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ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 13 (14): 2334-2341, 2014
ISSN 1812-5638 / DOI: 10.3923/itj.2014.2334.2341

Photonic Frequency Sixupler for Millimeter Wave Generation by using Dual Electrode Modulator in Radio Over Fiber System

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Abstract: In this study, we have demonstrated two schemes for the generation of millimeter-wave (mm-wave) using optical frequency sixupler with a dual-electrode modulator (MZM). For scheme one and scheme two, the phase of RF signal is shifted by 180 degrees, drives the two electrodes of MZM at different bias levels and then high order sidebands is removed by optical bandpass filter. Theoretical analysis and simulation results show that the performance of millimeter-wave for scheme two is better than that of scheme one.

Key words: Mm-wave, sixupler, MZM

INTRODUCTION

For the future broadboard access networks, generation and distribution of high frequency millimeter-wave become a key techniques. High power loss of high frequency millimeter-wave has make base station more costly. As consequence, Radio over Fiber (RoF) technique has been considered a cost-effective and promising candiation for the distribution of the future access networks. Now, reasearch about generation and distribution millimeter-wave in RoF system is intensively conducted. All optical photonic up-conversion has become a promising resolution for optical millimeter-wave generation such as using four-wave mixing in high nonlinear dispersion fiber (Ma *et al*., 2006; Dong *et al*., 2009; Jia *et al*., 2005; Yu *et al*., 2005a) or semiconductor optical amplifer and cross-gain modulation or cross-phase modulation in EAM (Yu *et al*., 2005b; Seo *et al*., 2006) and optical heterodyne techniques (Yu *et al*., 2006), using external modulation to realize frequency doubling (O'Reilly and Lane, 1994), frequency quadrupling and sextupling using Optical Frequency Multiplication (OFM) (He *et al*., 2009; Chi and Yao, 2008; Lin *et al*., 2008; Wang *et al*., 2006; Zhang *et al*., 2007; Shih *et al*., 2009; Chang *et al*., 2008; Mohamed *et al*., 2008).

The principle of OFM is to modulate the power of sidebands through settting the value of peak-to-peak amplitude of RF signal and bias voltage of MZM and then through O/E conversion, desired millimeter-wave is generate. It can use only low frequency oscillator to generate high frequency. OFM techniques is based on the inherent nonlinearality of the response of modulator and this can be well studied in microwave photonic fields which can reduce the bandwidth requirement of modulator. Futhermore, signal processing in optical domain can eliminate the effect of electronic bottleneck and shift more complex component to Central Station (CS) which can reduce the cost of Base Station (BS). O'Reilly and Lane (1994) proposed another method to generate a frequency-quadrupled electrical signal. Recently, an approach using an optical phase modulator to generate a frequency-quadrupled electrical signal was proposed (Shen *et al*., 2003). In this scheme, a F-P filter was proposed to select two second order sidebands. Qi *et al*. (2005) is using a intensity modulator and a notch filter to generate a wide-band continuous frequency tunable millimeter-wave. When the frequency multiplication factor is higher than four, the method so far typically depended on four-wave mixing using semiconductor combined with optical filter or using two cascaded single arm intensity modulators which could result in complicate structure and high cost.

In this study, we have comprehensively demonstrate two schemes for the generation of millimeter-wave using frequency sixupler with a dual-electronic modulator (MZM) theoretically and simulatedly. At first, the generation of millimeter-wave and its dispersion performance when transimitting SMF, is analyzed theoretically and then performance of the generation millimeter-wave for two schemes is evaluated by

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simulation. With comparing system, performance at different modulation index and in the case of whether system has optical filter or no optical filter and the impact of extinction ratio of modulator is inverstiagted. At last, it has been concluded that the performance of the generated millimeter-wave for scheme two is better than that for scheme one.

COMPARISON BETWEEN TWO SCHEMES

Theoretical analysis: It is assumed that wavelength launched from DFB laser is continuous wave in nature, it can expressed as $E_{in}(t) = E_0 \cos(\omega_0 t)$ and the electrical RF signal can be expressed as $V_{RF}(t) = V_m \cos(\omega_{RF} t)$ and then the electrical signal is splitted into two parts by an electrical splitter and the two outputs directly drives the two electrodes of the MZM. For scheme one and scheme two, odd optical sidebands are generated. The output electrical field after dual-electrode MZM can be expressed as:

$$\begin{aligned}E_{out}(t) &= \frac{E_0}{10^{(k/20)}}\left\{\begin{matrix}\gamma\cos\left[\omega_0 t+\pi\dfrac{V_1\cos(\omega_{RF}t+\theta)}{V_{1\pi}}\right]+ \\ (1-\gamma)\cos\left[\omega_0 t+\pi\dfrac{V\cos(\omega_{RF}t)}{V_{1\pi}}+\pi\dfrac{V(t)}{V_{\pi DC}}\right]\end{matrix}\right\} \\ &= \frac{E_0}{10^{(k/20)}}\left\{\gamma\cos(\omega_0 t)\left[J_0(\beta g(t))+2\sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta g(t))\cos 2n(\omega_{RF}t+\varphi_1+\theta)\right]\right\} \\ &-\gamma\sin(\omega_0 t)\left\{-2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta g(t))\cos[(2n-1)(\omega_{RF}t+\varphi_1+\theta)]\right\} \\ &+(1-\gamma)\cos\left(\omega_0 t+\pi\frac{V(t)}{V_{\pi DC}}\right)\left[J_0(\beta g(t))+2\sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta g(t))\cos 2n(\omega_{RF}t+\varphi_1)\right] \\ &-(1-\gamma)\sin\left(\omega_0 t+\pi\frac{V(t)}{V_{\pi DC}}\right)\left\{-2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta g(t))\cos[(2n-1)(\omega_{RF}t+\varphi_1)]\right\}\end{aligned} \tag{1}$$

where, splitting ratio:

$$\gamma = \left(\sqrt{\varepsilon}-1\right)/\left(\sqrt{\varepsilon}+1\right)$$

ε is the MZM extinction ratio, g (t) is digital signal. If the value of ε is bulky, splitting ratio γ = 1/2. When optical power is boosted by amplifer and undesirable sidebands is removed by optical filter, the electrical field of optical signal can be expressed as:

$$E_{out}(t) = \frac{E_0}{10^{(k/20)}}\left\{\begin{matrix}\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta g(t))H_F[(2n-1)\omega_{RF}] \\ [\sin(\omega_0 t+(2n-1)\omega_{RF}t)+\sin(\omega_0 t-(2n-1)\omega_{RF}t]\end{matrix}\right\} \tag{2}$$

where, $H_F(n\omega_{RF})$ is the transfer function of optical filter.

After fiber transmission, the optical field can be expressed as:

$$E_{out}(t) = \frac{E_0}{10^{(k/20)}}\left\{\begin{matrix}\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta g(t))H_F[(2n-1)\omega_{RF}] \\ \left[\begin{matrix}\sin(\omega_0+(2n-1)\omega_{RF})(t+\tau_{(2n-1)^+})+ \\ \sin(\omega_0-(2n-1)\omega_{RF})(t+\tau_{(2n-1)-})\end{matrix}\right]\end{matrix}\right\} \tag{3}$$

Due to limited bandwidth of electrical spectrum analyser, higher order sidebands is not visable. For scheme one, the electrical field of photocurrent at $6\omega_{RF}$ after O/E conversion can be expressed as:

$$I_{6\omega_{RF}} = J_3^2(\beta)+J_1(\beta)J_5(\beta)\cos(12\omega_{RF}^2\beta'(\omega_0)L) \tag{4}$$

Equation 4 clearly shows that the generated mm-wave at frequency 60 GHz mainly be composed of harmonics that is result from beating of optical components at $\pm 3\omega_{RF}$ which is almost independent of inter-sidebands beating interference caused by fiber chromatic dispersion but walk off which will induce broadening of optical pulse width and result in Inter-Symbol Interference (ISI) and harmonics that is generated from beating of optical components at $\pm\omega_{RF}$ and $\pm 5\omega_{RF}$ which has a dispersion term $\cos(12\omega_{RF}^2\beta''(\omega_0)L)$ which can lead to periodic destructive and constructive interaction caused by fiber chromatic dispersion. When optical filtering, the output of the photocurrent at the frequency of $6\omega_{RF}$ is given by:

$$\begin{aligned}I_{6\omega_{RF}} = J_3^2(\beta)H_F^2(3\omega_{RF})+J_1(\beta)J_5(\beta)H_F(\omega_{RF}) \\ H_F(5\omega_{RF})\cos(12\omega_{RF}^2\beta''(\omega_0)L)\end{aligned} \tag{5}$$

For scheme two, when optical filtering, the ouput of the photocurrent at the frequency of $6\omega_{RF}$ is given by:

$$\begin{aligned}I_{6\omega_{RF}}(t) = J_3^2(\beta)H_F^2(3\omega_{RF})+J_1(\beta)J_5(\beta)H_F(\omega_{RF}) \\ H_F(5\omega_{RF})\cos(12\omega_{RF}^2\beta''(\omega_0)L)-J_1(\beta)J_7(\beta) \\ H_F(\omega_{RF})H_F(7\omega_{RF})\cos(24\omega_{RF}^2\beta'(\omega_0)L)\end{aligned} \tag{6}$$

Where:

$$H_F(f) = \exp\left\{-\ln\sqrt{2}\left[\frac{2(f-f_c)}{B}^{2N}\right]\right\}$$

N is order of filter, B is bandwidth of filter, f_c is the center frequency of optical bandpass filter.

Simulation analysis: Figure 1a and b show that the principle of generation mm-wave using dual-electrode

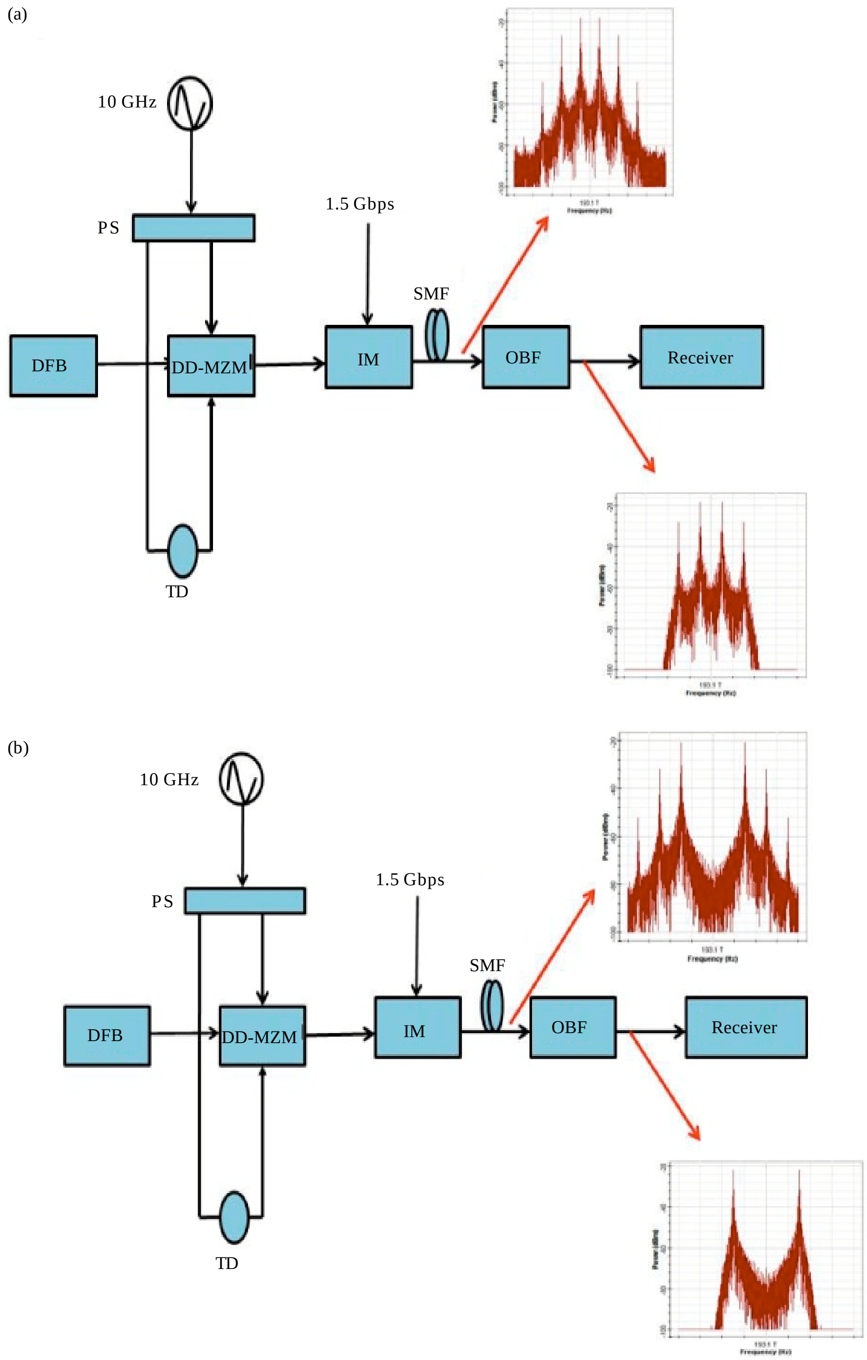

Fig. 1(a-b): Principle of three optical modulation techniques for mm-wave generation using a dual electrode MZM (a) Scheme one and (b) Scheme two

modulator for two modulation schemes. For the simulation of scheme one and scheme two, a Continuous Wave (CW) laser is assumed to have a wavelength of $\lambda_0 = 1552.52$ nm, a linewidth of 10 MHz, the frequency of RF signal is 10 GHz and the phase of electrical signal is shifted by 180 degrees and then the RF signal is split into two parts by an electrical splitter and the two outputs directly drives the two electrodes of the MZM. The DC

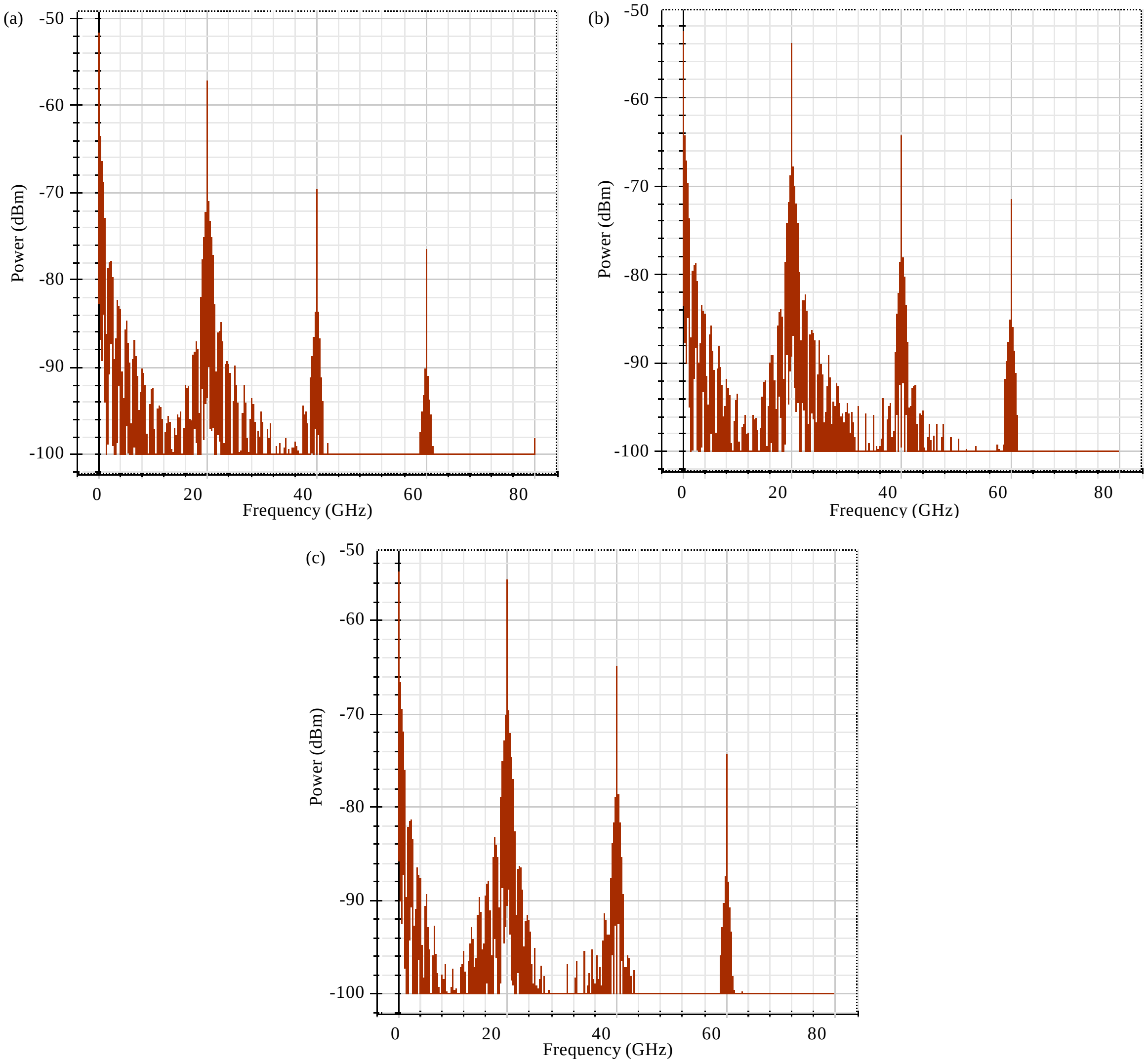

Fig. 2(a-c): Electrical spectra of the generated photocurrent though O/E conversion after fiber transmission over (a) 3.95 km, (b) 6.19 km and (c) 11.85 km

voltage of two arms of MZM is set at different values for scheme one and scheme two. For scheme one, the bias voltage of MZM is set for V_{DC} = 6V, the power ratio between third-order sidebands and first-order is -8.5 dBm and for scheme two, the bias voltage of MZM is set for V_{DC} = 9.76V, the power ratio between third-order sidebands and first-order is 52 dBm. The extinction ratio of MZM is 35 dB. In simulation, the filter has a 3rd order Gaussian transfer function with a bandwidth of 68 GHz and a central wavelength of 1552.52 nm. After optical filtering, through optical signal transmission SMF, the photocurrent is generated with O/E conversion by photodiode and BER analysis is made. Optical receiver is composed of photodiode, electrical bandpass filter, lowpass electrical filter and mixer. The dark current is I_d = 10 nA, responsibility is $\Re$ = 1 A/W and the bandwidth of electrical Gaussian bandpass filter is 1.5 bitrate, centered at 60 GHz the bandwidth of electrical lowpass Gaussian bandpass filter is 0.75 bitrate. In practice, this mm-wave is launched into air by antenna. The frequency component of photocurrent after O/E conversion is 20, 40 and 60 GHz.

The mm-wave signal at 60 GHz is selected by electrical bandpass filter and is mixed with 60 GHz LO signal and then baseband signal is selected by lowpass filter. At last, baseband signal is BER analyzed.

Simulation results analysis: Figure 2 shows the spectrum that the photocurrent at different components through transmission different lengths of SMF. With theoretical analysis, the power of frequency component at 40 and 60 GHz has increased due to L = 6.19, that is fading node when optical signal transmission is 6.19 km in SMF due to term of $\cos(12\omega_{RF}^2\beta''(\omega_0)L)\approx 1$, from this equation, it can be calucated that L = 6.19×k but when L = 11.85 km, the power of frequency at 40 GHz is increasing continuously and the power of frequency at 60 GHz is minimized due to term of $\cos(12\omega_{RF}^2\beta''(\omega_0)L)\approx -1$, it can be calculated that transmission length L = 3.95×(25-1). These constructive and destructive interactions between the two contributions are periodic due to the term $\cos(12\omega_{RF}^2\beta''(\omega_0)L)$.

Now we investigate the impact of optical filter on the performance of mm-wave for two schemes. Figure 3 shows that the impact of fiber length transmission on Q-factor of mm-wave due to fiber chromantic dispersion for scheme one. This figure shows that the fluctuation of Q-factor is different between using optical filter and no optical filter. It is resulted from that, after optical filtering, beating interference among undesirable sidebands is removed which can lead to reduce fluctuation of Q-factor of mm-wave. When no optical filter is used, the fluctuation of Q-factor is large and the curve of Q-factor of mm-wave is in irregular status. From above theoretical analysis, when transmission length of 3.95 km in SMF, the Q-factor is at the lowest point of curve due to transfer function of mm-wave power at fading node, so Q-factor is decreasing when transimission length is range from 0-3.95 km. When transmission length of SMF is 6.19 km, the curve of Q-factor is at the second peak due to transfer function of mm-wave power at fading loop, so Q-factor is increasing when transmission length is range from 3.95-6.19 km. But when transmission lenth of SMF is L = 11.85 km and L = 12.38 km, the curve of Q-factor is decreasing which is contrast to above theoretical analysis. It shows that, when no optical filter is used in simulation, the performance of mm-wave is easily affected by fiber chromatic dispersion and inter-sidebands beating interference. But when optical filter is used in system, the curve of Q-factor is increasing slightly. It is implied that the performance of mm-wave is not affected by inter-sidebands beating interference and fiber chromatic dispersion for scheme two.

Figure 4 shows the comparsion of simualted Q-factor of mm-wave versus fiber length for scheme two between the two cases of using optical filter and no optical filter. It shows that the fluctuation of curve of Q-factor is nearly the same when no optical filter and no optical filter is used in the simulation. It shows that the power of first-order sidebands is small which can lead to suppression of frequency component beating between first-order sidebands and other undesirable sidebands, so this scheme is hardly suffered from data inferference from other components falling within the same mm-wave frequency.

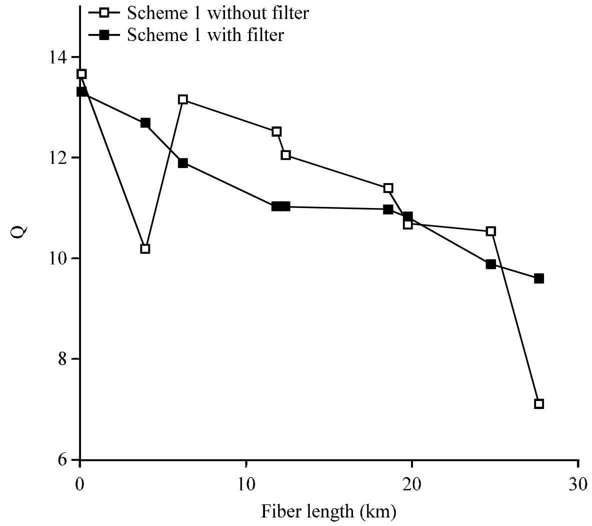

Fig. 3: Two curves of Q-factor for scheme one vs. fiber length about two cases of using optical filter and no optical filter

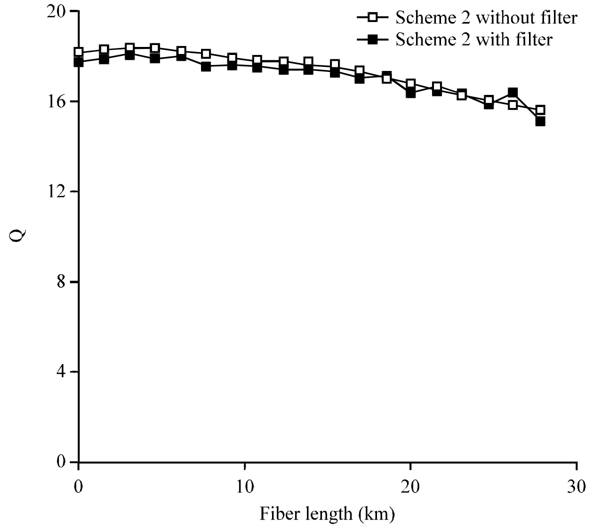

Fig. 4: Two curves of Q-factor for scheme two vs. fiber length about two cases of using optical filter and no optical filter

Harmonic Convertion Ratio (HCR) is a parameter that is used to evaluate the performance of generated mm-wave. It is defined as “the average power ratio between power of generated frequency component that inter-sidebands beating and power of generated frequency component that self-beating". In simulation, for the power of 60 GHz mm-wave, the power of generated spectral component beating between +3 and -3 order sidebands is power of generated frequency component that is through self-beating. But +1rd and -5rd sidebands and frequency electrical component generated from beating between +1rd sidebands and +7rd sidebands is the power of frequency component of self-beating. So, the performance of generated mm-wave is dependent on the power ratio between the two values. The more value of HCR, the more serious the beating interference which can lead to deterioration of the performance of generated mm-wave and when the value of HCR is decreasing, the performance of mm-wave is better.

For scheme one, it is assumed that the modulation index β = 1.5π, extinction ratio is 35 dB, when no optical bandpass filter is established, it is calculated that HCR value of generated mm-wave is:

$$\mathrm{HCR} = \frac{J_1(\beta)J_5(\beta)}{J_3^2(\beta)} \approx -14\mathrm{dB}$$

when, 3rd optical filter is used, whose bandwidth is 68 GHz, its HCR is:

$$\mathrm{HCR} = \frac{J_1(\beta)H_F(\omega_{RF})J_5(\beta)H_F(5\omega_{RF})}{J_3^2(\beta)H_F^2(3\omega_{RF})} \approx -42\ \mathrm{dB}$$

It is showed that, for scheme one, the difference between two cases that optical filter is used and no optical filter is used is large. It is implied that the performance of mm-wave is easily affected by inter-sidebands beating, so the quality of mm-wave is reduced.

For scheme two, it is assumed that modulation depth is β = 2.44π, extinction ratio is 35 dB, when no optical bandpass filter is established, it is calculated that HCR value of generated mm-wave is:

$$\mathrm{HCR} = \frac{J_1(\beta)J_5(\beta)+J_1(\beta)J_7(\beta)}{J_3^2(\beta)} \approx -69\ \mathrm{dB}$$

when 3rd optical filter is used, whose bandwidth is 68 GHz, its HCR is:

$$\mathrm{HCR} = \frac{J_1(\beta)J_5(\beta)H_F(\omega_{RF})H_F(5\omega_{RF})}{J_3^2(\beta)H_F^2(3\omega_{RF})} \approx -82.4\ \mathrm{dB}$$

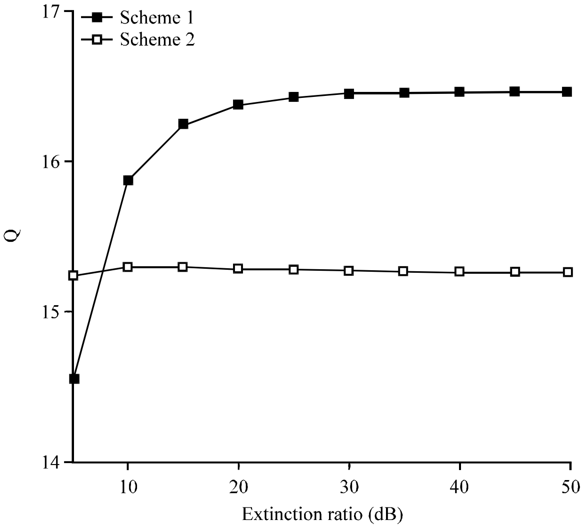

Fig. 5: Simulated Q-factor vs. MZM extinction ratio using scheme one and scheme two

The theoretical analysis shows that for scheme two, the fluctuation of HCR is slight between the case of optical filter is used and no optical filter is used. The HCR for scheme two is smaller than that of scheme one, it shows that the performance of generated mm-wave for scheme two is better than that for scheme one and the generated mm-wave for scheme two is hardly sensitive to fiber chromantic dispersion.

In the above analysis, a constant extinction ratio of MZM is used. It is known that sidebands suppression ratio is dependent on extinction ratio of MZM and thus the performance of mm-wave may also be affected. To investigate the performance of the two modulation schemes impacted by extinction ratio of the MZMs, we have measured the Q-factor versus MZM extinction ratio ranged from 5-50 dB by simulation and the results is show in Fig. 5. It shows that for two schemes, Q-factor is immune to extinction ratio if more than 25 dB. Moreover, scheme two leads to better performance than scheme one and thus the curve of Q-factor for scheme two is smooth.

CONCLUSION

In this study, we have demonstrated two schemes using for the generation of millimeter-wave using frequency sixupler with a dual-electronic modulator (MZM). At first, the generation mm-wave and the performance of mm-wave being impacted by fiber chromantic dispersion is analyzed theoretically and then compare the two schemes by simulation and the performance of two schemes is investigated by measuring

Q-factor and comparing two cases betweem optical filter is used and no optical filter is used simulatedly. According to theoretical analysis, the fluctuation of the power of generated mm-wave is periodic due to inter-sidebands beating if no optical filter is established in the system and thus the performance of mm-wave is instable. When optical filter is required, the performance of mm-wave is improved. Then, the HCR for scheme two is calculated and make comparsion. The result shows that the performance of generated mm-wave for scheme two is better than that of scheme one. Then make simulation and the simulation results show that for scheme one, the power of generated mm-wave is easily sensitive to fiber chromatic dispersion due to inter-sidebandes beating and for scheme two, the performance of generated mm-wave is immune to chromantic dispersion due to reduction of the power of first-order sidebands which can lead to destruction of interference resulted from beating among sidebands. Moreover, we have considered the performance of the generated mm-wave impacted by extinction ratio of MZM. At last, we found that the performance of generated mm-wave for scheme two is better than that of scheme one.

ACKNOWLEDGMENTS

This study was financially supported by the Hunan Provincial Natural Science Foundation of China (12JJ2040), the Construct Program of the Key Discipline in Hunan Province, China, the Aid Program for Science and Technology Innovative Research Team in Higher Educational Institute of Hunan Provinve, China.

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