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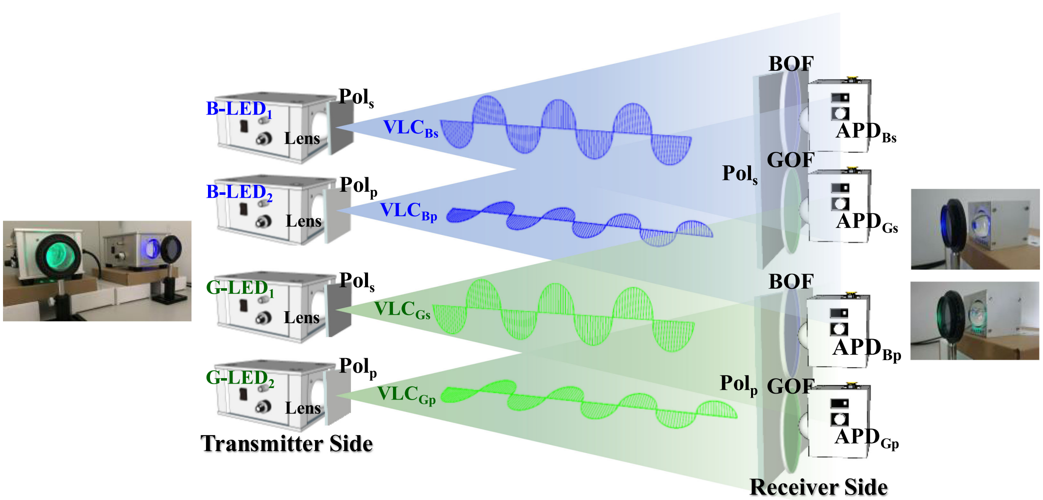
Chien-Hung Yeh
Jui-Hung Weng
Chi-Wai Chow
Chien-Ming Luo
Yue-Ru Xie
Chien-Ju Chen
Meng-Chyi Wu



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1.7 to 2.3 Gbps OOK LED VLC Transmission Based on 4 × 4 Color-Polarization-Multiplexing at Extremely Low Illumination

Chien-Hung Yeh,[1] **Jui-Hung Weng**,[1] **Chi-Wai Chow**,[2] **Chien-Ming Luo**,[1] **Yue-Ru Xie**,[1] **Chien-Ju Chen**,[3] **and Meng-Chyi Wu**[3]

[1]Department of Photonics, Feng Chia University, Taichung 40724, Taiwan
[2]Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[3]Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan

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Abstract: To achieve the high traffic rate of a GaN LED-based visible light communication (VLC), a 4 × 4 color-polarization-multiplexing system is demonstrated by using two blue and two green LEDs. In the measurement, an available bandwidth of blue and green LEDs can be greater than 465 MHz for VLC modulation traffic by using the suitable analogy front end circuit. Hence, the proposed VLC system can deliver 1.7 to 2.3 Gbit/s ON–OFF keying traffic rates in the free space transmission length of 1–4 m under the extremely low illumination of 6.9–136.1 lux for the indoor application. Moreover, the measured BER of each LED is less than the forward error correction target of 3.8×10^{-3} to maintain the better signal performance.

Index Terms: Visible light communication (VLC), LED, polarization-multiplexing, optical MIMO.

1. Introduction

Due to the advantages of long lifetime, high-efficiency, lower power consumption and cost-effectiveness, light-emitting diode (LED) is one of the most promising lighting devices for illumination [1]. Besides, LED is also a promising candidate in the visible light communication (VLC) system due to its wider bandwidth, network security, no electromagnetic interference (EMI), and license-free [2]. However, the available bandwidth of commercial LED devices is between 2 and 20 MHz [3], [4]. The insufficient bandwidth of LED would result in the lower modulation data rate of VLC traffic. To accomplish a higher transmission capacity of using commercial LED, employing pre- post-equalization techniques [3], [5]–[6], advanced modulation format [7], [8], optical parallel transmission method [9], wavelength-multiplexing RGB-LED [10], optical multi-input multi-output (MIMO) design [11], and polarization-multiplexing technique [12], [13] have been proposed and demonstrated. Moreover, to extend the modulation bandwidth to a few hundred MHz for VLC traffic, GaN-based characteristics LEDs have also been studied [14], [15]. However, the wide bandwidth

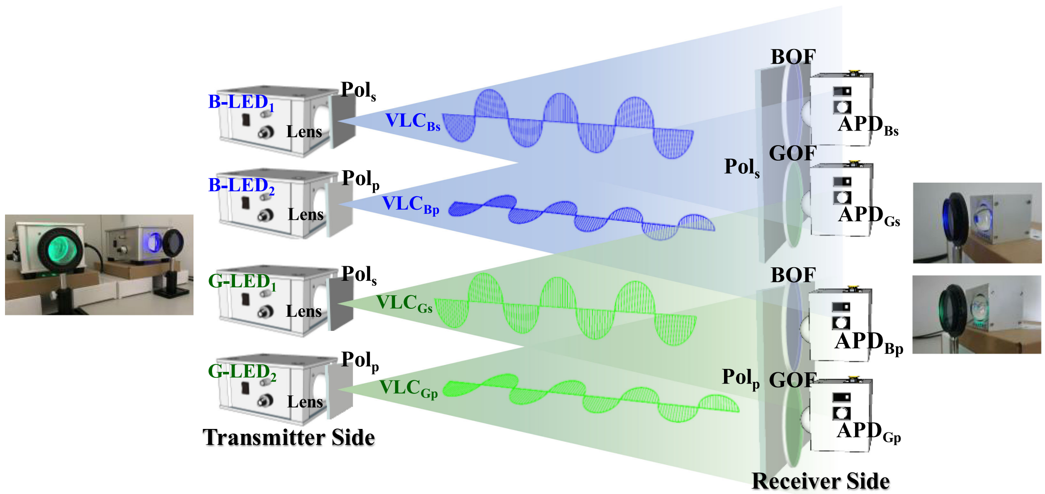

Fig. 1. Experimental setup of proposed 4 × 4 color polarization-multiplexing LED VLC transmission.

of GaN LED would also produce the weaker illumination for lighting. Furthermore, using commercial phosphor LEDs for VLC transmissions have also been demonstrated and worked well for the lighting and dense access network [16], [17].

In this paper, we first propose and investigate a 4 × 4 color-polarization-multiplexing method to obtain a higher traffic rate in the GaN-based LED VLC system. In the proposed VLC system, the available bandwidth of blue and green LEDs can be greater than 465 MHz for signal modulation when using suitable analogy front end (AFE) circuit together with pre-equalization. Here, the maximum modulation rate of blue and green LEDs can achieve 650 and 500 Mbit/s, respectively. Hence, two blue and two green LEDs are used simultaneously to deliver the 1.7 to 2.3 Gbit/s on-off keying (OOK) traffic rate in the proposed MIMO VLC system. Avalanched photodiode (APD)-based receiver (Rx) is used to support the wireless transmission lengths of 4 m under the very low illuminations from 6.9 lux. Moreover, the measured BER of each LED is less than the forward error correction (FEC) target of 3.8×10^{-3} to maintain the better signal performance.

2. Experiment and Results

To accomplish a higher transmission data rate in the LED-based VLC system, 4 × 4 color-polarization-multiplexing technique is proposed and demonstrated, as shown in Fig. 1. In the experiment, two blue-LEDs (B-LED_1 and B-LED_2) and two green-LEDs (G-LED_1 and G-LED_2) are used in the transmitter (Tx) side for delivering VLC traffic. As shown in Fig. 1, the focusing lens is placed in front of each LED for reducing the divergence range of VLC signal and increasing the detected illumination. Besides, we also add two orthogonal polarizers (Pol_s and Pol_p) in front of the B-LED_1 and B-LED_2, and G-LED_1 and G-LED_2, respectively, before sending the VLC signal. The Pol_s and Pol_p can achieve two orthogonal polarizations of B-and G-LED VLC signals, respectively. After passing through a free space transmission length, the four VLC signals are detected in the receiver (Rx) side. Here, the Pol_s, Pol_p, blue optical filter (BOF) and green optical filter (GOF) are also applied in the Rx side to allow and capture the corresponding VLC_{Bs}, VLC_{Gs}, VLC_{Bp} and VLC_{Gp} signals into the APD_{Bs} and APD_{Gs}, and APD_{Bp} and APD_{Gp} for decoding signal, respectively, as illustrated in Fig. 1. The photos of Fig. 1 are the corresponding setups of Tx and Rx sides. In addition, the corresponding lens can be also applied in Rx side to enhance the detected optical signal to noise ratio (OSNR). In the experiment, the field of view (FOV) and diameter of lens at the Tx side are 20° and 50 mm. Besides, the diameter of focus lens at the Rx side is also 50 mm. Therefore, the proposed 4 × 4 Color-polarization-multiplexing LED VLC can be applied for the static

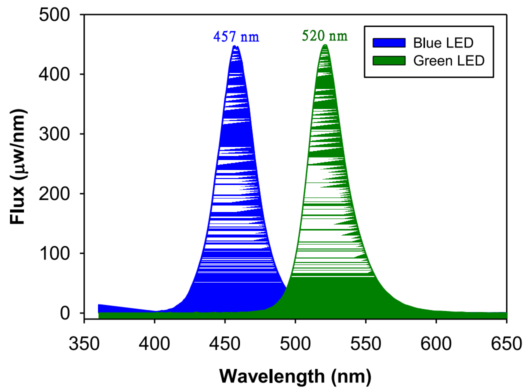

Fig. 2. Measured output spectra of the blue and green LEDs at the operated current of 9 mA.

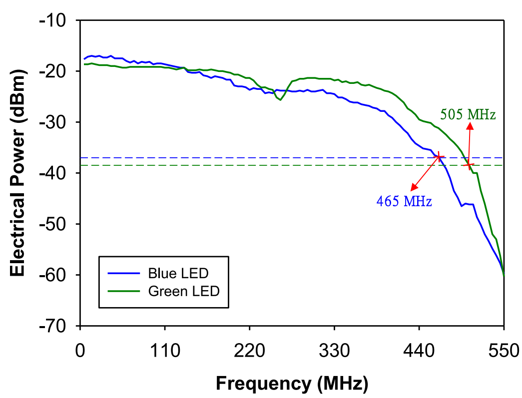

Fig. 3. Measured output spectra of the blue and green LEDs at the operated current of 9 mA.

free space optical communication (FSO) indoors. However, the intensity of unpolarized light would be halved after passing through the first polarizer. Besides, the second polarizer only induce 5% absorption. Overall, the polarizers could lower the illumination for VLC traffic and affect the OSNR performance.

In the experiment, we utilize two blue (B) and two green (G) GaN-based LEDs serving as the VLC signals. Moreover, the related fabrication and characteristic of the GaN-based LEDs are studied in the previous work [14]. Fig. 2 presents the measured output spectrum of B-and G-LED, respectively, when the operated currents are set at 9 mA simultaneously. Here, the spectra of Fig. 2 are measured after the second polarizer. The observed wavelength peaks are around 457 nm and 520 nm respectively. In VLC system, the effective modulation bandwidth of LED is very important issue for data transmission. Hence, first of all, we need to realize the available modulation bandwidths of B-LED and G-LED. Here, a properly analogy front end (AFE) circuit with pre-equalization is designed and utilized for measurement [17]. We add the properly bias current and modulated signal on AFE simultaneously to drive the LED for VLC transmission. Different bias current and free space transmission length would result in the various detected illumination. Here, we set the current of 9 mA to optimize the VLC traffic. We use the signal generator to produce electrical signal with -10 dBm input power applying on LED for scanning the frequency bandwidth from 0 to 550 MHz with 5 MHz measuring step. Then, the electrical signal is detected by APD through 1 m free space transmission. Hence, Fig. 3 shows measured electrical spectrum B-and G-LEDs, respectively. The measured 20 dB available bandwidths of B-and G-LEDs can accomplish 465 and 505 MHz respectively, as seen in Fig. 3. As a result, $>$450 MHz operation bandwidth of LED can be used to support the proposed 4 $\times$ 4 color-polarization-multiplexing VLC system at

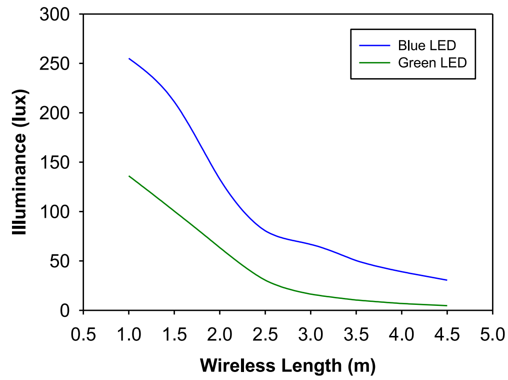

Fig. 4. Detected illuminations of the blue and green LEDs under different free space transmission lengths.

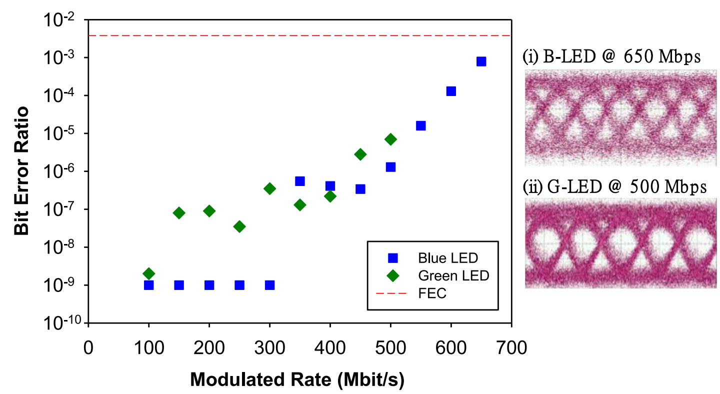

Fig. 5. Measured BER performances of B-and G-LED VLC traffics with various modulation rates in 1 m wireless transmission length. Insets of (i) and (ii) are the corresponding eye diagrams.

least. Here, the proposed VLC traffic is executed under general indoor lighting with illumination of 200 lux.

Then, we also measure the illuminations of B-and G-LEDs under the free space transmission length from 1 to 4.5 m, while the bias currents are operated at 9 mA. As shown in Fig. 4, the obtained illuminations of B-and G-LEDs are between 30.5 and 255.1 lux, and 4.7 and 136.1 lux, respectively. Moreover, the observed illuminations of B-and G-LEDs are 255.1, 132.8, 66.7 and 39.1 lux, and 136.1, 63.5, 16.4 and 6.9 lux, respectively, when the wireless transmission lengths are 1, 2, 3 and 4 m. In the measurement, the detected illumination from the G-LED is smaller than that of B-LED due to the different physical characteristics of the two LEDs. Next, we can utilize the non-return-to-zero pseudo random binary sequence (NRZ-PRBS) by using the bit error rate tester (BERT) to generate different on-off keying (OOK) modulation rates. Here, OOK modulation is used in order to reduce the complexity of the VLC Tx and Rx and facilitate the practical deployment. However, spectral efficient modulation formats of OFDM could be used in order to further enhance the transmission capacity in previous work [8]. Here, the $2^{15} - 1$ pattern length of OOK format can be applied on the B-and G-LED via the AFE circuit for directly modulation. Commonly, the free space length of indoor VLC is around 1 to 4 m. Hence, we would set the free space transmission length at 1 and 4 m to demonstrate the proposed 4×4 color polarization-multiplexing LED VLC system. To receive and decode the lower illumination of LED VLC signal, a 500 MHz bandwidth APD-based Rx is used in the experiment. Hence, the detected OOK signal can also be decoded by the BERT. Fig. 5 displays the measured bit error ratio (BER) performances of B-and G-LED VLC signals with the modulated rates from 100 to 650 Mbit/s, respectively, in a wireless transmission

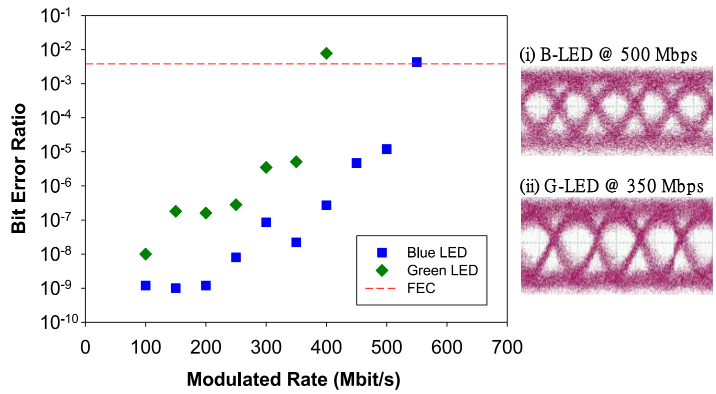

Fig. 6. Measured BER performances of B-and G-LED VLC traffics with various modulation rates in 4 m wireless transmission length. Insets of (i) and (ii) are the corresponding eye diagrams.

TABLE 1
Obtained Relationships of Color LED VLC Traffic, Corresponding Illumination and Wireless Transmission Length

Transmission Length (m)		1	2	3	4
Traffic Rate (Mbit/s)	Blue LED	650	600	550	500
	Green LED	500	500	400	350
Illumination (lux)	Blue LED	225.1	132.8	66.7	39.1
	Green LED	136.1	63.5	16.4	6.9
Total VLC Rate (Mbit/s)		2300	2200	1900	1700

length of 1 m. As illustrated in Fig. 5, with increase of modulation rates for the two LEDs gradually, the measured BERs also become worse. Besides, to meet the forward error correction (FEC) limit, the corresponding BER must be smaller than 3.8×10^{-3}. In the measurement, all of the observed BERs are less than FEC target of 3.8×10^{-3}. Here, the maximum modulation capacities of 650 and 500 Mbit/s are achieved for the B-and G-LED VLC traffics, respectively, as seen in Fig. 5. The insets of Fig. 5(i) and (ii) are the corresponding eye diagrams respectively. Compared with B-LED VLC traffic, only 500 Mbit/s of green VLC can be obtained due to the weaker illumination of G-LED. As a result, the proposed 4×4 B/G LED VLC system would accomplish the total traffic rate of 2300 Mbit/s after 1 m free space transmission length.

When the free space transmission length is 4 m long, the observed BER measurements of B- and G-LED VLC signals with the various modulation rates are shown in Fig. 6. According to the measured results, the maximum VLC capacities of B-and G-LEDs are 500 and 350 Mbit/s after through 4 m wireless traffic length, respectively, when the BERs are below than 3.8×10^{-3}. Here, the insets of Fig. 6(i) and (ii) are the corresponding eye diagrams. The two observed eyes are open and clear.

The relationships of color LED VLC traffic, corresponding illumination and wireless transmission length are also shown in Table 1. Hence, according to the measured results, the maximum total VLC rates are 2300, 2200, 1900 and 1700 Mbit/s, respectively, when the free space transmission lengths are 1, 2, 3 and 4 m in the proposed 4×4 color-polarization-multiplexing VLC system. The B-and G-LEDs can support higher VLC modulation capacity with lower illuminations from 6.9 to 225.1 lux under longer indoor wireless transmission length on the proposed VLC system. Compared to the previous studies [12], [13], their presented polarization-multiplexing VLC systems could accomplish the total data rates of 380 Mbit/s OFDM and 1 Gbit/s 16-QAM Nyquist modulations, respectively.

However, the free space transmission lengths of their proposed VLCs only reached <1 m together with larger illumination.

3. Conclusion

In summary, we proposed and investigated a 4 $\times$ 4 color-polarization-multiplexing technology to accomplish higher data rate of LED-VLC transmission. In the proposed optical MIMO VLC system, the 20-dB effective bandwidth of blue and green LEDs could be greater than 465 MHz for signal modulation, when the properly AFE circuit with pre-equalization was used in the Tx side. The maximum and minimum modulation rates of blue and green LEDs would achieve 650 and 500 Mbit/s, and 500 and 350 Mbit/s, respectively. Hence, two blue and two green LEDs were utilized simultaneously to achieve the 1.7 to 2.3 Gbit/s OOK total rate in the proposed MIMO VLC system. Here, OOK modulation was used to reduce the Tx and Rx complexity. However, spectral efficient modulation formats, such as OFDM can be used in order to further enhance the transmission capacity. In addition, the proposed LED VLC system also could provide a free space transmission length of 1 to 4 m together with the lower illumination from 225.1 to 6.9 lux for the indoor application. The measured BER of each LED would be less than the FEC target of 3.8 $\times$ 10^{-3} to complete the better VLC performance.

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