A Continuously Tunable and Filter-Less QPSK Modulated Millimeter-Wave Signal Generation with Frequency Quadrupling Just Based on an MZM

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Abstract: In this paper, we propose a new frequency quadrupling scheme to generate a quadrature phase shift keying (QPSK) modulated vector millimeter-wave signal, in which an optical filter is not necessary. To eliminate constellation overlapping of the generated vector millimeter-wave signal caused by phase multiplication in the process of frequency multiplication, a precoding assisted technique is adopted. The principle and feasibility of the proposed scheme is deduced by a detailed mathematical formula. Simulations are carried out to generate 40 GHz QPSK modulated vector millimeter-wave signals using a 10 GHz radio frequency source and the BER performance is analyzed in detail. The results show that BER of the generated 5/10-Gbaud vector millimeter-wave signal is below 3.8 × 10⁻³, when the input optical power for into photo-detector is higher than −20.67 dBm.

Keywords: millimeter-wave signal generation; frequency quadrupling; Mach-Zehnder modulator (MZM); radio over fiber

1. Introduction

The fifth-generation communication (5G) era is coming. Various intelligent products and big data platforms are emerging, the demand for data rate and capacity is higher and higher, and the data transmission mode is gradually developing towards wireless and broadband systems [1,2]. The question concerning how to realize an ultra-high-speed wireless signal has become an urgent problem to be solved. As we all know, optical fiber communication can provide huge transmission capacity and ultra-long transmission distance, but its location is fixed and cannot fully cover any location. Wireless communication technology can cover all locations in an ideal situation, but its spectrum resources are not significant and there will be a lot of damage in the transmission process. Therefore, the transmission distance of this communication mode is short, which cannot meet the needs of long-distance transmission [3–5]. Enhanced mobile broadband (eMBB) communications, such as one of the three typical application scenarios of the 5G mobile communication networks, will be required to meet the demands of future ubiquitous VR/AR, 4k/8k high-definition video, artificial intelligence, and so on. Therefore, eMBB will motivate the explosive increase of mobile data traffic and rates, which requires more bandwidth at higher carrier frequencies. Mm-wave band (30–300 GHz) is one of the promising candidates for 5G, since it has larger available bandwidth to accommodate higher mobile data traffic and rates [6,7]. Millimeter wave over fiber communication has the advantages of optical fiber communication and wireless communication, and meets the requirements of communication bandwidth and mobility in future communication.
networks [8–10]. Moreover, millimeter wave has rich spectrum resources and has great potential in wireless transmission capacity and transmission distance. It is the main carrier in 5G and the next generation mobile communication network. Today, with the increasing shortage of spectrum resources, it has attracted more and more attention of scientists and scholars [11–19]. However, due to the limited bandwidth and other electronic bottlenecks, it would be more challenging to generate millimeter wave signals based on traditional methods [20–23].

To overcome these defects, photonic assisted mm-wave generation schemes using external modulator and frequency multiplication technology are proposed [24–27]. However, for some cases, such as signals modulating quadrature phase shift keying (QPSK), m-order quadrature amplitude modulation (m-QAM), or other higher order vector data, frequency multiplication will synchronously bring about the same multiplicative factor for phase after square law detection in photo-detector (PD), which will result in the phase to be disordered. To this end, several research groups have proposed and tested simulation or experiment to realize the vector millimeter wave generation scheme based on precoding aided technique [18–31]. However, in these reported schemes, additional expensive wavelength selective filter is used to select out two specific optical tones, which will limit the bandwidth adjustable range of the system [32,33].

For generating high frequency and free phase damage vector mm-wave signal, we propose a novel symmetrical frequency quadrupling and optical filter-less scheme. In this scheme, a Mach-Zehnder modulator (MZM) is used to produce symmetrical frequency quadrupling vector mm-wave signal, and a precoding aided technique is used to cancel constellation overlap caused by phase multiplication. In addition, no optical filter is employed, which can increase the tunability of the system and make the cost of the system reduction. We also realize 5Gbaud and 10Gbud quadrature phase shift keying (QPSK) modulated vector mm-wave signal transmission over 5 km distance single mode fiber (SMF) in the simulation surrounding, and investigate the performance of bit error rate (BER) for the generated W-band 40 GHz vector mm-wave signals. The results show when the input power for the generated vector mm-wave with the symbol rate of 10-Gbaud into PD is not less than −5 dBm, the BER are below the 7% hard-decision forward-error-correction threshold $3.8 \times 10^{-3}$, which demonstrate that the generated optical filter-less vector millimeter-wave signal can work well.

2. Principle and Theoretical Analysis

Figure 1 schematically illustrates the principle of photonic filter-less scheme for QPSK modulated millimeter-wave signal generation with frequency quadrupling. In this scheme, only push-pull MZM is used to generate optical tones, and no optical filter is needed to filter out harmonics. At the transmitter, the pseudo-random binary sequence (PRBS) with a fixed length of $2^{16}−1$, is first mapped into QPSK, phase precoding and low-pass filtered to generate vector data, then up-converted into RF band at $f_l$, in which the RF vector signal can be formulated as

$$V_{RF}(t)=V_0 \cos(2\pi f_l t + \phi),$$

where $V_0$ is the amplitude of driving RF signal source, $A$ and $\phi$ denote the amplitude and phase information of the vector data symbol, respectively. Next, the RF vector signal is used to drive a push-pull MZM. Here, different kinds of constant modulus modulation formats can be applied, such as QPSK, 8QAM, 16QAM and so on.
Figure 1. Principle of photonic filter-less scheme for generating frequency quadrupling vector mm-wave signal. CW Laser, continuous wave laser; MZM, Mach-Zehnder modulator; PS, Phase shifter; OATT, Optical attenuator; EDFA, Erbium doped fiber amplifier; DSP, Digital signal processing; ADC, Analog to digital conversion; SMF, Single-mode fiber; PD, photodetector.

The light emitted from a continuous wave (CW) laser is separated into two channels, one is injected into an MZM to produce multifrequency optical sidebands, the other is subject to optical attenuator and optical phase shifter to adjust the phase and amplitude of light wave, which is employed to suppress the output 0th order optical carrier from MZM. The CW light-wave is defined as $E_t = E_c \exp(j2\pi f_c t)$, where $E_c$ represents the amplitude of CW, and $f_c$ denotes the frequency of CW.

For push-pull MZM, the output light field can be written as:

$$E_{out}(t) = \frac{E_m}{2} e^{j \left[ V_{dc1} + V_{dc2} \right]/2} \sum_{n=-\infty}^{\infty} J_n(\beta) e^{in\varphi} \cos \left( \frac{n\pi}{2} + \frac{n\pi}{2} \right),$$

(2)

Here $V_{dc1}$ and $V_{dc2}$ represent the dc-bias voltage of MZM, $\beta = \pi V_m/V_s$ represents the modulation index of the MZM, $V_m$ is the amplitude of RF drive signal, $V_s$ is the switching voltage, $\varphi$ is the phase of the baseband signal, respectively. One must set the MZM bias at the maximum transmission point to suppress the odd order sidebands and realize the even order sideband modulation. In the scenario of small signal modulation (that is, the modulation index $\beta \approx 1$, the value of higher order Bessel function can be neglected and the output light fields after the MZM can be approximately described as follows):

$$E_{MZM}(t) = \frac{E_m}{2} \sum_{n=-\infty}^{\infty} J_n(\beta) e^{in\varphi} \cos \left( \frac{n\pi}{2} \right),$$

$$= \frac{E_m}{2} \left[ J_0(\beta) - J_2(\beta) e^{i2\varphi} - J_2(\beta) e^{-i2\varphi} \right]$$

(3)

The output from the optical attenuator is an unmodulated optical carrier. Adjusting the optical attenuator to make the output power from the optical attenuator equals the zeroth order sideband power from the MZM. Next, adjusting the optical phase shifter to ensure the phase difference between the output optical field of MZM and the output of the optical attenuator is $\pi$. Then, after the optical coupler, the 0th-order sideband will disappear due to destructive interference. The output optical field can be described as
The electrical frequency quadrupling mm-wave signal will be obtained after the square-law detection based on a photodetector, and the detail process can be expressed as

$$I_{PD}(t) = \zeta E_{out} \times E_{out}^* = \zeta \left\{ E \left[ -J_2(\beta) e^{i(\omega_1 - 2\omega_2)t - j2\varphi} - J_2(\beta) e^{i(\omega_1 + 2\omega_2)t + j2\varphi} \right] \right\}^*$$

$$\times \left\{ E \left[ -J_2(\beta) e^{i(\omega_1 - 2\omega_2)t - j2\varphi} - J_2(\beta) e^{i(\omega_1 + 2\omega_2)t + j2\varphi} \right] \right\}$$

$$= 2\zeta E^2 J_2^2 (\beta) \cos(4\omega_1 t + 4\varphi)$$

Here $\zeta$ represents the sensitivity for PD. Equation (5) shows a pure high frequency at $4\omega$ vector mm-wave signal is obtained, which is quadrupling of the RF source drive signal.

Therefore, employing this scheme, the photonic frequency quadrupling vector mm-wave signal generation is easily realized. However, frequency quadrupling will simultaneously cause quadrupling for phase after photo-detector, which will cause the constellation overlapping. To directly obtain the accurate phase of the transmitter constant-amplitude PSK data after photo-detector conversion, the phase $\varphi$ of the driving RF signal shall meet $\varphi_{data} = 4\varphi$, where $\varphi_{data}$ denotes the phase of the original transmitter constant-amplitude PSK data. Therefore, we need to pre-code the phase of the driving RF source signal at the transmitter end. Figure 2 shows the principle for QPSK modulated format precoding vector data generation with angular frequency $\omega$, which could be enabled by a computer program to implement and is up-loaded into an arbitrary waveform generator (AWG) in our simulation.

![Figure 2. Principle diagram of the precoding QPSK signal. (a) Standard QPSK constellation; (b) QPSK constellation after precoding.](image)

3. Simulation Setup and Results

To demonstrate the mechanism of the proposed phase precoding QPSK-modulated vector mm-wave signals generation scheme, simulation is performed by the schematic setup as shown in Figure 1. A certain length of series PRBS with $2^{20}-1$ is mapped into QPSK data, carrying out phase precoding, and then up-converted into RF band with frequency $f_i = 10$ GHz, which can be generated by computer software, such as MATLAB.
The offline data is imported into arbitrary waveform generator (AWG), and then to drive MZM. The half-wave voltage of MZM is 3.2 V, the extinction ratio is 30 dB, and the insertion loss is 5 dB. The center frequency of CW laser is 193.1 THz, the power is 20 dBm and the linewidth is 10 MHz. The attenuation coefficient of optical attenuator-1 is set to 7.24 dB. The phase shift value of the optical phase shifter is set to 180 degrees. Detailed parameters are shown in Table 1.

Table 1. All of the used components and their parameters.

| Device     | Parameter     | Value       |
|------------|---------------|-------------|
| CW Laser   | Frequency     | 193.1 THz   |
|            | Linewidth     | 10 MHz      |
| RF source  | Frequency     | 10 GHz      |
| PS         | Shift value   | 180 degrees |
|            | Half-wave voltage | 3.2 V    |
| MZM        | Insertion loss | 5 dB       |
|            | Extinction ratio | 30 dB    |
|            | Attenuation coefficient | 7.24 dB |
| Attenuator-1 | Length     | 5 km      |
| SMF        | Attenuation   | 0.2 dB/km  |
|            | Dispersion    | 16.75 ps/nm/km |
| PD         | Responsivity  | 1 A/W      |
|            | Dark current  | 10 nA      |

Figure 3a gives the output optical spectra after push-pull MZM. We can find that the positive and negative second-order optical sidebands and a 0-order optical carrier are obtained, in which the frequency interval between the positive and negative second-order two optical sidebands is 40 GHz. Figure 3b depicts another optical wave, which is used to eliminate the 0-order optical carrier output by MZM. By controlling the phase and amplitude of another optical wave, the 0-order optical carrier output by MZM can be eliminated, and then only ±2-order optical sidebands can be retained, as shown in Figure 3c. Finally, two optical sidebands with a frequency interval of 40 GHz are injected into a photodetector for beat frequency, and the vector millimeter wave signal with a frequency of 40 GHz modulated by QPSK is realized, as shown in Figure 3d.

To further evaluate the effectiveness of the proposed scheme, the influence of different incident optical power into PD versus BER performance under the condition of back to back (BTB) and a 10 km SSMF transmission at 5G baud/s and 10Gbaud is analyzed and discussed, as shown in Figure 4. From Figure 4, we can see that the BER of the generated 5-Gbaud and 10-Gbaud QPSK modulated vector mm-wave signal at BTB transmission could be below 7% hard-decision forward error correcting threshold (HD-FEC) with $3.8 \times 10^{-3}$, when the received optical power into PD is greater than $-23.7$ dBm and $-22.1$ dBm, respectively. Furthermore, after 5 km SSMF transmission, the generated 5-Gbaud and 10-Gbaud QPSK modulated vector mm-wave signal can still satisfy the threshold of $3.8 \times 10^{-3}$, when the received optical power into PD is greater than $-23.5$ dBm and $-20.67$ dBm, respectively. Besides, with the baud rate increasing, the BER performance of the vector mm-wave signal changes obviously since the signal is more sensitive to the nonlinear effect as the symbol rate increased. In the high-speed millimeter-wave over fiber system, in order to increase the transmission rate of the system, the most direct way is to increase the baud rate of the signal, thereby increasing the bandwidth of the signal. However, on the one hand, the improvement of device bandwidth has encountered a bottleneck, which makes it difficult for device bandwidth to keep up with the growth of signal bandwidth. In fact, the bandwidth limitation of the device can be equivalent to a low-pass filter, and the channel damage it brings is Inter-Symbol Interference (ISI). The inset in Figure 4 shows the constellations for 10-Gbaud 40 GHz QPSK-modulated vector mm-wave signal with 5
km SMF transmission when the received optical power into PD is −17.1 dBm. To achieve the same BER performance, the generated mm-wave signal transmitted through optical fiber needs higher received optical power due to chromatic dispersion. Fiber chromatic dispersion will cause a cosine power fading, which greatly limits the transmission distance of high-speed optical millimeter wave systems.

Figure 3. (a) Output optical spectra after MZM; (b) output optical spectra after CW laser; (c) output spectrum after eliminating the 0-order optical carrier; (d) electrical spectra of received QPSK vector signals after square-law photo-detector.
Figure 4. The measured BER results versus launched optical power into PD.

Figure 5 shows the error vector magnitude (EVM) performance of 40G QPSK mm-wave vector signals through 5Gbaud, 10Gbaud transmission under different link fiber length. It can be seen from Figure 5 that the EVM gradually take a turn for the worse with the increase of the link fiber length. When the signal baud rate increases, the EVM changes accordingly. Note that the EVM performance is worse when the SMF transmission distance increases due to the influence of the dispersion walk-off effect.

Figure 5. The measured EVM results versus the link fiber length.
Figure 6 shows the EVM performance of 40G QPSK mm-wave vector signals through 5Gbaud, 10Gbaud transmission under different received optical power. It can be seen from Figure 6 that the EVM gradually decreases with the increase of the received optical power. When the signal baud rate increases, the EVM changes accordingly.

![Figure 6. The measured EVM results versus launched optical power into PD.](image)

4. Conclusions

In this paper, a simple and filter-less symmetrical frequency quadrupling vector mm-wave signal generation scheme is proposed, which just adopts a single MZM integrated with precoding assisted technique. The MZM is employed for the generation of asymmetrical −2nd and +2nd order optical harmonics, which is used to beat frequency for generating the frequency quadrupling mm-wave vector signal. To avoid the phase damage caused by vector mm-wave signal frequency multiplication in PD, we carry out inverse operation according to the damage model to obtain the compensation function, and precoding vector data in advance at transmitter end. Based on our proposed scheme, we employ a 10 GHz RF source which can achieve a 40 G vector mm-wave signal generation. The principle and feasibility of the proposed scheme is deduced by detailed mathematical formula. The electrical 40 GHz vector mm-wave signal with 5-Gbaud and 10-Gbaud QPSK modulation can be obtained enabled by symmetrical ±2nd order optical subcarriers to beat frequency square law detection. Hence, through the analysis of BER, EVM curve, and constellation distribution, the proposed scheme is innovative.

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