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A simple independent triple-sideband THz signal generation and detection scheme based on delta-sigma modulation and heterodyne detection

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This paper proposes a scheme for the transmission and generation of independent triple-sideband (TSB) terahertz (THz) signals based on delta-sigma modulation (DSM) technology. The method converts multi-sideband high-order quadrature amplitude modulation (QAM) signals into a low-order quadrature phase shift keying (QPSK) signal, enabling the transmission of independent TSB 256/512QAM signals. Compared to directly transmitting high-order QAM signals over the standard single-mode fiber (SSMF), the signal after the DSM modulator reduces the average energy and enhances the system's noise resistance. The system achieves an improvement in optical signal-to-noise ratio (OSNR) gain of at least 2.5 dB. The receiver sensitivity gain for back-to-back (BTB) transmission and 60 km SSMF transmission is at least 1.5 dB and 2 dB higher, respectively. Additionally, at the receiver end, the original signal can be restored by simply eliminating out-of-band quantization noise through low-pass filtering, without the need for an additional digital-to-analog converter (DAC), which contributes to cost reduction. Simulation results demonstrate the successful transmission and detection of independent TSB 256/512QAM signals over SSMF at 320 GHz frequency, achieving a maximum transmission distance of 60 km. The bit error rate (BER) remains below the hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} , confirming the feasibility and effectiveness of the proposed scheme. © 2025 Optica Publishing Group. All rights, including for text and data mining (TDM), Artificial Intelligence (AI) training, and similar technologies, are reserved.

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With the exponential growth of data traffic in the Internet era and the continuous emergence of new broadband services, the demand for ultrahigh-speed optical communication systems is growing rapidly [1,2]. Compared to millimeter waves, terahertz (THz) waves offer a significantly broader bandwidth and higher data transmission rates, making them particularly suitable for densely populated areas or environments with high data traffic. As a result, THz waves have emerged as one of the key technologies for future 6 G communication [3–6]. To further increase channel capacity, higher-order quadrature amplitude modulation (QAM) signals are often considered an ideal choice, as they

can transmit more information compared to lower-order QAM signals. However, higher-order QAM signals are more susceptible to interference due to their smaller Euclidean distances. Additionally, THz wave communication faces challenges such as propagation loss.

In recent years, delta-sigma modulation (DSM) has gained significant attention and been widely applied [7,8]. DSM technology quantizes and modulates analog signals and enhances signal performance by combining oversampling, noise shaping, and filtering techniques.

Moreover, there has been increasing research interest in independent multi-sideband systems. In recent years, optical independent dual-sideband (DSB) systems have become one of the hot topics in the field. Zhao *et al.* proposed a simple DSB signal transmission structure, where a single photodetector (PD) is required to receive the independent dual-sideband signal [9]. In this system, separation is achieved in the electrical domain through a simple algorithm. Building on this, Ming *et al.* further enhanced the performance of DSB systems by combining geometric shaping and probabilistic shaping [10]. This approach not only improved the system's efficiency but also featured a low guard interval between the left and right sidebands, maximizing spectral efficiency. However, the aforementioned scheme is limited to generating and detecting DSB signals through relatively low-intensity modulation. Additionally, Pan *et al.* designed a photon-assisted dual-vector RF signal transmission scheme, and their experimental results demonstrated the feasibility of DSB high-order QAM signals in wireless transmission [11]. However, the aforementioned research has primarily focused on dual-sideband systems, leaving room for further exploration of multiband systems with more than two sidebands.

In this study, we propose an innovative approach for the generation and detection of independent TSB THz signals, leveraging 1 bit baseband DSM quantization technology. The photon-assisted method facilitates the generation of optical signals at a frequency of 320 GHz. The DSM modulator with a quantized signal-to-noise ratio of 29 dB is employed to enable the transmission of three 256/512QAM signals over a 60 km standard single-mode fiber (SSMF) and enhances the receiver sensitivity by at least 2 dB. In addition, traditional THz systems often use multiple optical modulators or wavelength division multiplexing (WDM) techniques to achieve simultaneous transmission

and reception of multiple signals, resulting in more complex system architectures. The independent TSB THz signal transmission system designed in this paper avoids the aforementioned drawbacks, enabling the simultaneous transmission of three independent high-order QAM signals without the need for WDM technology or multiple optical modulators, thereby further reducing system complexity.

Figure 1 depicts the schematic diagram and architecture of the optical independent TSB THz signal generation system, utilizing photon-assisted and DSM technologies. At the transmitter, MATLAB generates three distinct sets of pseudo-random binary sequences (PRBS), specifically PRBS1, PRBS2, and PRBS3. PRBS1, PRBS2, and PRBS3 are each mapped to respective QAM signals, denoted as QAM1, QAM2, and QAM3. The three QAM signals are filtered by a root raised cosine (RRC) filter. The real and imaginary parts of the filtered signals are fed into 1 bit DSM modulator. Within the modulator, quantizing the signal to 1 bit introduces significant quantization noise, which overlaps with the useful signal. To address this, oversampling is employed to expand the signal's frequency domain bandwidth, thereby compressing the in-band quantization noise. Subsequently, the signal transfer function is set to 1, while a noise transfer function is designed to transfer most of the in-band quantization noise to the out-of-band region, completing the quantization process. The three sets of quantized signals are up-converted to frequencies of $-f_s$, 0, and f_s ($f_s > 0$), respectively, resulting in the left-sideband-DSM (LSB-DSM), middle-band-DSM (MSB-DSM), and right-sideband-DSM (RSB-DSM) signals. The schematic spectrum of LSB-DSM, MSB-DSM, and RSB-DSM signals are shown in Fig. 1(i)–(iii). Finally, the three DSM signals were superimposed, and the schematic spectrum of the superimposed signal is illustrated in Fig. 1(iv). The real and imaginary parts of the combined signal are used as the I and Q paths for the I/Q modulator. The electrical signal is applied to an external cavity laser (ECL1) through an optical modulator. ECL1, with its frequency set to f_{c1} , is coupled with another ECL2, which has its frequency set to f_{c2} (where $f_{c1} > f_{c2}$). This coupling generates an optical signal with a frequency difference between the two laser sources. This optical signal is converted into an electrical signal by a photodetector and processed using digital signal processing (DSP). The schematic spectrum of the coupled signal after PD is presented in Fig. 1(v). for analysis. Here, $f_L = f_{c1} - f_{c2} - f_s$, $f_M = f_{c1} - f_{c2}$, $f_R = f_{c1} - f_{c2} + f_s$.

The simulation configuration of the proposed scheme is illustrated in Fig. 2. At the transmitter, three groups of PRBS, each of length 2^{14} , are first modulated using 256/512QAM. Subsequently, each group of QAM signal is passed through a RRC filter for pulse shaping, with the roll-off factor set to 0.1. Following this, the in-phase and quadrature components of each QAM signal undergo 1 bit DSM quantization, where the oversampling factor of the DSM is set to 8. This allows the DSM modulator to convert each 1 Gbaud 256/512QAM signal into a 16 Gbaud QPSK signal. The noise transfer function expression of the DSM modulator is shown in Eq. (1), which represents its noise shaping performance:

$$NTF = \frac{(z^2 - 1.982z + 1)(z^2 - 1.887z + 1)}{(z^2 - 1.182z + 0.3645)(z^2 - 1.405z + 0.6483)}. \quad (1)$$

The noise transfer function design of the DSM and the corresponding signal waveform after DSM processing are shown in Fig. 3. Each QPSK signal is then resampled with a resampling factor of 16 to match the subsequent THz signal processing.

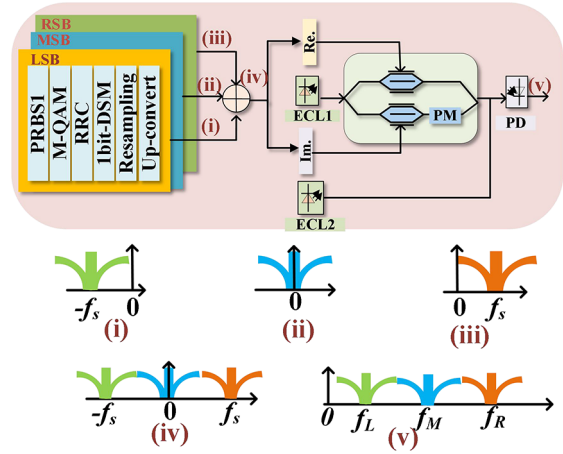


Fig. 1. Schematic diagram of the independent TSB THz signal generation. (i) Spectrum of the LSB-DSM signal. (ii) Spectrum of the MSB-DSM signal. (iii) Spectrum of the RSB-DSM signal. (iv) Spectrum of the ISB signal. (v) Spectrum of the received synthesized signal after PD.

Thereafter, two of the QPSK signals are frequency-shifted to $+17$ GHz and -17 GHz, respectively. At this stage, the transmitter generates three DSM signals: LSB-DSM, MSB-DSM, and RSB-DSM signals. The spectrum of the independent TSB signal is presented in Fig. 4. The three DSM signals are then combined to obtain their in-phase and quadrature components, which are subsequently applied as the I and Q inputs to the I/Q modulator. ECL1, with a linewidth of less than 100 KHz, operates at a frequency of 193.42 THz and delivers an output power of 16 dBm. The I and Q channel signals are modulated onto the optical carrier transmitted by ECL1 using an I/Q modulator. This modulator features a 30 GHz bandwidth and an insertion loss of approximately 7 dB and operates at the minimum bias point. The frequency interval between ECL2 and ECL1 is set to 320 GHz, with ECL2 having a linewidth of less than 100 KHz, a center frequency of 193.1 THz, and an output power of approximately -1 dBm. The resulting laser is combined with ECL1 to generate a 320 GHz optical QPSK signal. The coupled spectrum is shown in Fig. 5.

After propagating through the 60 km SSMF, which has an attenuation coefficient of 0.2 db/km, a differential group delay of 0.2 ps/km, and a dispersion slope of around 0.08 ps/nm²/km, a variable optical attenuator (VOA) is used to adjust the optical power. An optical bandpass filter (bandwidth < 350 GHz) is used to constrain the bandwidth of the optical signal before it is transmitted into the PD. After completing the beat frequency measurement in the PD, a 320 GHz electrical signal is obtained. The spectrum after the PD is shown in Fig. 6. This electrical signal is then mixed with a 280 GHz LO to produce a 40 GHz intermediate frequency (IF) signal. An electrical amplifier with a 30 dB gain is employed to compensate for signal power loss. Finally, relevant DSP is performed in the electrical domain, where the received signal undergoes downconversion, resampling, and QPSK signal equalization compensation, including clock recovery and constant modulus algorithm (CMA) processing. A hard decision is then applied to convert the signal into standard QPSK symbols. The original signal is recovered through a sequence of low-pass filtering, matched filtering, and

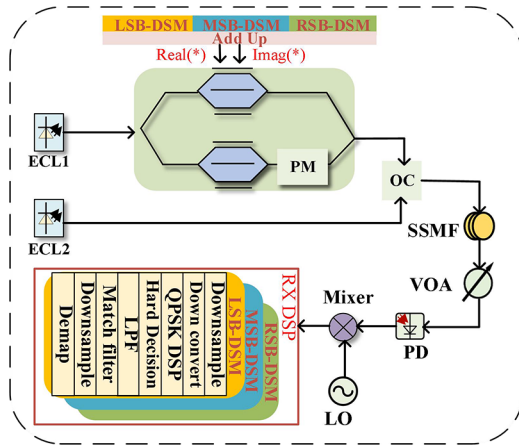


Fig. 2. Simulation setup of the independent TSB THz system based on DSM technology and heterodyne assistance. VOA, variable optical attenuator; PD, photodiode; LPF, low-pass filter; LO, local oscillation.

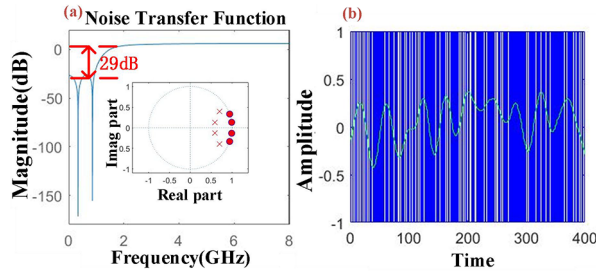


Fig. 3. (a) Noise transfer function curve and zero-pole diagram of the delta-sigma modulator. (b) Real part of the baseband 512QAM signal after DSM.

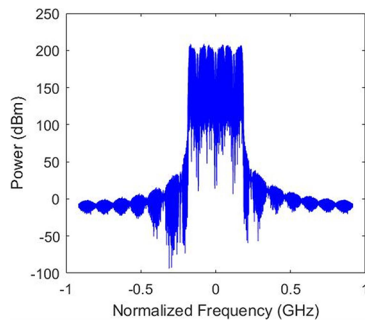


Fig. 4. Spectrum diagram of the independent TSB signal.

downsampling. Finally, the BER is calculated to evaluate system performance.

As shown in Fig. 7, we evaluated the BER and optical signal-to-noise ratio (OSNR) performance of 256QAM-TSB and 512QAM-TSB signals under back-to-back (BTB) transmission condition, comparing their performance with classical single-carrier (SC) 16QAM signal without DSM technology. All the simulation setting parameters are identical—e.g., they both use the same symbol rate (1 Gbaud) and are transmitted at 320 GHz. The received optical power (ROP) was set to -15 dBm. The results indicate that as the OSNR increases, the BER of the signals improves accordingly. When the OSNR exceeds

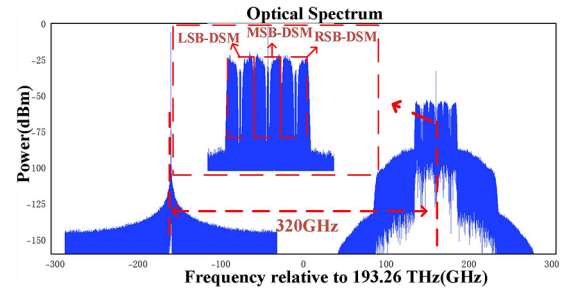


Fig. 5. Spectrum diagram of the independent TSB signal after coupling.

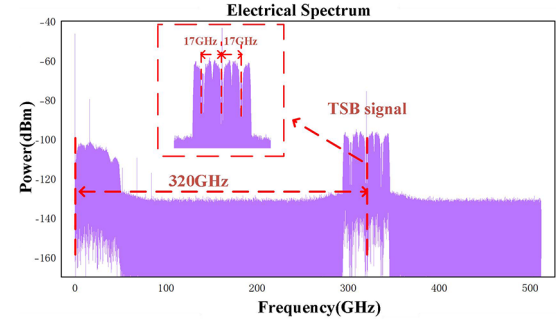


Fig. 6. Spectrum diagram of the independent TSB signal after PD.

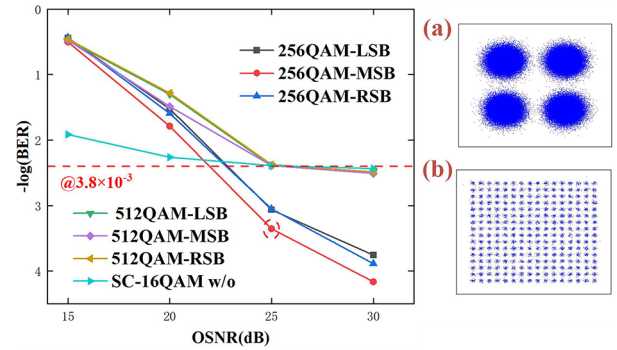


Fig. 7. BER versus OSNR for 256QAM-TSB, 512QAM-TSB, and SC-16QAM signals under BTB transmission. (a) Recovered constellation after QPSK DSP when the OSNR is 25 dB. (b) 256QAM-MSB constellation when the OSNR is 25 dB. w/o, without.

approximately 22 dB, the BER of the left-sideband-256QAM (256QAM-LSB), middle-sideband-256QAM (256QAM-MSB), and right-sideband-256QAM (256QAM-RSB) signals all fall below the predefined threshold, with comparable error rates across all sidebands. However, the BER curves degrade when the QAM order is increased from 256 to 512. At an OSNR of 25 dB and above, the BER of the 512QAM-LSB, 512QAM-RSB, and 512QAM-MSB signals also drops below the threshold. Additionally, when the BER falls below the threshold, the 256QAM-TSB signal requires a lower OSNR than the SC-16QAM signal (approximately 2.5 dB lower). Figure 7(a) presents the constellation diagram of the received QPSK signal after DSP, while Fig. 7(b) shows the constellation diagram for the 256QAM-MSB signal.

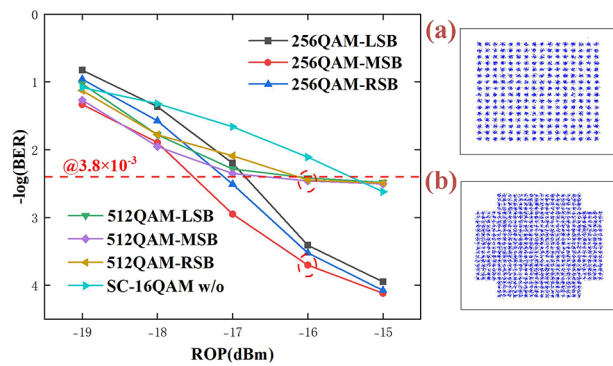


Fig. 8. BER versus ROP for 256QAM-TSB, 512QAM-TSB, and SC-16QAM signals under BTB transmission. (a) 256QAM-MSB constellation. (b) 512QAM-MSB constellation.

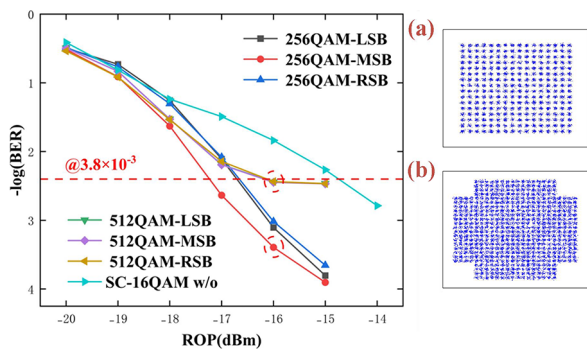


Fig. 9. BER versus ROP for 256QAM-TSB, 512QAM-TSB, and SC-16QAM signals under 60 km SSMF transmission. (a) 256QAM-MSB constellation. (b) 512QAM-MSB constellation

Figure 8 and Fig. 9 illustrate the BER performance versus ROP for both BTB and 60 km SSMF transmission scenarios, respectively, for 256QAM-TSB, 512QAM-TSB, and SC-16QAM signals. The BER curves for all signals exhibit similar trends, with BER decreasing as ROP increases. Under BTB conditions, 256QAM-TSB signals achieve virtually error-free transmission when ROP exceeds -15 dBm. When ROP surpasses -17 dBm, all three sidebands of the 256QAM signal maintain BER below the threshold. In contrast, 512QAM-TSB signals require ROP to exceed -16 dBm to achieve the same performance. Figures 8(a) and 8(b) display the constellation diagrams for 256QAM-MSB and 512QAM-MSB signals, respectively, at an ROP of -16 dBm. For 60 km SSMF transmission, both 256QAM-TSB and 512QAM-TSB signals achieve expected BER performance when ROP exceeds -16 dBm. However, at the threshold BER, the receiver sensitivity penalty for 512QAM-TSB signals is approximately 0.8 dB higher compared to 256QAM-TSB signals. In comparison to the SC-16QAM signal without DSM technology, the 256QAM-TSB signals demonstrate a receiver sensitivity improvement of approximately 1.5 dB for BTB transmission and about 2 dB for 60 km SSMF transmission. As

shown in Figs. 9(a) and 9(b), the constellation diagram of the 256QAM-MSB signal exhibits better clustering compared to the 512QAM-MSB signal. This can be attributed to the residual quantization noise within the signal band after receiver filtering, which scales proportionally with the QAM order.

In conclusion, this paper introduces an independent TSB THz signal communication scheme that integrates 1 bit baseband DSM with photon-assisted techniques. The proposed method employs DSM technology to quantize the real and imaginary components of high-order QAM signals into two-level OOK signals, effectively alleviating the nonlinear effect. Subsequently, the real and imaginary parts of these signals are combined separately and injected into the I/Q modulator as the I and Q paths. This process effectively converts three 1 Gbaud 256/512QAM signals into a single 48 Gbaud optical QPSK signal for transmission. OSNR gains exceeding 2.5 dB were achieved with BTB transmission, and receiver sensitivity gains exceeding 2 dB were achieved with 60 km of SSMF transmission. The system achieves a transmission distance of up to 60 km at a frequency of 320 GHz, with a BER below the hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} . Notably, to the best of our knowledge, this work represents the first implementation of DSM technology for independent TSB high-order QAM signal transmission in the THz band utilizing a single photodetector. The demonstrated 60 km transmission over SSMF aligns with the requirements for medium- to short-haul optical communication. We firmly believe that this innovative approach will significantly contribute to the advancement of future 6 G communication systems and holds immense potential for further development.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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