Optical Millimeter-Wave Signal Generation Via Frequency 12-Tupling

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***Abstract*—This work demonstrates the feasibility of optical millimeter-wave signal generation using frequency 12-tupling. Optical millimeter-wave signal with two sixth-order optical sidebands are generated using frequency quadrupling optical millimeter-wave generation along with optical four-wave-mixing. 210- and 120-GHz two-tone optical signals with optical carrier and undesired harmonic distortion suppression ratios of 20 and 30 dB are experimentally demonstrated. The proposed system provides an attractive method for millimeter-wave applications such as optical up-conversion in radio-over-fiber (RoF) communication systems at millimeter-wave band, phase-array antennas, optical sensors, radars, and tera-hertz applications.**

***Index Terms*—Nonlinear Optics, millimeter wave generation, optical communications, four-wave mixing.**

I. INTRODUCTION

MILLIMETER-WAVE signals have been extensively utilized in various applications, such as broadband wireless communication [1], Atacama large millimeter arrays (ALMA) [2], [3], radars, millimeter-wave imaging [4], radio-over-fiber systems [5], and tera-hertz applications. All-electronic millimeter-wave signal generation beyond 100 GHz remains a serious challenge because of restrictions on frequency responses of electronic devices and equipments. Accordingly, optical millimeter-wave signal generation techniques have become extremely attractive, due to the ability to generate optical millimeter-wave signals with frequencies of higher than 100 GHz. Moreover, the coverage of the optical millimeter-wave signal can be readily extended thanks to the low transmission loss of optical fibers. Many optical millimeter-wave generation approaches have recently been developed, including optical heterodyning with two laser sources [3], mode-locked lasers [6]–[9], and external modulation using electro-absorption modulators (EAM), phase modulators (PM), or Mach–Zehnder modulators (MZM) with a single wavelength laser source [5], [10]–[20].

Optical heterodyning using two laser sources is the most straightforward method for optical millimeter-wave signal generation. Nevertheless, optical phase-lock loop (OPLL) is required to stabilize the frequency fluctuation and minimize the phase noise of the generated optical millimeter-wave signal. The OPLL significantly increases system complexity and cost which hinder the implementation in many applications [21]. Mode-locked lasers that generate optical millimeter-wave signals with relatively low phase noise and frequencies of more than 100 GHz have been proposed [22], [23]. However, mode-locked lasers are sensitive to the environment variation including temperature fluctuation and vibrations. Therefore, a complex feedback system for long-term stabilization is usually required. [24], [25]

Using external optical modulators represent the most reliable solutions for optical millimeter-wave signal generation because these modulators have been extensively used in telecommunication system with proven stability and reliability. Optical millimeter-wave signal generations, which are based on double-sideband (DSB), single-sideband (SSB), and double-sideband with carrier suppression (DSB-CS) schemes, have been proposed [10]–[12]. The frequency of the generated optical millimeter-wave signal based on DSB, SSB, or DSB-CS is identical or doubles that of the radio-frequency (RF) driving signal. The frequency response of the optical modulators and electrical components still constrain the generation of optical millimeter-wave signal. Therefore, millimeter-wave generations using optical external modulators with frequency multiplication of more than two times that of the RF driving signal have become topics with great interest [13]–[17], [19], [20].

This work presents an optical frequency 12-tupling approach to generate high-purity optical two-tone signal for millimeter-wave generation with frequency up to 210 GHz, as the conceptual diagram shown in Fig. 1. The proposed approach consists of two main steps. The first step is the optical millimeter-wave signal generation by frequency quadrupling via a dual-parallel MZM [26], [27]. High purity two-tone optical signal with 36-dB optical carrier and harmonic distortion suppression ratio can be obtained. In the second step, a semiconductor optical amplifier (SOA) is utilized to perform four-wave mixing effect and thereby generating two new sixth-order optical sidebands. Due to the high optical carrier and harmonic distortion suppression ratios of the four-wave-mixing pump signal, the suppression ratios of the undesired optical sidebands are more than 16 dB relative to the sixth-order sidebands after four-wave mixing. Following, optical interleavers are employed to simultaneously suppress two undesired second-order sidebands, the optical carrier and undesired harmonic distortion

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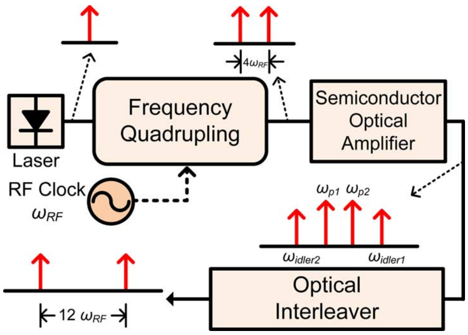

Fig. 1. Conceptual diagram of the optical millimeter-wave signal generation with frequency 12-tupling.

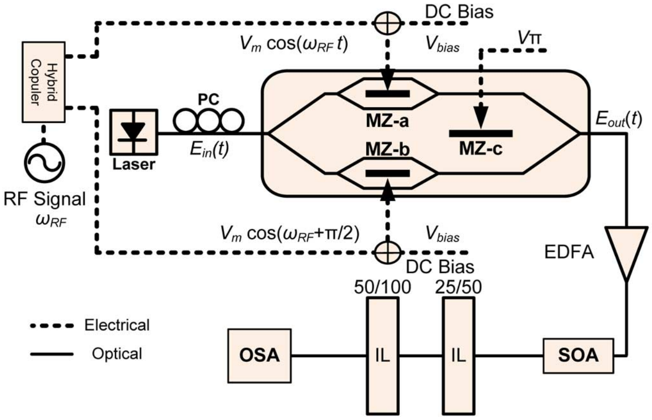

Fig. 2. Experimental setup of optical millimeter-wave generation using frequency 12-tupling. (MZ: Mach–Zehnder modulator; SOA: semiconductor optical amplifier; IL: optical interleaver; OSA: optical spectrum analyzer).

suppression ratios of the generated optical two-tone signals with 120-GHz and 210-GHz separation can exceed 30 and 20 dB, respectively. Because high frequency optical millimeter-wave signals can be generated using low frequency components and transmitted over low-loss optical fiber networks, the proposed system can be a potential candidate for next generation high frequency applications.

II. CONCEPTS AND EXPERIMENTAL SETUP

A. *Optical Millimeter-Wave Generation With Frequency Quadrupling*

Fig. 2 shows the experimental setup of the proposed system. A commercial distributed feedback (DFB) laser is employed as the optical source. Assume that the input optical field is defined as $E_{\rm in}(t) = E_o \cos(\omega_o t)$. The key of the optical millimeter-wave generation with frequency quadrupling is a commercially available dual-parallel MZM which 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 are biased at the maximum transmission point. The RF driving signals sent into MZ-a and MZ-b are $V_m \cos(\omega_{\rm RF} t)$ and $V_m \cos(\omega_{\rm RF} t + \pi/2)$, respectively. The optical field at the output of MZ-a and MZ-b can be expressed as

$$E_{\rm out-a} = 1/\sqrt{2} \cdot E_o \cdot \cos\left[m \cdot \cos(\omega_{\rm RF} t)\right] \cdot \cos(\omega_o t) \tag{1}$$

$$E_{\rm out-b} = 1/\sqrt{2} \cdot E_o \cdot \cos\left[m \cdot \sin(\omega_{\rm RF} t)\right] \cdot \cos(\omega_o t) \tag{2}$$

where m denotes the phase modulation index and is equal to $\pi V_m / 2V_\pi$. MZ-c is biased at the minimum transmission point and introduces a π phase shift between the optical output signal of the MZ-a and MZ-b. Therefore, the optical field at the output of the dual parallel MZM can be expressed as

$$E_{\rm out}({\rm t}) = \frac{1}{2} \cdot E_o \cdot \{\cos(\omega_o t) \cdot \cos[m \cdot \cos(\omega_{\rm RF} t)] - \cos(\omega_o t) \cdot \cos[m \cdot \cos(\omega_{\rm RF} t + \pi/2)]\} \tag{3}$$

Expanding (3) using Bessel function, the output optical field can be rewritten as

$$E_{\rm out}(t) = -E_o \sum_{n=1}^{\infty} J_{4n-2}(m) \times \left\{ \begin{array}{c} \cos[(\omega_o + (4n-2)\omega_{\rm RF})t] \\ + \cos[(\omega_o - (4n-2)\omega_{\rm RF})t] \end{array} \right\} \tag{4}$$

where J_n is the Bessel function of the first kind of order n. At the output of the dual-parallel MZM, the optical carrier is suppressed and only the optical sidebands of order $\pm(4n-2)$ can be observed, where n is a natural number. The properties of the Bessel function are such that optical sidebands of orders of higher than J_2 can be ignored without significant error. Only two second-order optical sidebands are considered in the following discussion and the optical field is given by

$$E_{\rm out}(t) = -E_o\{J_2(m)\cos[(\omega_o + 2\omega_{\rm RF})t] + J_2(m)\cos[(\omega_o - 2\omega_{\rm RF})t]\} \tag{5}$$

B. *Optical Four-Wave-Mixing via an SOA*

Four-wave mixing (FWM) is an optical nonlinear Kerr effect which relates to the third-order electric susceptibility. To demonstrate the concept and feasibility of the proposed method, we used an SOA whose potential to integrate with other photonic devices makes SOAs a reasonable choice [28]. After the optical millimeter-wave signal generation with frequency quadrupling, the optical four-wave mixing effect is created using an SOA. Two new optical sixth-order sidebands are emerged with a frequency separation of $12\omega_{\rm RF}$ when two optical second-order sidebands with a frequency separation of $4\omega_{\rm RF}$ are incident into the SOA (Uniphase CQF872). The bias current is set at 300 mA, with optical power gain of 20 dB, gain bandwidth of 60 nm and noise figure of 9 dB.

Consider that an optical signal composed of three different frequencies incidents into a nonlinear medium. The frequency of the newly emerging signal is a combination of the incident lightwave frequencies:

$$\omega_{\text{idler}} = \omega_{p1} + \omega_{p2} - \omega_{\text{probe}} \tag{6}$$

where ω_{idler} is the optical angular frequency of the newly emerging signal which is commonly called an "idler". ω_{p1} and ω_{p2} denotes the pump signal angular frequencies, and ω_{probe} is the probe signal angular frequency.

If an optical signal with only two different optical frequencies incident into the nonlinear medium, a special case that has been known as partially degenerate four-wave mixing arises. Each tone of the input optical signal can be the pump lightwave or the probe signal when they are sent into the nonlinear material. The optical frequency of the new emerged idler can be expressed as

$$\omega_{\text{idler}} = 2\omega_p - \omega_{\text{probe}} \tag{7}$$

where ω_p denotes the angular frequency of the pump signal. While the high-purity two-tone optical millimeter-wave signal is generated by frequency quadrupling and incident into the SOA, the second-order optical sidebands with angular frequencies of $\omega_o - 2\omega_{\text{RF}}$ and $\omega_o + 2\omega_{\text{RF}}$ lead to the partially degenerate four-wave mixing and the emergence of two new idlers. The idler frequencies can be expressed as

$$\begin{aligned}\omega_{\text{idler1}} &= 2\omega_{p1} - \omega_{\text{probe1}} \\ &= 2(\omega_o - 2\omega_{\text{RF}}) - (\omega_o + 2\omega_{\text{RF}}) \\ &= \omega_o - 6\omega_{\text{RF}} \end{aligned} \tag{8}$$

and

$$\begin{aligned}\omega_{\text{idler2}} &= 2\omega_{p2} - \omega_{\text{probe2}} \\ &= 2(\omega_o + 2\omega_{\text{RF}}) - (\omega_o - 2\omega_{\text{RF}}) \\ &= \omega_o + 6\omega_{\text{RF}} \end{aligned} \tag{9}$$

Two optical idler sidebands $(\omega_{\text{idler1}}, \omega_{\text{idler2}})$ are obtained with frequency spacing of 12 times that of the RF driving signal through optical four-wave mixing.

In this work, the average optical input power of the SOA is set at 9 dBm. After the FWM effect, the average optical output power of the SOA is about 14 dBm for both the 120 and 210-GHz optical two-tone signal generations.

C. *Optical Filtering Using Optical Interleavers*

After the four-wave-mixing, the sixth-order sidebands are emerged. However, the original two-tone pump lightwaves are also amplified by the SOA. In order to yield a high-purity optical millimeter-wave signal, these two optical pump signals $(\omega_{p1}, \omega_{p2})$ must be eliminated and optical interleavers are utilized to suppress those. The advantage of using optical interleavers is that two optical pump lightwaves can be simultaneously suppressed [5], [10], and [13]. Furthermore, this architecture can be implemented for wavelength divisions multiplexing (WDM) up-conversion in radio-over-fiber (RoF) systems [13].

Figs. 3(a) and (b) show the transmission spectra of the optical interleavers with 25- and 50-GHz channel spacings, respectively. The pass-band bandwidths of the 25- and 50-GHz interleavers are about 14 and 35 GHz, respectively. The output channels of both optical interleavers correspond to the International Telecommunication Union (ITU) channels. The pass-band insertion loss of the 25- and 50-GHz interleavers are 2.5 and 2 dB, respectively. After the optical filtering, the optical millimeter-wave signals can be expressed as

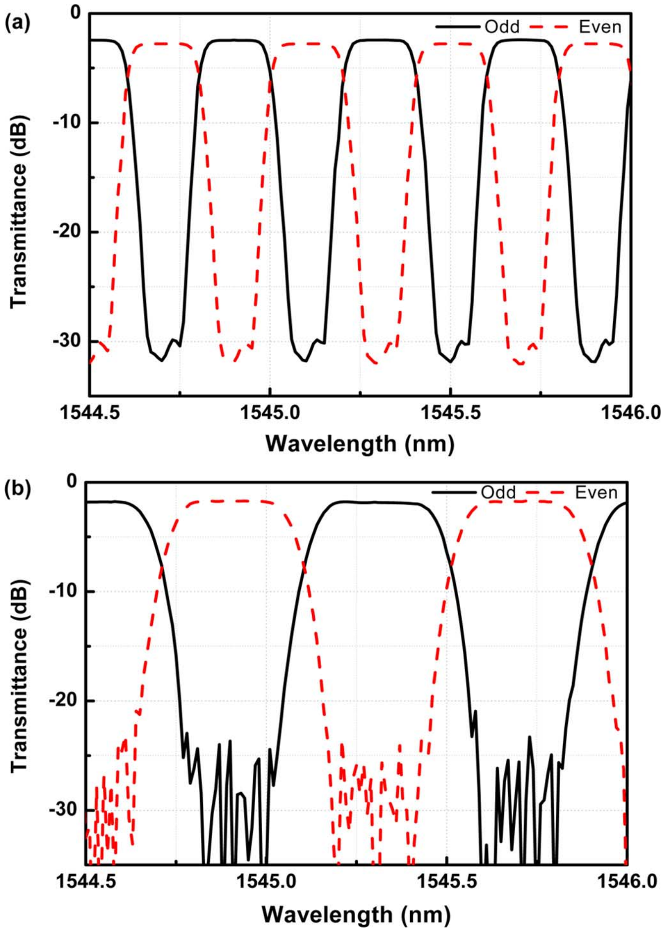

Fig. 3. Transmission spectra of the optical interleavers with (a) 25-GHz and (b) 50-GHz channel spacings.

$$E_{12\omega_{\text{RF}}}(t) = \varepsilon_o\{\cos[(\omega_o + 6\omega_{\text{RF}})t] + \cos[(\omega_o - 6\omega_{\text{RF}})t]\}, \tag{10}$$

where ε_o is the electrical filed amplitude of the generated optical millimeter-wave signal.

Fig. 4 presents the conceptual diagrams of high-purity 120- and 210-GHz two-tone signal generations. For the 120-GHz optical two-tone signal generation, two second order sidebands with 40-GHz frequency spacing along with two sixth-order sidebands with 120-GHz frequency spacing are obtained after the four-wave-mixing, as shown in inset (i) of Fig. 4(a). To suppress undesired optical sidebands, lightwaves generated from SOA are sent into the first optical interleaver with a channel spacing of 25 GHz, as shown in inset (ii) of Fig. 4(a). At the odd channel output of the first optical interleaver, the original pump lightwaves are partially suppressed. However, the suppression is insufficient. Therefore, the second optical interleaver with a channel spacing of 50 GHz [29] is employed, as shown

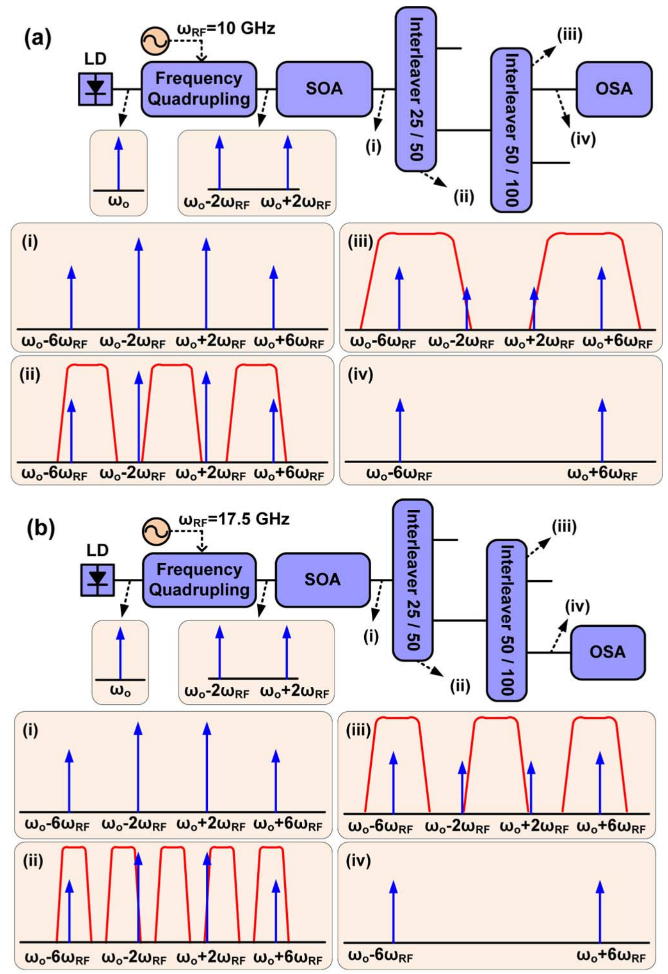

Fig. 4. Conceptual diagram of (a) 120-GHz and (b) 210-GHz optical millimeter-wave generations.

in inset (iii) of Fig. 4(a). Two-tone optical signal separated by 120 GHz with high optical carrier and harmonic distortion suppression ratio is obtained at the even output of the second optical interleaver, as displayed in inset (iv) of Fig. 4(a). On the other hand, 210-GHz optical two-tone signal can be obtained by using the same concept as shown in Fig. 4(b). Nevertheless, the 210-GHz optical two-tone signal is obtained at the odd output of the second optical interleaver, as shown in inset (iv) of Fig. 4(b).

III. Experimental Results and Discussion

To generate optical millimeter-wave signal using four-wave-mixing by high nonlinear materials, a high-purity pump signal is required. If the optical carrier and harmonic distortion suppression ratio is low, four-wave-mixing efficiency will be degraded and undesired optical sidebands will also be obtained. The proposed optical millimeter-wave signal generation technique with frequency quadrupling provides a high-purity pump signal for four-wave mixing. The MZM extinction ratio is an important factor in carrier suppressed optical millimeter-wave signal generation schemes. The optical carrier should be totally suppressed under ideal condition with infinite MZM extinction ratio. However, the extinction ratios of the commercially available MZMs are finite due to amplitude imbalance in MZM arms.

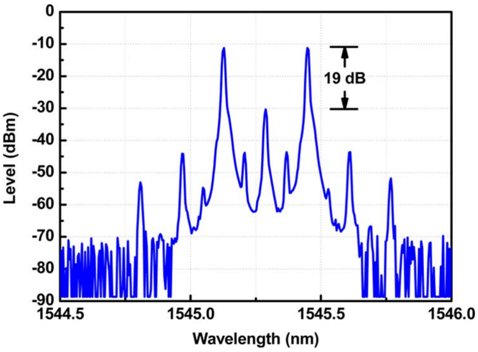

Fig. 5. Optical spectrum of the generated optical tones separated by 40 GHz without modulation-depth trimming.

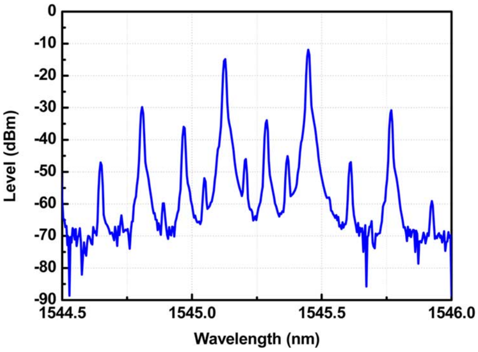

Fig. 6. Optical spectrum of the generated optical tones after the FWM for 120-GHz optical millimeter-wave signal generation without modulation-depth trimming.

The typical extinction ratios of commercially available MZMs are 20–30 dB which come from the fabrication errors. In the proposed frequency quadrupling technique, the amplitude imbalance can be compensated by trimming the modulation depth between MZ-a and MZ-b, and the extinction ratio of the MZ-c are improved.

Fig. 5 shows the optical spectrum of the generated optical tones separated by 40 GHz without modulation depth trimming. The resolution bandwidth of the optical spectrum analyzer (OSA) in this work is 0.01 nm. The optical carrier suppression ration is about 19 dB which is restricted by intrinsic MZM extinction ratio. After the four-wave-mixing in an SOA, not only the expected second and sixth order optical sidebands are obtained but the optical carrier and fourth order terms are obtained, as shown in Fig. 6. Low optical carrier suppression ratio pump signals degrades the efficiency of four-wave-mixing, and signals with unwanted sidebands could be obtained.

Fig. 7 shows the optical spectrum of the optical tones separated by 40 GHz that are generated from the 10-GHz RF driving signal using frequency quadrupling with modulation depth trimming. After employing modulation depth trimming, the optical carrier is suppressed and the undesired harmonic distortion suppression ratios exceed 36 dB. Take the high-purity two-tone signals as the pump signal and send into the SOA to perform the four-wave-mixing effect. Fig. 8 shows the optical spectrum after the four-wave-mixing in the SOA. Two new optical sixth order sidebands with a frequency spacing of 120 GHz are obtained along with the original 40-GHz optical tones.

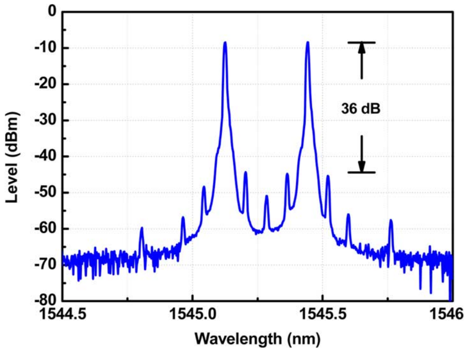

Fig. 7. Optical spectrum of the generated optical tones separated by 40 GHz.

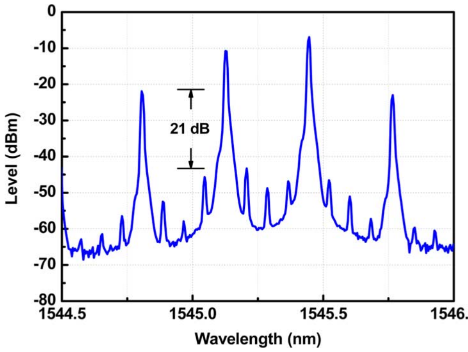

Fig. 8. Optical spectrum of the generated optical tones after the FWM for 120-GHz optical millimeter-wave signal generation.

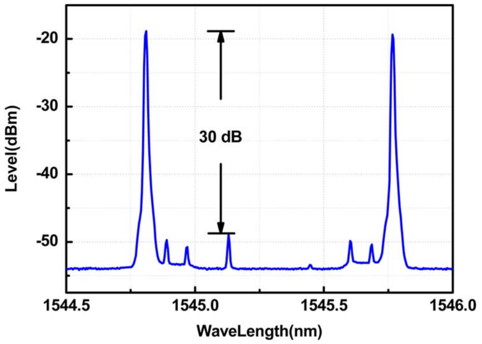

Fig. 9. Optical spectrum of the generated optical tones separated by 120 GHz.

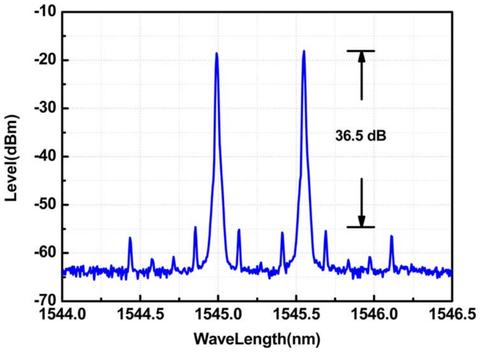

Fig. 10. Optical spectrum of the generated optical tones separated by 70 GHz.

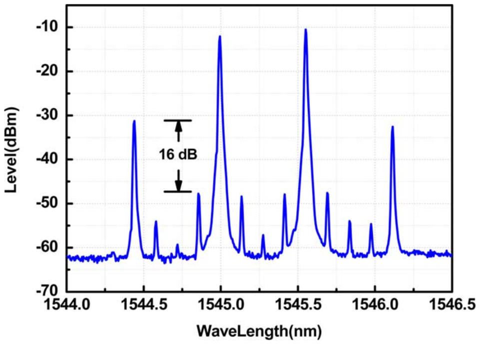

Fig. 11. Optical spectrum of the generated optical tones after the FWM for 210-GHz optical millimeter-wave signal generation.

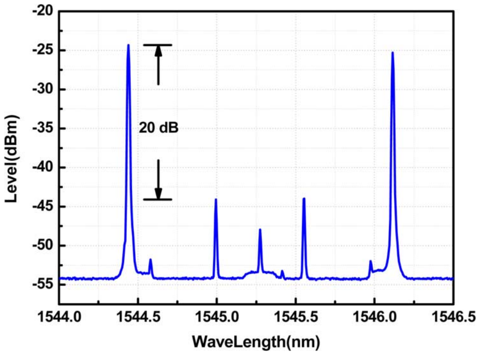

Fig. 12. Optical spectrum of the generated optical tones separated by 210 GHz.

Compared with the optical spectrum which is show in Fig. 6, the undesired optical sidebands are much lower than that in Fig. 8. After filtering using two optical interleavers, high-purity two-tone optical signal separated by 120 GHz is obtained with −9-dBm average optical power. The optical spectrum is shown in Fig. 9. The optical carrier and harmonic distortion suppression ratios exceed 30 dB, which is excellent in millimeter-wave applications.

Optical spectrum of optical tones separated by 210 GHz generated from a 17.5-GHz RF driving signal is also demonstrated experimentally in this work. Fig. 10 presents the optical tones separated by 70 GHz which is generated by frequency quadrupling with modulation depth trimming. By using the modulation depth trimming, the optical carrier is suppressed perfectly. The optical carrier and undesired harmonic distortion suppression ratios of the optical tones separated by 70 GHz are higher than 36 dB. The high-purity two-tone signal was also send into the SOA to perform four-wave-mixing. Fig. 11 shows the optical spectrum at the output of the SOA. Two sixth order sidebands with 210-GHz frequency spacing are emerged along with the original second order sidebands with 70-GHz frequency spacing. After the filtering of optical interleavers, high purity two-tone signal separated by 210 GHz are obtained as shown in Fig. 12. The optical power of the generated optical two-tone signal is about −11 dBm. The optical carrier and undesired harmonic distortion suppression ratios exceed 20 dB, which is good enough for most millimeter-wave application.

The generated optical millimeter-wave signals are particularly utilized as an RF carrier or local oscillator in various application systems, including phase array antenna, wireless communication, and radars. Therefore, the phase noise is a significant factor of the generated millimeter-wave signal. However,

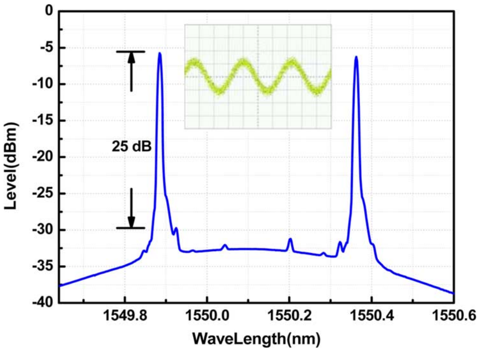

Fig. 13. Optical spectrum of the generated optical tones separated by 60 GHz and the waveform of the generated millimeter-wave signal.

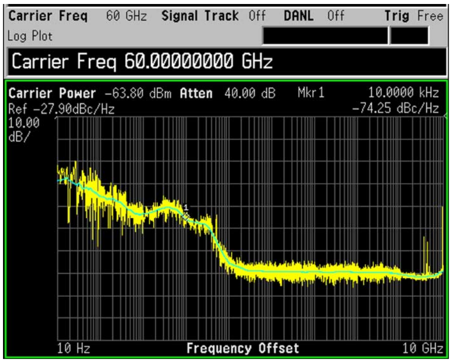
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Fig. 14. Single sideband (SSB) phase noise of the 60-GHz millimeter-wave signal.

the phase-noise analyses of the generated 120- and 210-GHz millimeter-wave still remain great challenge due to the limited bandwidth of the analysis system. To verify the phase noise of proposed optical millimeter-wave signal, a 60-GHz optical millimeter-wave signal is generated using the first filtering structure as shown in Fig. 4(a). Fig. 13 shows the optical spectrum of the generated optical tones separated by 60 GHz. The harmonic distortion suppression ratio is about 25 dB. The generated two-tone signal is received using a V-band photo-diode. The received 60-GHz time domain waveform is also shown in the inset of Fig. 13. The peak-to-peak voltage is more than 200-mV with −5-dBm average optical received power. Then, an electrical spectrum analyzer (Agilent E4440A) with a waveguide harmonic mixer (Agilent 11970V) is utilized for single sideband (SSB) phase noise analysis. The SSB phase noise of the generated 60-GHz millimeter-wave signal are about −57 dBc/Hz at 10 Hz and −97 dBc/Hz at 10 MHz, as shown in Fig. 14. The phase noise of the 5-GHz driving signal is −76 dBc/Hz at 10 Hz and −120 dBc/Hz at 10 MHz. The SSB phase noise diagram is also shown in Fig. 14.

IV. CONCLUSION

This work proposed a novel optical millimeter-wave signal generation with a frequency of 12 times that of the RF driving signal. The key to the proposed system is an optical high-purity millimeter-wave signal generation with frequency quadrupling using a commercially available dual-parallel MZM. 40- and 70-GHz high purity two-tone optical signals were experimentally demonstrated from 10- and 17.5-GHz RF driving signals. Modulation depth trimming between MZ-a and MZ-b are employed to compensate the amplitude imbalance between the MZM arms and improve the optical carrier suppression ratio. The optical carrier and harmonic distortion suppression ratios of the generated optical two-tone signals separated by 40 and 70 GHz using frequency quadrupling technique were more than 36 dB. Following optical frequency quadrupling, optical four-wave mixing was promoted utilizing an SOA. Since the excellent optical carrier and harmonic distortion suppression ratio of the four-wave-mixing pump signals, only the second and sixth order sidebands were obtained at the output of the SOA. After filtering out the undesired sidebands using optical interleavers, high-purity optical two-tone signals separated by 120 and 210 GHz were obtained. The optical carrier and harmonic distortion ratios of the generated 210- and 120-GHz optical two-tone signals were 20 and 30 dB, respectively. A 60-GHz optical millimeter-wave signal is also generated using the proposed system for signal performance analysis. The SSB phase noise is about −57 dBc/Hz at 10-Hz.

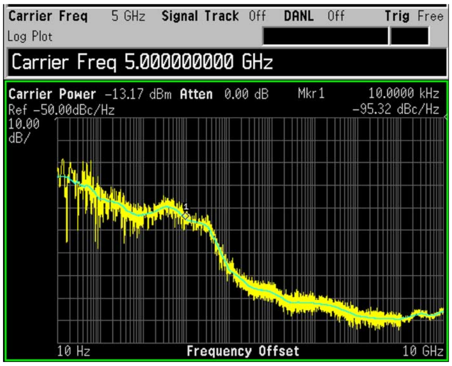
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Fig. 15. Single sideband (SSB) phase noise of the 5-GHz driving signal.

The frequency of the generated optical millimeter-wave signal is 12 times that of the RF driving signal. Millimeter-wave signals with frequency beyond 100 GHz can be easily achieved using low frequency RF equipments and components. Since the frequency response of the state-of-the-art MZM is up to 40 GHz, the proposed system provides a reliable and cost-effective solution for optical millimeter-wave generation with frequencies of up to 480 GHz and is a promising candidate for broadband wireless communications, ALMA, optical sensors, radar, and tera-hertz applications.

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