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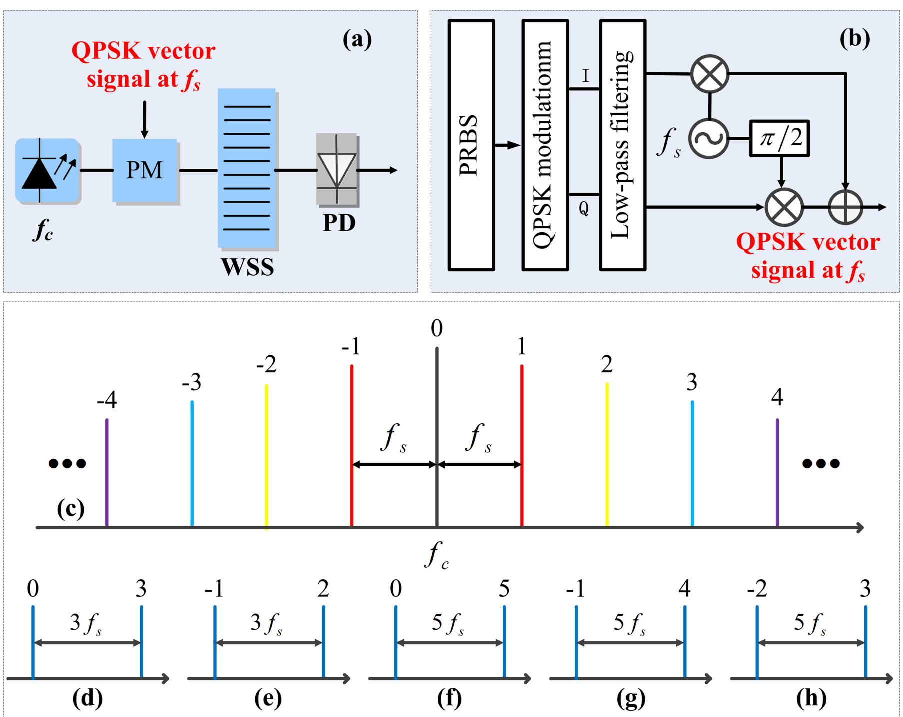

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QPSK Vector Millimeter-Wave Signal Generation Based on Odd Times of Frequency Without Precoding

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Abstract: In this paper, we propose a novel quadrature phase-shift keying (QPSK) vector millimeter-wave (mm-wave) signal generation based on odd times of frequency without precoding. The radio frequency (RF) vector signal generation module is universal for the generation of millimeter-wave signal with any odd frequency multiplication. Instead of phase precoding, the phases of electrical mm-wave signal are multiplied by the frequency multiplication number at the receiver after carrier phase estimation. The frequency tripling, quintupling, and septupling schemes are achieved by simulation, and bit-error-ratio curves demonstrate that the proposed QPSK vector mm-wave signal generation scheme works well.

Index Terms: Millimeter wave, quadrature phase-shift keying, odd frequency multiplication, without precoding.

1. Introduction

With the increase in bandwidth and bit rate requirements, low frequency radio frequency (RF) signal cannot meet the requirements. Millimeter-wave (Mm-wave) can provide huge bandwidth. However, due to the high frequency of mm-wave signal, the transmission loss of mm-wave signal is very large in free space, which seriously affects the transmission distance of mm-wave signal. Aiming at the problem of mm-wave transmission distance limited, the radio over fiber (RoF) technology based on the mm-wave RF remote arises at the historic moment. The generation of vector mm-wave signal is an important problem in RoF system. Recently, many mm-wave generation schemes based on photonics technologies have been proposed [1]–[23]. Among them, the remote heterodyne [15]–[20] and external phase or intensity modulation [21]–[23] are the main mm-wave signal generation schemes. Remote heterodyne is simple and low-cost, but the quality of generated mm-wave signal is poor due to unlocked frequency. External phase or intensity modulation, which makes use of the beating of the two sidebands generated by external phase or intensity modulator driven by a RF signal, can offer very stable mm-wave carrier, the frequency of which only depend on the RF signal and the selected sidebands. Mm-wave signal generation based on external modulation technology can be combined with frequency multiplication technology to realize mm-wave signal generation by low RF signal. Frequency doubling [24], tripling [25], quadrupling [26]–[29], sextupling [30], [31],

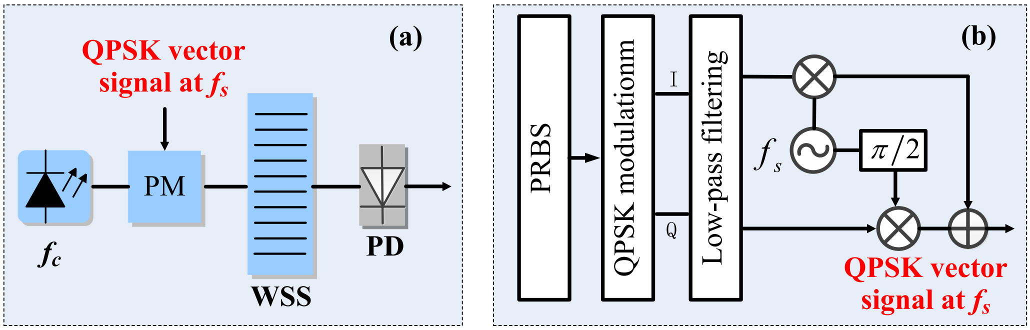

Fig. 1. (a) Principle of photonic QPSK vector signal generation at mm-wave bands based on odd times of frequency scheme. (b) Vector-modulated RF QPSK signal generation. PM: Phase Modulator, WSS: wavelength selective switch, PD: photodiode, PRBS: pseudo random binary sequence.

octupling [32], [33], and even nonupling [34], [35] have been achieved based on external phase or intensity modulator. However, in order to attain electrical QPSK/QAM vector mm-wave signal, the RF vector signal need to be phase and/or amplitude pre-coded before driving the phase or intensity modulator. The phase precoding can be divided into imbalanced phase precoding technology and balanced phase precoding technology. The imbalanced phase precoding technology leads to all constellations imbalanced distribution, for example, constellation points of QPSK signal are located in the first quadrant after precoding for frequency quadrupling scheme, which will degrade the overall system performance. Ref. [36] proposed and experimentally demonstrated a balanced phase precoding scheme for vector signal generation based on frequency doubling technology. However, the balanced precoding scheme is only suitable for low-order QAM modulation formats. Ref. [37] proposed and experimentally demonstrated that the performance of balanced phase precoding is worse than that of the unbalanced phase precoding when employed in high-order QAM modulation formats due to the asymmetrical output and limited bandwidth of devices, and the rotation and overlapping of the randomly, asymmetrically scattered signal constellation points.

In this paper, we propose a novel QPSK vector mm-wave signal generation with odd times of RF signal based on a phase modulator (PM) and a wavelength selective switch (WSS). Phase precoding is unnecessary for the generation of RF vector signal at the transmitter. Instead, we only multiply the phases by the frequency multiplication number at the receiver after carrier phase estimation (CPE). So the RF vector signal generation module is universal for the generation of QPSK vector mm-wave signal with any odd frequency multiplication. The frequency tripling, quintupling and septupling schemes are achieved by simulation. For tripling, quintupling, and septupling schemes, the bit-error-ratio (BER) of 2 Gbaud QPSK vector signal can reach 10^{-6} when the input optical power are −12 dBm,−13 dBm and −12.3 dBm, respectively.

2. Principle of QPSK Vector mm-Wave Signal Generation Without Precoding

Fig. 1(a) illustrates the schematic diagram of photonic QPSK vector signal generation at mm-wave bands, using an odd frequency multiplication scheme enabled by a single PM combined with a WSS. Fig. 1(b) shows the MATLAB-based generation procedure of driving precoded RF signal at frequency f_s carrying QPSK data. Here, the generated QPSK signal is directly up-converted into RF signal by simultaneous cosine and sine functions after low-pass filtering. No amplitude or phase precoding is required in our scheme.

As shown in Fig. 1(a), the continuous wave (CW) lightwave at frequency f_c from a laser is modulated by an RF carrier at frequency f_s, which carries a vector-modulated QPSK data and drives the PM. Assume that the CW lightwave at frequency f_c can be expressed as

$$E_{CW}(t) = E_0 \exp(j2\pi f_c t) \tag{1}$$

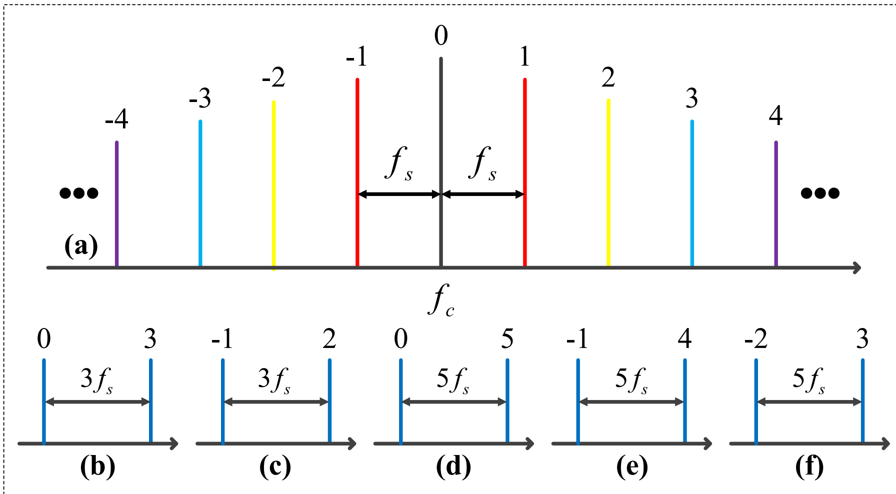

Fig. 2. (a) The output optical spectra of PM. (b)–(c): The output optical spectra of WSS based on frequency tripling. (d)–(f): The output optical spectra of WSS based on frequency quintupling. PM: Phase Modulator; PD: photodiode; PRBS: pseudo random binary sequence.

where E_0 is constant and denotes the amplitude of the CW output at frequency f_c. Assume that the vector-modulated RF signal at frequency f_s can be formulated as

$$E_{RF}(t) = V_{RF} V_0 \cos[2\pi f_s t + \varphi(t)] \tag{2}$$

where V_0 and φ are the amplitude and phase of the vector-modulated RF signal at frequency f_s, respectively. V_{RF} is the deriving RF voltage on the phase modulator. V_0 is a constant for QPSK modulation. Therefore, the output optical signal from the PM can be formulated as

$$\begin{aligned} E_{PM}(t) &= E_0 \exp(j2\pi f_c t + j\pi V_{RF} V_0 \cos[2\pi f_s t + \varphi(t)]/V_\pi) \\ &= E_0 \sum_{n=-\infty}^{\infty} j^n J_n(\kappa) exp[j2\pi(f_c + nf_s)t + jn\varphi(t)] \end{aligned} \tag{3}$$

where J_n is the Bessel function of the first kind and order n, V_π is the half-wave voltage of the PM, and $\kappa = \pi V_{RF} V_0/V_\pi$. Therefore, the output optical signal of PM can be represented as the optical central carrier and a series of optical sidebands, as shown in Fig. 2(a). The frequency multiplication is accomplish by subsequent WSS or interleaver (IL), which randomly selects two different optical subcarriers with the order n_1($n_1 = \ldots, -2, -1, 0, 1, 2\ldots$) and n_2 ($n_2 = \ldots, -2, -1, 0, 1, 2\ldots$) and n_1 is greater than n_2, as shown in Fig. 2(b)–2(f). Considering the symmetry of the signal, we can set (n1, n2) to (3, 0) or (2, – 1) for frequency tripling scheme. Similarly, we can set (n1, n2) to (5, 0), (4, –1) or (3, –2) and (7, 0), (6, – 1), (5, –2) or (4, –3) for frequency quintupling and septupling scheme. The output of WSS or IL can be expressed as

$$E_{IL}(t) = E_0\{j^{n_1} J_{n_1}(\kappa) exp[j2\pi(f_c + n_1 f_s)t + jn_1\varphi(t)] + j^{n_2} J_{n_2}(\kappa) exp[j2\pi(f_c + n_2 f_s)t + jn_2\varphi(t)]\} \tag{4}$$

Then the photonic vector signal after WSS or IL is converted into electrical mm-wave signal by a PD. The PD conversion follows the square-law rule and the output current of the PD after isolating DC can be expressed as

$$i_{PD}(t) = \frac{1}{2} R J_{n_1}(\kappa) J_{n_2}(\kappa) \cos[2\pi \cdot N f_s t + N\varphi(t)] \tag{5}$$

where R denotes the PD sensitivity and $N = n_1 - n_2$. We can see from (5) that the frequency and phase of signal after PD is N times that of the driving RF signal. If N is an even number, we get the even frequency multiplication of RF signal. Otherwise, we get the odd frequency multiplication

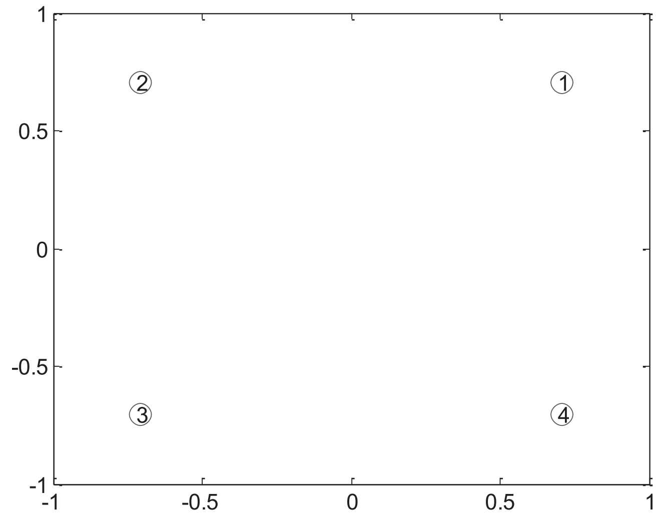

Fig. 3. QPSK constellation diagram at the transmitter.

of RF signal. Fig. 3 shows the QPSK constellation diagram at the transmitter. ①, ②, ③ and ④ in Fig. 3 represent $\pi/4$, $3\pi/4$, $5\pi/4$ and $7\pi/4$, respectively.

When N is an even number, let $N = 2k\ (k = 1, 2, 3 \cdots)$, the phases after PD are $\{k\pi/2, 3k\pi/2, k\pi/2, 3k\pi/2\}$ since the period of phase is 2π. Some or all of the phase information is lost, so phase precoding is necessary for even frequency multiplication.

When N is an odd number, let $N = 2k + 1\ (k = 0, 1, 2 \cdots)$, the phases after PD are $\{k\pi/2 + \pi/4, 3k\pi/2 + 3\pi/4, 5k\pi/2 + 5\pi/4, 7k\pi/2 + 7k\pi/4\}$. The phase difference of adjacent items are all $\pi/2$ or$-\pi/2$. The signal at the receiver is still the constellation distribution of the QPSK signal. No phase information is lost, so phase precoding is unnecessary for odd frequency multiplication. The phases are rotated after frequency multiplication, but the constellation diagrams after frequency multiplication are also QPSK constellation.

Assuming $N = 2k + 1\ (k = 0, 1, 2 \cdots)$, the phases at the receiver are $\{N\pi/4, 3N\pi/4, 5N\pi/4, 7N\pi/4\}$. If we multiply the phases by N at the receiver, the phases are

$$\begin{aligned}&\{N^2\pi/4, 3N^2\pi/4, 5N^2\pi/4, 7N^2\pi/4\}\\&= \{k(k+1)\pi + \pi/4, 3k(k+1)\pi + 3\pi/4, 5k(k+1)\pi + 5\pi/4, 7k(k+1)\pi + 7\pi/4\}\end{aligned} \quad (6)$$

since $k(k+1)$, $3k(k+1)$, $5k(k+1)$ and $7k(k+1)$ are all even numbers and the period of phase is 2π, the phases at the receiver are $\{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$ after multiply by N, these are the same as the transmitter. So we only multiply the phases by N at the receiver and the phase precoding is unnecessary for odd frequency multiplication.

3. Simulation Setup and Results

As shown in Fig. 1, we built the simulation platform and investigate the odd frequency multiplication QPSK vector mm-wave signal generation scheme without phase precoding. The CW output with central frequency 193.1 THz from an external cavity laser (ECL), is modulated by a 2 Gbaud QPSK modulated vector signal at 10 GHz via a single PM with $V_\pi = 4$V. The ECL has a linewidth of about 1 MHz with the average output power of 10 dBm. The output optical spectrum of ECL is shown in Fig. 5(a). The RF signal carrying 2-Gbaud QPSK-modulated transmitter data is generated by MATLAB programming. The baseband QPSK signal is mapped from a pseudo-random binary sequence (PRBS) with the word length of $2^{12}-1$ and up-converted into RF signal after low-pass filtering. In order to ensure that the two main sidebands selected by WSS or IL have equal relatively larger amplitude while the other sidebands are relatively smaller, we need to amplify QPSK vector

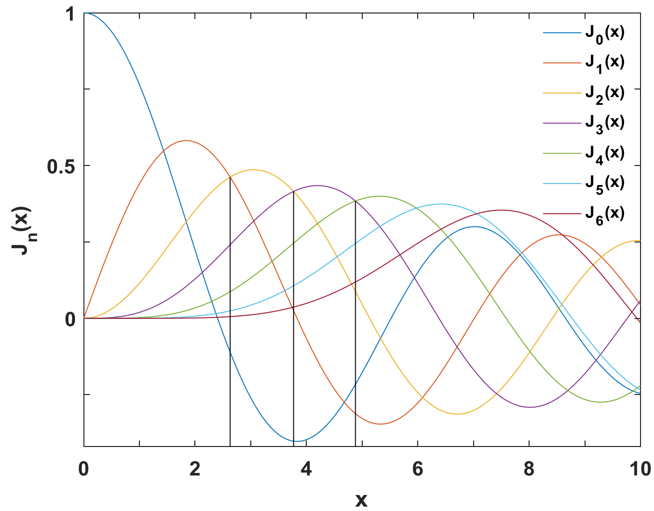

Fig. 4. Bessel function of the first kind.

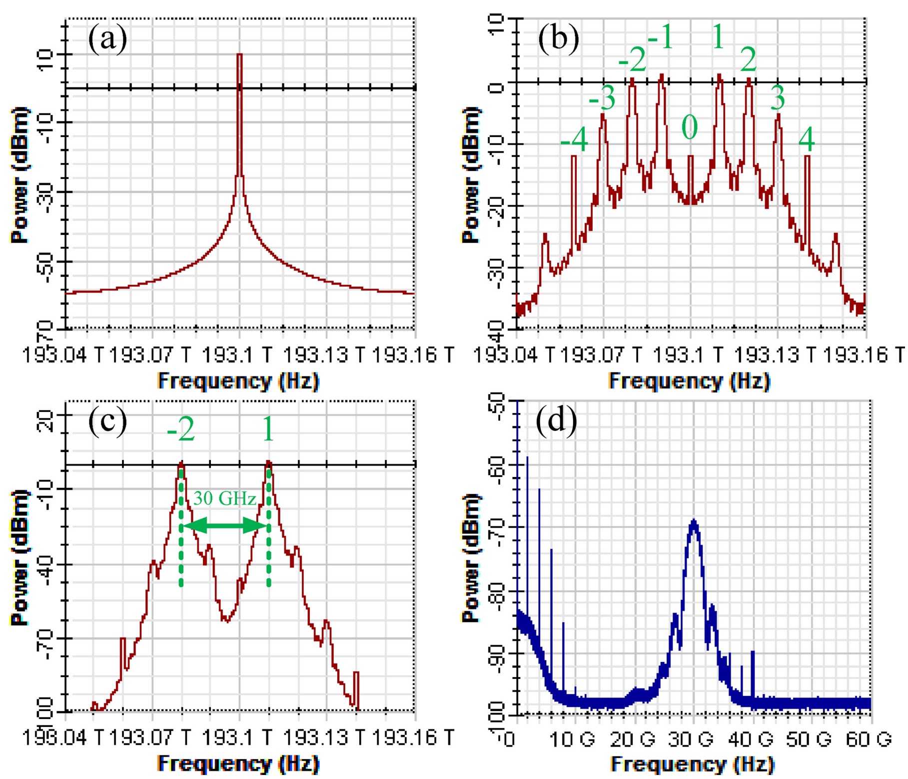

Fig. 5. (a) Optical spectra after ECL (0.01 nm resolution). (b) Optical spectra after PM (0.01 nm resolution). (c) Optical spectra after IL (0.01 nm resolution). (d) RF spectra after PD.

signal to different amplitudes to get different modulation indexes for different frequency multiplication number. The Bessel function of the first kind is shown in Fig. 4.

For frequency tripling scheme, the minus second-order (−2nd) and first-order (1st) sidebands are selected by IL with frequency spacing of 15 GHz and bandwidth of 5 GHz. The modulation index is 2.630 from Fig. 4, so the corresponding amplitudes of QPSK vector signal should amplify to 3.348 V according to $\kappa = \pi V_{RF} V_0 / V_\pi$. The optical spectrum after PM is shown in Fig. 5(b), the

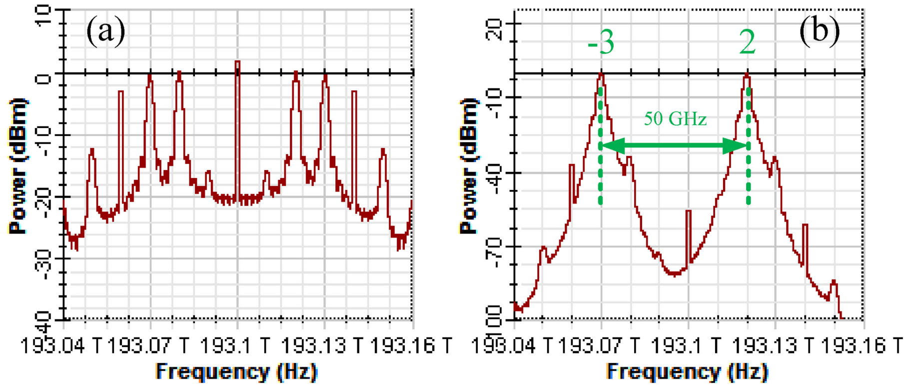

Fig. 6. Optical spectra (0.01 nm resolution) of frequency quintupling scheme (a) After PM. (b) After IL.

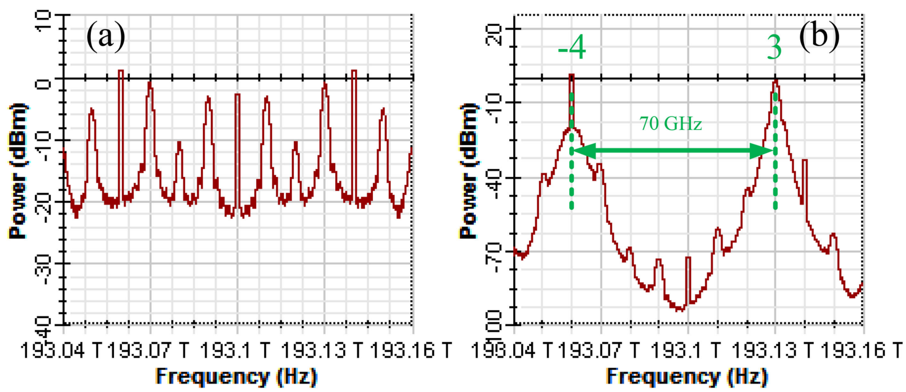

Fig. 7. Optical spectra (0.01 nm resolution) of frequency septupling scheme (a) After PM. (b) After IL.

optical spectrum consists of optical central carrier and a series of optical sidebands, the frequency space is 10 GHz. The amplitude of optical central carrier is relatively small, this is consistent with Fig. 4. The optical spectrum after IL is shown in Fig. 5(c), two selected optical sidebands have a frequency spacing of 30 GHz. The side lobe suppression ratio is larger than 25 dB. For frequency quintupling scheme, the minus third-order (−3rd) and second-order (2nd) sidebands are selected by IL with frequency spacing of 25 GHz and bandwidth of 5 GHz. The modulation index is 3.769 from Fig. 4, so the corresponding amplitudes of QPSK vector signal should amplify to 4.799V according to $\kappa = \pi V_{RF} V_0 / V_\pi$. Fig. 6(a)–(b) show the optical spectra after PM, and after IL, respectively. Two selected optical sidebands have a frequency spacing of 50 GHz in Fig. 6 (b). For frequency septupling scheme, the minus fourth-order (−4th) and third-order (3rd) sidebands are selected by IL with frequency spacing of 35 GHz and bandwidth of 5 GHz. The modulation index is 4.880 from Fig. 4, so the corresponding amplitudes of QPSK vector signal should amplify to 6.214 V according to $\kappa = \pi V_{RF} V_0 / V_\pi$. Fig. 7(a)–(b) show the optical spectra after PM, and after IL, respectively. Two selected optical sidebands have a frequency spacing of 70 GHz in Fig. 7 (b). After being boosted by an Erbium-doped fiber amplifier (EDFA), the generated optical mm-wave signal is sent into single-mode fiber-28 (SMF-28) with attention coefficient of 0.18 dB/km, chromatic dispersion (CD) of 16.75 ps/km/nm at 1550 nm, dispersion slope of 0.075 ps/km/nm^2, and PMD coefficient of 0.5 ps/km$^{1/2}$.

At the receiver, the optical mm-wave is detected by a square-law PD with the sensitivity of 1 A/W, and the signal-ASE noise, ASE-ASE noise, thermal noise at 10^{-20} W/Hz, Gaussian shot noise are included. Fig 5(d) shows the RF spectrum of mm-wave after PD for frequency tripling scheme when there is no fiber transmission and the input optical power into PD is −6 dBm. It can be seen that the 30 GHz QPSK mm-wave signal is dominant, while the harmonic at 40 GHz is

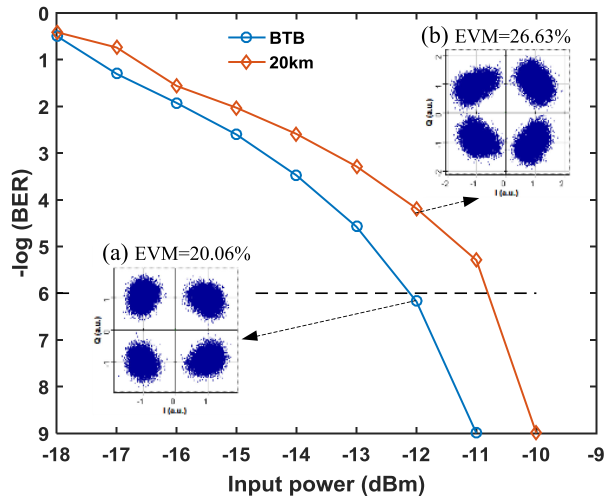

Fig. 8. BER versus the launched optical power into PD for 2-Gbaud 30 GHz QPSK mm-wave vector signal.

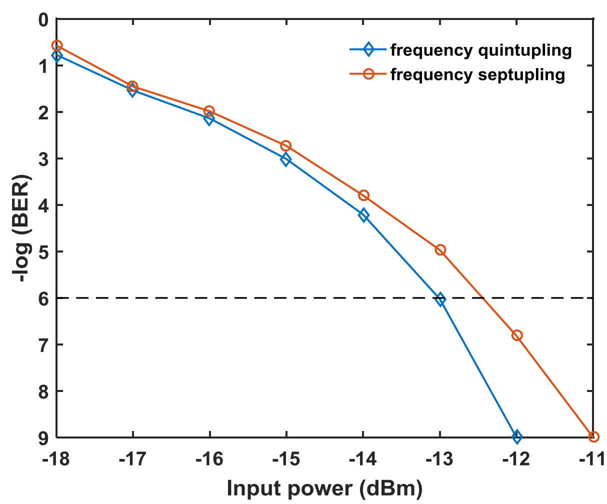

Fig. 9. BER versus the launched optical power into PD without fiber transmission.

generation by the beating of +2nd and −2nd-order sidebands. The generated electrical mm-wave signal passes through a RF amplifier with 30 dB gain and bandpass bessel filter with 30/50/70 GHz central frequency and 1.5 GHz bandwidth in turn, and then coherent demodulation by a 30/50/70 GHz local oscillator signal. Finally, the transmitter data can be recovered from DSP [38], [39], including down conversion, dispersion compensation, constant modulus algorithm (CMA) equalization, frequency offset estimation (FOE), CPE, multiply the phase by N (N is the number of frequency multiplication), and BER calculation. The blind phase search algorithm (BPS) is used for noise estimation and compensation in the receiver side [40]. The number of test phases is 32 in BPS, and CPE symbols per block are 40.

Fig. 8 shows the BER versus the launched optical power into PD for 2-Gbaud 30 GHz QPSK mm-wave vector signal. It can be seen that 20 km SMF-28 transmission causes about 1.3 dB power penalty with the BER of 10^{-6}. The insets in Fig. 8 show the constellation diagrams of 30 GHz mm-wave vector signal after offline DSP at the received optical power of −12 dBm. The constellation diagram of BTB case is clearer than the constellation diagram of 20 km SMF-28 transmission case. This is due to the dispersion effect of the fiber.

Fig. 9 shows the BER versus the launched optical power into PD without fiber transmission. For frequency quintupling scheme, the BER can reach 10^{-6} when the received optical power is -13 dBm. For frequency septupling scheme, the BER can reach 10^{-6} when the received optical power is -12.3 dBm.

4. Conclusion

We propose a novel QPSK vector mm-wave signal generation based on odd times of frequency without precoding in this paper. Since phase precoding is unnecessary, the RF vector signal generation module is universal for the generation of mm-wave signal with any odd frequency multiplication. We only need to multiply the phases by the frequency multiplication number at the receiver after carrier phase estimation. We have generated 30/50/70 GHz QPSK vector mm-wave signal at 2 Gbaud based on a single PM and a WSS with frequency tripling, quintupling, and septupling by simulation.

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