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Influence of phase shift drift and splitting ratio on 80 GHz optical mm-wave generation*

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For the scheme of 80 GHz optical millimeter-wave (mm-wave) generation using two cascaded Mach-Zehnder modulators (MZMs), an exact analytical solution for the optical mm-wave affected by phase shift drift and splitting ratio is derived with the method of expanding Bessel series. The results show that for the carrier and the fourth-order sideband, the influence caused by phase shift drift is dominant, while the first-order, the second-order and the third-order sidebands are influenced by both phase shift drift and splitting ratio. It follows that the undesired sideband suppression ratio is at least 35.9 dB when the splitting ratio deviation is 0.001, and the phase shift drift is 1º. The performance of the system is perfect if the accuracy is achieved.

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Radio-over-fiber (RoF) is a promising technique in increasing the capacity and mobility as well as decreasing the system costs, while the millimeter-wave (mm-wave) is a promising frequency resource for future broadband communication[1]. To simplify the implementation and reduce the cost of the RoF system, mm-wave signals are generated in optical domain[2]. The frequency multiplication of mm-wave signals using low frequency RF oscillators and narrow-band electro-optical converters is a cost-effective solution to generate optical mm-wave.

Recently, many different approaches have been proposed to generate optical mm-wave[3-14]. In Refs.[3-8], the frequency quadrupling technique based on Mach-Zehnder modulator (MZM) is used to generate optical mm-wave. However, the repetitive frequency of the optical mm-wave is only four times of that of the local oscillator (LO) signal, which still requires expensive electrical equipments to generate 80 GHz mm-wave. In Refs.[9-13], the frequency octupling technique is used. But their theoretical and numerical simulations are based on the assumption that the system parameters are ideal. In Ref.[14], several non-ideal factors are considered, such as non-ideal optical splitting ratio, the phase shift deviation from -π/2 between the two RF signals applied to MZM and the length difference between two arms of MZM, while the phase shift deviation from π between the two RF signals applied to MZM is ignored. But this factor can lead to the degradation of the generated optical mm-wave signal.

In this paper the influence of the suppression ratio of sideband caused by phase shift drift and splitting ratio is analyzed, and an integrated expression involving non-ideal factors is given. The undesired sideband suppression ratios versus non-ideal factors are plotted, and the results are consistent with the analysis.

Fig.1 shows the 80 GHz optical mm-wave generation scheme proposed in Ref.[14]. Two MZMs biased at the maximum transmission point ($V_{dc1}=V_{dc2}=0$) are cascaded, and an RF signal is applied to the two MZMs with phase difference of -π/2. The phase difference of RF signals between the two arms of MZM1 and MZM2 is π.

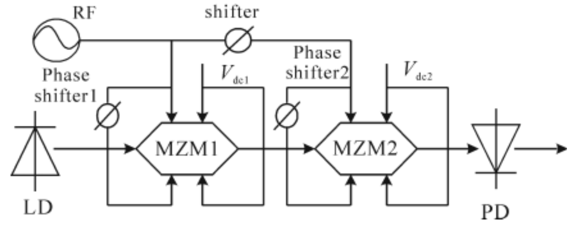

Fig.1 Scheme of 80 GHz optical mm-wave generation[14]

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The optical signal at the input of MZM1 is

$$E_{\text{in}}(t)=E_0\exp(\mathrm{j}\omega_{\text{c}}t) . \tag{1}$$

The voltage of the RF driving signal is

$$V_{\text{RF}}(t)=V_{\text{RF}}\cos(\omega_m t) . \tag{2}$$

So the output of MZM2 can be expressed as[14]

$$E_{\text{out}2}(t)=\alpha^2 E_0\sum_{n=-\infty}^{+\infty}\{\cos(\pi n/2)\cos(\pi n/4)\times J_n(\sqrt{2}m)\exp[\mathrm{j}(\omega_{\text{c}}+n\omega_m)t+\mathrm{j}\pi n/2]\} , \tag{3}$$

where E_0 and ω_{c} are the amplitude and angular frequency of the optical signal, respectively, V_{RF} and ω_m are the amplitude and angular frequency of the RF signal, respectively, α is modulator insertion loss, V_π is the half-wave voltage of MZM, m is the RF modulation index defined as $m=\pi V_{\text{RF}}/V_\pi$, and $J_n(\cdot)$ is the nth-order Bessel function of the first kind.

After considering the phase shift deviation from π, Eq.(3) can be expressed as

$$E_{\text{out2}}(t) = \alpha^2 E_{\text{in}}(t)\{r_1 r_2\exp[\mathrm{j}\sqrt{2}\, m\cos(\omega_m t-\pi/4)] + r_1(1-r_2)\exp[\mathrm{j}2m\sin(\omega_m t+\theta_2/2+\pi/4)\cos(\theta_2/2-\pi/4)] + (1-r_1)r_2\exp[\mathrm{j}2m\cos(\omega_m t+\theta_1/2+3\pi/4)\sin(\theta_1/2-\pi/4)] + (1-r_1)(1-r_2)\exp[\mathrm{j}2m\sin(\omega_m t+\theta_1/2+\theta_2/2+\pi/4)\times\cos(\theta_1/2-\theta_2/2+\pi/4)]\} , \tag{4}$$

where r_1 and r_2 are the splitting ratios of MZM1 and MZM2, respectively, and θ_1 and θ_2 are the phase shift drifts of phase shifter 1 and phase shifter 2, respectively.

With the method of expanding Bessel series[8], Eq.(4) can be expressed as

$$E_{\text{out}2}(t)=\alpha^2 E_0\sum_{n=-\infty}^{+\infty}A_n\exp\{\mathrm{j}[(n\omega_m+\omega_{\text{c}})t+n\pi/4]\} , \tag{5}$$

$$A_n=r_1r_2J_n(\sqrt{2}\,m) + r_1(1-r_2)J_n[2m\cos(\theta_2/2-\pi/4)]\exp(\mathrm{j}n\theta_2/2) + (1-r_1)r_2J_n[2m\sin(\theta_1/2-\pi/4)]\exp[\mathrm{j}n(\theta_1/2+\pi)] + (1-r_1)(1-r_2)J_n[2m\cos(\theta_1/2-\theta_2/2+\pi/4)]\times\exp[\mathrm{j}n(\theta_1/2+\theta_2/2)] . \tag{6}$$

When the splitting ratio is $r_1=r_2=r=0.5$, Eq.(6) can be expressed as

$$A_n=\begin{cases}0.25\{J_{4k}(\sqrt{2}m)+J_{4k}[2m\cos(\theta_2/2-\pi/4)]\exp(\mathrm{j}2k\theta_2)+\\ \quad J_{4k}[2m\sin(\theta_1/2-\pi/4)]\exp(\mathrm{j}2k\theta_1)+J_{4k}[2m\cos(\theta_1/2-\theta_2/2+\pi/4)]\exp[\mathrm{j}2k(\theta_1+\theta_2)]\}, & n=4k\\ 0.25\{J_{4k+1}(\sqrt{2}m)+J_{4k+1}[2m\cos(\theta_2/2-\pi/4)]\exp[\mathrm{j}(2k+1/2)\theta_2]-\\ \quad J_{4k+1}[2m\sin(\theta_1/2-\pi/4)]\exp[\mathrm{j}(2k+1/2)\theta_1]+J_{4k+1}[2m\cos(\theta_1/2-\theta_2/2+\pi/4)]\exp[\mathrm{j}(2k+1/2)(\theta_1+\theta_2)]\}, & n=4k+1\\ 0.25\{J_{4k+2}(\sqrt{2}m)+J_{4k+2}[2m\cos(\theta_2/2-\pi/4)]\exp[\mathrm{j}(2k+1)\theta_2]+\\ \quad J_{4k+2}[2m\sin(\theta_1/2-\pi/4)]\exp[\mathrm{j}(2k+1)\theta_1]+J_{4k+2}[2m\cos(\theta_1/2-\theta_2/2+\pi/4)]\exp[\mathrm{j}(2k+1)(\theta_1+\theta_2)]\}, & n=4k+2\\ 0.25\{J_{4k+3}(\sqrt{2}m)+J_{4k+3}[2m\cos(\theta_2/2-\pi/4)]\exp[\mathrm{j}(2k+3/2)\theta_2]-\\ \quad J_{4k+3}[2m\sin(\theta_1/2-\pi/4)]\exp[\mathrm{j}(2k+3/2)\theta_1]+J_{4k+3}[2m\cos(\theta_1/2-\theta_2/2+\pi/4)]\exp[\mathrm{j}(2k+3/2)(\theta_1+\theta_2)]\}, & n=4k+3 .\end{cases} \tag{7}$$

When the phase shift drift is taken into account, it is obvious from Eq.(7) that all the sidebands appear in the output of MZM2. When assuming $\theta_1=\theta_2=\theta$, Eq.(7) can be simplified as

$$A_n=\begin{cases}0.25\{J_{4k}(\sqrt{2}m)+\{J_{4k}[2m\cos(\theta/2-\pi/4)]+J_{4k}[2m\sin(\theta/2-\pi/4)]\}\exp(\mathrm{j}2k\theta)+J_{4k}(\sqrt{2}m)\exp(\mathrm{j}4k\theta)\}, & n=4k\\ 0.25\{J_{4k+1}(\sqrt{2}m)+\{J_{4k+1}[2m\cos(\theta/2-\pi/4)]-J_{4k+1}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+1/2)\theta]+J_{4k+1}(\sqrt{2}m)\exp[\mathrm{j}(4k+1)\theta]\}, & n=4k+1\\ 0.25\{J_{4k+2}(\sqrt{2}m)+\{J_{4k+2}[2m\cos(\theta/2-\pi/4)]+J_{4k+2}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+1)\theta]+J_{4k+2}(\sqrt{2}m)\exp[\mathrm{j}(4k+2)\theta]\}, & n=4k+2\\ 0.25\{J_{4k+3}(\sqrt{2}m)+J_{4k+3}[2m\cos(\theta/2-\pi/4)]-J_{4k+3}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+3/2)\theta]+J_{4k+3}(\sqrt{2}m)\exp[\mathrm{j}(4k+3)\theta]\}, & n=4k+3.\end{cases} \tag{8}$$

When the insertion ratio is $\alpha=0.5$, the input power is 100 mW, the RF voltage is V_{RF}=2.707 V, and the half-wave voltage is V_π= 5 V, the power values of the carrier and the first-order to the fourth-order sidebands are shown in Fig.2.

According to Fig.2, for the third-order sideband, a drift of 2° from π shifts the power from −∞ to −49.4 dBm, while the same power allows a drift of 5°, 13° and 20° for the carrier, the first-order and the second-order sidebands, respectively. However, the fourth-order sideband is insensitive to phase shift drift. A drift of 20° only brings a power decrease of 0.83 dB .

Non-ideal optical splitting ratio of the MZMs yields a finite extinction ratio. The influence of non-ideal splitting ratio on the power of different sidebands has been analyzed in Ref. [14]. Based on analyzing the influence of phase shift drift on optical mm-wave generation, the influence of phase shift drift and splitting ratio on the power of different sidebands is con-

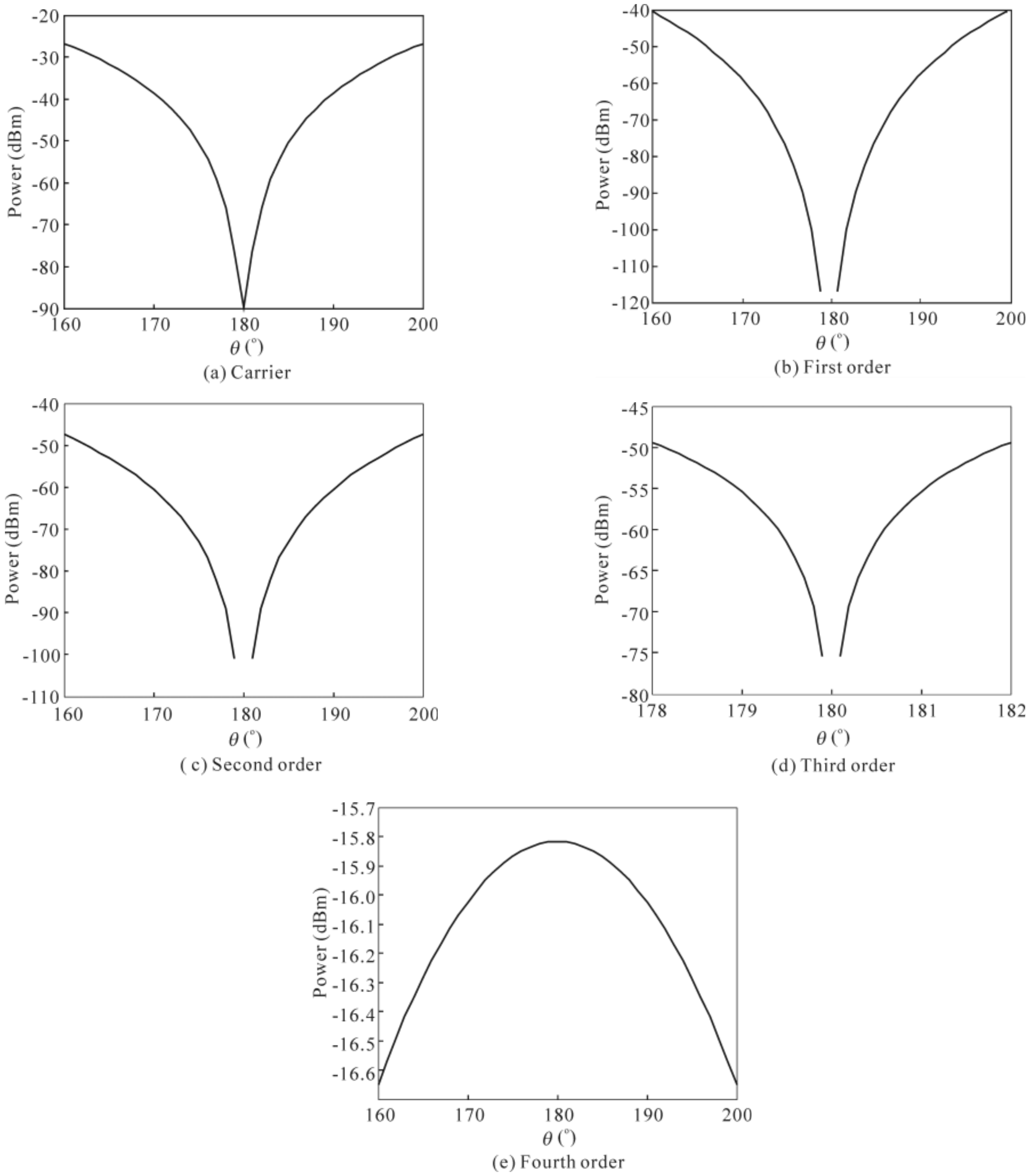

Fig.2 Influence of the phase shift drift on the power values of carrier and the first-order to the fourth-order sidebands of the generated mm-wave

sidered in this paper.

Assuming $r_1 = r_2 = r$ varying from 0.45 to 0.50, $\theta_1=\theta_2=\theta$ from 160° to 200°, Eq.(6) can be expressed as

$$A_n=\begin{cases} r^2J_{4k}(\sqrt{2}m)+r(1-r)\{J_{4k}[2m\cos(\theta/2-\pi/4)]+J_{4k}[2m\sin(\theta/2-\pi/4)]\}\exp(\mathrm{j}2k\theta)+(1-r)^2J_{4k}(\sqrt{2}m)\exp(\mathrm{j}4k\theta), & n=4k \\ r^2J_{4k+1}(\sqrt{2}m)+r(1-r)\{J_{4k+1}[2m\cos(\theta/2-\pi/4)]-J_{4k+1}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+1/2)\theta]+(1-r)^2J_{4k+1}(\sqrt{2}m)\exp[\mathrm{j}(4k+1)\theta], & n=4k+1 \\ r^2J_{4k+2}(\sqrt{2}m)+r(1-r)\{J_{4k+2}[2m\cos(\theta/2-\pi/4)]+J_{4k+2}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+1)\theta]+(1-r)^2(\sqrt{2}m)\exp[\mathrm{j}(4k+2)\theta], & n=4k+2 \\ r^2J_{4k+3}(\sqrt{2}m)+r(1-r)\{J_{4k+3}[2m\cos(\theta/2-\pi/4)]-J_{4k+3}[2m\sin(\theta/2-\pi/4)]\}\exp[\mathrm{j}(2k+3/2)\theta]+(1-r)^2J_{4k+3}(\sqrt{2}m)\exp[\mathrm{j}(4k+3)\theta], & n=4k+3 \end{cases}. \quad (9)$$

According to Fig.3, for the carrier and the fourth-order sideband, the influence caused by phase shift drift is dominant. When r varies from 0.49 to 0.50, the power of the first-order and the third-order sidebands is sensitive to both phase shift drift and splitting ratio. When r varies from 0.49 to 0.50 and θ varies from 175° to 185°, the power of the second-order sideband is influenced mainly by phase shift drift and splitting ratio.

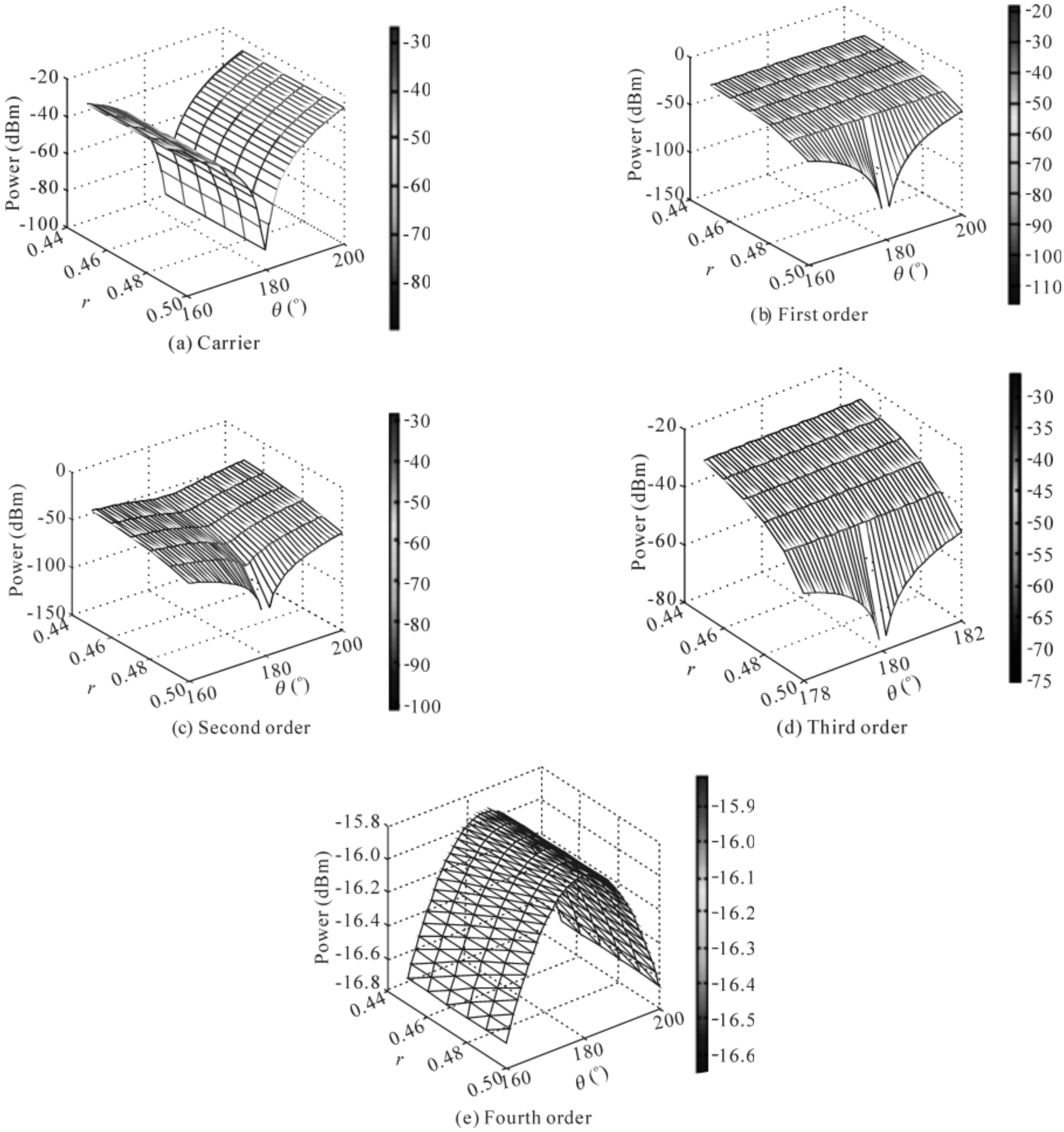

Fig.3 Influence of the phase shift drift and splitting ratio on the power values of carrier and the first-order to the fourth-order sidebands of the generated mm-wave

In order to further analyze the influence of phase shift drift and splitting ratio, undesired sideband suppression ratio degradation with the non-ideal factors is also investigated in Figs.4 and 5. According to Fig.4, when r =0.5, if the phase shift drift is 5º, the fourth-order sideband is 34.60 dB, 60.41 dB, 57.06 dB and 25.59 dB higher than the carrier, the first-order, the second-order and the third-order sidebands, respectively. It can be seen that the third-order sideband is the main limiting factor when only phase shift drift is taken into account. If the phase shift drift is 1º, the result is 60.54 dB, 100.30 dB, 85.18 dB and 39.58 dB. The system performance is perfect if the accuracy is achieved. When r=0.499, if the phase shift drift is 1º, the fourth-order sideband is 60.54 dB, 35.90 dB, 72.60 dB and 38.30 dB higher than the carrier, the first-order, the second-order and the third-order sidebands, respectively. The harmonic influence can be neglected in this case, and the system performance is good enough.

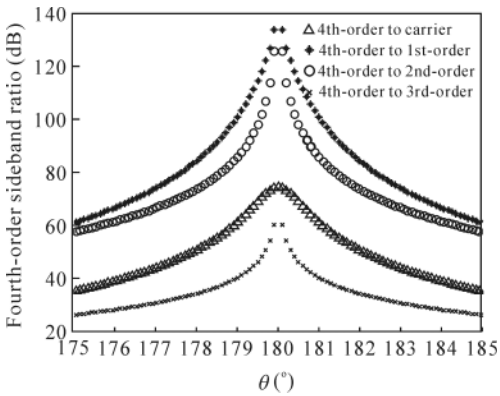

Fig.4 Undesired sideband suppression ratio versus phase shift drift when r = 0.5

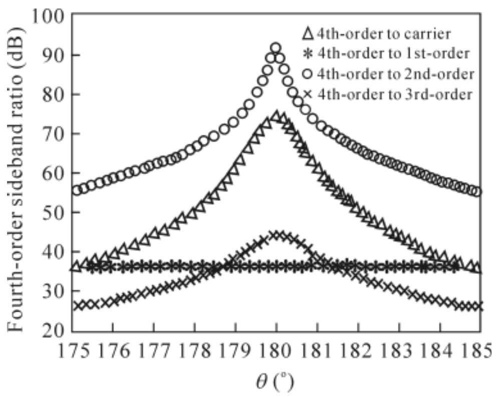

Fig.5 Undesired sideband suppression ratio versus phase shift drift when r =0.499

This paper theoretically analyzes the influence of the phase shift drift and splitting ratio on 80 GHz optical mm-wave generation. An integrated expression of output signal involving several non-ideal factors is given, and the non-ideal factors are discussed in detail. The undesired sideband suppression ratio versus phase shift drift is plotted. When the undesired sideband suppression ratio is at least 35.9 dB under the condition that the splitting ratio deviation is 0.001 and the phase shift drift is 1°, the system performance is perfect.

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