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A novel frequency sextupling scheme for optical mm-wave generation utilizing an integrated dual-parallel Mach-Zehnder modulator

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ABSTRACT

A novel scheme is proposed for frequency sextupling mm-wave generation based on a laser and an integrated dual-parallel Mach-Zehnder modulator (MZM) without optical filter. Theoretical analysis is presented to suppress the undesired optical sidebands for the high quality generation of frequency sextupling mm-wave signal. The performance of the proposed scheme is evaluated by simulations. Utilizing the integrated MZM consisted of two sub-MZMs with extinction ratio of 30 dB, the optical sideband suppression ratio (OSSR) is as high as 29.9 dB and the radio frequency spurious suppression ratio (RFSSR) exceeds 24 dB without any optical or electrical filter. The impact of the nonideal RF driven voltage and phase difference of RF driven signal applied to two sub-MZMs of the integrated MZM on OSSR and RFSSR is discussed and analyzed. After transmission over fiber, the generated optical mm-wave signal demonstrates good performance. Furthermore, the performance of two cases for the proposed scheme is also compared.

1. Introduction

Radio over fiber (ROF) technology has important application in future broadband wireless access networks operating at mm-wave band. In ROF system, the high quality and cost-effective generation of high frequency mm-wave signals is of the utmost importance. Optical method is effective to generate the high frequency mm-wave signals. By beating the two high-order optical sidebands with good coherence in the photodiode, a laser with optical external modulator is a promising and attractive technology to generate the high frequency mm-wave signal generation, whose frequency can be several-folds of the RF local oscillator. In this technology, high optical sidebands suppression ratio (OSSR) is extremely desired to generate the high quality mm-wave signal.

Many schemes have been proposed to generate the high quality mm-wave signal for frequency doubling and frequency quadrulping, based on a laser with optical external phase or intensity modulator [1–10]. Recently, two schemes are proposed for the optical frequency sextupling mm-wave signal generation with two cascaded external modulators. By employing cascaded phase and intensity modulator, Zhang demonstrated the 36 GHz mm-wave signal generation using the 6 GHz RF local oscillator without optical filter [11]. Because the undesired optical sidebands are not well suppressed, the lower OSSR leads to the lower radio frequency spurious suppression ratio (RFSSR) of the generated RF spectrum and in turn degrades the quality of the desired frequency sextupling mm-wave signal. M. Mohamed et al. presented another scheme for the frequency sextupling mm-wave signal generation with two cascaded intensity modulators [12]. However, the optical filter is necessary to remove the undesired optical sidebands. Therefore, the high quality generation of mm-wave signal without optical filter is of great interest for the frequency sextupling scheme.

In this paper, a novel scheme based on a laser with an integrated dual-parallel MZM is first proposed to our best knowledge for the optical frequency sextupling mm-wave generation without optical filter. Theoretical analysis is presented to implement the two-tone optical frequency sextupling. The validity of the proposed scheme is verified by the numerical simulation with the VPItransmisssionMaker tool. Simulation results show that the OSSR can be as high as about 30 dB without optical filter and the RFSSR exceeds 24 dB without electrical filter before transmission over fiber. When RF driven voltage and phase difference of RF driven signal applied to sub-MZMs of the integrated MZM deviates from the desired value, its impact on the quality of the generated mm-wave signal is discussed and analyzed. In terms of Q-factor and EOP (eye opening penalty) of the system, the performance of the generated optical mm-wave after transmission over fiber without optical filter is also investigated. At the same time, two cases of the proposed scheme are also compared.

2. Principle

The schematic diagram of the proposed scheme for frequency sextupling is shown in Fig. 1. The light wave at angular frequency of ω_0 with amplitude of E_0 emitted from a CW laser is modulated by an integrated dual-parallel MZM, in which MZM-a and MZM-b are

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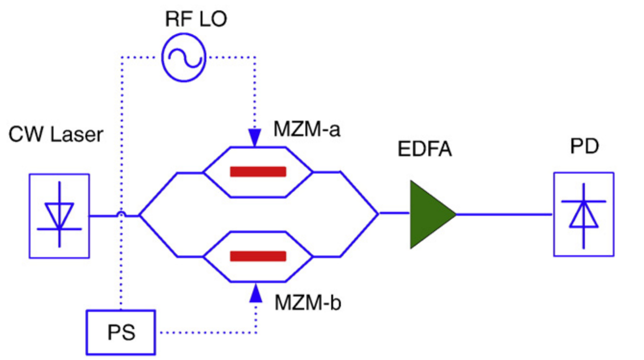

Fig. 1. The schematic diagram of the proposed scheme for the frequency sextupling mm-wave signal generation. (RF LO: RF local oscillator; PS: electrical phase shifter; EDFA: erbium-doped fiber amplifier; and PD: photondiode).

embedded in the two arms of a main MZM. The integrated MZM is driven by the RF drive signals with the amplitude of V_{RF} and angular frequency of ω_{RF}. Because the input power of RF driven signal is attenuated 3-dB by the electrical power splitter before two sub-MZMs, the RF driven signal applied to MZM-a and MZM-b are $V_a(t) = \frac{\sqrt{2}}{2}V_{RF}\sin(\omega_{RF}t + \phi_0)$ and $V_b(t) = \frac{\sqrt{2}}{2}V_{RF}\sin(\omega_{RF}t + \phi_0 + \Delta\phi)$, respectively. ϕ_0 and $\phi_0+\Delta\phi$ are the phase of the RF drive signal. Another 3-dB electrical power splitter is also utilized before two electrodes of each sub-MZM. Therefore, the amplitude of RF driven signal applied to the electrodes of MZM is $\frac{V_{RF}}{2}$. The two MZMs are both biased at the null point, thus all even-order optical sidebands are suppressed.

If the insert loss of the integrated is neglected and the extinction ratio of the two sub-MZMs is assumed to be infinite, the output optical field of the integrated MZM can be written as

$$\begin{aligned}E(t) &= \frac{1}{4}E_0e^{j\omega_0t}\left\{e^{j\frac{\pi}{2V_\pi}[V_{RF}sin(\omega_{RF}t + \phi_0)]} - e^{-j\frac{\pi}{2V_\pi}[V_{RF}sin(\omega_{RF}t + \phi_0)]}\right\}\\ &+ \frac{1}{4}E_0e^{j\omega_0t}\left\{e^{j\frac{\pi}{2V_\pi}[V_{RF}sin(\omega_{RF}t + \phi_0 + \Delta\phi)]} - e^{-j\frac{\pi}{2V_\pi}[V_{RF}sin(\omega_{RF}t + \phi_0 + \Delta\phi)]}\right\}\\ &= \frac{1}{2}E_0e^{j\omega_0t}\sum_{n=-\infty}^{+\infty}J_{2n+1}(m)e^{j(2n+1)\omega_{RF}t} \times \left[e^{j(2n+1)\phi_0} + e^{j(2n+1)(\phi_0+\Delta\phi)}\right],\end{aligned} \tag{1}$$

where V_π is the switching voltage of MZM, m is the phase modulation index defined as $m = \pi\frac{V_{RF}}{2V_\pi}$, J_{2n+1} is the first-kind Bessel function of $2n+1$ order.

In order to implement the high-quality frequency sextupling with high OSSR, the two third-order optical sidebands should be kept and maximized, and the other optical sidebands should be well suppressed. Among these undesired odd-order optical sidebands, the first and fifth-order optical sidebands have much higher amplitude than others and have obvious influence on OSSR. If they are not well suppressed, the quality of the generated mm-wave signal will greatly degrade. Therefore, it is crucial to eliminate the first and fifth-order optical sidebands for high quality frequency sextupling mm-wave signal generation. It can be found from Eq. (1) that the first and fifth-order optical sidebands vanish when the following conditions are satisfied

$$J_1(m) = 0, \tag{2a}$$

$$1 + e^{\pm j5\Delta\phi} = 0. \tag{2b}$$

From Eq. (2), we can obtain

$$m = 3.8317, \text{or}\, V_{RF} = 2.44V_\pi, \tag{3a}$$

$$\Delta\phi = \frac{\pi}{5}, \text{or}\, \frac{3\pi}{5}. \tag{3b}$$

Because $J_3(3.8317)/J_7(3.8317) \approx 35.8$ and $J_3(3.8317)/J_9(3.8317) \approx 637.4$, the optical sidebands higher than seven-order can be ignored.

In the above analysis, MZM is assumed to have the ideal S21 Bandwidth response for RF driven signals with various frequencies. In fact, the insert loss after S21 filter is different when the RF driven signal at different frequencies is applied to the electrode of MZM. If the insert loss of S21 filter is assumed to be γ dB, two key conditions in Eq. (3) should be rewritten as

$$m = 10^{\frac{\gamma}{20}}3.8317, \text{or}\, V_{RF} = 10^{\frac{\gamma}{20}}2.44V_\pi, \tag{4a}$$

$$\Delta\phi = \frac{\pi}{5}, \text{or}\, \frac{3\pi}{5}. \tag{4b}$$

Eq. (4) is available for RF local oscillator at various frequencies. Note that the amplitude of the optical sidebands is only related with modulation index and phase difference of MZM in Eq. (3). $m = 3.8317$ can also be called as the desired effective modulation index. Therefore, the output optical field of the integrated MZM can be approximately rewritten as

$$\begin{aligned}E(t) = \frac{1}{2}E_0\Big\{&J_3(3.8317)\left[e^{j(\omega_0+3\omega_{RF})t}\left(1 + e^{j3\Delta\phi}\right)e^{j3\phi_0} - e^{j(\omega_0-3\omega_{RF})t}\left(1 + e^{-j3\Delta\phi}\right)e^{-j3\phi_0}\right]\\ &+ J_7(3.8317)\left[e^{j(\omega_0+7\omega_{RF})t}\left(1 + e^{j7\Delta\phi}\right)e^{j7\phi_0} - e^{j(\omega_0-7\omega_{RF})t}\left(1 + e^{-j7\Delta\phi}\right)e^{-j7\phi_0}\right]\Big\},\end{aligned} \tag{5}$$

where $\Delta\phi$ represents $\pi/5$ or $3\pi/5$, and it is the same in the following analysis of this section. If nonlinear effect is neglected, the optical field after transmission over fiber can be expressed as

$$\begin{aligned}E(L,t) = \frac{1}{2}e^{-\frac{\alpha}{2}L}E_0\{&J_3(3.8317)[e^{j(\omega_0+3\omega_{RF})t - j\beta(\omega_0+3\omega_{RF})L}\left(1 + e^{j3\Delta\phi}\right)e^{j3\phi_0}\\ &-e^{j(\omega_0-3\omega_{RF})t - j\beta(\omega_0-3\omega_{RF})L}\left(1 + e^{-j3\Delta\phi}\right)e^{-j3\phi_0}]\\ &+J_7(3.8317)[e^{j(\omega_0+7\omega_{RF})t - j\beta(\omega_0+7\omega_{RF})L}\left(1 + e^{j7\Delta\phi}\right)e^{j7\phi_0}\\ &-e^{j(\omega_0-7\omega_{RF})t - j\beta(\omega_0-7\omega_{RF})L}\left(1 + e^{-j7\Delta\phi}\right)e^{-j7\phi_0}]\},\end{aligned} \tag{6}$$

where $E(L, t)$ is the optical field of the generated optical mm-wave after transmission over fiber length of L, α is loss coefficients and $\beta(\omega_0 \pm n\omega_{RF})$ is the propagation constant for the n-order optical sidebands. For $\beta(\omega_0 \pm n\omega_{RF})$, it can be expanded approximately at the frequency of ω_0 as

$$\beta(\omega_0 \pm n\omega_{RF}) \simeq \beta_0 \pm \beta_1 n\omega_{RF} + \frac{1}{2}\beta_2 n^2\omega_{RF}^2, \tag{7}$$

where $\beta_1 = \frac{1}{v_g}$ and $\beta_2 = -D\frac{\lambda^2}{2\pi c}$, V_g is group velocity, D is dispersion parameter. When the optical mm-wave signal is injected into PD, the photocurrent can be written as

$$I_{PD} = \Re|E(L,t)|^2, \tag{8}$$

where $\Re$ is the responsivity of the PD. From Eqs. (6), (7) and (8), the current of the desired 60 GHz mm-wave signal is given by

$$I_{6\omega_{RF}}(t) = \Re\frac{E_0^2}{2}e^{-\alpha L}J_3^2(3.8317)[1 + cos(3\Delta\phi)]cos[6\omega_{RF}(t + \beta_1L) + 3\Delta\phi + 6\phi_0]. \tag{9}$$

Eq. (9) shows the amplitude of the current for the desired frequency sextupling mm-wave signal is independent of fiber dispersion. Therefore, the desired frequency sextupling mm-wave does not suffer from power fading induced fiber dispersion if it is only generated by beating of the two third-order optical sidebands.