Filterless frequency sextupling and 18-tupling optical millimeter-wave generation using Mach-Zehnder modulators

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Filterless photonic technique for millimeter-wave generation using three cascaded-parallel Mach-Zehnder modulators with frequency multiplication factor of 6 and 18 has been proposed in this paper. A local oscillator of 5 GHz frequency is 18-tupled to 90 GHz and sextupled to 30 GHz respectively. The proposed system works as frequency sextupler in broad range of modulation index of 1-2.2 with optical side band suppression ratio well above 30 dB. At modulation index of 4.88, the system operates as a frequency 18-tupler with acceptable tolerance to small variations in the modulation index. Further, the proposed system performance is independent of extinction ratio change of optical modulators.

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Keywords: Mach-Zehnder modulator, Splitting ratio, Optical millimeter wave generation, Frequency tupling, Optical sideband suppression ratio

1. Introduction

Different materials such as lithium niobate ($LiNbO_3$), gallium arsenide (GaAS), potassium dihydogen phosphate (KH_2PO_4, KDP), ammonium dihydrogen phosphate ($NH_4H_2PO_4$ or ADP), etc. lack inverse symmetry or are non-centrosymmetric. Therefore, when electric field is applied across such materials, their refractive index also shows proportional change. This effect is called as Pockels effect and finds application in optical modulators such as Mach-Zehnder modulator (MZM) [1]. Mach-Zehnder modulators apart from optical data modulation for communication applications, have been proposed for optical frequency synthesis. In such systems, MZMs are used to generate optical sidebands and are either operated at maximum transmission bias point (MATP) or minimum transmission bias point (MITP). In general, biasing at MATP and MITP is used to generate even order optical bands and odd order sidebands respectively. However, there is also presence of unwanted optical bands due to non-ideal splitting ratio (γ) of power coupled to arms of MZM. Thus, amount of power is γ units in one arm and $\beta = (1-\gamma)$ units in another arm of an MZM. Extinction ratio (ER) is related to splitting ratio (γ) as, $\gamma = \left(1 - \frac{1}{\sqrt{\epsilon_r}}\right)/2$, where $\epsilon_r = 10^{(ER)/10}$. For example $\gamma \approx 0.484$ implies the extinction ratio of about 30 dB. Fig. 1 shows how extinction ratio varies with splitting ratio. The ideal splitting ratio is $\gamma = \beta = 0.5$ implies zero output power in case of perfect destructive interference at the modulator output. Thus, in order to completely eliminate the generation of unwanted optical bands the key solution is to fabricate modulators with very high extinction ratio. T. Kawanishi et al. have proposed integrated optical modulator with ER as high as 70 dB [2-4]. The proposed structure is composed of a two sub-MZMs integrated with main MZM. To obtain such high value of ER, we require three non-fluctuating DC supplies to bias two sub-MZMs and main MZM to actively control amplitude balances and phase difference in two arms respectively. In other proposed technique, with the help of photorefractive trimming local micro-size tailoring of refractive index is done to improve ER [5, 6]. However, currently most of commercial modulators have extinction ratio below 35 dB.

In literature, different MZM based setups have been proposed to generate millimeter-waves with the assumption that ER of MZM is 35 dB [7], 40 dB [8, 9], 60 dB [10, 11], and 100 dB [12-14]. An 80 GHz mm-wave is generated by 10 GHz local oscillator signal with 62 dB OSSR and 54 dB RFSSR where both SSRs are tolerant towards extinction ratio by Asha et al. [15]. Furthermore, it can be observed in most of these proposed systems that optical side band suppression ratio (OSSR) of the optical bands saturate as the ER increases above 50 dB. In this work, we have proposed to generate an 18-tupled frequency with extinction ratio independent optical sideband suppression ratio (OSSR) and radio frequency spurious sideband ratio (RFSSR) of 38 dB and 32 dB respectively.

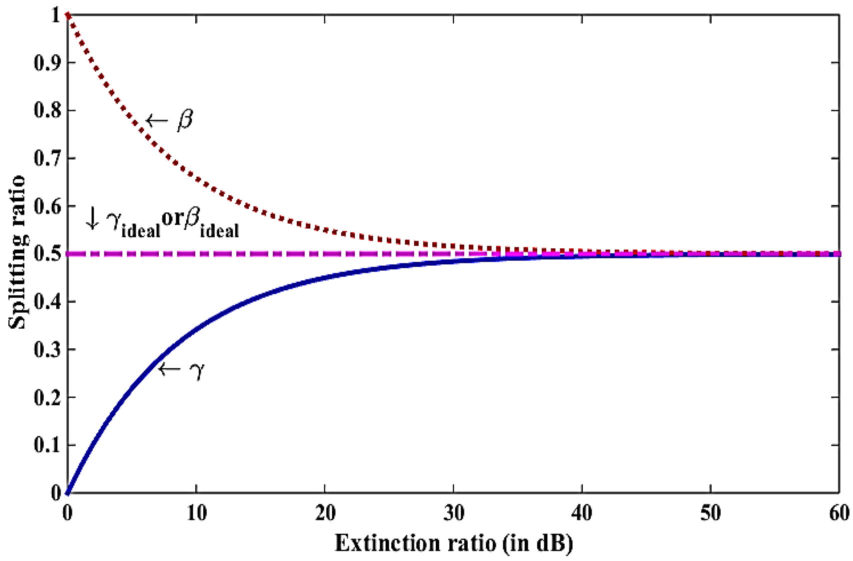

Fig. 1. Splitting ratio of MZM as function of its extinction ratio [22] (colour online)

The remaining of paper is organised as follows. Section 2 provides the principle of extinction ratio tolerant band generation to yield 9th order optical bands for frequency 18-tupling. In section 3, results are provided and explained along with brief discussion on 18-tupling systems already proposed in literature. Finally conclusion is presented in section 4.

2. Principle and system setup

The proposed system as shown in Fig. 2 consists of laser diode, radio frequency source, optical amplifier, photodiode, cascaded MZM configuration (I, II, and III) and phase shifters. The configuration consists of two dual-drive MZMs connected in parallel using optical splitter and combiner. The parallel configuration behaves like an MZM with very high extinction ratio at MITP. Therefore, in the system setup, we have shown cascaded MZM configurations as MZM I, MZM-II, and MZM-III. The light wave at 193.1 THz is fed to cascaded MZM configurations, which are driven by RF signal of 5 GHz with progressive phase shift of π/3. The output of an MZM can be written as [16-18];

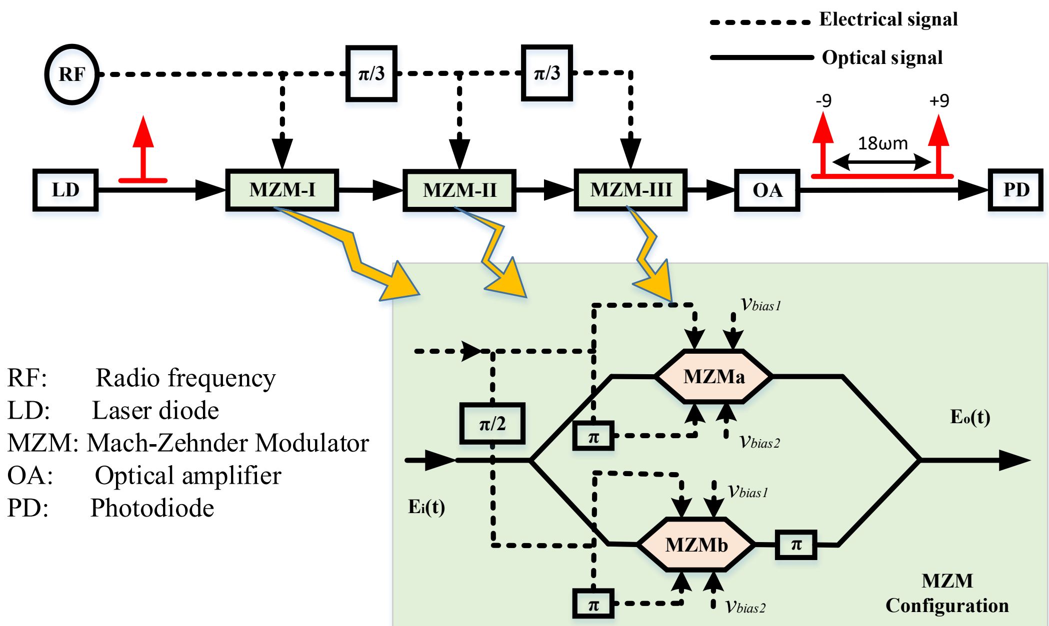

Fig. 2. Proposed system (colour online)

$$E_o(t) \propto E_i(t)\left[\gamma e^{j\pi\left(\frac{v_2(t)}{v_\pi}+\frac{v_{bias2}}{v_\pi}\right)} + (1-\gamma)e^{j\pi\left(\frac{v_1(t)}{v_\pi}+\frac{v_{bias1}}{v_\pi}\right)}\right] \quad (1)$$

where, v_π is half wave voltage of an MZM. If $v_{bias2} = -2V$, $v_{bias1} = 2V$, $v_\pi = 4V$ and modulating signal $v(t) = v_m sin(\omega_m t)$, then output optical field $E_o(t)$ for parallel MZM configuration as shown in Fig. 2 can be given as

$$E_o(t) = E_{oMZM-a}(t) + E_{oMZM-b}(t) \quad (2)$$

$$E_o(t) \propto E_i(t)\left\{\left[\gamma_a e^{j\pi\left(\frac{v_m sin(\omega_m t+\pi)}{v_\pi}\right)} e^{-j\frac{\pi}{2}} + \beta_a e^{j\pi\left(\frac{v_m sin(\omega_m t)}{v_\pi}\right)} e^{j\frac{\pi}{2}}\right] - \left[\gamma_b e^{j\pi\left(\frac{v_m sin(\omega_m t)}{v_\pi}\right)} e^{-j\frac{\pi}{2}} + \beta_b e^{j\pi\left(\frac{v_m sin(\omega_m t+\pi)}{v_\pi}\right)} e^{j\frac{\pi}{2}}\right]\right\} \quad (3)$$

Upon simplification, eq. (3) can written as.

$$E_o(t) \propto \begin{cases} E_0 \sum_{n=-\infty}^{\infty} J_n(m) e^{j(\omega_c+n\omega_m)t}, \; n = 2k+1 \\ 2E_0 \sum_{n=-\infty}^{\infty} J_n(m) e^{j(\omega_c+n\omega_m)t} (\gamma_b - \gamma_a), \; n = 2k \end{cases} \quad (4)$$

where, $m = \frac{\pi v_m}{v_\pi}$, is the modulation index. It can be noted from eq. (4) that even-order optical sidebands along with carrier band are extinction ratio dependent as these bands have $(\gamma_b - \gamma_a)$ as multiplying factor. Further, odd order optical sidebands are independent of extinction ratio. Therefore, for similar parallel MZMs, $\gamma_b \approx \gamma_a$, eq. (4) can be simply expressed as

$$E_o(t) \propto E_0 e^{j\omega_c t} \sum_{n=-\infty}^{\infty} J_{2n+1}(m) e^{j(2n+1)\omega_m t} \quad (5)$$

Therefore, output spectrum contains only odd-order optical sidebands, similar to that of ideal MZM operated at MITP. The equation showing the output of parallel MZM is equal to output of MZM-I. Therefore, the output of proposed system can written as

$$E(t) \propto E_{MZM-I}(t) \times E_{oMZM-II}(t) \times E_{MZM-III}(t) \quad (6)$$

The eq. (6) can be simplified to

$$E(t) \propto E_0 \{C_3 e^{j(\omega_c \pm 3\omega_m)t} + C_9 e^{j(\omega_c \pm 9\omega_m)t} + C_{15} e^{j(\omega_c \pm 15\omega_m)t} + \cdots\} \quad (7)$$

where, C_3, C_9 and C_{15} are coefficients of 3rd, 9th and 15th order optical sideband respectively and are approximately given by following relations

$$C_3 \cong -J_1^3(m) + 3\big(J_3^3(m) - J_1^2(m)J_3(m) - J_1^2(m)J_5(m) - J_3(m)J_5^2(m) - J_1(m)J_3(m)J_5(m)\big)$$

$$C_9 \cong J_3^3(m) + 3\big(-J_1(m)J_5^2(m) - J_3(m)J_5^2(m) - J_1(m)J_3(m)J_5(m)\big)$$

$$C_{15} \cong -J_5^3(m)$$

At modulation index of 4.88, the power of 3rd and 15th order optical side-bands can be calculated as C_3 = 0.0355, C_9 = 0.2011 and C_{15} = -0.0148. It is clear that the 3rd and 15th order sidebands can be neglected in comparison to 9th harmonic. Therefore, the output of the photodetector can be given as

$$I(t) = \Re E(t)E^*(t) \propto \cos 18\omega_m t \quad (8)$$

The above equation clearly states that the local oscillator frequency (ω_m) is optically frequency 18-tupled, with extinction ratio tolerance.

3. Results and discussion

The proposed system is simulated using Optisystem software. Various parameters used in simulation of the proposed system are enlisted in Table 1.

Table 1. Simulation parameters

Parameter	Values
CW laser Frequency	193.1 THZ
CW laser Power	15 dBm
CW laser Linewidth	10 MHz
Local oscillator frequency (ω_m)	5 GHz
Amplitude of RF source	6.21
Extinction ratio of MZM	20 to 60
Insertion loss of each MZM	5 dB

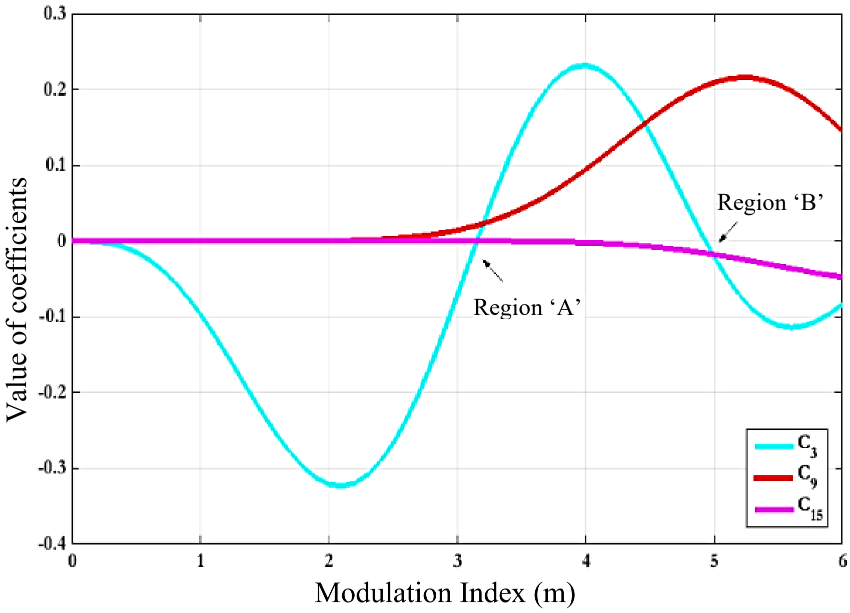

Fig. 3. Variation of coefficients with modulation index (colour online)

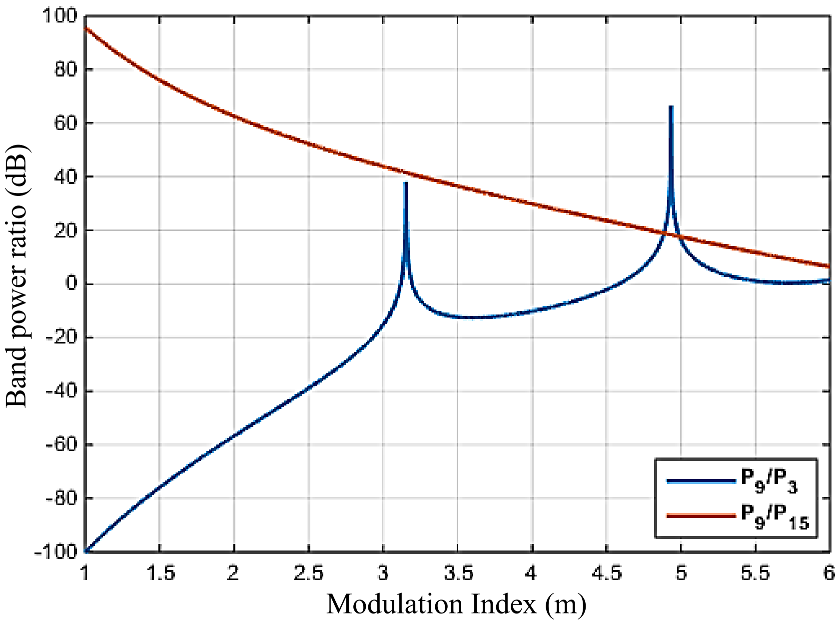

Fig. 4. Variation of band power ratio with modulation index (colour online)

As already discussed in previous section, eq. (7) suggests the presence of 3rd, 9th and 15th order optical bands. Variation of coefficients and band power ratios P_9/P_3 and P_9/P_{15} with modulation index have been evaluated using eq. (7), and plotted as shown in Fig. 3 and Fig. 4 respectively. The two figures provide an insight about operating conditions with respective outcome for the proposed system. It can be observed from Fig. 3 that below modulation index of 2.5, only coefficient $'C_3'$ is active while values of coefficients $'C_9'$ and $'C_{15}'$ are negligible. Thus, the proposed setup can be used for frequency sextupler in optical domain in the modulation index range of 1 to 2.2, with optimal performance occurring at modulation index of 1.73. The optical and radio frequency spectrum at modulation index of 1.73 (lying in the range of 1 to 2.2) are shown in Fig. 5(a) and Fig. 5(b), respectively. The reason for choosing m=1.73 is that the spectrum is free of all other harmonics and we get a clear optical and radio frequency spectrum. Now, consider the region 'A', value of coefficient $'C_3'$ tends to zero and $'C_9'$ is active (as seen from Fig. 4, $P_9/P_3 \approx 38\,dB$). Thus, it can be concluded that biasing MZMs at certain modulation index in region ‘A’ will result in frequency 18-tupling. Fig. 6(a) shows the optical spectrum containing 9th order optical sidebands with insignificant 3rd order optical bands at $m \approx 3.189$. At this modulation index, the proposed system can be used as frequency 18-tupler. Furthermore, it can be noted $P_9 \approx P_3$ around the region ‘A’ (see Fig. 4), as curve P_9/P_3 crosses 0 dB line twice. It implies that at these two values of modulation index, the proposed system can be used to generate four channel optical comb and as a frequency 18-tupler simultaneously as reflected from Fig. 6(b) where, $m \approx 3.142$.

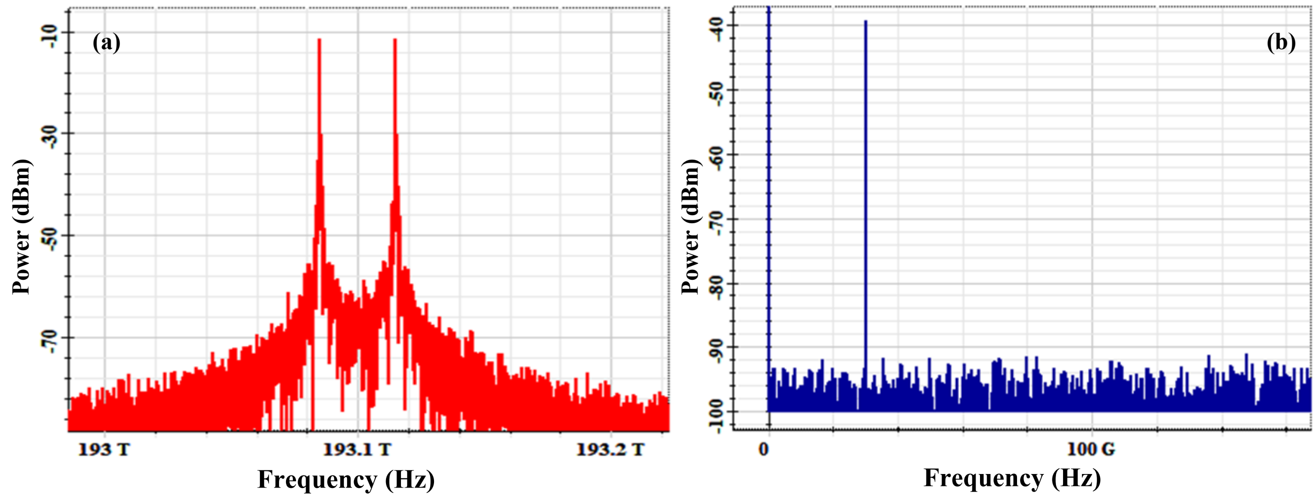

Fig. 5. (a) Optical spectrum and (b) Radio frequency spectrum of proposed system at m=1.73 (colour online)

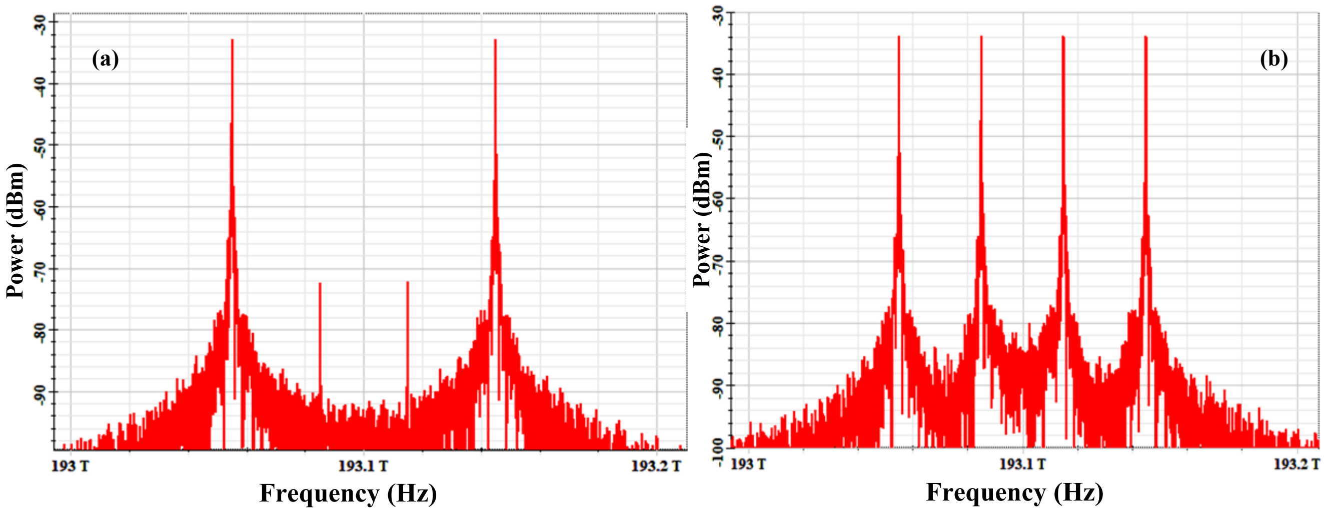

Fig. 6. Optical spectrum of proposed system at (a) m=3.189 and (b) m=3.142 (colour online)

The proposed setup acts as frequency 18-tupling system as suggested by region ‘B’ of Fig. 3 and Fig. 4 both. At modulation index of 4.88, the optical spectrum and radio frequency spectrum is shown in Fig. 7(a) and Fig. 7(b) respectively. Recall that in region ‘A’ also, system acts as a frequency 18-tupler. However, optical sideband suppression ratio (OSSR) is well above 20 dB for wider range of modulation index in region ‘B’. This reflects region ‘B’ is more stable than region ‘A’. The value of OSSR is limited by band power ratio $P_9/P_{15} \approx 38$ dB and band power ratio P_9/P_3 can be increased above 60 dB by proper adjustment of modulation index. The radio frequency spurious suppression ratio (RFSSR) of radio signal generated after detection using photodiode is 32 dB.

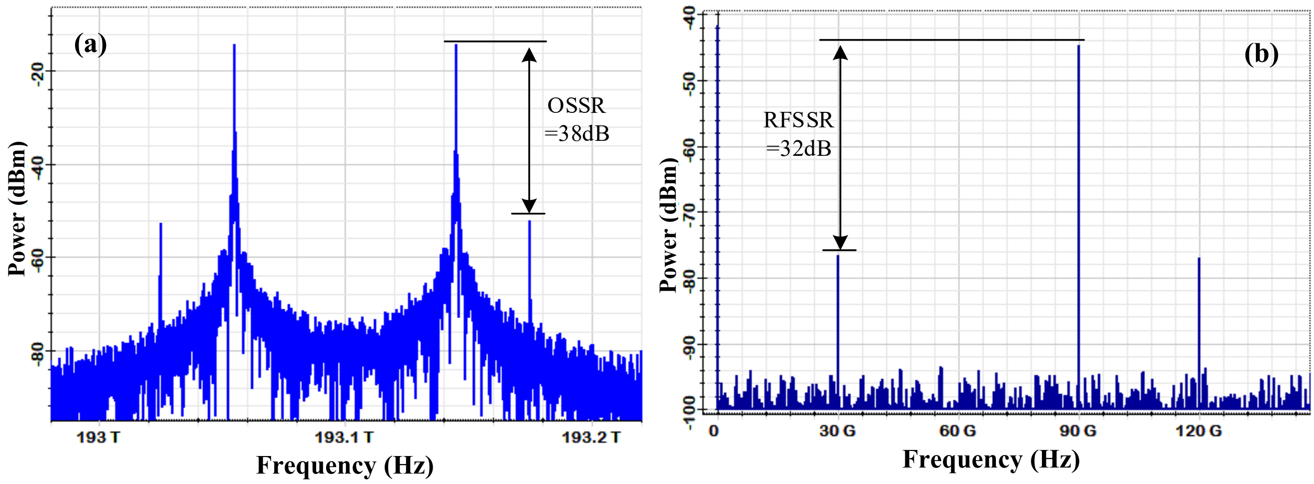

Fig. 7. (a) Optical spectrum and (b) Radio frequency spectrum of proposed system at m=4.88 (colour online)

To show the effect of extinction ratio independence, the system proposed by Ankita et al. has been also simulated at different extinction ratios [11]. Fig. 8 shows the optical spectrum at extinction ratio of 20 dB with modulation index of 4.88. It can be noted that the variation of OSSR is not limited by band power ratios, P_9/P_{15} and P_9/P_3, but by other spurious bands. Therefore, the variation of OSSR and spurious band power ratio (SBPR) with extinction ratio of the two systems has been evaluated and plotted as shown in Fig. 9. It can be observed from the figure, that for our proposed system, the band power ratio and hence OSSR remains constant for change in extinction ratio of modulators. However, band power ratio increases linearly with increase in extinction ratio from 20 dB to 60 dB for the setup proposed by Ankita et al. However, OSSR saturates to 38 dB as we have noted from Fig. 4 that OSSR of proposed system is limited by P_9/P_{15}.

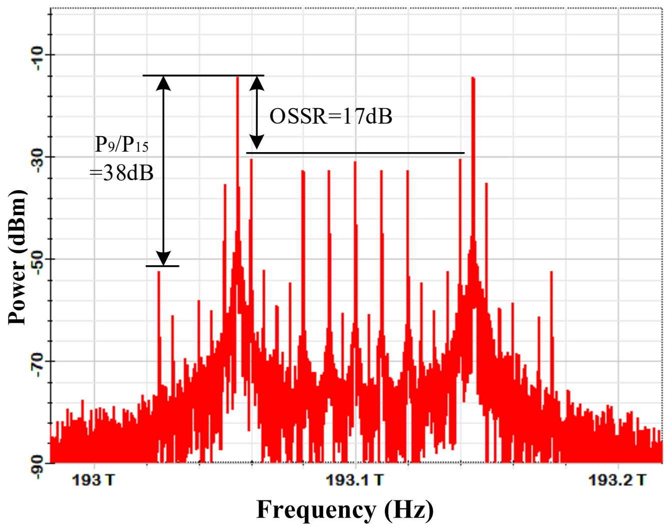

Fig. 8. Optical spectrum at m=4.88 extinction ratio of 20 dB [11] (colour online)

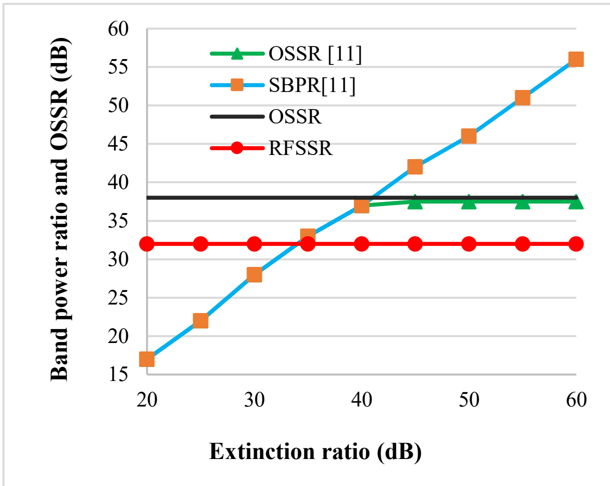

Fig. 9. Variation of OSSR and spurious band power ratio (colour online)

Table 2 shows the comparative analysis of different proposed frequency 18-tuplers in literature. It can be observed that proposed work is filterless and can be used at any local oscillator frequency. Therefore, apart from being extinction ratio tolerant system, it also provides frequency tunability. It is to be noted that such advantages of proposed system comes at expense of increased cost and complexity. We have avoided the analysis of effect of offset in phase shifters and ER of parallel MZMs as it has been already discussed in detailed manner in previous works [11, 22-24].

Table 2. Comparative analysis of different proposed frequency 18-tuplers in literature

Research work	Setup structure	Modulation index	Extinction ratio tolerance	Use of filter	Remarks
[11]	Three cascaded MZMs	4.8804	No	No	Each MZM operated at MITP with ER assumed to be 60dB.
[19]	MZM followed by SOA	3.832	No	Yes	MZM followed by optical band pass to produce two optical bands. These band are followed by SOA to induce FWM.
[20]	Three MZMs connected in parallel	6.380, or 9.761	No	No	At m=6.380, OSSR is only 11dB, while at m=9.761, OSSR is 32dB. However such high modulation index require high voltage local oscillator.
[21]	MZM followed by SOA	____	No	Yes	MZM followed by optical band pass to produce two optical bands. These band arefollowed by SOA to induce FWM.
Proposed work	Three cascaded parallel MZMs	4.88	Yes	No	Each parallel MZM acts as as single MZM with very high ER at MITP.

4. Conclusion

In this paper, we have proposed a system to generate millimeter waves in optical domain by frequency up-conversion by factor of 18 and 6. The optical side band suppression ratios of optical bands generated are independent of extinction ratio of Mach-Zehnder modulators. The setup works as frequency sextupler in modulation index range of 1-2.2 and frequency 18-tupler at modulation index of 4.88. For the frequency 18-tupling, OSSR and RFSSR of the system are 38 dB and 32 dB respectively. The operation of system is filterless which provides tunability of frequency for local radio frequency oscillator.

Declaration

The authors declare that there is not any potential conflict of interest.

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