter is always used, which limits the frequency tuning speed and tunable range. Recently, an approach to achieve frequency quadrupling

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using only one PolM in a Sagnac loop without an optical filter was proposed [15]. The functionality was realized due to the bidirectional use of the PolM which could perform effective modulation for a light wave along the clock-wise direction while no modulation was impressed on a light wave along the counter-clockwise direction due to the velocity mismatch. However, the frequency multiplication factor (FMF) is only four. To generate an electrical signal with a frequency up to the sub-terahertz range, it still requires relatively high-frequency microwave drive signal and electro-optic devices.

In this paper, a dual-parallel PolM (DPPolM) is proposed to generate frequency-sextupled microwave signal without an optical filter. A theoretical analysis leading to the operating conditions to achieve frequency sextupling is developed. The performance of the signal in terms of optical sidebands suppression ratio (OSSR) and RF spurious suppression ratio (RFSSR) is discussed, and the effects of several non-ideal factors on OSSR and RFSSR are analyzed.

2. Principle

Fig. 1 shows our proposed frequency-sextupled microwave signal generation system. A continuous-wave light wave from a laser diode (LD) is sent to a dual-parallel PolM (DPPolM) via a polarization controller (PC1). The DPPolM is composed of a polarization beam splitter (PBS), two polarization modulators (PolMs), two PC, and a polarization beam combiner (PBC) [16]. A low-frequency microwave signal from a microwave source (MS) is divided into two paths after amplified by an electrical amplifier (EA), introduced a phase difference by a tunable electrical phase shifter (TEPS), and then applied to the two PolMs. The microwave signals are polarization modulated onto two orthogonal polarized optical carriers, and then converted to intensity modulation at the output of the DPPolM. Two orthogonal polarized intensity modulation signals are combined by a polarizer (Pol). By properly controlling the polarization direction of PC2, PC3, Pol, the powers of the microwave signal applied to the two PolMs, and the phase shift of the TEPS, only two dominant optical sidebands at the ± 3 orders are obtained. After amplified by a erbium-doped fiber amplifier (EDFA) and detected by a photodetector (PD), a high-quality frequency-sextupled microwave signal is generated. Because no bias is needed for the PolM, the system is free from bias drift, and a stable operation is guaranteed.

The linearly polarized light wave emitted from the LD is divided into two paths by the PBS, on the upper path, the linearly polarized light wave with its state of polarization aligned at an angle of $-45°$ to one principal axis of the PolM1 is sent to the PolM1, the output along the x and y directions can be expressed as

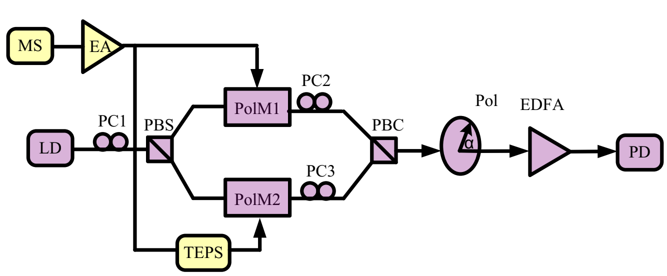

Fig. 1. Schematic diagram of a frequency-sextupled system using a dual-parallel PolM. LD: laser diode; PC: polarization controller; PBS: polarization beam splitter; PolM: polarization modulator; PBC: polarization beam combiner; Pol: polarizer; EDFA: erbium-doped fiber amplifier; PD: photodetector; MS: microwave source; EA: electrical amplifier; TEPS: tunable electrical phase shifter.

$$\begin{bmatrix} E_{1x} \\ E_{1y} \end{bmatrix} = \frac{1}{2}E_c \begin{Bmatrix} \exp\left[jw_c t + jm_1\ \cos(w_m t)\right] \\ -\exp\left[jw_c t - jm_1\ \cos(w_m t)\right] \end{Bmatrix} \tag{1}$$

where E_c is the amplitude of the optical carrier, w_c and w_m are the angular frequencies of the light wave and the input microwave signal, respectively, m_1 is the modulation index of the PolM1.

The polarization modulated optical signal at the output of PolM1 is then sent into the PC2, which is used to rotate the polarization direction of the incoming light wave by 90° along the clockwise direction. Thus, the output of PC2 can be written as

$$\begin{bmatrix} E_{1x} \\ E_{1y} \end{bmatrix} = \frac{1}{2}E_c \begin{Bmatrix} -\exp\left[jw_c t - jm_1\ \cos(w_m t)\right] \\ -\exp\left[jw_c t + jm_1\ \cos(w_m t)\right] \end{Bmatrix} \tag{2}$$

On the lower path, the linearly polarized light wave with its state of polarization aligned at an angle of 45° to one principal axis of the PolM2 is sent to the PolM2, the output along the x and y directions can be expressed as

$$\begin{bmatrix} E_{2x} \\ E_{2y} \end{bmatrix} = \frac{1}{2}E_c \begin{Bmatrix} \exp\left[jw_c t + jm_2\ \cos(w_m t + \varphi)\right] \\ \exp\left[jw_c t - jm_2\ \cos(w_m t + \varphi)\right] \end{Bmatrix} \tag{3}$$

where m_2 is the modulation index of the PolM2, and ϕ is the phase difference between two microwave drive signals applied to the DPPolM.

The polarization modulated optical signal at the output of PolM2 is then sent into the PC3, which is used to rotate the polarization direction of the incoming light wave by 90° along the clockwise direction. Thus, the output of PC3 can be written as

$$\begin{bmatrix} E_{2x} \\ E_{2y} \end{bmatrix} = \frac{1}{2}E_c \begin{Bmatrix} \exp\left[jw_c t - jm_2\ \cos(w_m t + \varphi)\right] \\ -\exp\left[jw_c t + jm_2\ \cos(w_m t + \varphi)\right] \end{Bmatrix} \tag{4}$$

After polarized combined by the PBC, the output of DPPolM can be written as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \frac{E_{1x}}{2} - \frac{E_{1y}}{2} \\ -\frac{E_{1x}}{2} + \frac{E_{1y}}{2} \end{bmatrix} + \begin{bmatrix} \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \\ \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \end{bmatrix} = \begin{bmatrix} \frac{E_{1x}}{2} - \frac{E_{1y}}{2} + \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \\ -\frac{E_{1x}}{2} + \frac{E_{1y}}{2} + \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \end{bmatrix} \tag{5}$$

When the angle of Pol $\alpha = 0°$, the output of Pol can be written as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{E_{1x}}{2} - \frac{E_{1y}}{2} + \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \\ -\frac{E_{1x}}{2} + \frac{E_{1y}}{2} + \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \end{bmatrix} = \begin{bmatrix} \frac{E_{1x}}{2} - \frac{E_{1y}}{2} + \frac{E_{2x}}{2} + \frac{E_{2y}}{2} \\ 0 \end{bmatrix} \tag{6}$$

Using the Jacobi-Auger expansion, the output of Pol can be expanded as