450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM

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Abstract: A TO-38-can packaged Gallium nitride (GaN) blue laser diode (LD) based free-space visible light communication (VLC) with 64-quadrature amplitude modulation (QAM) and 32-subcarrier orthogonal frequency division multiplexing (OFDM) transmission at 9 Gbps is preliminarily demonstrated over a 5-m free-space link. The 3-dB analog modulation bandwidth of the TO-38-can packaged GaN blue LD biased at 65 mA and controlled at 25°C is only 900 MHz, which can be extended to 1.5 GHz for OFDM encoding after throughput intensity optimization. When delivering the 4-Gbps 16-QAM OFDM data within 1-GHz bandwidth, the error vector magnitude (EVM), signal-to-noise ratio (SNR) and bit-error-rate (BER) of the received data are observed as 8.4%, 22.4 dB and 3.5×10^{-8}, respectively. By increasing the encoded bandwidth to 1.5 GHz, the TO-38-can packaged GaN blue LD enlarges its transmission capacity to 6 Gbps but degrades its transmitted BER to 1.7×10^{-3}. The same transmission capacity of 6 Gbps can also be achieved with a BER of 1×10^{-6} by encoding 64-QAM OFDM data within 1-GHz bandwidth. Using the 1.5-GHz full bandwidth of the TO-38-can packaged GaN blue LD provides the 64-QAM OFDM transmission up to 9 Gbps, which successfully delivers data with an EVM of 5.1%, an SNR of 22 dB and a BER of 3.6×10^{-3} passed the forward error correction (FEC) criterion.

OCIS codes: (140.7300) Visible lasers; (140.2020) Diode lasers; (060.2630) Frequency modulation; (060.2605) Free-space optical communication.

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1. Introduction

Over past few decades, the visible light emitting diodes (LEDs) with wavelengths ranging from 350 to 750 nm have been widely used in displays, traffic signals and ubiquitous lighting systems because of its high brightness, low power consumption and long lifetime. In particular, the visible light communication (VLC) system implemented with aforementioned LEDs has been considered as a promising candidate for free-space or underwater communications [1–4], which has distinct features when compared with the traditional radio frequency (RF)- and optical fiber-based communication links, such as electromagnetic interference (EMI) free and free-space data transmission [5,6]. These features provide a new level of flexibility for applications in different environments including flying aircrafts, hospitals and indoor wireless networks. However, the data rate of the LED based VLC systems is significantly limited by the finite direct modulation bandwidth of LEDs (usually from tens to hundreds MHz) [1,4,7]. The use of μ-LED with a large injection current density and a small device capacitance would be a promising strategy to increase the encodable bandwidth of LED [8]; however, the increasing of injection current density would lead to a well-known disadvantage of efficiency droop due to the electron overflow [9]. This issue is still not perfectly solved or eliminated although numerous efforts, such as ternary or quarternary electron-blocking layers (EBLs) [10,11], graded EBL [12] and superlattice EBL [13], etc. have been comprehensively investigated. In contrast to LEDs, the visible laser

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diodes (LDs) reveal high direct modulation speed and high pumping efficiency with the absence of efficiency droop effect, which becomes a research spotlight for developing alternative VLC systems. Recently, Hanson *et al*. demonstrated 532-nm VLC at 1 Gbps through 2-m water pipe [14]. Chen *et al*. used red laser diode to demonstrate bidirectional VLC with 16-quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) data at 2.5 Gbps over 20-km single-mode fiber (SMF) and 15-m free-space [15]. The directly-modulated 641-nm laser pointer based VLC with 4-QAM OFDM data is proposed by Singh *et al* [16]. Among all visible wavelengths, the Gallium nitride (GaN)-based blue LD is one of the mainly considered VLC transmitters because of its cost-effective and high spectral power features, which enables the fusion with concurrent white lighting system after combining with a yellow phosphor or the exploration of underwater VLC because of its low absorption and scattering coefficients. More recently, Watson *et al.* have preliminarily demonstrated a 2.5-Gbps nonreturn-to-zero on-off-keying (NRZ-OOK) modulation scheme by using a GaN blue laser diode in a free space link [17]; however, its transmission capacity is still limited by the inefficient modulation format.

In this study, the premier demonstration on directly encoding the 64-QAM OFDM data to a transistor outline can (TO-38-can) packaged GaN blue LD is presented for visible optical communication over 5 m in free space. The optimization on the allowable encoding bandwidth and transmission performances of the TO-38-can packaged GaN blue LD with DC bias adjustment is also performed to maximize the usable raw data rate of up to 9 Gbps.

2. Experimental setup

The TO-38-can packaged GaN blue LD (OSRAM Opto Semiconductors, PL 450B) mounted with a thermo-electric cooler and a copper-based heat sink is illustrated in Fig. 1 for subsequent 16- or 64-QAM OFDM data transmission over 5 m in free space, in which the single transverse mode GaN blue LD with a lasing wavelength of 450 nm, a spectral linewidth of 0.67 nm and a maximum vertical/horizontal beam divergence of 11/25 degree was packaged in a conventional TO-38-can. The electrical QAM OFDM data with various QAM-level and OFDM carrier bandwidth were generated by a homemade MATLAB program with a FFT size of 512 and a cyclic prefix (CP) of 1/32, and uploaded into an arbitrary waveform generator (AWG, Tektronix, 70001A) with a sampling rate of 24 GSa/s. Firstly, the incoming serial on-off keying data-stream is divided into parallel low-speed data blocks, and the M-QAM mapping is employed to distribute these parallel data blocks onto the equally-spaced OFDM subcarriers for inverse fast Fourier transformation (IFFT). The AWG used in our work enables the generation of data-stream with its bandwidth of up to 12 GHz according to the Nyquist-Shanon sampling theorem.

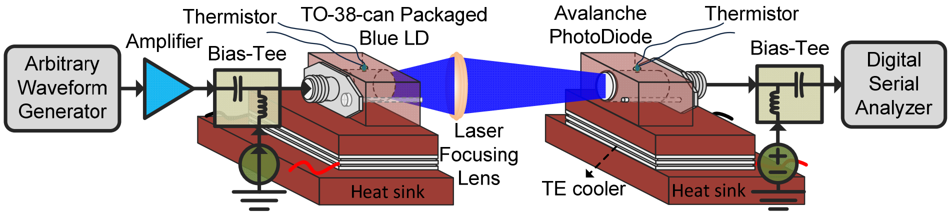

Fig. 1. The TO-38-can packaged GaN blue LD with a copper-based cooling mount for QAM OFDM data transmission over a free-space link.

The detailed serial-to-parallel data mapping and encoding procedure may refer to textbook and works [18–20]. Therein, the negative frequency points of OFDM subcarriers are complex conjugates of positive counterparts which deliver real-value waveform. Therefore, the total OFDM subcarriers in the FFT matrix will occupy a bandwidth of 2 × 12 GHz, some of them are set as null since the TO-38-can packaged GaN blue LD cannot response to the whole bandwidth. After IFFT, the waveform of distributed OFDM subcarriers is converted from frequency-domain to time-domain. A CP is further inserted to suppress the inter-symbol-interference (ISI) in a transmission link. After digital-to-analog conversion (DAC), the analog waveform is used to directly encode the TO-38-can packaged GaN blue LD. At receiving part, an analog-to-digital converter (ADC) is employed to convert the received waveform to digital symbols, and then the CP is subsequently removed. Later on, the time-domain waveform are inversely converted to frequency-domain subcarriers by FFT process, which can be re-mapped back to the M-QAM symbols such that its EVM and SNR in I-Q domain can be calculated. Finally, the parallel M-QAM symbols are converted into the serial on-off-keying data for evaluating its BER through bit-to-bit comparison. The conceptual illustration for aforementioned procedure is shown in Fig. 2.

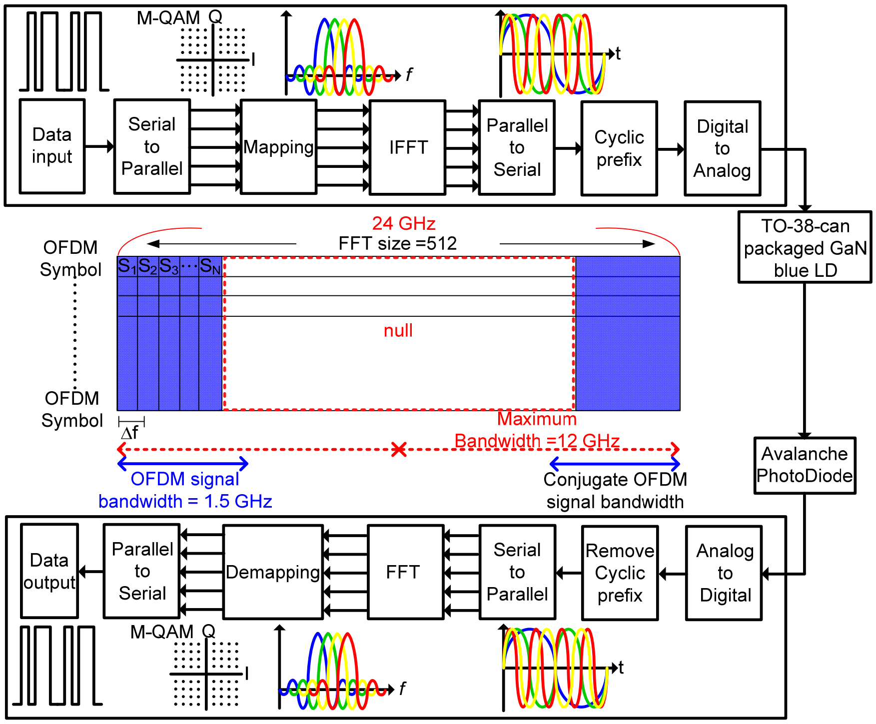

Fig. 2. Conceptual diagram for OFDM transmitter and receiver, Inset: the matrix of the OFDM generation.

During experiment, the QAM OFDM data with QAM levels of 16 and 64 with corresponding OFDM subcarrier numbers of 21- and 32-s, respectively, were employed in latter transmission experiment. In addition, the allowable OFDM bandwidths of 1 and 1.5 GHz were employed to achieve the total data rates of 4 and 6 Gbps for 16-QAM OFDM data and 6 and 9 Gbps for 64-QAM OFDM data, respectively. For the M-QAM OFDM data, its raw bit rate in unit of bit/sec can be calculated by multiplying the OFDM subcarrier spacing in unit of 1/sec with the OFDM subcarrier number and the QAM level in unit of bit/symbol [19,21]. Therein, the OFDM subcarrier spacing is defined as Δf = Sampling rate (samples/sec) / FFT size (samples). For example, by substituting with the AWG sampling rate of 24 GSa/s, the FFT size of 512, the subcarrier number of 32, the QAM-level of 6 and the bandwidth of 1.5 GHz, a raw bit rate of 9 Gbps for the 64-QAM OFDM data-stream is obtained in our case. Note that there is no any pre-emphasis technique, such as the carrier amplitude pre-leveling or the bit loading added on the electrical QAM-OFDM data except the one-tap frequency domain equalizer in the program. In addition, since this work focuses on developing the maximal data rate of the bandwidth-limited TO-38-can packaged GaN blue

LD, the high oversampling which defined as a ratio of signal sampling rate to two times of signal bandwidth [22] is employed to overcome the frequency selective fading of the transmitted data at a cost of slightly increased inter-carrier interference (ICI).

After electrical pre-amplification with an ultra-broadband amplifier (Picosecond Pulse Labs, 5828) of 10-dB gain, the QAM OFDM data was used to directly modulate the TO-38-can packaged GaN blue LD through its pin soldered with an SMA connector. Both the DC bias current and the QAM OFDM data were fed into the TO-38-can packaged GaN blue LD by combining each other with a bias-tee (Mini-Circuit, ZX85-12G-S +). At the output port of TO-38-can packaged GaN blue LD, the divergent light with QAM OFDM data was launched into a focusing hyper-hemispherical lens, then transmitted in free-space and refocused with the lens of same type prior to an avalanche photodiode (APD, Hamamatsu, S9073) with a cut-off frequency of 900 MHz. After optoelectronic conversion, the received QAM OFDM data was captured by a digital serial analyzer (Tektronix, DSA71604C) with a sampling rate of 100 GSa/s and analyzed offline by the homemade MATLAB program to evaluate its constellation plot and corresponding error vector magnitude (EVM), signal-to-noise ratio (SNR) and bit error rate (BER) performances.

3. Results and discussions

The self-feedback temperature controlling system for the TO-38-can packaged GaN blue LD is shown in Fig. 3(a) [23], which consists of a copper mount based heat sink, a SMA jack connector, a thermoelectric (TE) cooler, a thermistor, two plastic screws and nuts. After threading through a reserved hole of the copper mount, the TO-38-can packaged GaN blue LD is directly connected with the SubMiniature version A (SMA) jack. To avoid the parasitic capacitance and inductance induced by the mount, the electrically isolated thermal tape was employed to wrap around the laser diode, and the plastic screws/nuts were used to firm the TO-38-can package with the whole housing for complete electrical isolation. Therefore, the notch-free modulation frequency response of the TO-38-can packaged GaN blue LD is obtained and insensitive to the copper mount. The thermistor and the TE cooler help to monitor and control the temperature within ± 0.05°C for such a copper mount based TO-38-can packaged GaN blue LD. Besides, the APD is also set with the same temperature controller at a room temperature of 25°C.

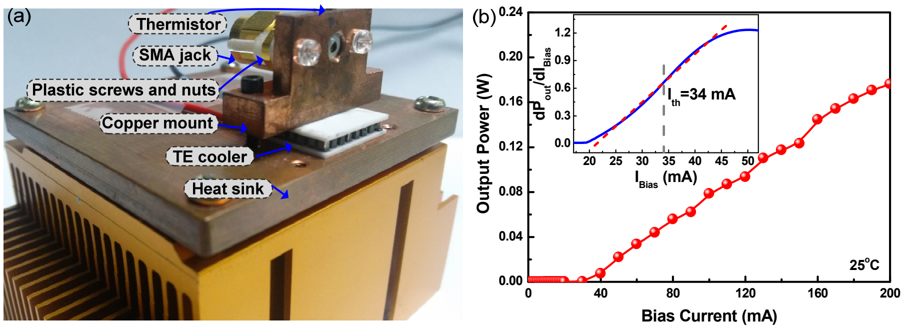

Fig. 3. (a) The TO-38-can packaged GaN blue LD with a self-designed temperature controlling system. (b) Power-to-current curve of the TO-38-can packaged GaN blue LD.

The power-to-current response of the TO-38-can packaged GaN blue LD reveals a threshold current of 34 mA, as shown in Fig. 3(b). The dP/dI slope of 1.8 W/A above threshold gives a differential quantum efficiency of 0.65. Before transmitting the QAM OFDM data, the frequency response is characterized as a figure of merit to evaluate allowable direct-modulation bandwidth of the TO-38-can packaged GaN blue LD. Figure 4(a) shows the throughput responses under small-signal modulation at different biased currents. As expected, raising the DC biased level makes the TO-38-can packaged GaN blue LD up-shift its relaxation oscillation frequency to extend its modulation bandwidth; however, the throughout intensity at high frequencies is inevitably declined by the TO-38-can package and the 900-MHz cut-off frequency bandwidth of the APD used in this experiment. Straightforwardly, this limitation confines the allowable OFDM data bandwidth for transmission. Although the enlarged biased current also declines the modulation throughput response at low frequencies, it can significantly suppress the relative intensity noise (RIN) to compromise the degradation on direct encoding performance. A modulation bandwidth of 900 MHz for the TO-38-can packaged GaN blue LD biased at 60 mA (nearly twice the threshold) is observed, which reveals the optimized total throughput intensity within 1.5-GHz bandwidth when comparing with those based at lower or higher currents. To confirm, the RF spectra of the 4-Gbps 16-QAM OFDM data delivered by the TO-38-can packaged GaN blue LD at different DC biases are compared in Fig. 4(b). Note that the highly biased operation contributes to the suppression on RIN level of the TO-38-can packaged GaN blue LD output, and up-shifts the RIN peak away from the OFDM bandwidth. However, the declination on modulation throughput within OFDM bandwidth is also observed with slightly increased negative power-to-frequency slope.

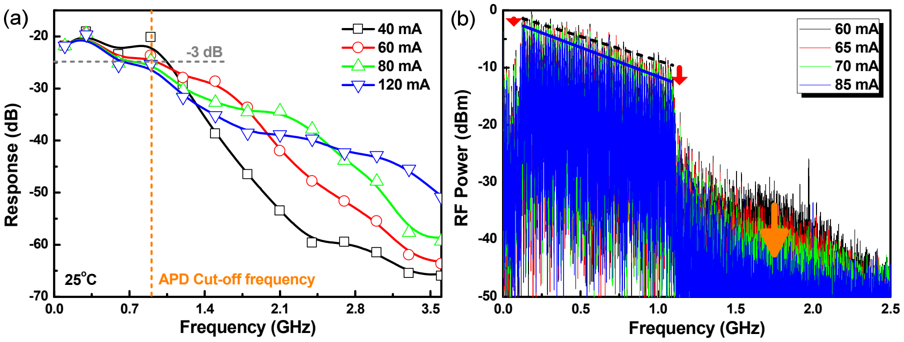

Fig. 4. (a) The small-signal frequency response of the TO-38-can packaged GaN blue LD. (b) The RF spectra of 4-Gbps 16-QAM OFDM data carried by the TO-38-can packaged GaN blue LD at different biased currents.

To further discuss the transmission performance by analyzing the constellation plot, SNR and BER, the 4-Gbps 16-QAM OFDM data is employed to directly encode the TO-38-can packaged GaN blue LD biased at different currents, as shown in Fig. 5. Increasing the biased current from 60 to 65 mA improves the average SNR from 22.1 to 22.4 dB for the transmitted 4-Gbps 16-QAM OFDM data, because the suppressed RIN dominates more than the declined modulation throughput of the TO-38-can packaged GaN blue LD, as shown in Fig. 5(a). The overly DC bias of up to 85 mA seriously degrades the high-frequency subcarrier power of the 4-Gbps 16-QAM OFDM data, which results in a slightly decreased SNR of 21.6 dB. Biasing the TO-38-can packaged GaN blue LD within 60-85 mA can successfully deliver the 4-Gbps 16-QAM OFDM data in free-space with clear constellation plot after receiving, as shown in Fig. 4(b). At the optimized biased current of 65 mA, the lowest EVM of 8.4% is observed for the TO-38-can packaged GaN blue LD carried 4-Gbps 16-QAM OFDM data. Most important, the BER of the received 4-Gbps 16-QAM OFDM data is degraded from 3.5×10^{-8} to 1×10^{-7} by further reducing the DC bias from 65 to 60 mA, as shown in Fig. 5(b). Similarly, the BER is increased to 3.7×10^{-7} when enlarging DC bias to 85 mA because of the modulation throughput declination of the QAM OFDM data carried by the TO-38-can packaged GaN blue LD.

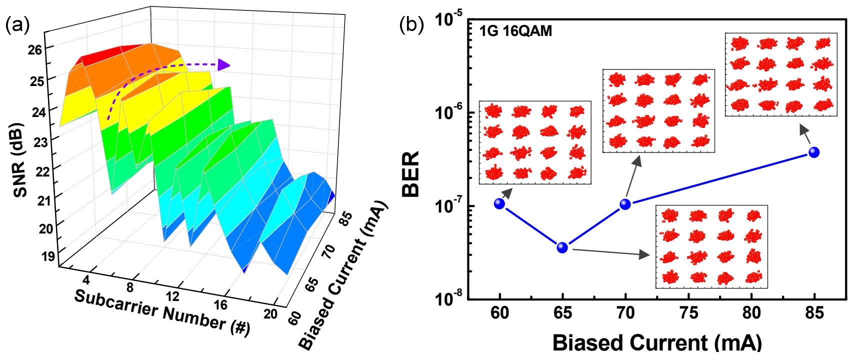

Fig. 5. The (a) SNRs, (b) constellation plots and related BERs of 4-Gbps 16-QAM OFDM data carried by the TO-38-can packaged GaN blue LD biased at different currents.

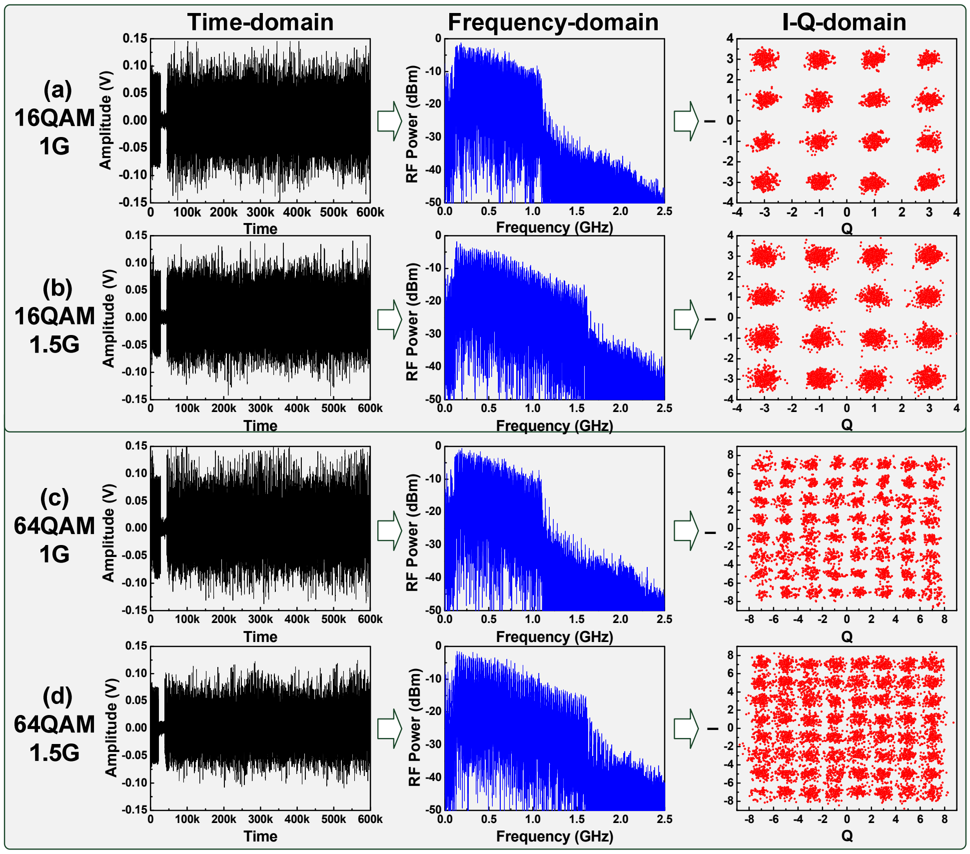

Fig. 6. The received (a) waveforms, (b) RF spectra and (c) constellation plots of 16/64-QAM OFDM data covering the bandwidth of 1 and 1.5 GHz, respectively.

For 16-QAM OFDM and 64-QAM OFDM transmissions covering the bandwidth of 1 and 1.5 GHz, respectively, the time-domain waveforms, the frequency-domain spectra, and the re-mapped constellation plots of the received data-streams are summarized in Fig. 6 for comparison. After receiving the 1.5-GHz 16-QAM OFDM data with a raw data rate of 6 Gbps directly encoded onto the TO-38-can packaged GaN blue LD biased at 65 mA, the obtained average SNR of 21.6 dB is significantly higher than that of 15.19 dB required for the forward-error-correction (FEC) decoding, as shown in Fig. 7(a). Later on, to determine the allowable transmission capacity of the TO-38-can packaged GaN blue LD, the encoded QAM

OFDM data enlarges its QAM level to 64 and extends its OFDM bandwidth to 1.5 GHz so as to increase the transmitted raw data rate up to 9 Gbps, which corresponds a real data rate of 8.71875 Gbit/s after removing the CP. Enlarging the QAM level to 64 also raises the corresponding FEC criterion to 21.12 dB; however, the TO-38-can packaged GaN blue LD carried 9-Gbps 64-QAM OFDM data exhibits an average SNR of 22 dB that is still beyond the FEC limitation. To compare, the constellation plots and related BER responses of 16- and 64-QAM OFDM data with different data bandwidths carried by the TO-38-can packaged GaN blue LD biased at 65 mA are compared in Fig. 7(b). By increasing the 16-QAM OFDM data bandwidth from 1 to 1.5 GHz, the transmission capacity of the TO-38-can packaged GaN blue LD is enlarged from 4 to 6 Gbps at a cost of slightly degraded BER from 3.5 × 10^{-8} to 1.7 × 10^{-3} after transmission. Meanwhile, the constellation plot of the transmitted 16-QAM OFDM data at 6 Gbps becomes relatively blurred with an EVM of 9.5%.

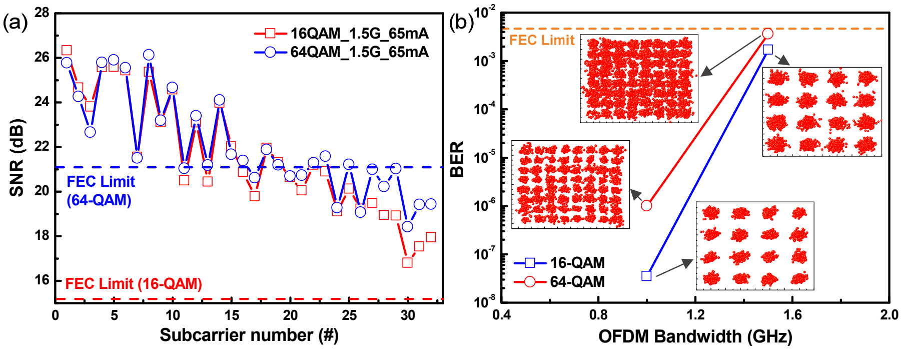

Fig. 7. The (a) SNRs, constellation plots and related BERs of TO-38-can packaged GaN blue LD delivered QAM OFDM data with different QAM levels and OFDM bandwidths.

Under the same requirement on transmission capacity of 6 Gbps, the TO-38-can packaged GaN blue LD can also save its usable modulation bandwidth by 0.5 GHz with the use of 64-QAM OFDM encoding, which greatly reduces the EVM and the BER to 4.47% and 1 × 10^{-6}, respectively. If the 64-QAM OFDM data bandwidth is further extended to 1.5 GHz for upgrading the raw data rate to 9 Gbps, an acceptable constellation plot with an EVM of 5.1% and a BER of 3.6 × 10^{-3} can still pass the FEC criterion (set as 3.8 × 10^{-3}). These results preliminarily declare the capability of the GaN blue LD in carrying the direct QAM OFDM encoded data for free-space VLC. Currently, the blue laser diode has been considered as a suitable transmitter for versatile application scenarios in optical communications, including free-space, visible light and undersea communications, which even can potentially be a white light source in the future application. In this work, we aim to characterize the transmission capability and performance of the commercially available blue laser diode when carrying digital signal with new data format.

4. Conclusion

The GaN blue LD based free-space VLC link with 64-QAM OFDM transmission of up to 9 Gbps over 5 m in free space is demonstrated. With the electrically isolated self-feedback temperature controlling at 25°C, the directly encoded TO-38-can packaged GaN blue LD biased at 65 mA provides a notch-free modulation bandwidth of 900 MHz, which permits the QAM OFDM encoding with allowable bandwidth extended to 1.5 GHz after throughput intensity optimization. The GaN blue LD based VLC transmitter easily delivers 4-Gbps 16-QAM OFDM data within 1-GHz bandwidth, providing an EVM of 8.4%, an SNR of 22.4 dB and a BER of 3.5 × 10^{-8}. Broadening the encoded bandwidth to 1.5 GHz effectively enlarges the transmission capacity to 6 Gbps at a cost of significantly degraded BER to 1.7 × 10^{-3}. Raising the QAM level from 16 to 64 within the same OFDM bandwidth of 1 GHz can also reach the same transmission capacity of 6 Gbps at a BER as small as 1 × 10^{-6}. The ultimate transmission performance is obtained with using the full encodable bandwidth of 1.5 GHz given by the TO-38-can packaged GaN blue LD, which supports the 9-Gbps 64-QAM OFDM transmission with an EVM of 5.1%, an SNR of 22 dB and a BER of 3.6 × 10^{-3} passed the FEC criterion. These experiments preliminarily declare the capability of the GaN blue LD in carrying the direct QAM OFDM encoded data for free-space VLC.

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