High-speed White Light Visible Light Communication (VLC) Based on Semipolar (20-21) Blue micro-Light Emitting Diode (μ-LED)

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Abstract: We demonstrate a record 2.473-Gbit/s white-light visible-light-communication (VLC) using semipolar (20-21) blue InGaN/GaN μ-LED with yellow-phosphor. The measured 3-dB-bandwidth of blue and white lights are 1042.5 MHz and 772.4 MHz respectively.
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1. Introduction

The recent development of the high efficient solid-state lighting allows the light emitting diode to replace traditional lighting sources. White-light LED using blue LED with yellow phosphor is a low cost and popular choice for the illumination systems nowadays. Besides, visible light communication (VLC) based on white-light LED has attracted considerable attention in recent years [1]. VLC uses the visible light spectrum for communication; hence, it is license-free and electromagnetic-interference (EMI) free. It can also offer illumination and communication simultaneously. Recently, micro (μ)-LED has been extensively studied for the display industry. Due to the smaller chip size and lower junction capacitance, μ-LED is also a promising candidate for the high-speed VLC system. S. Mei *et al* reported a 300 Mbit/s VLC system based on a GaN blue μ-LED exciting perovskite quantum dots [2]. H. Cao *et al* demonstrated a 675 Mbit/s VLC system using a blue μ-LED combined with CdSe/ZnS quantum dots [3]. H. Chun *et al* reported a high speed 1.68 Gbit/s VLC system using a blue GaN μ-LED and a yellow fluorescent copolymer [4]. Besides, some high bandwidth white-light μ-LED based on blue LED with yellow phosphor [5] and InGaN yellow quantum wells [6] were reported. However, no VLC transmission results were presented. Table 1 summaries of different of white-light μ-LED performances. Moreover, traditional GaN-based LEDs are usually grown on "polar" (0001) c-plane sapphire substrate, which may result in a strong quantum-confined Stark effect (QCSE) decreasing the efficiency (i.e., efficiency droop) at high driving current density. Semipolar epitaxial structures could effectively suppress the QCSE [7]. They also offer shorter carrier lifetime, and larger modulation bandwidths than the c-plane LEDs.

Table 1 summaries of different of white-light μ-LED performances

Year	Conversion Method	Bandwidth (MHz)	Modulation	Data Rate
2014 [4]	Fluorescent Polymer	531 (White)	QAM-OFDM	1.68 Gbit/s
2018 [2]	Perovskite QDs	85 (White)	NRZ-OOK	300 Mbit/s
2018 [5]	Yellow Phosphor	127.3 (White)	–	–
2019 [3]	CdSe/ZnS QDs	637.6 (White)	NRZ-OOK	675 Mbit/s
2020 [6]	InGaN Yellow quantum wells	660 (White)	–	–
This work	Yellow Phosphor	1042.5 (Blue) 772.4 (White)	QAM-OFDM	2.473 Gbit/s

In this work, we demonstrate a record 2.473 Gbit/s high speed white-light VLC system using a blue semipolar (20-21) InGaN/GaN μ-LED array with yellow phosphor film for the first time up the authors' knowledge, fulfilling the pre-forward-error-correction bit-error-rate (pre-FEC BER = 3.8×10^{-3}) threshold. The correlated color temperature (CCT) of the white-light is 7500K. With better epitaxial technology and chip architecture design, the measured 3-dB-bandwidth of blue and white lights are 1042.5 MHz and 772.4 MHz respectively.

2. µ-LED Device Fabrication and Experimental Setup

Fig. 1(a) shows the architecture of the semipolar (20-21) blue µ-LED array. Metal organic chemical vapor deposition (MOCVD) was used to grow Ge-doped semipolar (20−21) GaN on top of a pattern sapphire substrate (PSS) with (22−43) orientation. The PSS was produced by inductively coupled plasma reactive-ion etching (ICP-RIE). Ge-doping was used to avoid the generation of stacking fault (SF) during GaN coalescence. After this, an un-doped GaN with thickness of 8 µm was grown as a bulk layer. Then, n-type GaN layer with thickness of 1.5 µm, InGaN/GaN single quantum well (SQW), and p-type GaN layer with thickness of 100 nm were grown. Finally, an indium tin oxide (ITO) layer with thickness of 200 nm was deposited. After the ITO and mesa etching, Ti/Al/Ni/Au with thickness of 20/125/45/75 nm was deposited as the electrodes. Al_2O_3/SiO_2 passivation layer was grown. Ti/Al/Au with thickness of 20/250/300 nm was deposited as metal pads. Fig. 1(b) shows the measured optical spectrum of the white-light µ-LED array with blue and yellow component peaks at 445 nm and 545 nm respectively. Fig. 1(c) shows the measured CIE 1931 color gamut, illustrating the color temperature of 7500 K white-light.

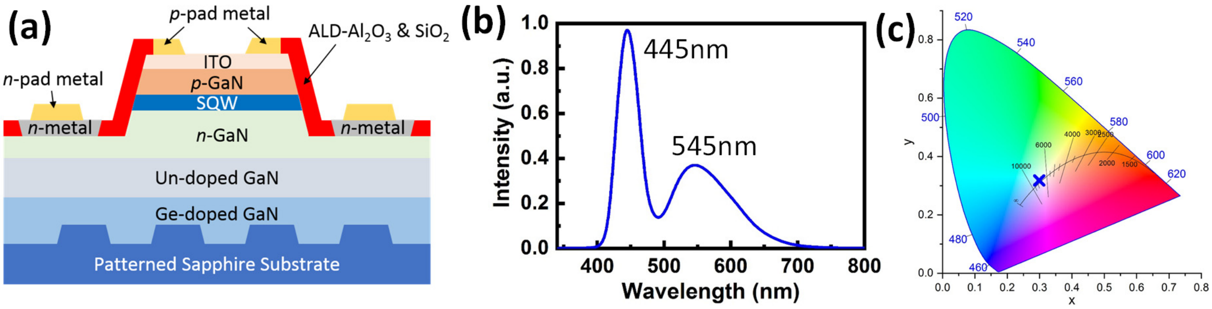

Fig. 1. (a) Architecture of semipolar (20-21) blue µ-LED array. Measured (b) optical spectrum and (c) CIE 1931 color gamut.

Fig. 2(a) shows the normalized frequency responses of µ-LED array driven at 40 mA measured by a vector network analyzer (VNA, Rohde & Schwarz®). The measured 3-dB-bandwidth of blue and white lights are 1042.5 MHz and 772.4 MHz respectively. Figs. 2(b) and (c) show the microscopic images of the proposed 2 × 4 µ-LED array at "OFF" and "ON" states respectively. The fabricated 2 × 4 µ-LED array is mounted on a sub-mount, which is soldered to a printed circuit board (PCB) for electrical driving. A yellow phosphor film is attached on the µ-LED array. Figs. 3(d) and (c) show the photos of the emitted white-light before and after a focusing lens is installed for VLC transmission.

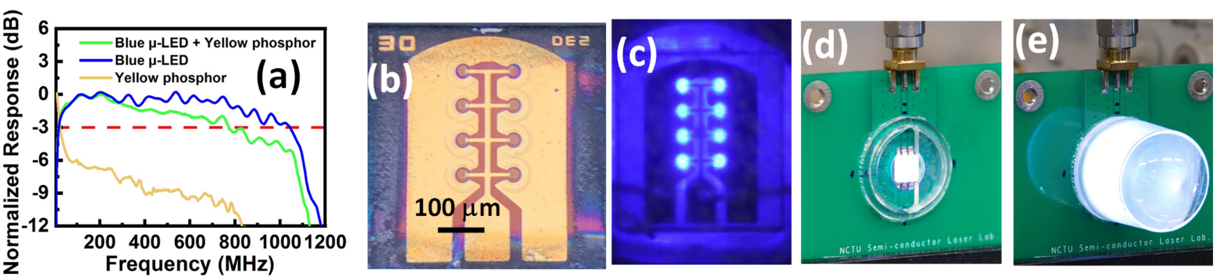

Fig. 2. (a) Measured normalized frequency responses of µ-LED array. Photos of microscopic images at (b) "OFF" and (c) "ON". Photos of emitted white-light (d) before and (e) after a focusing lens is installed.

Figs. 3(a) and (b) show the experimental setup and photo of the white-light VLC system using semipolar µ-LED array. The µ-LED was electrically driven by an arbitrary waveform generator (AWG; Tektronix® AWG70001) via a bias-tee. Orthogonal frequency division multiplexing (OFDM) signal with bit and power loaded was employed. The OFDM encoding and decoding procedure are illustrated in Figs. 3(a). During the OFDM encoding, random data was serial-to-parallel (S/P) converted, symbol mapping (SM) to different levels of quadrature-amplitude-modulation (QAM), and then inverse-fast-Fourier-transformed (IFFT). Afterwards, the data is parallel-to-serial (P/S) converted to insert the cyclic-prefix (CP). Then, the white-light OFDM optical signal was received by an avalanche photodiode (APD, Menlo Systems® APD210) connecting to a real-time oscilloscope (RTO, Teledyne LeCroy® 816ZI-B) after

~10 cm free-space transmission. No optical blue filter is employed. Fig. 3(a) also illustrate the OFDM decoding. When the received signal was CP removed. Then, S/P conversion, FFT, equalization, symbol de-mapping, and P/S conversion were performed.

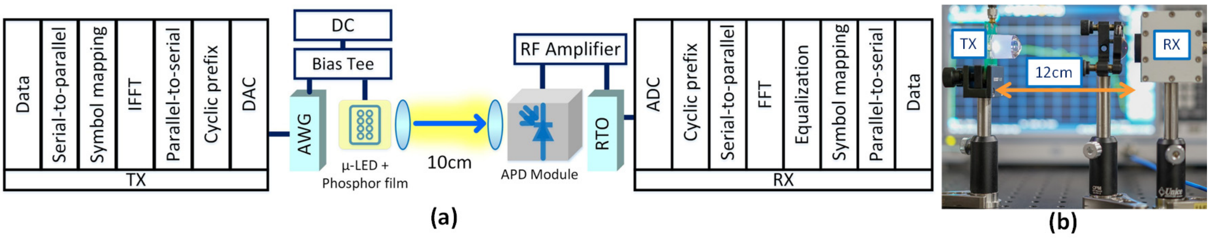

Fig. 3. (a) Experimental setup and (b) photo of the white-light VLC system using semipolar μ-LED array.

3. Results and Discussion

In the white-light VLC experiment, bit and power loaded OFDM signal was used to enhance the spectral efficiency. They were applied based on the received signal-to-noise ratios (SNRs) of different OFDM subcarriers. Figs. 4 (a)-(c) show the measured SNRs with bit-loading, power-loading, and BER performance of the white-light OFDM signal respectively. The average SNR of all the 220 OFDM subcarriers is 11.28 dB. For the higher SNR OFDM subcarriers, bit-loading order of 3, corresponding to 8-QAM is employed. For the lower SNR OFDM subcarriers, bit-loading order of 2, corresponding to quadrature phase shift keying (QPSK) is used. The corresponding constellation diagrams of 8-QAM and QPSK are shown in Fig. 4(b). The achieved net data rate of the white-light VLC system is 2.473 Gbit/s at BER of 2.73×10^{-3} at the received power of 0.43 mW, fulfilling the pre-FEC BER threshold.

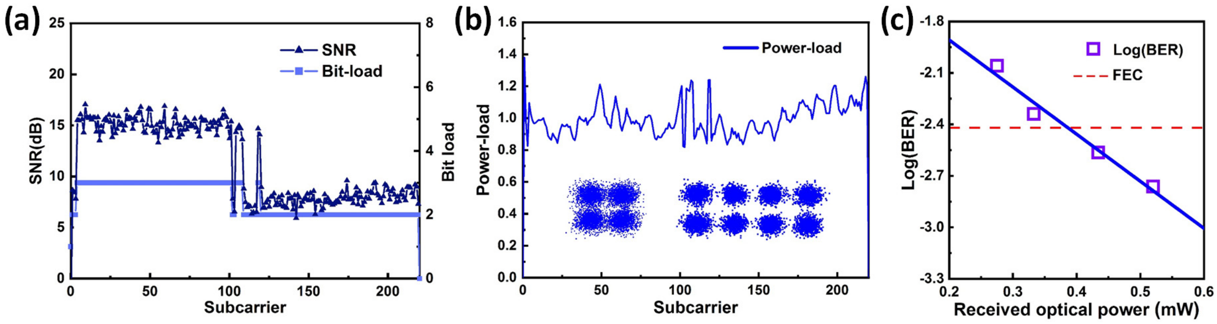

Fig. 4. Measured (a) SNRs and bit-loaded, (b) power-loaded, and (c) BER performance of white-light μ-LED array.

4. Conclusion

We demonstrated a record 2.473 Gbit/s high speed white-light VLC system using a blue (20-21) semipolar InGaN/GaN μ-LED array with yellow phosphor film with ~10 cm free-space transmission, fulfilling the pre-FEC BER threshold. The average SNR of all the 220 OFDM subcarriers is 11.28 dB. The CCT of the white-light is 7500K. The measured 3-dB-bandwidth of blue and white lights are 1042.5 MHz and 772.4 MHz respectively.

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