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Filter-less frequency-doubling microwave signal generator with tunable phase shift

Yueqin Li, Li Pei*, Jing Li, Yiqun Wang, Jin Yuan

Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

A prototype for frequency-doubling microwave signal generator with tunable phase shift based on a filter-less architecture is proposed and analyzed. In the proposal, one dual parallel polarization modulator is used as the key component to generate two ±1st order sidebands along the orthogonal polarization directions with suppressed carrier. Then the polarization states of the two sidebands are aligned with the principal axes of an electro-optical phase modulator (EOPM). Tunable phase shift is implemented by controlling the direct current voltage applied to the EOPM. Without using any filters or wavelength-dependent components, the system possesses good frequency tunability and it can be applied to multi-wavelength operation. Taking advantage of the ability of frequency multiplication, the frequency tuning range can be wider than the operation bandwidth of the modulator. By theoretical analyses and simulated verifications, a frequency-doubling microwave signal ranging from 22 to 40 GHz with full range phase shift is achieved.

1. Introduction

Microwave signal generator realized by photonic techniques has captured broad attention due to its competitive advantages beyond the traditional approaches, such as large bandwidth, flexible tunability and immunity to magnetic interference [1]. Recent years, in order to generate high-frequency microwave signal with wide bandwidth and good tunability, researchers have been focusing more on solving the problem which is triggered by the limited bandwidth of modulators or other optoelectronic devices. Thus, several methods for generating doubling or quadrupling frequency microwave signal have been proposed. In [2], by using a low frequency intensity modulator and an optical notch filter, a wide-band tunable microwave signal has been generated. Afterwards, a frequency quadrupler employing two cascaded intensity modulators [3] and an approach using a polarization modulator (PolM) in a Sagnac loop [4] have also been reported. Meanwhile, there is an increasing requirement for multiple applications in different fields. For instance, in broadband wireless communications [5], phased array antennas [6], sensing and military systems, the microwave signal generators are supposed to be equipped with microwave phase shift technology. Recently, some novel photonic schemes for implementing microwave phase shifter have been reported. They have been based on dual-sideband phase-control [7], carrier wavelength conversion in a fiber Bragg grating [8], stimulated Brillouin scattering [9] and separation or combination of the signals in different polarization directions [10,11].

Based on the researches of frequency multiplication and phase shift technology respectively, more recent studies have combined these two functions within a system, which is quite promising for future applications. An approach for generating frequency-quadrupling millimeter-wave signals with tunable phase shift has been proposed in Ref. [12]. In this system, an optical notch filter has been used to remove the optical carrier. Then by using a polarization-maintaining fiber Bragg grating (PM-FBG), two orthogonally-polarized sidebands can be obtained. However, the PM-FBG is required to have very small wavelength spacing and wide transmission bands, which may cause complex fabrication. Moreover, it is unlikely to achieve multi-wavelength operation because the wavelength of the PM-FBG is fixed. Whereafter, another scheme for generating a frequency-doubling microwave signal with phase shift has also been studied [13]. It has been realized by a programmable filter which can select the two specific harmonic sidebands with phase modulated. The programmable filter should be set with optimized parameters, so that the optical carrier is located at the center of the stopband, while the two first order sidebands are in the two passband respectively. But using the programmable filter may result in relatively complex parameter manipulation. Especially, both the two methods depend on the use of filters, which may limit the frequency range of the system. Then the frequency tunability may be less flexible.

* Corresponding author.
E-mail address: lipei@bjtu.edu.cn (L. Pei).

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In this paper, we propose a filter-less approach for the generation of frequency-doubling microwave signal with tunable phase shift. Unlike the approaches using filters in Refs. [12,13], our proposal is based on a dual parallel polarization modulator (DP-PolM) [14,15]. Avoiding using any electrical or optical filters, the system can achieve good frequency tunability. By properly setting the inherent static phase difference of DP-PolM, an optical signal with two orthogonally polarized $\pm$1st order sidebands and suppressed carrier can be realized. Then via a polarization controller, the polarization states of the two $\pm$1st order sidebands are aligned with the principal axes of an electro-optical phase modulator (EOPM). The EOPM can introduce a phase difference between the two sidebands, which is simply controlled by the direct current voltage applied to the EOPM. Through applying the output signal from the polarizer to the photodetector (PD), a frequency-doubling microwave signal with full range phase shift over a bandwidth of 22–40 GHz is implemented by simulation. In the previous reported schemes, filters are usually inevitable, resulting in a limited frequency tunability. Besides, the schemes are usually wavelength dependent so they cannot satisfy the demand of multi-wavelength operation. While in our scheme, the specific sidebands are obtained by the manipulation of polarization states. Without using any filters or wavelength-dependent devices, desirable frequency tunability and multi-wavelength compatibility can be obtained simultaneously. Furthermore, the realization of frequency doubling makes the scheme superior to the traditional microwave shifters. Higher frequency beyond the operation bandwidth of the modulator and the electrical hybrid can be achieved in the system.

2. Principle

The schematic setup of the proposed system for the frequency-doubling microwave signal generator with tunable phase shift is shown in Fig. 1(a) and the evolution of the polarization directions is illustrated in Fig. 1(b). A lightwave from a laser diode (LD) is firstly linear polarized with 45° via a polarization controller (PC1). Then it is sent into a DP-PolM, which is consist of two PolMs, two polarization beam splitters (PBSs) and four PCs. The PC before and after the PolM is used to align the principle axis of the PolM at a specific angle to the axis of the PBS1 and PBS2. Assuming that the principal axes of PBS and PolM are identical, we clockwise rotate the PC4 and PC5 before the PolM with 45° and counterclockwise rotate PC6 and PC7 after the PolM with 45°, so that the principal axes of each PolM are aligned to have an angle of 45° to those of the PBS1 and PBS2. The DP-PolM has to be driven by two quadrature RF signals, i.e. sin(Ωt) and cos(Ωt), thus it is necessary to use an electrical 90° hybrid to split the input RF signal. By using Jacobi–Anger expansion, the output signal under small signal modulation can be expressed as [15]:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{\sqrt{2}}{2}\cdot E_{in}\cdot e^{jw_0 t}\begin{bmatrix} \exp(jm_1\sin\Omega t + j\beta_1) + \exp(-jm_1\sin\Omega t) \\ \exp(jm_2\cos\Omega t + j\beta_2) + \exp(-jm_2\cos\Omega t) \end{bmatrix} = \frac{\sqrt{2}}{2}\cdot E_{in} \cdot e^{jw_0 t}\begin{Bmatrix} [1+\exp(j\beta_1)]\cdot J_0(m_1) + [1-\exp(j\beta_1)]\cdot J_1(m_1) \\ \cdot[\exp(j\Omega t) - \exp(-j\Omega t)] \\ [1+\exp(j\beta_2)]\cdot J_0(m_2) + j[1-\exp(j\beta_2)]\cdot J_1(m_2) \\ \cdot[\exp(j\Omega t) + \exp(-j\Omega t)] \end{Bmatrix} \tag{1}$$

where E_{in} is the amplitude of the optical carrier, w_0 and Ω are the angular frequencies of the carrier and the input RF signal, β_1 and β_2 are the inherent static phase differences of the upper and lower branches, m_1 and m_2 are the modulation indexes of PolM1 and PolM2 and J_n is the Bessel function of the first kind of order n.

To suppress the optical carrier, β_1 and β_2 are set to be equal and $\beta_1 = \beta_2 = \pi$. The two $\pm$1st order sidebands along the two principal axes of the DP-PolM can be obtained, whose polarization directions are shown in Fig. 1(b). Meanwhile, m_1 and m_2 are also set to be same and they are represented by m. Thus, the $\pm$1st order sidebands of E_x and E_y have equal amplitudes and the output optical field is

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \sqrt{2}\cdot E_{in}\cdot e^{jw_0 t}\cdot J_1(m)\cdot\begin{bmatrix} \exp(j\Omega t) - \exp(-j\Omega t) \\ j\exp(j\Omega t) + j\exp(-j\Omega t) \end{bmatrix} \tag{2}$$

Then the optical signal output from DP-PolM is transmitted to an EOPM via PC2 for phase modulation. In order to align the polarization directions with the two principal axes of the EOPM, PC2 is carefully adjusted with a rotation angle of 45° and the phase difference between E_x and E_y which is introduced by PC2 is $-45°$. The output signal after PC2 is:

$$\begin{bmatrix} E_{x1} \\ E_{y1} \end{bmatrix} = \begin{bmatrix} \cos 45° & -\sin 45° \\ \sin 45° & \cos 45° \end{bmatrix}\begin{bmatrix} e^{j45°} & 0 \\ 0 & e^{-j45°} \end{bmatrix}\begin{bmatrix} E_x \\ E_y \end{bmatrix} = 2\cdot E_{in}\cdot J_1(m)\cdot e^{jw_0 t - j\frac{\pi}{4}}\begin{bmatrix} -\exp(j\Omega t) \\ \exp(-j\Omega t) \end{bmatrix} \tag{3}$$

Thus two orthogonally-polarized first order sidebands can be obtained after PC2. They are aligned with the two principal axes of the EOPM by transverse-magnetic (TM) and transverse-electric (TE) modes respectively. When a direct current (DC) voltage is

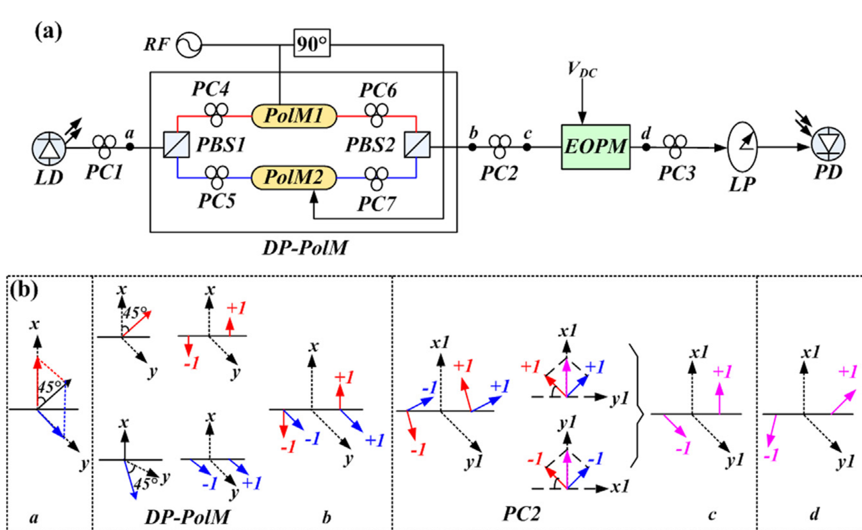

Fig. 1. (a) Schematic of the proposed system; (b) evolution of the polarization directions.