A Filterless Frequency 32-Tupling Photonic Scheme To Generate Sub-Terahertz Wave Signal Enabled By Optical Polarization Modulators

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A filterless frequency 32-tupling photonic scheme to generate Sub-Terahertz wave signal enabled by optical polarization modulators

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Abstract A novel scheme based on polarization modulators to generate Sub-Terahertz wave (Sub-THz) signal with frequency 32-tupling is proposed. The system consists of two subsystems in cascade, and each subsystem consists of 4 paralleled polarization modulators. In this scheme, by properly controlling two subsystems, an optical signal with optical carrier and ± 16 th-order optical sidebands is achieved. Next, by adjusting the optical attenuator and optical phase shifter, the optical carrier can be canceled. Finally, the Sub-THz wave with frequency 32-tupling can be obtained after beaten in the photodetector. The results show the ± 16 th-order optical sideband suppression ratio (OSSR) is derived as 55.7 dB and the radio frequency sideband suppression ratio (RFSSR) of the 32-tupling Sub-THz wave is derived as 43.66 dB, which are consistent with the theoretical analysis very well. Meanwhile, the effects of phase offset, modulation index, and attenuator deviation on suppression ratio are analyzed.

Keywords Polarization modulator · Sub-Terahertz wave · OSSR · RFSSR

Mathematics Subject Classification (2020) MSC code1 · MSC code2 · more

1 Introduction

To meet the increasing demand of mobile communication and multimedia services, higher capacity wireless access network is necessary. Sub-Terahertz carrier frequency is a potential solution for growing data demands. The first IEEE standard over Sub-Terahertz (specifically, 253–322 GHz), IEEE std. 802.15.3d -2017, primarily illustrates the feasibility of Sub-THz communications[1, 2]. Compared with the conventional technology in electrical domain, the optical generation scheme for millimeter wave (mm-wave) is desirable, since it can produce signal with higher frequency, wider bandwidth, and anti-electromagnetic interference[3]. Therefore, the optical generation of high frequency mm-wave or Sub-Terahertz wave has aroused much interest in recent years.

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Many photonic schemes based on external modulation to generate mm-wave draw great attention, due to its stable operation, low complexity and cost effective [4]. In order to eliminate the harmonic sidebands which will induce fiber dispersion, some wavelength selection devices are used in these schemes, such as a wavelength-fixed optical notch filter [5], optical interleavers [6, 7], or fiber Bragg gratings [8]. Nevertheless, the frequency tunability is limited for the fixed bandwidth of these devices. To solve the challenging problem caused by restricted frequency tunability, the filterless methods to produce mm-wave are preferred. There have been many demonstrations on the filterless generation of mm-wave based on Mach-Zehnder Modulator (MZM) in parallel [9], or in cascade [10]. Moreover, Wang et al. have proposed several schemes to generate vector mm-wave based on MZM and digital modulation format combinations. Compared with conventional mm-wave signals, vector mm-wave can simultaneously load signals containing amplitude information and phase information, thus improving the spectrum efficiency of the system [11–13].

However, the generation of high-frequency mm-wave based on MZM has a problem of offset drift, which requires a complex offset control circuit. Because optical generation mm-wave by polarization modulator (PolM) does not require DC bias, the system shows better stability [14]. Zhu et al. have proposed a common approach to generate frequency octupling, sextupling, or quadrupling mm-wave by two PolMs [15]. Abouelez et al. have proposed a scheme to generate a frequency 12-tupling mm-wave by cascaded dual parallel polarization modulator (DP-PolM) [16]. Kumar et al. have proposed a method to generate frequency 24-tupling mm-wave signal by optical filters and SOA, but the usage of optical filter limits the frequency tuning range [17]. Chaudhuri et al. have proposed a plan to generate mm-wave with frequency 24-tupling by two DP-PolMs [18]. The generated mm-wave has an OSSR and RFSSR of about 34.4 dB and 25.8 dB.

In this paper, a filterless photonic scheme to generate Sub-Terahertz wave signal with frequency 32-tupling is proposed and demonstrated. By properly controlling the two subsystems, optical signals with mainly 16th-order sidebands and carrier component are achieved. Then, by tuning the optical attenuator and optical phase shifter, the optical carrier can be canceled. Finally, the frequency 32-tupling Sub-Terahertz wave is generated after the photodetector beating.

2 System design and principle

The schematic diagram of generating frequency 32-tupling Sub-THz wave based on polarization modulators is shown in Fig. 1. The system consists of two subsystems (i.e., Sub A and Sub B) in cascade, and each subsystem consists of 4 paralleled polarization modulators and a polarizer (Pol). A PolM is made up of a polarization beam splitter, two phase modulators, and a polarization beam combiner [16]. The PolM is a special phase modulator that supports both TE and TM modes with opposite phase modulation indexes. The joint operation of a PolM, a PC (polarization controller), and a polarizer is equivalent to an MZM, with the bias point being controlled by adjusting the phase difference between the two orthogonal modes via tuning the PC.

Fig. 1: Schematic diagram of generating frequency 32-tupling Sub-THz wave based on polarization modulators. CW Laser: continuous wave laser; PC: polarization controller; RF LO: radio frequency local oscillator; OATT: optical attenuator; OA: optical amplifier; PD: photodiode.

The optical carrier emitted from the continuous wave laser (CW Laser) is assumed as

$$E_{in} = E_c \exp(j\omega_c t) \quad (1)$$

where E_c and ω_c are amplitude and angular frequency of the optical carrier, respectively. The optical carrier is then converted into a linearly polarized light by PC with an angle of 45° between the polarization direction and the transmission axis. The optical wave is divided into two beams by a 1×2 power splitter. One is sent into the cascaded system of Sub A and Sub B, and the other passes through the optical phase shifter and the optical attenuator.

Fig. 2: schematic diagram of Sub A

As shown in Fig. 2, the input optical signal is divided into 4 beams by a 1×4 power splitter in Sub A. Afterwards, the 4 branches are severally injected into four PolMs in parallel, named PolM-ai ($i=1,2,3,4$), respectively. The RF driving signal applied to PolM-ai is defined as

$$V(t) = V_{\text{RF}} \sin(\omega_{\text{RF}} t + (i-1) \Delta\varphi) \quad (2)$$

where V_{RF} and ω_{RF} are amplitude and angular frequency of the RF driving signal, $\Delta\varphi$ is the phase difference of the driving signal between two adjacent PolM-ai. Thus, the output of each PolM-ai can be expressed as

$$\begin{aligned} \begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix} &= \frac{1}{8} E_{\text{in}} \begin{bmatrix} \cos 45^\circ \exp(jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \\ \sin 45^\circ \exp(-jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \end{bmatrix} \\ &= \frac{\sqrt{2}}{16} E_c \exp(j\omega_c t) \begin{bmatrix} \exp(jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \\ \exp(-jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \end{bmatrix} \end{aligned} \quad (3)$$

where m is the modulation index of PolM and it is equal to $\pi V_{\text{RF}}/V_\pi$. V_π is the half-wave voltage. Consequently, the output signal after the 4×1 power combiner can be given by

$$\begin{aligned} E_i &= \sum_{i=1}^4 \begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix} \\ &= \frac{\sqrt{2}}{16} E_c \exp(j\omega_c t) \sum_{i=1}^4 \begin{bmatrix} \exp(jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \\ \exp(-jm \cos(\omega_{\text{RF}} t + (i-1) \Delta\varphi)) \end{bmatrix} \end{aligned} \quad (4)$$

As Pol has an orientation of 45° to the transmission axis, its output is expressed as

$$\begin{aligned} E_A &= \cos 45^\circ \sum_{i=1}^4 E_{ix} + \sin 45^\circ \sum_{i=1}^4 E_{iy} \\ &= \frac{1}{16} E_c \exp(j\omega_c t) \sum_{i=1}^4 \exp\{jm \cos[\omega_{\text{RF}} t + (i-1) \Delta\varphi]\} \\ &\quad + \frac{1}{16} E_c \exp(j\omega_c t) \sum_{i=1}^4 \exp\{-jm \cos[\omega_{\text{RF}} t + (i-1) \Delta\varphi]\} \\ &= \frac{1}{8} E_c \exp(j\omega_c t) \sum_{i=1}^4 \cos\{m \cos[\omega_{\text{RF}} t + (i-1) \Delta\varphi]\} \end{aligned} \quad (5)$$

According to Eq. (5), the output optical signal of the polarizer has been converted from a phase modulation signal to an intensity modulation signal, where the amplitude modulation factor is $\cos\{m \cos[\omega_{\text{RF}} t + (i-1) \Delta\varphi]\}$.

Using the Jacobi-Anger formula, Eq. (5) can be expanded as

$$\begin{aligned} E_A &= \frac{1}{8} E_c \exp(j\omega_c t) \left\{ 4 J_0(m) + \sum_{i=1}^4 \left[2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(m) \cos(2n\omega_{\text{RF}} t + 2n(i-1)\pi/4) \right] \right\} \\ &= \frac{1}{2} E_c \exp(j\omega_c t) [J_0(m) + 2J_8(m) \cos(8\omega_{\text{RF}} t) + 2J_{16}(m) \cos(16\omega_{\text{RF}} t) \dots] \end{aligned} \quad (6)$$

where $J_n(m)$ denotes the Bessel function of the first kind of n th-order.

Fig. 3: Graph of the first-class Bessel function of 0th-order, 8th-order, and 16th-order

Eq. (6) shows that 8nth-order optical sidebands have been retained in the output optical signal of sub A. Graph of the first-class Bessel function of 0th-order, 8th-order, and 16th-order is shown in Fig. 3. As demonstrated, when the modulation index m is equal to 8.6535, the values of $J_0(m)$, $J_8(m)$, and $J_{16}(m)$ are 0, 0.2817, and 2.3×10^{-4} , separately. As a result, when m equals 8.6535, the optical carrier is suppressed, and the optical sideband signals above 16th-order are small and can be ignored.

The output signal from Sub A can be written as

$$E_A = E_c \exp(j\omega_c t) [J_8(m) \cos(8\omega_{RF}t) + J_{16}(m) \cos(16\omega_{RF}t)] \quad (7)$$

Sub B's structure is the same as Sub A's. Substituting for E_A and expanding, the output of Sub B can be expressed as

$$\begin{aligned} E_B &= 2E_A \odot [J_8(m) \cos(8\omega_{RF}t) + J_{16}(m) \cos(16\omega_{RF}t)] \\ &= 2E_c \exp(j\omega_c t) [J_8(m) \cos(8\omega_{RF}t) + J_{16}(m) \cos(16\omega_{RF}t)] \\ &\quad \odot [J_8(m) \cos(8\omega_{RF}t) + J_{16}(m) \cos(16\omega_{RF}t)] \\ &= E_c \exp(j\omega_c t) \left\{ J_8^2(m) + J_{16}^2(m) + 2 J_8(m) J_{16}(m) \cos(8\omega_{RF}t) \right. \\ &\quad \left. + J_8^2(m) \cos(16\omega_{RF}t) + 2 J_8(m) J_{16}(m) \cos(24\omega_{RF}t) \right. \\ &\quad \left. + J_{16}^2(m) \cos(32\omega_{RF}t) \right\} \end{aligned} \quad (8)$$

Eq. (8) shows that a new harmonic optical signal is generated at the center frequency, which is also the maximum harmonic optical signal.

The output optical signal of sub B combines with the optic signal from the attenuator by a 2×1 power combiner, and the carrier component can be canceled[19]. In order to cancel the carrier component, the value of the optical phase shifter is set to be 180° , and the attenuation of the optical attenuator is adjusted to be

$$\alpha = 20 \log_{10} \left\{ 2 \left[J_8^2(8.6535) + J_{16}^2(8.6535) \right] \right\}^{-1} = 15.985 \text{ dB} \quad (9)$$

where α is the attenuation value. The output signal of the power combiner, as illustrated in Fig. 1(C), can be simplified as

$$E_D(t) = E_c \exp(j\omega_c t) \left\{ 2 J_8(m) J_{16}(m) \cos(8\omega_{RF} t) + J_8^2(m) \cos(16\omega_{RF} t) \right. \\ \left. + 2 J_8(m) J_{16}(m) \cos(24\omega_{RF} t) + J_{16}^2(m) \cos(32\omega_{RF} t) \right\} \quad (10)$$

After the square-law detection using a photodetector, ignoring higher-order optical sidebands greater than $32\omega_{RF}$, the photocurrent output from the photodetector (PD) is described by

$$I_{PD}(t) \propto \Re E_D \times E_D^* \\ = \Re E_c^2 \left\{ \left[4 J_8^2(m) J_{16}^2(m) + J_8^4(m)/2 \right] \right. \\ + 4 J_8^3(m) J_{16}(m) \cos(8\omega_{RF} t) + 6 J_8^2(m) J_{16}^2(m) \cos(16\omega_{RF} t) \\ + 2 J_8^3(m) J_{16}(m) \cos(24\omega_{RF} t) \\ + \left[4 J_8^2(m) J_{16}^2(m) + J_8^4(m)/2 \right] \cos(32\omega_{RF} t) \\ \left. + 2 J_8^3(m) J_{16}(m) \cos(40\omega_{RF} t) + 2 J_8^2(m) J_{16}^2(m) \cos(48\omega_{RF} t) \right\} \quad (11)$$

where $\Re$ is the responsivity of the photodetector. It can be seen from Eq. (11) that the system generates the 32-tupling frequency millimeter wave.

From Eq. (10), we can see that the 8th-order optical sideband signal has the largest amplitude in harmonic component. According to the definition of optical sideband suppression ratio (OSSR), it can be given by

$$\text{OSSR} \approx 10 \log_{10} \left[\frac{J_8^2(8.6535)}{2 J_{16}(8.6535) J_8(8.6535)} \right]^2 = 55.7 \text{ dB} \quad (12)$$

Besides, radio frequency sideband suppression ratio (RFSSR) is described as

$$\text{RFSSR} \approx 10 \log_{10} \left[\frac{4 J_8^2(8.6535) J_{16}^2(8.6535) + J_8^4(8.6535)/2}{4 J_8^3(8.6535) J_{16}(8.6535)} \right]^2 = 43.66 \text{ dB} \quad (13)$$

3 Simulation results

The simulation system of generating frequency 32-tupling Sub-THz wave by PolMs in cascade is designed by OptiSystem according to Fig. 1. The main parameters in simulation are set in Table 1.

Fig. 4(a) is the optical spectrum at point A in Fig. 1, which is the output of sub A. It can be seen that ± 8 -order and ± 16 -order optical sidebands are the main optical sideband. These optical sidebands above 16th-order can be ignored. From Fig. 4(b) is the optical spectrum at point B, we can see that the main optical component are the carrier and ± 16 th-order optical sidebands in the Sub B. The ± 8 th-order and ± 24 th-order optical sidebands are small and can be ignored. Fig. 4(c) is the optical spectrum at point C, which is the composite optical signal from combiner. As shown in Fig. 4(c), the carrier component and harmonic optical sidebands are well suppressed. The 16th-order sidebands' power is 53.38 dB higher

Table 1: Main parameters involved in simulation

Parameters Involved	Values
Central frequency of CW Laser	193.1 THz
Linewidth of CW Laser	10 MHz
Power of CW Laser	10 dBm
Local Oscillator frequency	10 GHz
Gain of Amplifier	20 dB
Noise figure of Amplifier	4 dB
Responsivity of Photodiode	0.8 A/W
Dark current of Photodiode	10 nA

Fig. 4: output optical spectrum at (a) point A; (b) point B;(C) point C

than that of the 8th-order's. It is consistent with the theoretical calculation of 55.7dB.

Fig. 5 is the electrical signal spectrum obtained by photodetector beating. It shows that the Sub-THz wave signal desired has been generated at 320 GHz frequency, which is 32 times of the input 10 GHz RF driving signal. It is generated by beating ± 16 th-order optical sidebands in PD. There is also a visible harmonic mm-wave at 80 GHz frequency. However, the 320 GHz frequency signal's power is 42 dB higher than the harmonic mm-wave. It is in good accordance with the theoretical calculation of 43.66 dB above.

From the previous theoretical analysis, it is evident that the initial phase value of the RF driving signal, the modulation index of PolMs, and the attenuation of attenuator impact the purity of frequency 32-tupling Sub-THz wave signal. Thus, it is necessary to study the effect on the Sub-THz wave's purity, when these parameters deviate from the theoretical value above.

3.1 effect on the OSSR and RFSSR by the offset of RF driving signal phase

Fig. 6 shows the spectrum of the synthesized optical signal at Point C and the output spectrum at PD when RF driving phase deviates by 5° . As the phase deviates from the theoretical value, the odd order sideband cannot be well suppressed. The residual optical sideband is the main factor that leads to the decrease of signal performance. It can be seen from Fig. 6(a) that the power of the 16th-order optical

Fig. 5: Spectrum of electrical signal from photodetector

sideband is 18.3 dB higher than the maximum residual band. As the power of the unexpected optical sideband becomes larger, the power of the harmonic sidebands in the electrical signal increases greatly, as shown in Fig. 6(b).

Fig. 6: Optical Spectrum and electrical spectrum when the phase offset is 5°

To analyze the influence of the initial phase of the RF driving signal, the PolM-a1 is selected as $\pm 5^\circ$ deviations from theoretical value of 0° . As shown in Fig. 7, the OSSR and RFSSR of the optical signal and Sub-THz wave signal vary with the phase deviations. It indicates that when the phase deviation reaches $\pm 5^\circ$, the values of OSSR and RFSSR greatly drop from 53.38 dB to 18.36 dB, and RFSSR drops from 42 dB to around 12 dB. This is because when the initial phase deviates from its theoretical value, the different optical sidebands cannot be completely canceled out, resulting in a substantial increase in harmonic sidebands power and a decrease in rejection ratio. However, as long as the phase deviations are within

the range of about $\pm 3^\circ$, the suppression ratio will be greater than 15 dB, which suffices most transmission requirements [20].

Fig. 7: effect on the OSSR and RFSSR by the offset of RF driving signal phase

3.2 effect on the OSSR and RFSSR by the offset of modulation index

When the modulation index of PolM deviates from the theoretical value, the OSSR and RFSSR decrease sharply. Fig. 8 is the spectral figure measured at point A and Point C when the modulation index deviates by 0.0314. As the modulation index deviates from the theoretical value, the suppression of sub A on the carrier component decreases. There is a component of -32 dBm located at the center carrier, as shown in Fig. 8(a). Then the output optical signal enters into Sub B. Due to the nonlinear effect, the power of the 8th-order optical sideband component in Eq. (6) increases. The optical signal at Point C is shown in Fig. 8(b).

Fig. 8: Optical Spectrum when the modulation index deviation is 0.0314.

When the modulation index's value deviates from the theoretical value, OSSR and RFSSR of the optical Sub-Terahertz wave decrease sharply. From Fig. 9, when the modulation index deviates from theoretical value by 1.4%, OSSR drops from 53 dB to 12 dB, and RFSSR drops from 42 dB to 6 dB. When the modulation index deviates from theoretical value, the carrier component of the output signal from Sub A will be poorly restrained, which results in increased harmonic sidebands power and decreased suppression ratio.

Fig. 9: Effect on the OSSR and RFSSR by the offset of modulation index

3.3 effect on the OSSR and RFSSR by attenuation deviation

According to Eq. (10), when the attenuator's attenuation deviates from 15.985 dB, the optical carrier component in Fig. 4(b) will not be completely canceled, resulting in the Sub-THz wave quality deteriorating. Fig. 10 shows the effect on OSSR and RFSSR by attenuation deviation, where OSSR is the suppression ratio between ± 16 th-order optical sidebands and optical carrier component. As shown in Fig. 10, OSSR decreases gradually with deviation value. When the deviation value is above 0.28%, the RFSSR of the Sub-THz wave decreases with the increase of the deviation value. This is because when the deviation value increases, the optical carrier component power of the system will also increase, causing the clutter power at the 160GHz frequency after beaten in PD to be greater, which becomes the main factor affecting the Sub-THz wave RFSSR. When the deviation value is within 0.28%, the suppression ratio of ± 16 th-order optical sidebands to the optical carrier component is above 40 dB. The optical carrier component is not the main factor affecting the quality of submillimeter wave. Therefore, when the deviation value of the optical attenuator is less than 0.28%, the optical carrier component will be well suppressed; when the deviation value is less than 5%, the RFSSR will be above 15dB, meeting the requirements of the general transmission system.

Fig. 10: Effect on OSSR and RFSSR by attenuation deviation

4 Conclusion

A novel scheme to generate 32-tupling Sub-THz wave signals by PolM in cascade is proposed. The system consists of Sub A and Sub B, and each subsystem consists of 4 paralleled PolMs. The Sub A is used to pick out $\pm 8^{\text{th}}$ -order optical sidebands. The Sub B is used to pick out 16^{th} -order optical sidebands. An optical phase shifter and an adjustable attenuator are used to cancel the optical carrier component. Through the $\pm 8^{\text{th}}$ -order optical sideband beaten in PD, the frequency 32-tupling Sub-THz wave is obtained. According to the scheme proposed, a simulation system is built by OptiSystem, and 32-tupling Sub-THz wave is obtained. The OSSR of the optical signal and RFSSR of the generated 32-tupling Sub-THz are 53dB and 42dB which are consistent with the theoretical value and verify our proposed scheme's feasibility. How the RF drive signal phase and the modulation index of PolM in the system affect the purity of the 32-tupling Sub-THz wave are also analyzed. We get the conclusion that when the phase deviation is within $\pm 3^\circ$, the modulation index deviation is within 0.04, and the attenuator's attenuation deviation is within 5%, the transmission demand can be satisfied.

The proposed scheme does not require an optical filter or DC bias circuit, has a flexible adjustment range, simple structure, and high purity of the generated Sub-Terahertz wave signal. It has greatly potential application in the THz wave application. Since multiple polarization modulators are used in the scheme, fewer modulators will be considered in subsequent studies to achieve higher frequency Sub-THz wave.

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