A continuously tunable and filterless optical millimeter-wave generation via frequency octupling

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Abstract: This work proposes a cost-effective, continuously tunable and filterless optical millimeter-wave (MMW) signal generation employing frequency octupling. Optical MMW signals with 30-dB undesired sideband suppression ratios can be obtained. Since no optical filtering is required, the proposed system can be readily implemented in wavelength-division-multiplexing (WDM) systems. V-band 60-GHz and W-band 80-GHz optical MMW signals are experimentally demonstrated. Because of the high undesired sideband suppression ratio, 60-GHz waveform with 50% duty cycle is observed. The single-sideband (SSB) phase noise of the generated 60-GHz signal is −73 dBc/Hz at 10 kHz. The proposed system is a viable solution for the future ultra-high frequency MMW applications up to 320 GHz using the external modulator with a limited bandwidth of 40 GHz.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.2330) Fiber optics communications; (060.5625) Radio frequency photonics.

References and links

1. Z. Jia, J. Yu, G. Ellinas, and G. K. Chang, "Key Enabling Technologies for Optical–Wireless Networks: Optical Millimeter-Wave Generation, Wavelength Reuse, and Architecture," IEEE J. Lightwave Technol. **25**(11), 3452–3471 (2007).
2. J. F. Cliche, B. Shillue, M. Tetu, and M. Poulin, "A 100-GHz-tunable photonic millimeter wave synthesizer for the Atacama Large Millimeter Array radiotelescope," in Proc. International Microw. Theory and Tech. Society, (Honolulu, Hawaii, US, 2007), 349–352 (2007).
3. A. Sasaki, and T. Nagatsuma, "Reflection-Type CW-Millimeter-Wave Imaging with a High-Sensitivity Waveguide-Mounted Electro-Optic Sensor," Jpn. J. Appl. Phys. **41**(Part 2, No. 1A/B), L83–L86 (2002).
4. J. Yu, Z. Jia, L. Yi, Y. Su, G. K. Chang, and T. Wang, "Optical Millimeter-Wave Generation or Up-Conversion Using External Modulators," IEEE Photon. Technol. Lett. **18**(1), 265–267 (2006).
5. H. Chi, and J. Yao, "Frequency Quadrupling and Upconversion in a Radio Over Fiber Link," IEEE J. Lightwave Technol. **26**(15), 2706–2711 (2008).
6. M. Mohamed, X. Zhang, B. Hraimel, and K. Wu, "Frequency sixupler for millimeter-wave over fiber systems," Optics Exp. **15**, 16737–16747 (2007).
7. T. Wang, M. Chen, H. Chen, J. Zhang, and S. Xie, "Millimeter-Wave Signal Generation Using Two Cascaded Optical Modulators and FWM Effect in Semiconductor Optical Amplifier," IEEE Photon. Technol. Lett. **19**(16), 1191–1193 (2007).
8. K. H. Lee, W. Y. Choi, Y. A. Leem, and K. H. Park, "Harmonic Millimeter-Wave Generation and Frequency Up-Conversion Using a Passively Mode-Locked Multisection DFB Laser Under External Optical Injection," IEEE Photon. Technol. Lett. **19**(3), 161–163 (2007).
9. P. T. Shih, C. T. Lin, W. J. Jiang, J. J. Chen, H. S. Huang, Y. H. Chen, P. C. Peng, and S. Chi, "WDM up-conversion employing frequency quadrupling in optical modulator," Opt. Express **17**(3), 1726–1733 (2009).
10. C. T. Lin, J. Chen, S. P. Dai, P. C. Peng, and S. Chi, "Impact of Nonlinear Transfer Function and Imperfect Splitting Ratio of MZM on Optical Up-Conversion Employing Double Sideband with Carrier Suppression Modulation," IEEE J. Lightwave Technol. **26**(15), 2449–2459 (2008).

#114219 - $15.00 USD Received 15 Jul 2009; revised 29 Sep 2009; accepted 14 Oct 2009; published 16 Oct 2009

11. H. Kiuchi, T. Kawanishi, M. Yamada, T. Sakamoto, M. Tsuchiya, J. Amagai, and M. Izutsu, "High Extinction Ratio Mach–Zehnder Modulator Applied to a Highly Stable Optical Signal Generator," IEEE Trans. Microw. Theory Tech. **55**(9), 1964–1972 (2007).

1. Introduction

Millimeter-wave (MMW) signals have been widely used in numerous high frequency applications, such as broadband wireless communication [1], phase array antenna [2], MMW imaging [3], and radar. With the increasing of intended MMW frequency, MMW signal generations with frequency beyond 60 GHz are essential for various applications.

Although some CMOS technology can generate MMW signal beyond 60 GHz, the attenuation of MMW signal in copper wires is extremely high, which restricts the signal transmission distance. To transmit MMW signals over a long distance, optical MMW signal based on low transmission loss optical fiber network is a cost-effective and viable solution. Recently, several optical MMW signal generation systems have been proposed [4–8]. Among these systems, optical MMW signal generations using $LiNbO_3$ Mach-Zehnder modulator (MZM) are the most reliable approaches. Optical MMW signal generations based on single-sideband (SSB), double side-band (DSB) and double-sideband with carrier suppression (DSB-CS) have been widely investigated and demonstrated. Nevertheless, the generated optical MMW frequencies are still restricted by the bandwidth of $LiNbO_3$ modulators, which is typically less than 40 GHz. Moreover, radio-frequency (RF) components with frequency response over 26 GHz are considerably more expensive than those below 26 GHz. In order to achieve optical MMW generation with frequency beyond 60 GHz cost-effectively, optical MMW signal generations with frequency multiplication are highly desirable [4–6]. However, in most proposed systems, narrowband optical filters are usually required to remove undesired optical sidebands. This drawback will not only increase the system complexity, it also will hinder the implementation in wavelength-division-multiplexing (WDM) Radio-over-Fiber (RoF) systems.

Recently, a filterless optical MMW generation technique with frequency quadrupling has been demonstrated [9]. The undesired sideband suppression ratio of the generated optical MMW signal is higher than 30 dB. Since no optical filter is required, the proposed system can be utilized in WDM up-converted systems [9]. In order to support even higher frequency MMW applications, a filterless optical MMW signal generation with frequency octupling is proposed in this report. Two cascaded frequency quadrupling systems are key to the octupling system. V-band 60-GHz and W-band 80-GHz MMW signals are experimentally demonstrated in this work. Generated from 7.5 and 10-GHz sinusoid driving signals, the undesired sideband suppression ratios of 60 and 80-GHz optical MMW signals are higher than 30 dB. Since no narrow band optical filter is required, the proposed system can also be readily used in WDM systems. Optical MMW signals with frequencies up to 320-GHz can be achieved by the proposed octupling system if two commercially available 40-GHz dual-parallel MZMs (DP-MZM) are employed.

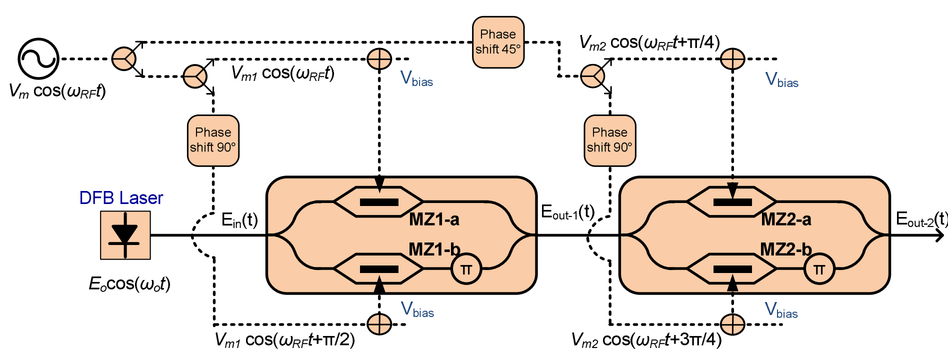

Fig. 1. Conceptual diagram and experimental setup of optical MMW signal generation using a frequency octupling technique.

#114219 - $15.00 USD Received 15 Jul 2009; revised 29 Sep 2009; accepted 14 Oct 2009; published 16 Oct 2009

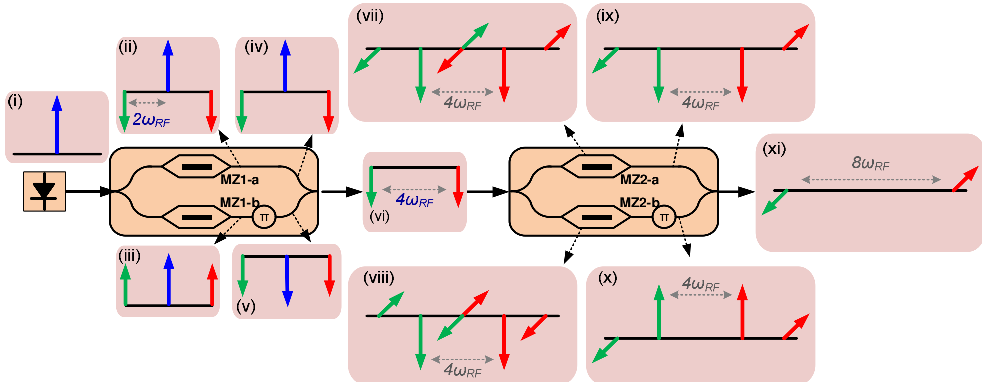

Fig. 2. Principle of the proposed optical MMW signal generation with frequency octupling.

This paper is organized as follows. Section 2 describes the concept, theoretical analysis and experimental setup of the frequency octupling system. Section 3 discusses the single sideband (SSB) phase noise of the 60-GHz MMW signal and undesired sideband suppression ratio degradations due to bias drifts. Finally, section 4 reviews the main conclusion of the paper.

2. Concept and experimental setup

Figure 1 shows the experimental setup of the optical MMW generation with frequency octupling using two cascaded DP-MZMs. Assume that the optical field at the input of the first DP-MZM is defined as $E_{in}(t) = E_o \cos(\omega_o t)$, where E_o is the amplitude of the optical field and ω_o is the angular frequency of the optical carrier. The DP-MZM is composed of three MZMs; two sub-MZMs are embedded in each arm of the main MZM. Both of the sub-MZMs (MZ1-a and MZ1-b) are biased at the full point while the main MZM of the first DP-MZM is biased at the null point and introduces a 180 deg difference between the output of the two sub-MZMs. A 90 deg phase delay is introduced between the RF driving signals of MZ1-a and MZ1-b. Therefore, the electrical RF driving signal sent into MZ1-a and MZ1-b can be expressed as $V_{a1}(t) = V_{m1}\cos(\omega_{RF} t)$ and $V_{b1}(t) = V_{m1}\cos(\omega_{RF} t + \frac{\pi}{2})$, respectively, where V_{m1} denotes the amplitude of the RF driving signal of the first dual-parallel MZM and ω_{RF} denotes the angular frequency of the RF driving signal. Therefore, the optical field at the output of the first DP- MZM can be expressed as:

$$E_{out\text{-}1}(t) = -E_o \sum_{n=1}^{\infty} J_{4n-2}(m_1) \times \left\{\cos\left[(\omega_o + (4n-2)\omega_{RF})t\right] + \cos\left[(\omega_o - (4n-2)\omega_{RF})t\right]\right\} \qquad (1)$$

where the phase modulation index m_1 is $\pi V_{m1}/2V_\pi$ and J_{4n-2} is the Bessel function of the first kind with order 4n-2. Only optical sidebands with the order of 4n-2 will be obtained. Due to the properties of Bessel function, without causing significant errors, it is reasonable to ignore order higher than second order. Therefore, the optical field at the output of the first DP-MZM can be further simplified as

$$E_{out-1}(t) = -E_o\{J_2(m_1)\cos[(\omega_o + 2\omega_{RF})t] + J_2(m_1)\cos[(\omega_o - 2\omega_{RF})t]\} \qquad (2)$$

Notably, optical frequency quadrupling is obtained after first DP-MZM. The generated optical MMW signal from the first DP-MZM is then send into the second DP-MZM. Both of the sub-MZMs (MZ2-a and MZ2-b) are biased at the full point while the main MZM is biased at the null point. Note that a 45 deg phase delay is introduced between the driving signals of the first and second DP-MZMs. Therefore, the electrical RF driving signal sent into MZ2-a and MZ2-b can be expressed as $V_{a2}(t)=V_{m2}\cos(\omega_{RF}t+\frac{\pi}{4})$ and $V_{b2}(t)=V_{m2}\cos(\omega_{RF}t+\frac{3\pi}{4})$, respectively. The optical field at the output of the second DP-MZM can be expressed as

$$\begin{aligned}E_{out-2}(t)&=\frac{1}{2}\cdot E_{out-1}\left\{\cos\left[m_2\cdot\cos(\omega_{RF}t+\frac{\pi}{4})\right]-\cos\left[m_2\cdot\cos(\omega_{RF}t+\frac{3\pi}{4})\right]\right\}\\&=\frac{1}{2}\cdot E_{out-1}\cdot\left\{J_0(m_2)+2\sum_{n=1}^{\infty}J_{2n}(m_2)\cdot(-1)^n\cdot\cos\left[n\cdot(2\omega_{RF}t+\frac{\pi}{2})\right]\right.\\&\qquad\left.-J_0(m)-2\sum_{n=1}^{\infty}J_{2n}(m_2)\cdot(-1)^n\cdot\cos\left[n\cdot(2\omega_{RF}t+\frac{3\pi}{2})\right]\right\}\end{aligned}\tag{3}$$

where the phase modulation index m_2 is $\pi V_{m2}/2V_{\pi}$. Ignore the high order terms; E_{out-2} can be simplified as

$$E_{out-2}=E_oJ_2(m_1)J_2(m_2)\{-\sin[(\omega_o+4\omega_{RF})t]+\sin[(\omega_o-4\omega_{RF})]\}\tag{4}$$

Only the fourth order optical sidebands are obtained at the output of the second DP-MZM. Notably, no optical filter is required to remove undesired optical sidebands. After square-law detection using a photo diode, the electrical signal with frequency eight times that of the RF driving signal is obtained.

Figure 2 schematically depicts the principle of the proposed MMW generation system. Since MZ1-a and MZ1-b are biased at the full point, optical spectra with two second-order sidebands are performed after MZ1-a and MZ1-b as shown in insets (ii) and (iii) of Fig. 2. The 90 deg phase delay between the driving signal of MZ1-a and MZ1-b causes the 180 deg phase difference of the two second order sidebands at the output of MZ1-a and MZ1-b. Since the main MZM is biased at the null point, an additional 180 deg phase delay is introduced between the output signals of MZ1-a and MZ1-b. After the combination at the output of the first DP-MZM, the original optical carrier is inherently suppressed. Optical MMW signal with frequency quadrupling is obtained at the output of the first DP-MZM as shown in the inset (vi) of Fig. 2. The generated second order sidebands from the first DP-MZM are treated as two new optical carriers and send into the second DP-MZM. Due to the 45 deg phase delay of the second DP-MZM driving signals, optical spectra as shown in insets (vii) and (viii) of Fig. 2 are generated from MZ2-a and MZ2-b, respectively. Optical sidebands with the same frequency as the original optical carrier are suppressed. The second main MZM, which is

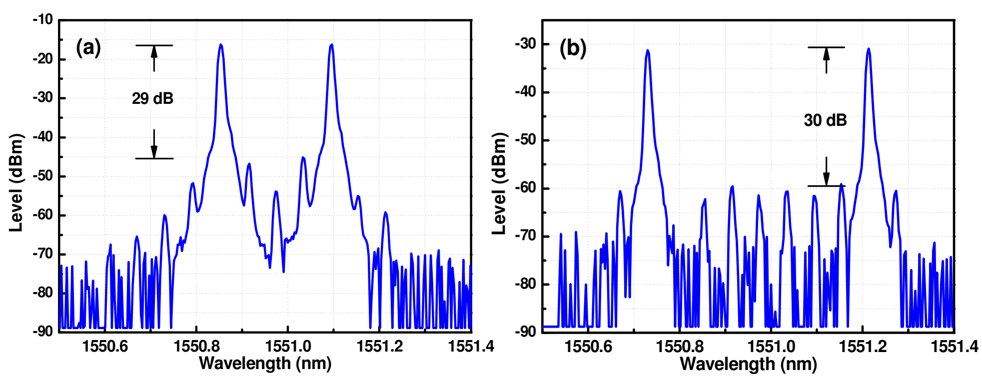

Fig. 3. Optical spectra of (a) the 30-GHz MMW signal generated from the first stage of the frequency octupling system; (b) the generated 60-GHz MMW signal from the frequency octupling system.

#114219 - $15.00 USD Received 15 Jul 2009; revised 29 Sep 2009; accepted 14 Oct 2009; published 16 Oct 2009

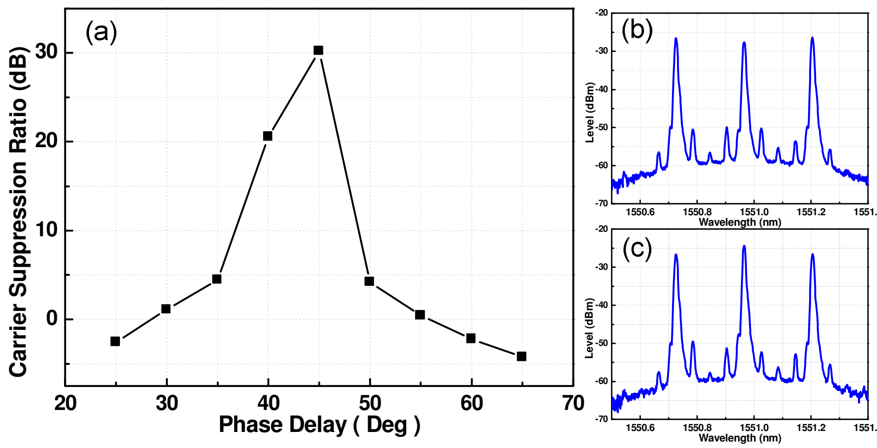

Fig. 4. (a) Optical carrier suppression ratio versus phase delay of two DP-MZMs and optical spectra of (b) 30 deg (c) 60 deg phase delay.

biased at null-point, introduces a 180 deg phase difference between the output signals of MZ2-a and MZ2-b as shown in insets (ix) and (x) of Fig. 2. After combination at the output of the second DP-MZM, an optical MMW signal with frequency eight times that of the driving signal is obtained as shown in inset (xi) of Fig. 2.

3. Results and discussion

Following the setup shown in Fig. 1, a continuous-wave (CW) laser with 4-dBm optical power is used as the optical source. To generate 60-GHz MMW signal, a 7.5-GHz sinusoid driving signal is utilized. The modulation indices of both DP-MZMs are about 1.6*(V_{π}/2). As shown in Fig. 3(a), a 30-GHz optical MMW signal with 29-dB undesired sideband suppression ratio and −6.8-dBm optical power is obtained after the first DP-MZM. The generated optical MMW signal is sent into the second DP-MZM. At the output of the second DP-MZM, a 60-GHz optical MMW signal with 30-dB undesired sideband suppression ratio and −19-dBm optical power is obtained. The optical spectrum is shown in Fig. 3 (b). After the frequency octupling system, an EDFA is utilized to boost the optical power. Because of the slight different V_{π} of the PD-MZMs, tunable attenuators are employed after the first electrical splitter to control the driving power of two DP-MZMs.

The 45 deg phase difference between the driving signal of the first and second DP-MZM is a key factor which affects the suppression of the original optical carrier. The optical carrier suppression ratio of the original carrier will degrade if the phase difference is not equal to 45 deg. Figure 4(a) shows the degradation of the optical carrier suppression ratio due to imperfect phase delay between two DP-MZM driving signals with varying phase delay from 30

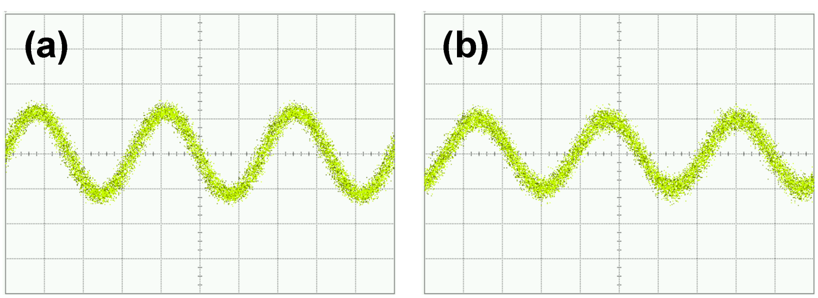

Fig. 5. Time domain waveform of the generated 60-GHz MMW signal (a) BTB (b) 25-km SMF Transmission. (100 mV/div; 5 ps/div)

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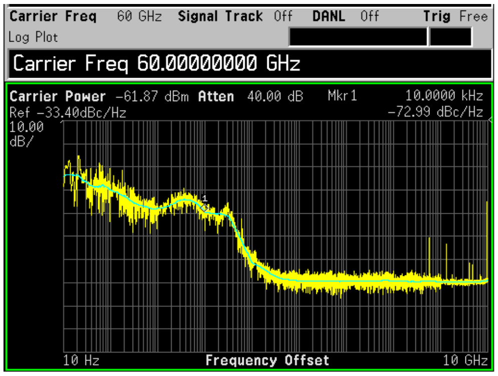

Fig. 6. SSB noise of the generated 60-GHz MMW signal.

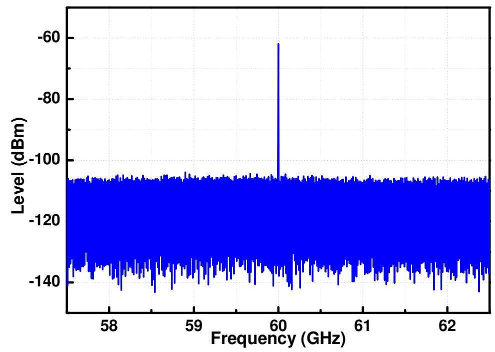

Fig. 7. Electrical spectrum of the generated 60-GHz MMW signal.

to 60-deg. The best carrier suppression ratio is obtained with 45-deg phase delay.The optical spectra with 30- and 60-deg are also shown in insets (b) and (c) of Fig. 4. Figure 5 (a) and (b) shows the waveform of the generated 60-GHz MMW signal using a V-band photo-diode at back-to-back (BTB) and after transmission of 25-km standard single mode fiber (SSMF), respectively. Because of the high undesired sideband suppression ratio, a 60-GHz MMW signal with a 50% duty cycle is observed. Moreover, no significant signal distortion is observed after fiber transmission.

SSB phase noise of the generated 60-GHz MMW is also analyzed using an electrical spectrum analyzer (Agilent E4440A) with a waveguide harmonic mixer (Agilent 11970V). Figure 6 shows the measurement results of the generated 60-GHz MMW signal. The SSB phase noise is about −73 dBc/Hz at 10 kHz, where that of the driving 7.5-GHz signal is about −91 dBc/Hz at 10 kHz. W-band optical MMW signal generation is also experimentally demonstrated. The electrical spectrum of the generated 60-GHz MMW signal is shown in Fig. 7.

To demonstrate W-band MMW signal generation, 80-GHz MMW signal is generated using 10-GHz driving signal. Figure 8 shows the optical spectrum of the generated 80-GHz optical MMW signal. The undesired sideband suppression ratio of the 80-GHz optical MMW signal is about 30-dB.

To evaluate the performance of the proposed system, undesired sideband suppression ratio degradation with DP-MZM bias drifts are also investigated. Figure 9 depicts the undesired sideband suppression ratio degradations with bias drifts of the first-stage DP-MZM. The undesired sideband suppression ratios degrade from 30 dB to 3 dB with 25% bias voltage deviation ratio. The bias voltage deviation ratio is defined as $(\Delta V/V_\pi) \times 100\%$, where ΔV is bias voltage deviation and V_π is the half-wave voltage of the sub-MZs. Optical spectra with

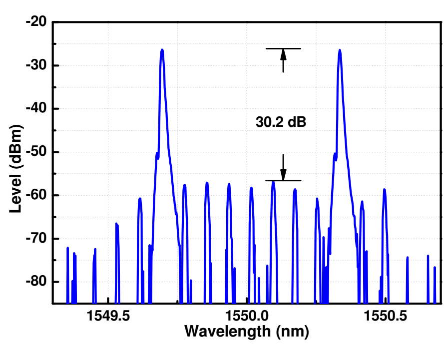

Fig. 8. Optical spectrum of the generated 80-GHz MMW signal

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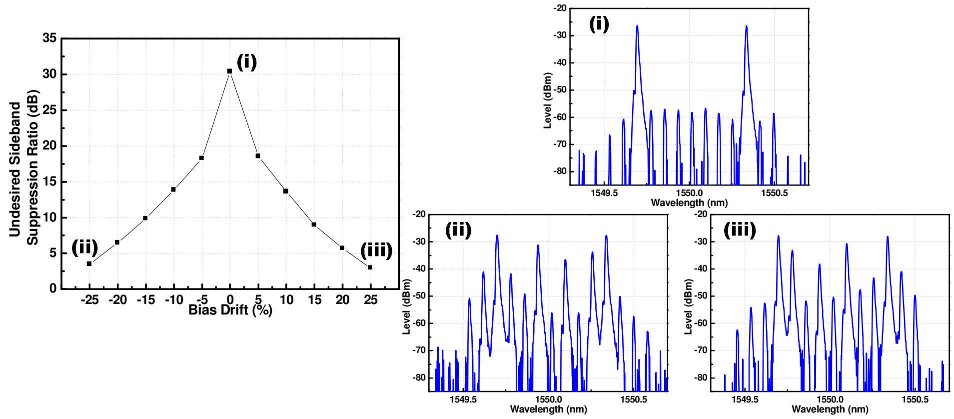

Fig. 9. Undesired sideband suppression ratio versus first DP-MZM bias deviation ratio, and optical spectra.

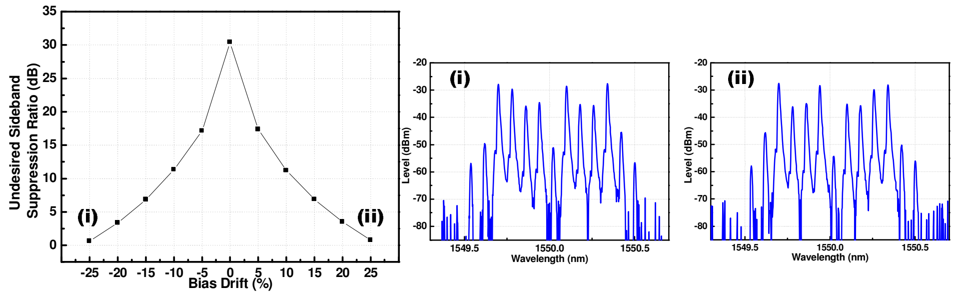

Fig. 10. Undesired sideband suppression ratio versus second DP-MZM bias deviation ratio, and optical spectra.

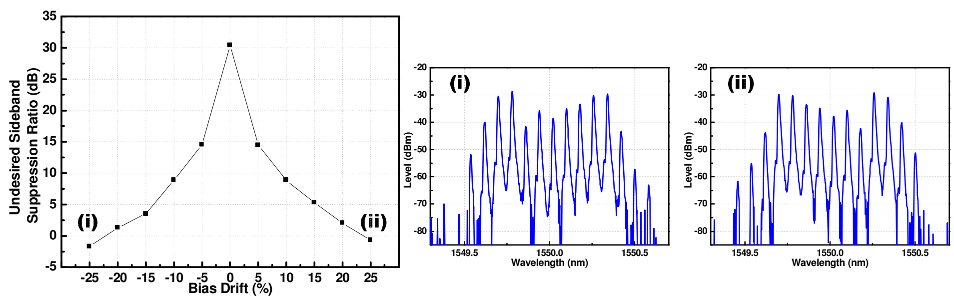

Fig. 11. Undesired sideband suppression ratio versus all DP-MZM bias deviation ratio, and optical spectra.

the optimal and 25% bias drift conditions are shown in insets of Fig. 9. The undesired sideband suppression ratio degradations and optical spectra with second-stage DP-MZM bias drifts are also shown in Fig. 10. 30-dB degradation is observed with 25% bias voltage deviation ratio. Figure 11 shows the undesired sideband suppression ratio degradation with all the DP-MZM bias drafts. About 30 dB undesired sideband suppression ratio degradation is observed with 25% bias voltage deviation ratio. The undesired sideband suppression ratio will be higher than 15 dB, which is sufficient for most MMW application when the bias voltage deviation ratios are controlled within ± 5% using bias feedback control circuits [10,11].

#114219 - $15.00 USD Received 15 Jul 2009; revised 29 Sep 2009; accepted 14 Oct 2009; published 16 Oct 2009

4. Conclusions

This work demonstrates a filterless optical MMW signal generation with frequency octupling for high frequency MMW applications. Two commercially available DP-MZMs are keys to the proposed system. V-band 60-GHz and W-band 80-GHz optical MMW signal are experimentally generated from 7.5- and 10-GHz driving signals with 30-dB undesired sideband suppression ratios. Time domain waveform with a 50% duty cycle is observed. After transmission of 25-km SSMF, no significant signal distortion is observed. The SSB phase noise of the 60-GHz MMW signal is about −73-dBc/Hz at 10-kHz. The undesired sideband suppression ratio is higher than 15 dB when the bias deviation ratios are less than ± 5% of the half-wave voltages. Optical MMW signal with frequency up to 320-GHz can be generated using the state-of-the-art 40-GHz DP-MZMs. The proposed frequency octupling optical MMW generation is a potential solution for the future ultra-high frequency MMW applications.

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