High-speed Visible Light Communication System Based on a Packaged Single Layer Quantum Dot Blue Micro-LED with 4-Gbps QAM-OFDM

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Abstract: We demonstrate a 3-meter 4-Gbps QAM-OFDM VLC system with 3.2×10^{-3} bit-error-rate (BER) by implementation of our own fabricated and packaged single layer quantum dot (QD) blue micro-LED with a record high 1.06 GHz modulation bandwidth. © 2020 The Author(s)
OCIS codes: (060.4510) Optical communications; (060.2605) Free-space optical communication; (230.0250) Optoelectronics; (230.3670) Light-emitting diodes; (230.5590) Quantum-well, -wire and -dot devices.

1. Introduction

As an important supplement to traditional radio frequency (RF) communications, visible light communication (VLC) combines solid-state lighting (SSL) with optical communications, providing a new promising option for future indoor high-speed access technologies [1, 2]. An indoor optical wireless network can be realized by installing numbers of white-light light-emitting diodes (LEDs). However, the commercial white LEDs are suffered from low modulation bandwidth caused by long radiative recombination carrier lifetime and large resistance capacitance (RC) delay [3]. Recently, gallium nitride (GaN) based micro-size LEDs (micro-LEDs) are then considered and applied for a high speed data communication. In some previous works, the modulation bandwidths could be up to hundreds of MHz by introducing sophisticated quantum well (QW) structure micro-LEDs [4]. In addition, various high data rate of Gbps VLC systems with different modulation formats were also reported [5-9]. Though Islim *et al*. attained a high data rate of 11.95 Gbps by quadrature-amplitude-modulation orthogonal-frequency-division-multiplexing (QAM-OFDM) with adaptive bit and energy loading, the modulation bandwidth of the micro-LED for a 27.5-cm transmission VLC system was 655 MHz with a current density of 11.5 kA/cm^2 [9]. Therefore, a more practical higher bandwidth LED design with lower current density for free space high-speed data communications and capable for longer reach has become a primary goal for this research community.

To lower RC delay, radiative carrier lifetime and operation current density of the micro-LED, an advanced single layer quantum dot (QD) micro-LED are designed, fabricated and packaged [10]. In this work, by using QAM-OFDM, it is the first time to present a 4-Gbps data rate QD micro-LED VLC system with a bit-error rate (BER) of 3.2×10^{-3} below the forward error correction (FEC) threshold 3.8×10^{-3} over 3 m transmission distance. Besides, the packaged micro-LED successfully achieves a record-high modulation bandwidth of 1.06 GHz at 178.8 A/cm^2.

2. Devices Fabrication and Experimental Setup

2.1 Structure and Characteristics of 75 μm Micro-LED

The LED sample was grown on a 430-μm-thick 2-inch (0001) sapphire substrate with an AIXTRON 2000HT MOVPE system. The epitaxial structure of the sample contains a 3.5-μm Si-doped GaN layer, an n-type 10-pair of $In_{0.03}Ga_{0.97}N$ (3 nm)/GaN (3 nm) superlattice (SL), a 1.5-nm InGaN QDs layer, a 20-nm undoped GaN barrier, a 20-nm Mg-doped $Al_{0.2}Ga_{0.8}N$ electron blocking layer (EBL), and a 150-nm Mg-doped GaN contact layer. The main InGaN QD material was formed via a growth interruption method [11, 12]. After the epitaxy, the indium tin oxide (ITO) layer was deposited on the QD micro-LED to form an ohmic contact layer. After defining the active region with a diameter of 75 μm by wet etching and creating the mesa by dry etching, we created a ring-shaped electrode contacting to the ITO layer was created. The L-I-V characteristic and wavelength spectra characteristic of the packaged QD micro-LED are shown in Fig. 1. In this experiment, we set the static point at the voltage of 5.5 V, corresponding to current density was 178.82 A/cm^2 and the emitting optical power was 0.39 mW. A micro-spectrometer (PG2000-Pro, ideaoptics) was used for measure the spectra characteristic of the micro-LED and the normalized intensity versus wavelength at the driving voltage of 5.5 V is shown in the Fig. 1(b). The peak wavelength is 490 nm at room temperature.

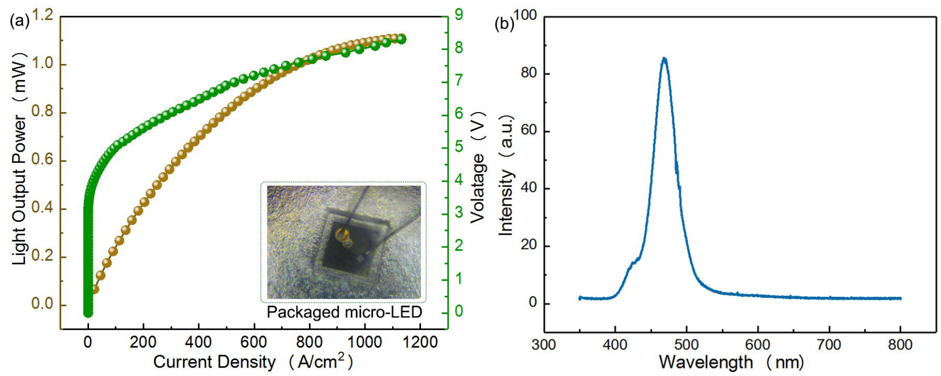

Fig. 1. (a) L-I-V characteristics (Inset: image of the packaged QD micro-LED) and (b) measured optical spectrum of the packaged QD blue micro-LED.

2.2 Experimental Setup and QAM-OFDM Processing

Our experiment includes both real-time communication part and off-line processing part, and the block diagram of the micro-LED based QAM-OFDM VLC system is shown in Fig. 2 (a). The QD micro-LED is firstly fabricated and then high-frequency TO-can packaged before being implemented for the transmitter (TX) as shown in Fig. 2 (b). A high-sensitivity silicon APD module (APD210, Menlo Systems) is used as the receiver (RX) of the VLC system which can be seen in Fig. 2 (c). And Fig. 2 (d) shows the image of the whole QD micro-LED based VLC system with a 3-m communication link. In addition, a vector network analyzer (VNA, N5227A, Agilent) is used to measure the modulation bandwidth of the VLC system with 0 dBm input signal power over a 3-m transmission distance. For QAM-OFDM signal, the random binary data is generated and mapped into 4-QAM format in the MATLAB ®. Before inverse fast Fourier transform (IFFT), the modulated data is converted from serial into parallel and then transformed into the Hermitian symmetry format. The cyclic prefix (CP) is inserted into the signals and then converted back into serial format. After adding a synchronizing sequence, the signal is up-sampled and sent to the arbitrary waveform generator (AWG). Subsequently, the signals are amplified through an amplifier (ZX60-43+, Mini-circuit), combined with direct current (DC) by a bias-Tee (ZFBT-6GW+, Mini-circuit) under 5.5 V bias voltage, and finally applied to the packaged QD micro-LED. Two convex lenses at the TX and RX sides are used to avoid the beam divergence and hence the 3-m communication distance can be achieved. The optical signal is converted into electronic signal and then recorded by a real-time oscilloscope (OSC, DPO75902SX, Tektronix) after passing through an amplifier (ZX60-43+, Mini-circuit). For QAM-OFDM demodulation, after down-sampling and synchronizing, the signal is converted into parallel format and the CP is removed. Then the time-domain signals are transformed into frequency-domain signals by a fast Fourier transform (FFT) with size of 256 to perform channel estimation and equalization. Finally, the converted serial QAM signal is de-mapped into a base-band signal for the output.

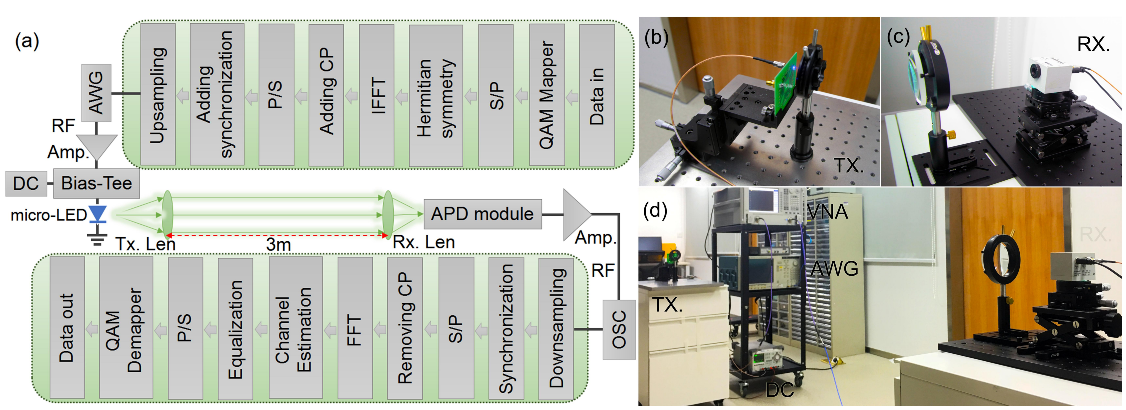

Fig. 2. (a) Schematic setup of the proposed micro-LED based QAM-OFDM VLC system; (b) Micro-LED transmitter and (c) APD 210 module receiver; (d) Images of the micro-LED based VLC system.(DC: direct current, Amp.: amplifier).

3. Result Analysis and Discussions

The normalized frequency response of the QD micro-LED based VLC system under different driving current was measured as shown in Fig. 3(a) and the values of -3 dB modulation bandwidth is extracted and presented in Fig. 3(b). When the driving voltage is 5 V, the modulation bandwidth can rise up to 1.06 GHz, and slightly decrease at 1.03 GHz under a 7-V driving voltage. The inset of Fig. 3(b) shows the received optical power under different current densities from 19.26 A/cm^2 to 528.54 A/cm^2. The BER performance of 4 QAM-OFDM with different data rates is illustrated in the Fig. 3(c). The maximum data rate can reach up to 4 Gbps with a corresponding BER of 3.2×10^{-3} which is slightly under the FEC threshold 3.8×10^{-3}. The received 4-QAM constellations under different data rates from 1 Gbps to 5 Gbps are also shown in the Fig 3(c).

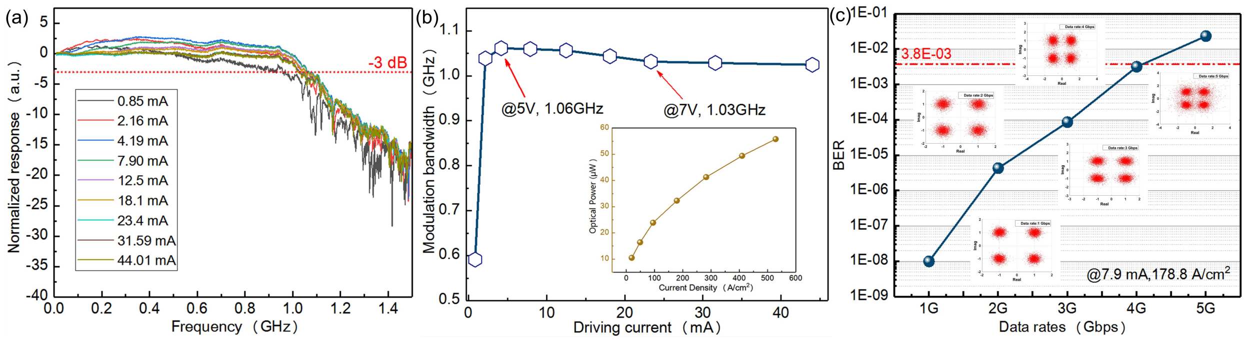

Fig. 3. (a) Normalized frequency responses of the VLC system with different driving currents; (b) the extracted 3 dB modulation bandwidth and received optical power; (c) The BER versus data rate at transmission distances of 3 m. (Inset: measured constellation diagrams for 4-QAM-OFDM with 1 Gbps, 2 Gbps, 3 Gbps, 4 Gbps and 5 Gbps data rate).

4. Conclusion

We have proposed and experimentally demonstrated a 4-Gbps high-speed VLC system based on QAM-OFDM by using a packaged ultra-high bandwidth 75 μm single layer QD blue-light micro-LED at an ultra-low current density 178.8 A/cm^2 over a transmission distance of 3 m for the first time. The corresponding BER of 3.2×10^{-3} is below the FEC threshold which indicates the potential of practical free-space implementation of this VLC system.

5. Acknowledgements

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