8.205-Gbit/s Visible Light Communication Utilizing 4×4 Si-substrate μLED-based Photodetector Array

Wenqing Niu[1], Jianyang Shi[1], Zengyi Xu[1], Dong Li[1], Weihuang Xiao[2], Guangxu Wang[2,*1], Jianli Zhang[2,*2] , Zhixue He[3] , Chao Shen[1] and Nan Chi[1,*3]

[1]Key Laboratory for Information Science of Electromagnetic Waves (MoE), Fudan University, No. 220, Handan Road, Shanghai, China
[2]National Institute of LED on Silicon Substrate, Nanchang University, Nanchang 330096, China
[3]Peng Cheng Laboratory, Shenzhen, China
*[*1]guangxuwang@ncu.edu.cn, [*2]zhangjianli@ncu.edu.cn, [*3]nanchi@fudan.edu.cn*

Abstract: We demonstrate an 8.205-Gbit/s VLC transmission over 0.5-m free-space link based on 4×4 Si-substrate InGaN/GaN MQW micro-LED-based photodetector array. Adaptive bit-power-loading scheme is applied to maximize the spectral efficiency for the OFDM VLC system. © 2022

1. Introduction

The next-generation (6G) wireless networks are expected to provide extremely high capacity and wide coverage [1], while the current wireless communication networks based on the radio-frequency (RF) spectrum are not sufficient to support the rapid growing demands. Hence, visible light communication (VLC), which uses the broad unlicensed spectrum resources ranging from 380 to 780 nm, has attracted worldwide interest.

Many research efforts have been invested in high-speed visible light transmitters, such as laser diodes (LDs), superluminescent diodes (SLDs), and micro light emitting diodes (μLEDs). However, as for receiver, the peak responsivity of most commercially available Si photodetectors (PDs) is near-infrared-light, and the broad-wavelength responsivity leads to background-light noise. Recently, GaN-based photodetectors have been demonstrated to offer gigabit-per-second visible light transmission [2]-[4]. In [2], a 3.2 Gbit/s orthogonal frequency division multiplex (OFDM) VLC system is demonstrated using InGaN/GaN c-plane MQW micro-PD (μPD) on sapphire substrate. The data rate has reached 7.4 Gbit/s based on semipolar InGaN/GaN MQW μPD [3]. Most of the reported works are on sapphire substrate or semipolar devices. Alternatively, Si-substrate GaN devices have the merits of low-cost, high heat conductivity and CMOS-compatible process, and thus Si-substrate μLED-based PD is worthy of investigation.

In this work, a 4×4 Si-substrate InGaN/GaN MQW μLED array is used as micro-photodetector array in a 0.5-m free space VLC system. A 450 nm LD is used as transmitter as the highest responsivity of the μLED-based PD array is within 375 to 500 nm. Adaptive bit-loading and power-loading scheme is used to maximize the spectral efficiency. Under the bias voltage of -11V for the μLED-based PD array, a record data rate of 8.205 Gbit/s is achieved with the bit error rate (BER) below 3.8×10^{-3}.

2. Micro-PD and Experimental setup

The optical microscope image of the device and the schematic of single μLED chip are shown in Fig.1 (a). The device is packaged in a lumen-like package. 4×4 μLED-based PDs are connected in parallel with a common P electrode. Each single μLED is fabricated into 50μm×50μm vertical structure on the Si substrate. A layer of Ag is deposited to increase single-side luminescence and provide good ohmic contact with P-GaN. The active region consists periods of InGaN/GaN multi-quantum wells.

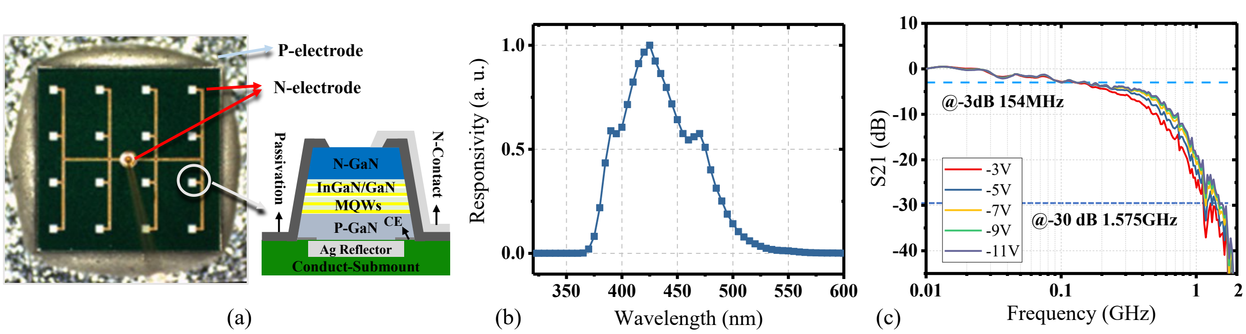

Fig.1. (a) Optical microscope image of the 4×4 μLED-based PD array and vertical structure of the single chip. (b) Normalized Responsivity spectrum. (c) Normalized frequency response measured at bias of -3 to -11V.

Fig.1 (b) is the measured responsivity of the μLED-based PD array. The responsivity spectrum (at -4V) exhibits high wavelength selectivity ranging from 375 to 500 nm and a maximum responsivity at the wavelength of 425 nm. The frequency response of the device is measured using a network analyzer (Agilent, N5230C). As Fig.1 (c) shows, as the inverse bias voltage increases from 3 to 11V the frequency response is improved. There is no significant improvement when the inverse bias voltage increases beyond 11V. The -3 dB bandwidth at -11V is approximately 154MHz, and the -30 dB bandwidth at -11V is approximately 1.575GHz. Although the frequency response is not flat, through frequency-division multiplexing, the frequency response of each individual subcarrier is supposed to be flat. Then suitable bit number and power ratio can be allocated adaptively to maximize the spectral efficiency.

In order to evaluate the performance in visible light communication system, a μLED-based PD array based OFDM VLC system is established. The experimental setup and the photos are shown in Fig.2. An arbitrary waveform generator (Tektronix, AWG710B) is used to convert the digital sequence into the analog signal. The sampling rate is 4 GSa/s. The peak-to-peak voltage of the transmitted signal is 1V. An electrical amplifier (EA, Mini circuits, ZFL-2500VH+) is used to amplify the transmitted signal. Then a bias-Tee (Mini circuits, ZFBT-4R2GW-FT+) is used to couple the signal and the bias current to drive the blue LD(OSRAM PL 450B) mounted on a portable optical platform as part of a tricolor-LD [5]. After 0.5 m free-space transmission and a focusing lens, the μLED-based PD array is used for optical-electrical (O/E) conversion. A source-measuring unit (Keithley 2641) is used to provide inverse bias voltage through the bias-Tee (Mini circuits, ZX85-12G-S+) and monitor the photocurrent. The output signal of bias-Tee is amplified by two cascaded EAs (Mini circuits, ZX60-43-s+), and then fed into an oscilloscope (OSC, Agilent MSO9254A). The sampling rate of OSC is 5 GSa/s.

The principle of bit-power loading OFDM scheme is in the upper of the schematic in Fig.2. In this experiment, 512 subcarriers are used, and the baud rate is fixed at 1.506 GBaud. First, the signal-to-noise ratio (SNR) of each subcarrier is estimated by transmitting OFDM quadrature phase shift keying (QPSK) signal as training signal. Next, according to the estimated SNR and expected bit error rate (BER) threshold, suitable bit number and power ratio are allocated through Levin-Campello (LC) algorithm [6]. Then, the bit sequence is mapped to quadrature amplitude modulation (QAM) symbol sequence. After up-sampling, serial to parallel conversion, inverse fast Fourier transform (IFFT), and adding cyclic prefix (CP), the real and imaginary parts of the complex-valued signal are multiplexed by $\cos(f_c t)$ and $\sin(f_c t)$ respectively for upconversion. As Fig.3 (a) shows, there is low-frequency noise in the system, and thus f_c is set as 776.5 MHz. After parallel to serial conversion, the signal is sent to AWG. At the receiver, the received signal is resampled and OFDM demodulated. A decision-directed least mean square (DD-LMS) equalizer is applied to recover the received signal. Finally, after QAM de-mapping, BER can be calculated.

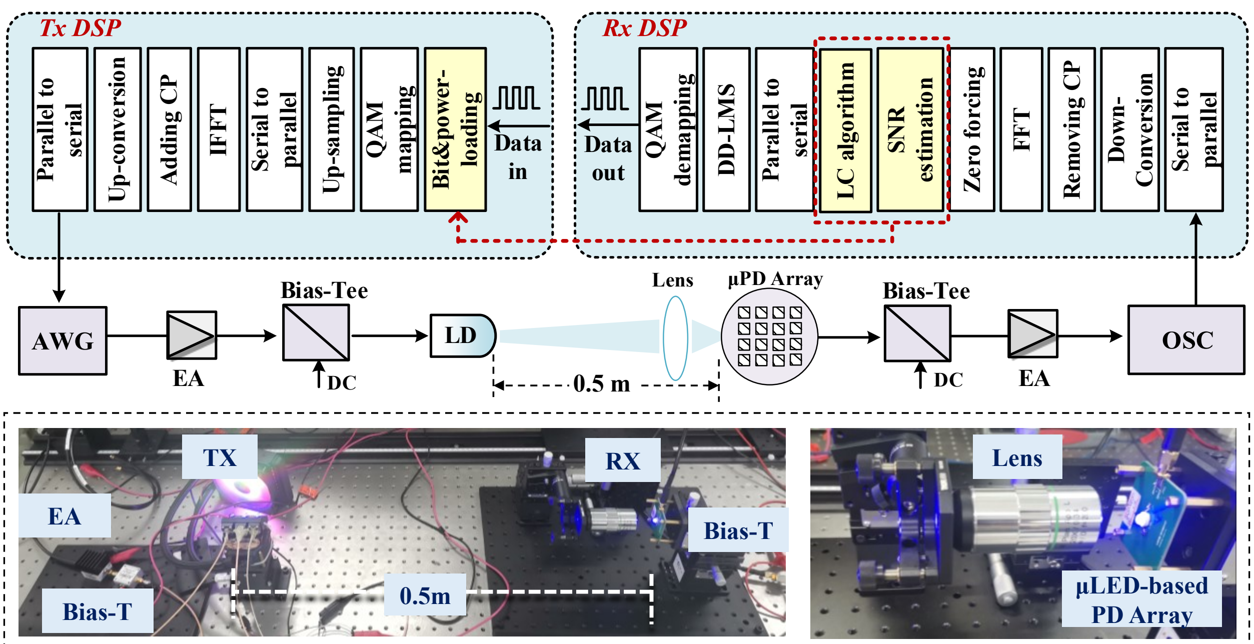

Fig.2. Experimental setup of the VLC system utilizing μLED-based PD array.

3. Results and Discussion

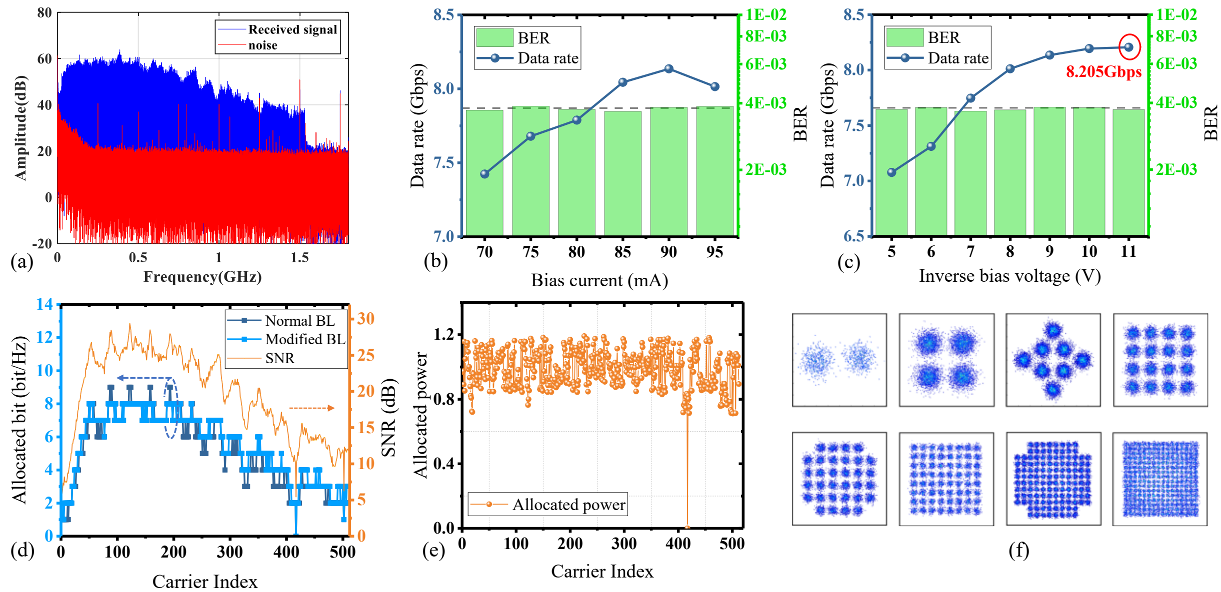

Fig.3. (a) Spectrum of the received signal and noise. Data rate and BER versus (b) bias current for the Tx LD, and (c) inverse bias voltage for the µLED-based PD array. (d) The SNR and allocated bit for subcarriers. (e) Allocated power for subcarriers. (f) Constellation diagrams with different bit number.

Fig.3 (b) illustrates the data rate and BER versus the bias current for the LD when the inverse bias current for µLED-based PD array is -9V. As bias current increases, there is a turning point. The optimal bias current in this system is 90mA. We have ensured that the BER can satisfy the hard decision forward error correction (HD-FEC) threshold. Next, the data rate and BER versus the inverse bias voltage of µLED-based PD array are measured under 90mA, the corresponding results are shown in Fig.3 (c). Obviously, as the inverse bias voltage increases, the data rate is improved. When the inverse bias voltage reaches 9V, the improvement becomes marginal. As a result, the data rate exceeds 8.205 Gbit/s at -11V under HD-FEC threshold of 3.8×10^{-3}. The spectral efficiency is 5.449 bit/Hz. The estimated SNR and allocated bit for subcarriers at the highest data rate are shown in Fig. 3 (d). The SNR curve exhibits fluctuations in the signal band. Note that although the normal bit loading (BL) curve indicates the highest bit number of 9 bit/Hz is feasible for several subcarriers, we modified the BL strategy that the highest bit number is no more than 8 bit/Hz in this system. In addition, due to the low-frequency noise shown in Fig.3 (a), the SNR is unsatisfactory in this region, so that the allocated bit number is decreased. The allocated power for subcarriers and constellation diagrams with different bit number are given in Fig. 3 (e) and (f) respectively. There is a sudden SNR drop at about 1.2 GHz, corresponding to the carrier index of 417, which is consistent with the measured frequency response in Fig.1 (c).

4. Conclusion

In this paper, we demonstrate a high-speed VLC system using a 4×4 Si-substrate InGaN/GaN MQW µLED-based PD array. The wavelength selectivity of the µLED-based PD array is within 375 to 500 nm. Adaptive bit-loading and power-loading scheme is used to maximize the spectrum efficiency in the OFDM VLC system. A record data rate of 8.205 Gbit/s is achieved when the bias voltage for the µLED-based PD array is -11V.

Acknowledgements

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5. Reference

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