Efficient THz Generation Via Optical Frequency 24-Tupling without Optical Filter

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***Abstract*—In this paper, a novel optical frequency 24-tupling scheme for THz signal generation is proposed and demonstrated. Based on two cascaded Dual-Parallel Mach-Zehnder Modulators (DPMZM) and three phase shifters, optical signal with only ±12th-order sidebands is achieved without optical filter. Theoretical analysis and simulation results show that the scheme can generate 0.12THz signal from a 5GHz radio frequency local oscillator (LO), and the harmonic distortion suppression ratio is more than 55 dB.**

I. INTRODUCTION

Radio-over-Fiber (RoF) system has been considered a promising technique to wireless access networks, becuase it could increase the capacity, mobility and bandwidth of the networks [1,2]. In RoF system, high frequency millimeter-wave can be generated directly in optical domain. However, due to the limitation of the frequency response of optical modulator, the generation of high frequency millimeter-wave remains a huge challenge in various optical fiber-supported systems.

Recently, some technologies for optical millimeter-wave generation with excellent performance have been reported [3-7]. In [3], a new approach to generate optical carrier suppression millimeter-wave is proposed. However, the frequency of millimeter-wave is only two times frequency of the local oscillator (LO). In order to generate high frequency millimeter-wave, expensive electrical equipments are still needed. In [6], a new approach to generate frequency 12-tupling millimeter-wave is proposed. The millimeter-wave with two sixth-order optical sidebands are generated using frequency quadrupling millimeter-wave generation along with optical four-wave-mixing. The key limitation is that the fore-wave-mixing will bring the frequency 12-tupling approach poor stability.

In this paper, an efficient THz generation scheme via optical frequency 24-tupling is investigated. The scheme is achieved by two cascaded Dual-Parallel Mach-Zehnder Modulators (DPMZM) and three phase shifters. By properly adjusting the DPMZMs DC biases voltages and the local oscillator (LO) voltages and phases, optical signal with only ±12th-order sidebands is achieved without optical filter. Theoretical analysis and simulation results show that the scheme can generate THz signal from a low frequency LO. Moreover, with the help of Erbium Doped Fiber Amplifier (EDFA), the power of THz signal can be adjusting flexibly.

II. PRINCIPLE

Fig. 1 shows the experimental setup of the proposed scheme. A light wave emitted from a distributed feedback (DFB) laser can be expressed as $E_{in}(t) = (E_0/\sqrt{2})\exp(j\omega_c t)$. Where E_0 is the light wave amplitude, and ω_c is the angular frequency. The key of the THz signal generation with frequency 24-tupling is two commercially available DPMZMs. DPMZM is composed of three sub-MZMs. One sub-MZM (MZ-a or MZ-b) is embedded in each arm of the main modulator (MZ-c). Both MZ-a and MZ-b of two DPMZMs are biased at the maximum transmission point, and MZ-c of two DPMZMs are biased at the minimum transmission point. In this scheme, DPMZMs are driven by a 5GHz LO with phase difference of 45°, and phase difference between MZ-a and MZ-b are 90°. An EDFA is used to amplify the optical power.

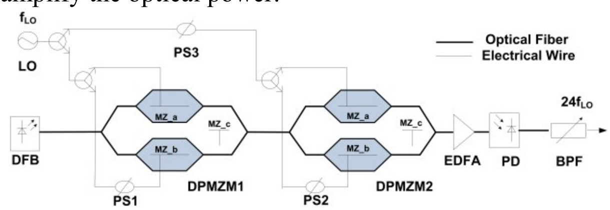


Fig.1 Experimental setup of the THz generation via optical frequency 24-tupling. Photodetector (PD), phase shifter (PS), band pass filter (BPF).

The LO signals injected into MZ-a and MZ-b of DPMZM1 can be expressed as

$$\begin{aligned} V_{LO1}(t) &= V_{LO}\sin\omega_{LO}t \\ V_{LO'1}(t) &= V_{LO}\sin(\omega_{LO}t+\phi_1) \end{aligned} \tag{1}$$

Where V_{LO} and ω_{LO} are the amplitude voltage and the angular frequency of LO signals, ϕ_1 is the phase difference between MZ-a and MZ-b, which is introduced by PS1 in Fig.1. The optical signal exported from DPMZM1 can be expressed as

$$\begin{aligned} E_{DPMZM1}(t) = &\frac{E_{in}}{4}[\exp(jm\sin(\omega_{LO}t)) + \exp(-jm\sin(\omega_{LO}t) - j\theta_1)] \\ &+ \frac{E_{in}}{4}\exp(j\theta_3)[\exp(jm\sin(\omega_{LO}t+\phi_1)) \\ &+ \exp(-jm\sin(\omega_{LO}t+\phi_1) - j\theta_2)] \end{aligned} \tag{2}$$

Where m is the modulation index defined as $m = \pi V_{LO}/V_\pi$. Because MZ-a and MZ-b of DPMZM1 is biased at the maximum transmission point, and MZ-c is biased at the minimum transmission point, $\phi_1 = \pi/2$, $\theta_1 = \theta_2 = 0$, $\theta_3 = \pi$. Therefore, optical signal exported from the DPMZM1 can be changed as

$$\begin{aligned} E_{DPMZM1}(t) = &\frac{E_{in}(t)}{4}[\exp(jm\sin(\omega_{LO}t)) + \exp(-jm\sin(\omega_{LO}t))] \\ &- \frac{E_{in}(t)}{4}[\exp(jm\sin(\omega_{LO}t+\frac{\pi}{2})) - \exp(-jm\sin(\omega_{LO}t+\frac{\pi}{2}))] \\ = &\frac{E_{in}(t)}{4}\sum_{n=-\infty}^{\infty}[J_n(m)\exp(jn\omega_{LO}t)] + \sum_{n=-\infty}^{\infty}[(-1)^n J_n(m)\exp(jn\omega_{LO}t)] \\ &- \frac{E_{in}(t)}{4}\sum_{n=-\infty}^{\infty}[J_n(m)\exp(jn\omega_{LO}t + jn\frac{\pi}{2})] - \sum_{n=-\infty}^{\infty}[(-1)^n J_n(m)\exp(jn\omega_{LO}t + jn\frac{\pi}{2})] \\ = &\frac{E_{in}(t)}{4}\sum_{n=-\infty}^{\infty} J_n(m)\exp[jn\omega_{LO}t][1+(-1)^n][1-\exp(jn\frac{\pi}{2})] \end{aligned} \tag{3}$$

From (3) it can be seen that (2n-1)-th order sidebands are suppressed when $1+(-1)^n = 0$. $J_n(m)$ is the n-th order Bessel function of the first kind. When m=5.1, ± 2-th order sidebands can be suppressed because $J_2(5.1) \approx 0$. Therefore, LO signals are modulated on the $\pm$6-th order sidebands, and the optical signal exported from DPMZM1 can be changed as

$$E_{DPMZM1}(t) \approx \frac{E_{in}(t)}{2}\{J_6(m)[\exp(6j\omega_{LO}t)+\exp(-6j\omega_{LO}t)]\} \tag{4}$$

In DPMZM2, DC biases and phase difference between MZ-a and MZ-b are the same as in DPMZM1. The LO signals injected into DPMZM2 are

$$\begin{aligned} V_{LO2}(t) &= V_{LO}\sin(\omega_{LO}t+\phi_3) \\ V_{LO'2}(t) &= V_{LO}\sin(\omega_{LO}t+\phi_2+\phi_3) \end{aligned} \tag{5}$$

Where $\phi_2=\phi_1=\pi/2$, and $\phi_3=\pi/4$. Therefore, the optical signal exported from DPMZM2 can be expressed as

$$\begin{aligned} E_{DPMZM2}(t) &\approx \frac{E_{DPMZM1}(t)}{2}\sum_{n=-\infty}^{\infty} J_{4n-2}(m)\exp[j(4n-2)(\omega_{LO}t+\frac{\pi}{4}) \\ &= \frac{E_{in}(t)}{4}\sum_{n=-\infty}^{\infty} J^2{}_{4n-2}(m)\exp[j(8n-4)\omega_{LO}t] \\ &\quad + J^2{}_{4n-2}(m)\exp[j\frac{(2n-1)\pi}{2}]\exp[j(4n-2)\omega_{LO}t) \end{aligned} \tag{6}$$

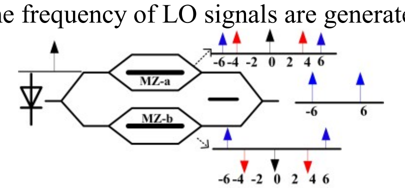
The Bessel function $J_{4n-2}(m)$ for n>2 is much smaller than that of n⩽2. So the higher order sidebands can be neglect. As shown in formula (3) and (6), LO signals between DPMZM1 and DPMZM2 are $\pi/4$ out of phase. The optical signal exported from the DPMZM2 can be changed as

$$\begin{aligned} E_{DPMZM2}(t) &\approx \frac{E_{in}(t)}{4}\{J^2{}_6(m)\exp(12j\omega_{LO}t) \\ &\quad + J^2{}_{-6}(m)\exp(-12j\omega_{LO}t)\} \end{aligned} \tag{7}$$

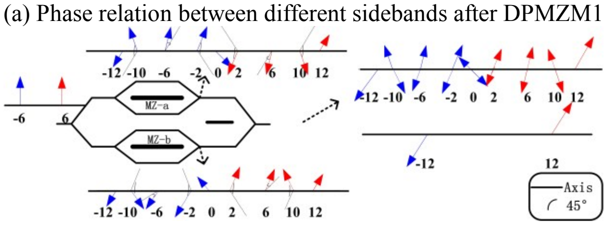
In back-to-back (BTB) case, $\pm$ 12-order sidebands are beated in PD, and then a frequency 24-tupling THz signal is generated. The photocurrent can be expressed as

$$\begin{aligned} I_{out} &= RP = R|E_{DPMZM2}(t)|^2 \\ &= R\frac{E^2{}_{in}(t)}{16}\left|J^2{}_6(m)\exp(12j\omega_{LO}t)+J^2{}_{-6}(m)\exp(-12j\omega_{LO}t)\right|^2 \\ &= R\frac{E^2{}_{in}(t)}{16}\{2J^4{}_6(m)+2J^4{}_6(m)\cos(24j\omega_{LO}t)\} \end{aligned} \tag{8}$$

Where R is the responsivity of PD. It can be seen that after PD, there is only DC item and frequency 24-tupling item exist. In this scheme, the phase relation betweeen different order sidebands are shown in Fig.2. In Fig. 2(a), symmetrical sidibands are 180° out of phase, and 0-order, $\pm$2-order, and $\pm$4-order sidebands suppressed each other. Only $\pm$6-order are generated. As the same in Fig. 2(b), only $\pm$12-order separated by 24 times the frequency of LO signals are generated.



(a) Phase relation between different sidebands after DPMZM1

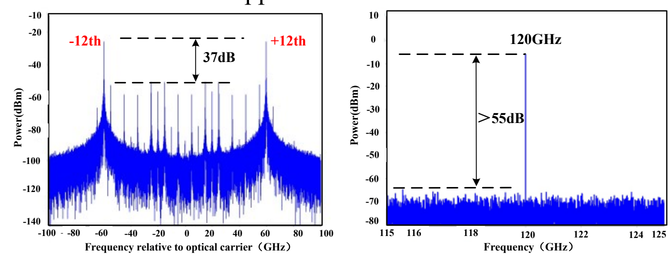


(b) Phase relation between different sidebands after DPMZM2

Fig.2 Phase relation between different sidebands after DPMZMs

III. Results

To study the performance of the THz generation scheme, a strict simulation is performed based on VPI transmissionMaker. The wavelength of DFB is 1553.6nm, with power of 13dBm. The modulation index of two DPMZMs are 5.136. The gain of EDFA is 30dB. Fig.3 (a) shows the optical spectrum result after two DPMZMs. Only ±12th-order sidebands are achieved, and the optical sideband suppression ratio (OSSR) is more than 37dB. Fig.3 (b) shows the electrical spectrum after PD. 0.12THz signal is generated with power of -8dBm, and the harmonic distortion suppression ratio is more than 55 dB.



(a) Optical spectrum after DPMZM2. (b) Electrical spectrum result after PD

Fig.3 Spectrum results of the simulation experiment.

IV. Summary

The authors successfully designed an efficient THz generation scheme via optical frequency 24-tupling. It shows a prospective way in laser driven THz source. Because there is no optical filter used, frequency range of the generated THz signal is decided only by LO source. Moreover, with the help of EDFA, the power of THz signal can be adjusting flexibly.

V. Acknowledgements

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