Optics Communications 335 (2015) 53–59

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High-power optical millimeter-wave signal generation with tunable frequency multiplication factor

Yi-shi Han*, Zhenyu Zheng, Zhixiao Luo, Zhixuan Min, Ou Xu, Jie Liu

School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form
29 August 2014
Accepted 1 September 2014
Available online 16 September 2014

Keywords:
Millimeter-wave generation
Phase modulator
Frequency multiplication
Optical multi-sideband modulation

ABSTRACT

This work demonstrates a simple and novel scheme for millimeter-wave (MMW) signal generation using optical multi-sidebands (OMSB) modulation. In the proposed methods, several pairs of optical sidebands can be generated by employing parallel phase modulators driven by a low frequency radio frequency (RF) signal. The optical sidebands will beat at a photodetector (PD) to generate high frequency MMW signal with tunable frequency multiplication factor, such as frequency octupling, 12-tupling, 16-tupling and 18-tupling. Since no optical filters or DC bias are used, the MMW signal has the evident character of high-power output. A generalized analytic expression and simulation verification for generating the frequency multi-tupling MMW signal are developed. The influences caused by non-ideal factors are discussed in detail, and undesired power ratios versus non-ideal factors are plotted and analyzed.

1. Introduction

Radio-over-fiber (RoF) is an attractive solution for future broadband wireless communication systems due to its large capacity and high flexibility for both fixed and mobile users. Millimeter-wave (MMW) generation is a key technique to realize low cost and high transmission performance in RoF systems. In electrical domain, MMW signals beyond 60 GHz are difficult to generate and process due to restrictions on frequency responses of electronic devices. Hence, all-optical generation and distribution of MMW signals have attracted interest in recent years [1,2].

The fundamental technique to generate a MMW signal in the optical domain is to heterodyne two optical waves of different wavelengths which beat at a photodetector (PD) [3]. The frequency of the MMW signal corresponds to the wavelength spacing of the two-tone-based optical sidebands. Therefore, the frequency multiplication is achieved from low-frequency reference sources [4]. In the past few years, numerous techniques have been proposed to generate frequency-multiplied MMW signals. For example frequency-quadrupled [5,6], sextupled [7–9], or octupled [10,11] MMW signals could be generated by heterodyning two-tone-based optical sidebands. As for higher frequency multiplication factor (FMF) for generating MMW signal, only few methods have been reported. All the methods can be divided into three categories generally: (1) External modulation [12–15], (2) nonlinear optical effect [16–18], and (3) multi-wavelength selection [19,20].

To achieve a high FMF, external modulation employing structurized Mach–Zehnder modulator (MZM) was proposed to produce two optical sidebands. The sidebands have a frequency spacing corresponding to FMF times the frequency of the microwave drive signal. In Ref. [12], two 6th-order sidebands were generated by using an integrated nested MZM and frequency 12-tupling was achieved without optical filter. In Ref. [13], two cascaded dual-parallel MZM were demonstrated to realize frequency 16-tupling, and 160 GHz MMW was generated with three optical interleavers. Besides, two methods were proposed using three parallel MZMs [14] and two parallel dual-parallel MZMs [15], which can be employed for 18-tupling and 16-tupling MMW signal generation respectively. External modulation employing structurized MZM has a good performance of the optical sideband suppression ratio (OSSR) and a high spectral purity of the generated MMW signal, but suffered from the bias drifting problem, which would lead to poor stability of the microwave generation system [14,15].

Frequency multiplication can also be achieved using the nonlinear optical effect based on four-wave mixing (FWM). In Refs. [16,17], two 6th-order sidebands were generated and frequency 12-tupling was realized by employing semiconductor optical amplifier (SOA) and polarization modulator [16], or using SOA with a dual-parallel MZM [17]. In Ref. [18], microwave multiplication with a FMF of 18 can be achieved by using two MZMs and two SOAs. The major problem in Refs. [16–18] is that employing SOA will produce redundant idle waves, which would degrade the spectral purity and power of the

* Corresponding author.
E-mail address: yshan@gdut.edu.cn (Y. Han).

http://dx.doi.org/10.1016/j.optcom.2014.09.002

generated MMW signal. So the extra optical filters, such as stimulated-Brillouin-scattering-assisted filter [16] or optical interleavers [17], should be used to remove the “harmful” spectral components. However these methods increase the system complexity and cost.

Besides, a kind of multi-wavelength selection technique can also be used to get a tunable multiplication factor. The main idea of this technique is that several multi-wavelength signals are generated by integrating phase modulator (PM) and MZM [19], or PMs and electro-absorption modulator (EAM) [20]. A wavelength selective filter should be employed to select two-tone-based optical sidebands with arbitrarily wavelength spacing, such as 25–325 GHz [19] and 40–440 GHz [20]. When the two optical sidebands beat at a PD, a tunable FMF can be achieved. The key limitation of these methods is the poor efficiency of the photomixer introducing as filter components, which suppressed most of the optical sidebands in the system.

In general, the proposed methods with high frequency multiplication factor (FMF > 8) are based on the idea of beating two optical sidebands at a PD. The major limitations of these methods lie in high complexity in frequency tuning since more than two parameters are needed to be adjusted simultaneously. And biasing the MZM to suppress the designed optical sidebands suffers from a dc bias-drifting problem, which reduces the robustness of the system. Besides, the power of the generated high frequency MMW signals is very low, even if an optical power amplifier is used. Ref. [21] has mentioned that the power of a generated 100 GHz MMW signal (frequency octupling) is only in the order of μW or less, which can barely meet the demands for practical application.

In this paper, we propose a novel optical multi-sidebands modulation (OMSB) to generate a high-power and high-frequency MMW signals. Several periodical optical sidebands are generated by employing parallel phase modulators. Unlike heterodyning two-tone-based waves, more than two optical sidebands will beat at a PD and contribute to generate a MMW signal with designed frequency. Since no optical filters or DC bias are used, the MMW signals have the evident character of high-power output. In additional, the MMW frequency with octupling, 12-tupling, 16-tupling or even higher FMF of the local oscillator can be implemented. A generalized analytic expression for the generated frequency multi-tupling MMW signal is developed. Simulation verifications and comparison results are also presented. Besides, the influences caused by non-ideal factors are discussed in detail, and undesired power ratios versus non-ideal factors are plotted and analyzed in the following sections.

2. Principle of operation

Fig. 1 shows a conceptual diagram of the optical MMW signals generation using OMSB. In Fig. 1, the optical signal of a laser diode (LD) is split into n parts with equal power, and then is injected into the n parallel phase modulators (n-PPMs). Meanwhile, a RF driving signal is applied to the n-PPMs with different initial phases 0, $2\pi/n$,…, $(n-1)(2\pi/n)$. So the driving signal sent into the jth-PPM can be expressed as

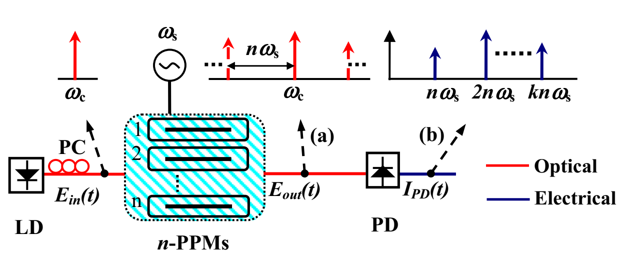

Fig. 1. The proposed millimeter-wave generation scheme using OMSB. LD: laser diode; PC: polarization controller; PPMs: parallel phase modulators; PD: photodiode.

$V_j(t) = V_{RF}\sin[\omega_s t + (j-1)2\pi/n]$, where V_{RF} and ω_s are the amplitude and angular frequency of the RF signals.

We assume that the optical signal applied to the input port is

$$E_{in}(t) = E_c\cos(\omega_c t) \tag{1}$$

where E_c and ω_c are the amplitude and angular frequency of the optical carrier. The optical field at the output of the n-PPMs can be expressed as

$$E_{out}(t) = \sum_{j=1}^{n} E_j(t) = \sum_{j=1}^{n}\frac{E_c}{n}\cos\left[\omega_c t + \beta\sin\left(\omega_s t + (j-1)\frac{2\pi}{n}\right)\right] \tag{2}$$

where β is the modulation index of the n-PPM given by $\beta = \pi V_{RF}/V_\pi$.

In Eq. (2), we find the $E_{out}(t)$ consists of optical carrier and several optical sidebands, which have the same periodical frequency space $n\omega_s$ as shown in Fig. 1(a). All pairs of optical sidebands will beat at a photodetector (PD). After square-law PD detection, a serial frequency multi-tupling MMW signals can be generated. The frequencies of the MMW signals are $kn\omega_s$, $k=1, 2, 3\ldots$, as shown in Fig. 1(b) and the parameter kn indicates the frequency multiplication factor (FMF).

2.1. Generation of periodical optical sidebands

Expanding Eq. (2) in term of Bessel functions of the first kind, the optical field at the output of the n-PPMs can be expressed as

$$E_{out}(t) = \sum_{i=-\infty}^{\infty}\frac{E_c}{n}J_i(\beta)\sum_{j=1}^{n}\cos\left(\omega_c t + i\omega_s t + (j-1)\frac{2i\pi}{n}\right) \tag{3}$$

where, $J_x(\bullet)$ is the xth-order Bessel function of the first kind.

In Eq. (3), i means the number of order of sideband, and the optical field of the ith-order sideband in Fig. 1(a) can be written as

$$\begin{aligned} E^{(i)}(t) &= \frac{E_c}{n}J_i(\beta)\sum_{j=1}^{n}\left\{\cos(\omega_c t + i\omega_s t) + (j-1)\frac{2i\pi}{n}\right\} \\ &= \frac{E_c}{n}J_i(\beta)\left\{\begin{array}{l} \cos(\omega_c t + i\omega_s t)\sum_{j=1}^{n}\cos\left[(j-1)\frac{2i\pi}{n}\right] \\ -\ \sin(\omega_c t + i\omega_s t)\sum_{j=1}^{n}\sin\left[(j-1)\frac{2i\pi}{n}\right] \end{array}\right\} \end{aligned} \tag{4}$$

In Eq. (4), given $i = \mathrm{mn}$, m is an integer, n is the number of the PPMs, then

$$\sum_{j=1}^{n}\cos\left[(j-1)\frac{2i\pi}{n}\right] = n;\quad \sum_{j=1}^{n}\sin\left[(j-1)\frac{2i\pi}{n}\right] = 0 \tag{5}$$

Given $i \neq \mathrm{mn}$, then

$$\sum_{j=1}^{n}\cos\left[(j-1)\frac{2i\pi}{n}\right] = 0;\quad \sum_{j=1}^{n}\sin\left[(j-1)\frac{2i\pi}{n}\right] = 0 \tag{6}$$

Substituting Eqs. (4)–(6) into Eq. (3), we have

$$E_{out}(t) = \sum_{i=-\infty}^{\infty}E^{(i)}(t) = \sum_{m=-\infty}^{\infty}E_c J_{mn}(\beta)\cos(\omega_c t + mn\omega_s t) \tag{7}$$

where m is an integer, n is the number of the PPMs, β is the modulation index of the PPMs

Eq. (7) is a generalized expression for generating periodical optical sidebands using n parallel phase modulators. We can find that only optical carrier and optical sidebands, whose orders have the integer times to the number of the n-PPMs, can be generated. The frequencies of these sidebands are periodical with frequency space $n\omega_s$ shown in Fig. 1(a).

Fig. 2 schematically depicts the principle of periodical optical sidebands generation with n-PPMs, here $n=3$ or 4. In Fig. 2(a), the electrical driving modulation signals sent into the 3-PPMs with initial phase 0, $2\pi/3$ and $4\pi/3$ respectively. All the first-order sidebands in each PM have equal power and different phase shift 0, $2\pi/3$, $4\pi/3$ accordingly, shown in insets (i–iii) of Fig. 2(a). At the output of the