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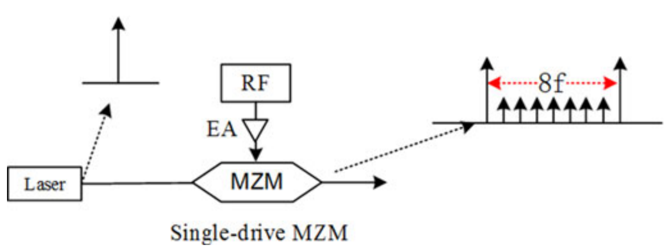

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A Novel Radio-Over-Fiber System Based on Carrier Suppressed Frequency Eightfold Millimeter Wave Generation

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Abstract: We propose a novel and simple scheme for photonic frequency eightfold millimeter wave (mm-wave) generation with optical carrier suppression based on only one single-drive Mach–Zehnder modulator (MZM). According to our theoretical analysis and experimental demonstration, by adopting designed direct current bias voltage of MZM and the amplitude voltage of the radio frequency (RF) drive signal, two fourth-order optical subcarriers are generated via a single-drive MZM. Furthermore, the corresponding optical central carrier and undesired sidebands are suppressed simultaneously. Based on our proposed scheme, the generation of 72-GHz optical mm-wave by an RF signal of 9 GHz without any optical filtering is experimentally demonstrated. The radio-over-fiber system with 3.5-Gb/s OOK downstream link based on this generated 72-GHz mm-wave is also experimentally demonstrated. As we know, it is the first time to realize frequency eightfold mm-wave signal generation with simultaneous carrier suppression by using only one single-drive MZM in experiment.

Index Terms: Millimeter wave, optical carrier suppression, frequency eightfold, single-drive Mach-Zehnder modulator.

1. Introduction

With the rapid development of ultra-broadband wireless access in the millimeter wave (mm-wave) band, it is of ultimate importance to cost-effectively generate the mm-wave radio frequency signal [1]–[3]. Radio-over-fiber (ROF) based on mm-wave utilization is a promising technique in providing broadband wireless access services in the emerging optical-wireless networks [4], [5]. There are many advantages and benefits of the ROF technology compared with electrical signal distribution such as low attenuation loss, large bandwidth, immunity to radio frequency interference, and can generate the mm-wave signal based on microwave photonics and distribute it over the fiber in the optical domain [6], [7]. One of the key techniques in ROF system is to generate optical carrier suppression (OCS) mm-wave signal. The optical carrier does not contain any information for downstream link although it consumes most the total optical power in the system. Therefore, optical carrier power needs to be essentially suppressed to improve performances of ROF system include

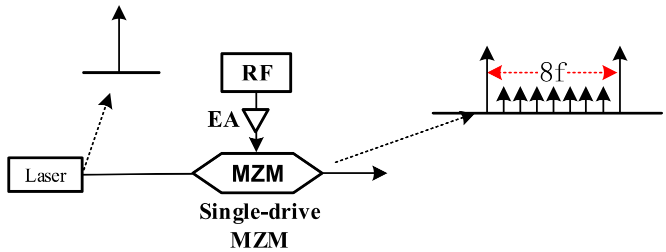

Fig. 1. Schematic for the frequency eightfold mm-wave generation with carrier suppression. RF: radio frequency. MZM: Mach-Zehnder modulator. EA: electric amplifier.

link gain and noise figure (NF). The optical carrier suppression can significantly reduce the noise contributions such as NF, thermal noise and shot noise [8].

Several methods have been proposed to directly generate OCS high-repetitive frequency mm-waves by using a low-cost and low-frequency radio frequency (RF) signal [9]–[17]. According to the existing reports, carrier suppression only utilizing one modulator has been proposed previously. But the system only achieved frequency-doubling [9]. Frequency quadrupling optical mm-wave generation by a modulator has also been reported [10], [11]. These studies have a common feature that optical carrier can't be suppressed by only using a modulator. Thus expensive optical filters are added to the link to achieve OCS, which not only greatly increases the complexity and cost of the system, but also reduces the optical signal-noise ratio (SNR) or power of optical mm-wave simultaneously. In addition, frequency sextupling and high multi-frequency mm-waves have been generated by multi-cascaded modulator [12]–[15]. For example, [13] proposed that utilizing two cascaded dual-electrode MZMs interleaved with Gaussian optical band-pass filter to realize frequency sextupled. However, the stability is realistic problem by using multi-cascaded modulators. Furthermore, some scholars proposed multi-frequency mm-wave based on four-wave-mixing (FWM) technique by using high nonlinear fiber and semiconductor optical amplifier [16], [17]. But the optical signal by FWM is affected by the noise sensitivity, the stability and SNR performance is also poor.

The optical mm-waves generation based on frequency multiplication technique using fewer modulators, lower frequency RF and simple architecture, are considered as the potential solutions to the future ROF system [18]–[24].

In this paper, we propose theoretically and experimentally demonstrate the generation of optical mm-wave based on frequency-eightfold with optical carrier suppression for the first time, which only using one single-drive modulator. By adjusting the direct current (DC) bias voltage of MZM and the amplitude voltage of the RF signal, the corresponding optical central carrier and undesired sidebands are suppressed. On this scheme, using a LO signal of 9 GHz generated an optical mm-wave with a frequency spacing of 72 GHz. Adopting this system can greatly reduce costs because only one single-drive modulator and low-frequency LO is used. The waveform of frequency eightfold mm-wave with carrier suppression based on one single-drive modulator has been generated and analyzed. Compared to previously reported methods, our scheme is more flexible and easy to implement, low-cost and excellent transmission performance of the stability and SNR.

2. Principle for the Frequency Eightfold MM-Wave Generation With Carrier Suppression

The principle for the frequency eightfold mm-wave generation with OCS is shown in Fig. 1. The continuous wave from an external cavity laser (ECL) is defined as

$$E_0(t) = E_0 \cdot \exp(j\omega_0 t), \tag{1}$$

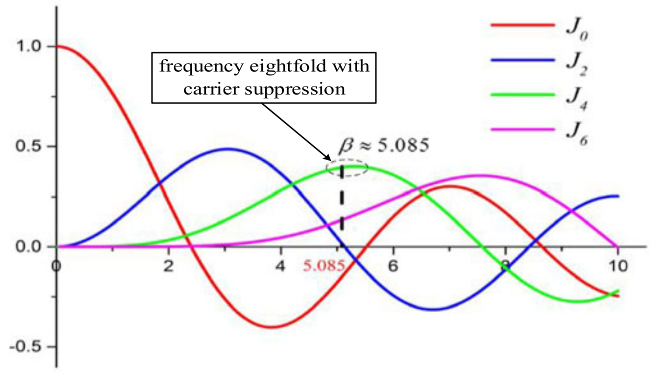

Fig. 2. Even-orders of the Bessel function of the first kind.

where E_0 and ω_0 are the optical field amplitude and angular frequency of the input optical carrier, respectively. The RF signal is represented by

$$V_{RFi}(t) = V_{RFi} \cdot \cos \omega_{RF} t, (i = 1, 2), \tag{2}$$

V_{RF} and ω_{RF} are the amplitude and angular frequency of the RF signal. After the power amplification by electrical amplifier (EA), the RF signal is used to drive the MZM, the optical field signal at the output of MZM can be expressed as

$$E_{out1}(t) = \frac{E_0(t)}{10^{\alpha/20}} \left[\gamma \cdot \exp\left(j\pi \frac{V_{RF2}(t)}{V_\pi} + j\pi \frac{V_{b2}}{V_\pi}\right) + (1-\gamma) \cdot \exp\left(j\pi \frac{V_{RF1}(t)}{V_\pi} + j\pi \frac{V_{b1}}{V_\pi}\right)\right] \tag{3}$$

where α is the insertion loss, and $\gamma = 1/2(1 - 1/\sqrt{\varepsilon_\gamma})$, where $\varepsilon_\gamma = 10^{ER/10}$, ER is the extinction ratio. In the ideal case, we assume that the extinction ratio is large and neglect the insertion loss. V_π is the half-wave voltage, and V_{b1}, V_{b2} are the DC bias voltage of the MZM.

Because we utilize the single-drive modulator, we assume that $V_{RF2} = 0$, so $V_{RF2}(t) = 0$.

For convenient calculation, $V_{b1} = 0$, then (3) can be simplified to

$$E_{out1} = \frac{E_0}{2}\left\{\cos\left[\omega_0 t + \frac{\pi V_{RF1}}{V_\pi} \cdot \cos \omega_{RF} t\right] + \cos\left[\omega_0 t + \frac{\pi V_{b2}}{V_\pi}\right]\right\} \tag{4}$$

where $\beta = \pi V_{RF1}/V_\pi$ is the modulation depth, $\varphi = \pi V_{b2}/V_\pi$ is the phase rotation caused by DC bias voltage.

According to the Bessel function expansion, (4) can be deduced as follows

$$\begin{aligned} E_{out1} = \frac{E_0}{2}\Bigg\{ & J_0(\beta) \cdot \cos \omega_0 t + \cos(\omega_0 t + \varphi) + 2\cos \omega_0 t \left[\sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta) \cos(2n\omega_{RF} t)\right] \\ & + 2\sin \omega_0 t \left[\sum_{n=1}^{\infty} (-1)^n J_{2n-1}(\beta) \cos((2n-1)\omega_{RF} t)\right]\Bigg\} \end{aligned} \tag{5}$$

where $J_n(\beta)$ is the Bessel function of the first kind. From (5) we can know that at the case of

$$J_0(\beta) \cdot \cos \omega_0 t + \cos(\omega_0 t + \varphi) = 0 \tag{6}$$

the optical central carrier will be suppressed. In other words, we can implement this kind of case by apply proper bias voltage V_{b2}.

Most odd-orders can be suppressed when we appropriately adjust the driving voltage of the single-drive MZM biased at its maximum transmission point. Fig. 2 shows the even-orders of the Bessel function of the first kind. We can see that when β is equal to 5.085, $J_4(\beta) = 0.395$, and $J_0(\beta)$, $J_2(\beta)$, $J_6(\beta)$ are much more small compared to $J_4(\beta)$, relatively. When we adjust the β to

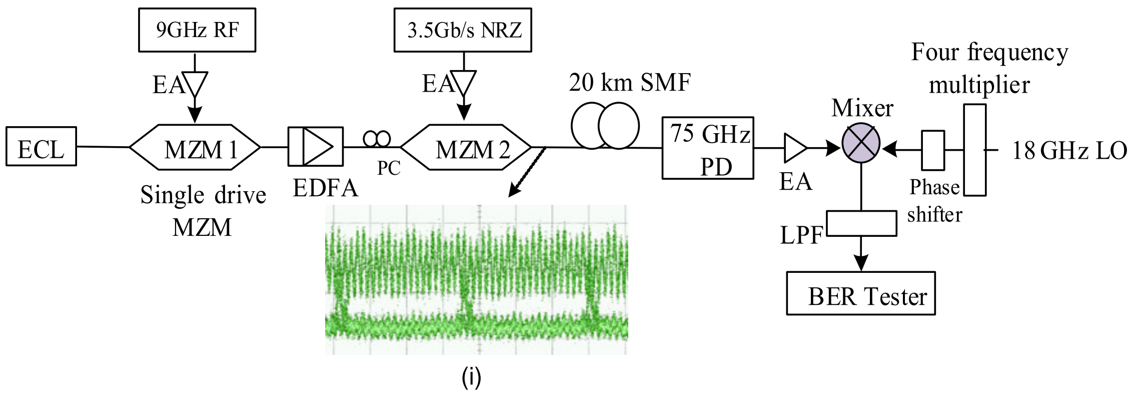

Fig. 3. Experimental setup for ROF system based on frequency eightfold optical mm-wave generation and optical carrier suppression via one single-drive MZM. ECL: external cavity laser. RF: radio frequency. MZM: Mach-Zehnder modulator. EA: electric amplifier. PC: polarization controller. PD: photodiode. LPF: low-pass filter. LO: local oscillator. (i) Optical eye diagram of the downstream mm-wave signal.

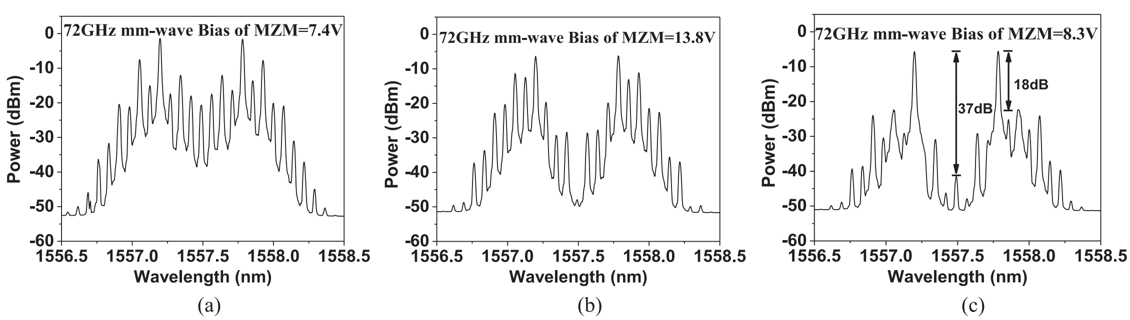

Fig. 4. (a)–(c): Output optical spectrums of the single-drive MZM with the DC bias voltage = 7.4 V, 13.8 V and 8.3 V, respectively.

make sure that is approximately equal to 5.085, and appropriately adjust the DC bias voltage V_{b2} of the single-drive MZM, the central optical carrier and undesired sidebands can be effectively suppressed.

3. Experimental Setup and Results

Fig. 3 shows the experimental setup for carrier suppressed frequency eightfold mm-wave generation based on our proposed scheme. The central wavelength at 1557.5 nm is generated by an external cavity laser (ECL) (TTX199475900N07, product by Newphotonics) with the line-width of less than 100 kHz and the output power of 14.5 dBm. The single-drive MZM1 and MZM2 (FTM7937EZ, product by Fujitsu) are with the electrical bandwidth of 30 GHz and the half-wave voltage of 5 V. The RF signal with the central frequency of 9 GHz is used to drive the MZM1 after the power amplification to 18 dBm by a narrowband electric amplifier (EA) (with 10 GHz bandwidth, 30 dBm Maximum output). Thus the V_{RF1} of the amplified RF signal defined in Section 2 after EA is set approximately to 7.8 V ($\beta \approx 4.9$) to achieve the frequency eightfold mm-wave generation. The output optical spectrum of the MZM1 measured by Ando AQ6317B (0.01\;nm resolution) are shown in Fig. 4. Fig. 4(a)–(c) shows the optical spectrums with the DC bias voltage of MZM1 set to 7.4, 13.8 and 8.3 V, respectively. It is noted that in order to optimize each optical spectrum, the V_{RF1} for Fig. 4(a)–(c) is set as 7.6 V ($\beta = 4.77$), 8.1 V ($\beta = 5.09$) and 7.8 V ($\beta = 4.9$), respectively. Frequency eightfold (two fourth-order sidebands) are realized in Fig. 4(b) with completely suppressed optical carrier. However, the power of residual sidebands is certainly high. Based on the results of Fig. 4(b), we

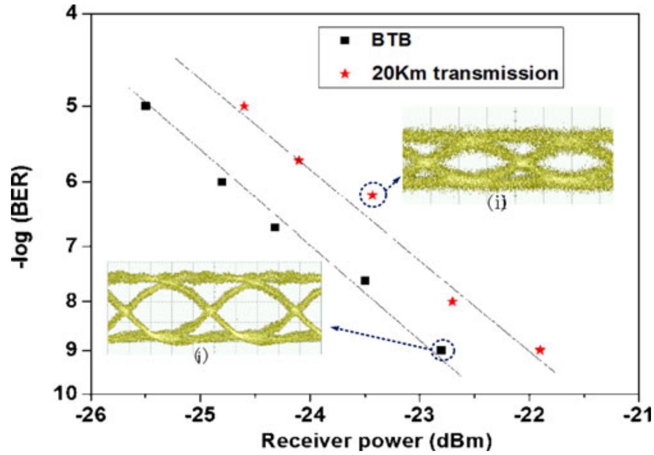

Fig. 5. BER performance. (i) The eye pattern of the downstream data signal for BTB. (ii) The eye pattern of the downstream data signal after 20 km SMF transmission.

not only adjust DC bias but also adjust the V_{RF1} lightly to make the optical spectrum more reliable. Certain sidebands in Fig. 4(c) are properly suppressed with much more accurate β by experimentally handle. The relative ideal case for frequency eightfold mm-wave generation is shown as Fig. 4(c). The carrier suppression ratio for the two fourth-order sidebands is 37 dB and the residual sidebands suppression ration is 18 dB.

At the output of MZM1, the 72 GHz optical mm-wave is generated by the parameters of Fig. 4(c). After the optical power amplification by EDFA, a 3.5 Gb/s OOK signal with the pseudorandom binary sequence (PRBS) length of $2^{31}-1$ is used to modulated the 72 GHz mm-wave via MZM2. The bias voltage of the MZM2 is 2.5 V. The eye diagram of 72 GHz mm-wave carried with 3.5 Gb/s based band signal is measured by digital serial analyzer, (DSA8300, 80E09B module, product by Tektronics), is shown as the inset (i) in Fig. 3. After 20 km SMF-28 transmission, 75 GHz electrical mm-wave is obtained by the optical-to-electrical (O/E) conversion via a 75 GHz photodiode (product by U2t) at the base station (BS). The input power of the optical mm-wave signal into the 20 km SMF-28 is 0 dBm. After the power broadcast, the 72 GHz electric mm-wave signal is down-converted by mixing with the 72 GHz local oscillator signal, which is frequency fourfold from an 18 GHz RF signal. A phase shifter with 3 dB bandwidth of 18 GHz is used for realizing the synchronization between the driving 72GHz mm-wave and the LO signal for down conversion. The 3.5 Gb/s baseband signal is retrieved, after passing through a 7.5 GHz low-pass filter, and then detected by an bit-error-rate (BER) tester. The measured BER performance is shown in Fig. 5. The received power sensitivity is -22.8 and -21.9 dBm at the BER of 1×10^{-9} before and after 20 km SMF-28 transmission, respectively. The eye diagrams before and after 20 km SMF-28 transmission are shown as inset Fig. 5 (i) and (ii). The power penalty is 0.9 dB due to the fiber dispersion.

4. Conclusion

We theoretically propose and experimentally demonstrate a simple scheme to realize frequency eightfold optical mm-wave signal generation with simultaneous carrier suppression by using only one single-drive MZM. In our theoretical analysis, by utilizing the modulation depth of 5.085 and adjusting the DC bias voltage of the modulator, the frequency eightfold mm-wave can be generated. In the experiment, the amplitude of the 9 GHz RF signal driven on the MZM is set to 7.8 V, the 72 GHz optical mm-wave is generated when the DC bias voltage of the modulator is set to 8.3 V. The 3.5 Gb/s downstream data carrying on the 72GHz mm-wave is also demonstrated. The power penalty is 0.9 dB after 20 km SMF transmission at the BER of 10^{-9}, and the eye pattern is also clearly visible on the receiving end. The described scheme is simple and the low-cost optical mm-wave generation suitable for the next generation broadband wireless access networking.

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