PHOTONICS Research

20.231 Gbit/s tricolor red/green/blue laser diode based bidirectional signal remodulation visible-light communication system

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We propose and experimentally demonstrate a recorded 1-m bidirectional 20.231-Gbit/s tricolor R/G/B laser diode (LD) based visible-light communication (VLC) system supporting signal remodulation. In the signal remodulation system, an LD source is not needed at the client side. The client reuses the downstream signal sent from the central office (CO) and remodulates it to produce the upstream signal. As the LD sources are located at the CO, the laser wavelength and temperature managements at the cost-sensitive client side are not needed. This is the first demonstration, to our knowledge, of a >20 Gbit/s data rate tricolor R/G/B VLC signal transmission supporting upstream remodulation. © 2018 Chinese Laser Press

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1. INTRODUCTION

Wireless communication is becoming more and more crucial in our daily lives. As the traditional radio-frequency communication band is highly congested, visible-light communication (VLC) has been proposed as a supplementary means of wireless communication providing high data rate (> gigabits per second transmission) and high security optical wireless communication for 5G and beyond mobile communication [1]. Although light emitting diodes have been traditionally used as transmitters (Txs) [2] in VLC, the demands of higher data rates in the gigabit per second range have brought laser diodes (LDs) under consideration as a potential Tx in VLC due to their much higher modulation bandwidth, beam convergence, and energy efficiency [3]. Demonstrations showed that LD-based VLC can provide illumination and communication simultaneously [4–6]. Although most LD-based VLC systems depend on line-of-sight transmission, in practical mobile systems, beam steering methods primarily used in free space optics can be employed. In the server room of a data center, visible laser light communication has been demonstrated to achieve a data rate of 100 Gbit/s by using the 8-LD multiple-input multiple-output technology [7]. Different LD-based VLC applications, such as for military underwater communications, have been reported [3]. Many LD-based VLC systems have been proposed and demonstrated. Lin *et al.* employed a 671 nm red LD and a 532 nm green LD to achieve a 500 Mbit/s VLC in 2012 [8]. Watson *et al.* employed a 422 nm GaN LD to achieve a 2.5 Gbit/s on–off keying (OOK) free-space transmission in 2013 [9]. In 2015, Lee *et al.* demonstrated a 4 Gbit/s OOK VLC transmission using a 450 nm GaN LD [10]; and Oubei *et al.* reported a 4.8 Gbit/s VLC transmission using a 450 nm LD with 16 quadrature-amplitude-modulation (QAM) orthogonal frequency division multiplexing (OFDM) format in underwater transmission [11]. In the same year, Chi *et al.* demonstrated a 9 Gbit/s high speed VLC free-space transmission using a 450 nm GaN LD [12]. Wu *et al.* reported an eye-safe red/green/blue (RGB) LD based VLC system for white-light communication, achieving a data rate of 8 Gbit/s [6]. Multicolor VLC systems using spatial multiplexing and color shift keying have been reported [13,14].

In the literatures, mainly single direction high speed LD-based VLC systems are reported. It is important to have a bidirectional transmission for practical VLC deployment. In this work, we propose and experimentally demonstrate a recorded bidirectional tricolor RGB LD-based VLC system supporting signal remodulation. In the signal remodulation system, an LD source is not needed at the client side. The client can reuse the downstream wavelength sent from the central office (CO) and remodulate it to produce the upstream signal. As the LD sources are located at the CO, the laser wavelength and temperature managements at the cost-sensitive client side are not needed; and the system could be cost effective and energy efficient. Here, the downstream is the tricolor RGB signal. A high spectral efficiency OFDM format with bit-loading is employed. A total data rate of 20.231 Gbit/s (R: 11.023 Gbit/s, G: 4.618 Gbit/s, B: 4.59 Gbit/s) OFDM downstream and 2 Mbit/s signal remodulated OOK upstream can be achieved in 1 m free-space transmission. This is the first demonstration, to our knowledge, of a >20 Gbit/s data rate tricolor RGB VLC signal transmission, with the support of upstream remodulation.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup of the tricolor RGB LD-based bidirectional VLC system. An arbitrary waveform generator (AWG, Tektronix AWG 7082C) acts as the digital-to-analog converter, which is used to produce the electrical OFDM signal to directly modulate the RGB LD at the CO. The LDs used in the CO are uncooled.

The three LDs are in TO packages with wavelengths of the red, green, and blue LDs of 676.6, 514.8, and 449.3 nm, respectively. Figure 2 shows the measured output optical powers against different biased currents of the R, G, and B LDs. The threshold currents of the R, G, and B LDs are 50, 45, and 20 mA, respectively. In the experiment, the output optical powers of the R, G, and B LDs are 3.7, 3.1, and 4.0 mW, which correspond to the biased currents of 58, 53, and 25 mA, respectively. The modulation bandwidth of each LD is about 1 GHz. The R, G, and B optical signals are combined at the CO via three dichroic mirrors (DMs) with different filtering characteristics. The inset of Fig. 2 shows the measured optical spectra of the R, G, and B signals.

Encoding and decoding of the OFDM signal are implemented by using offline MATLAB program. Figure 1(b) shows the OFDM signal encoding and decoding processes. During the OFDM encoding, the random data was first serial-to-parallel (S/P) converted. Then, symbol mapping (SM), inverse fast Fourier transform, parallel-to-serial conversion, and cyclic prefix (CP) (1/32) insertion are implemented. The fast Fourier transform (FFT) sizes of the red, green, and blue LDs were 256, 512, and 512, respectively. Based on the received signal-to-noise ratio

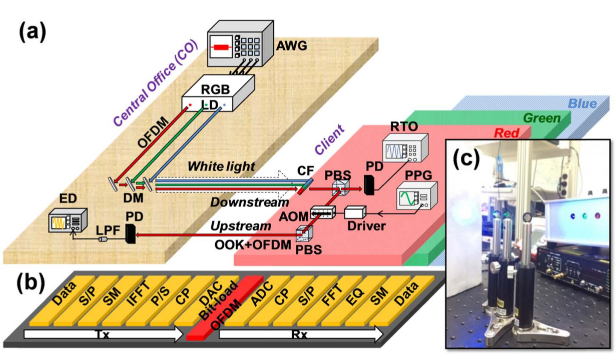

Fig. 1. (a) Experimental setup of tricolor RGB LD-based bidirectional VLC system. (b) OFDM signal encoding and decoding processes. (c) Photography of tricolor RGB LD to produce white light. AWG, arbitrary waveform generator; PBS, polarization beamsplitter; DM, dichroic mirror; PD, photodiode; RTO, real-time oscilloscope; CF, color filter; AOM, acousto-optic modulator; ED, error detector; PPG, pulse-pattern generator; LPF, low pass filter.

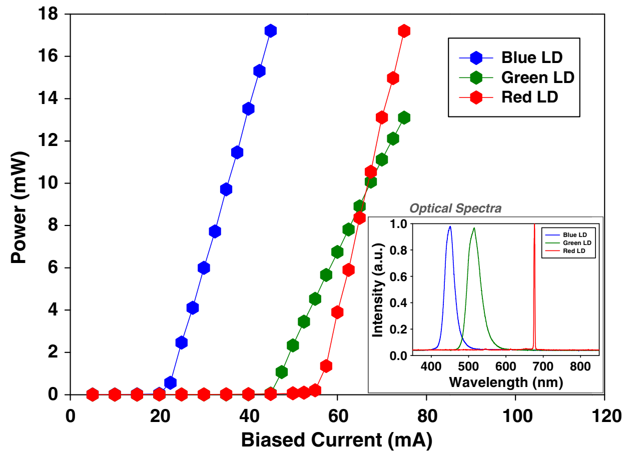

Fig. 2. Experimental output optical power and biased current responses of the RGB LDs. Inset: measured optical spectra.

(SNR) of each OFDM subcarrier, bit-loading schemes are employed, so that a high number of bits per symbol can be applied to the higher SNR OFDM subcarriers. Figure 1(c) shows the photograph of using the DMs to wavelength multiplex the RGB tricolor to produce the white light. After 1-m and 2.5-m free-space transmission distances, the tricolor RGB downstream signal is received at the client side. A paper is put between the CO and the user side to illustrate the combined white light.

Then the RGB signals are wavelength division demultiplexed by using three different color filters (red: 680 nm; green: 520 nm; blue: 450 nm) to select the red, green, and blue wavelength channels. In this VLC system, only the optical intensity of the LD is modulated, and the optical detection mechanism is based on intensity modulation/direct detection. The optical receiver used in the LD-based VLC is a silicon-based amplified positive–intrinsic–negative (PIN) photodiode (PD) (EOT, ET-2030A), which utilizes the photovoltaic effect to convert optical power into an electrical current, and a fixed gain trans-impedance amplifier for signal amplification. It has an optical-to-electrical bandwidth of 1.2 GHz, and active area diameter of 400 μm. A real-time oscilloscope (RTO, Tektronix DPO7354C) is used for OFDM demodulation. The RTO provided the function of an analog-to-digital converter for signal decoding and analysis. The OFDM decoding process is also shown in Fig. 1(b), including CP removal, S/P conversion, FFT, equalization, and SM. Finally, the bit-error ratio (BER) is calculated from the SNR of whole OFDM subcarriers. A survey of different channel models for VLC has been discussed in Ref. [15]. In general, VLC links can be classified as point-to-point links or diffuse links. As the transmission in this experiment is a few-meters indoor point-to-point link, the impacts of the channel, such as root mean square delay spread as well as the path loss due to different weather conditions, are negligible [15].

In order to produce the wavelength remodulated upstream signal, one part of the downstream signal will be taped out via a polarization beamsplitter (PBS). In this proof-of-concept demonstration, we use the red color channel to generate the upstream wavelength remodulation signal. The signal is launched into an acousto-optic modulator (AOM) connected to an electrical pulse-pattern generator (PPG) to produce the upstream OOK signal. Since there was only one AOM available in the laboratory, only the red upstream remodulated channel is demonstrated. The produced upstream remodulated signal is then received by another PIN PD connected to an error detector (ED) at the CO to measure the BER of the upstream signal.

At the CO, an electrical low pass filter (LPF) with 3-dB bandwidth of 20 MHz is connected after the PD to erase the high frequency downstream OFDM signal so that high quality of upstream remodulated OOK signal can be received. As the available AOM has a modulation bandwidth of only 1.8 MHz, we demonstrate the upstream remodulation operated at 2 and 1 Mbit/s. The upstream remodulated OOK signal is limited by the modulation bandwidth of the AOM, and higher data rates are possible if higher bandwidth AOMs are available.

3. RESULTS AND DISCUSSION

Figures 3–5 show the measured SNRs, bit-loading applied, and the corresponding QAM constellation diagrams for the red, green, and blue color channels, respectively. In the experiment, the modulation bandwidth of the red color LD is higher; hence higher SNR is observed in the red color channel and a high level of bit-loading is used. The highest bit-loading of 8 bits/symbol is applied to many low-frequency OFDM subcarriers as shown in Fig. 3(a), representing 256-QAM. For the green and blue color channels, the highest bit-loading of 6 bits/symbol is employed, representing 64-QAM. In the experiment, the tricolor RGB signal is transmitted over 1- and 2.5-m free space distances. The aggregated downstream data rate of 20.231 Gbit/s (R: 11.023 Gbit/s; G: 4.618 Gbit/s; B: 4.59 Gbit/s) is achieved at a 1-m transmission distance, and the aggregated data rate of 18.806 Gbit/s (R: 10.252 Gbit/s; G: 4.305 Gbit/s; B: 4.249 Gbit/s) is achieved at a 2.5-m transmission distance. All the R, G, and B channels after propagations of 1 and 2.5 m can satisfy the 7% hard-decision forward error correction (HD-FEC) threshold (the pre-FEC BER $\leq 3.8 \times 10^{-3}$ [16]).

Then, we evaluate the cross talk of the tricolor RGB channel. Figures 6–8 show the measured BER performances of the red, green, and blue color channels, respectively, with and without the operation of the other two color channels. The results show that the cross talks introduced by other adjacent channels are negligible.

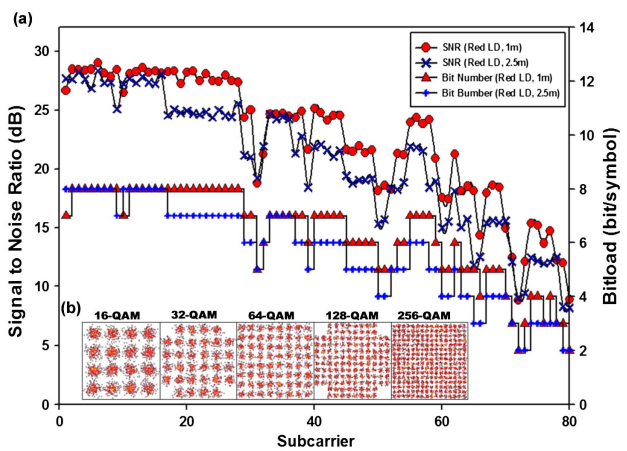

Fig. 3. (a) Measured SNRs and bit-loading of different OFDM subcarriers. (b) Constellation diagrams of 16, 32, 64, 128, 256-QAM of red LD.

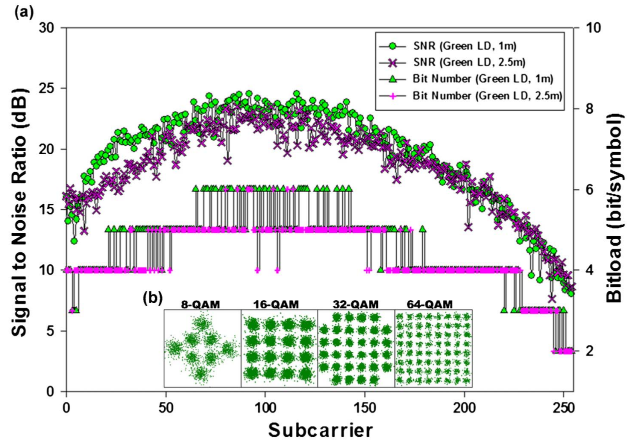

Fig. 4. (a) Measured SNRs and bit-loading of different OFDM subcarriers. (b) Constellation diagrams of 8, 16, 32, 64-QAM of green LD.

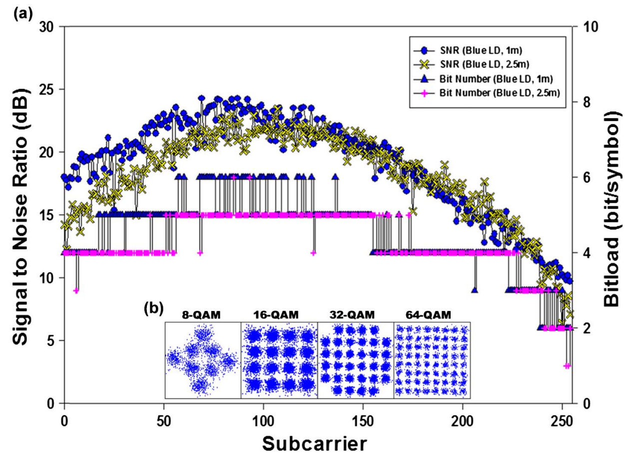

Fig. 5. (a) Measured SNRs and bit-loading of different OFDM subcarriers. (b) Constellation diagrams of 8, 16, 32, 64-QAM of blue LD.

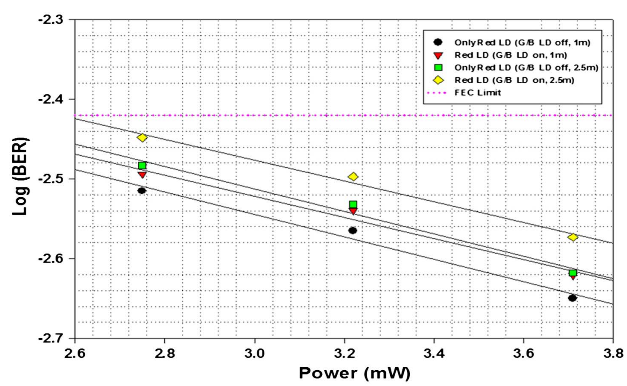

Fig. 6. Measured log(BER) of red LD at different received powers and influence on red LD with G/B LDs off and G/B LDs on.

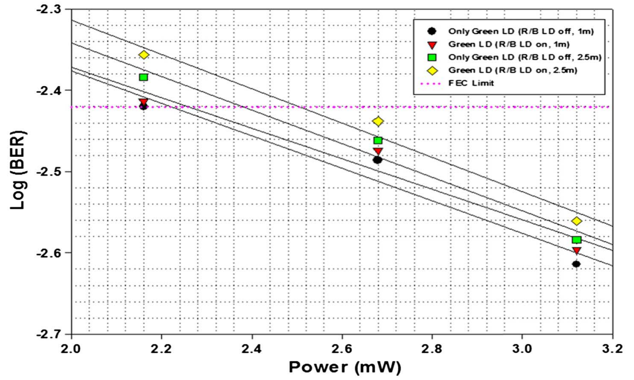

Fig. 7. Measured log(BER) of green LD at different received powers and influence on green LD with R/B LDs off and R/B LDs on.

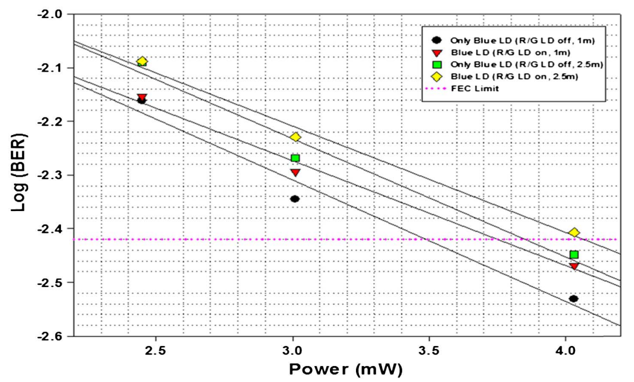

Fig. 8. Measured log(BER) of blue LD at different received powers and influence on blue LD with R/G LDs off and R/G LDs on.

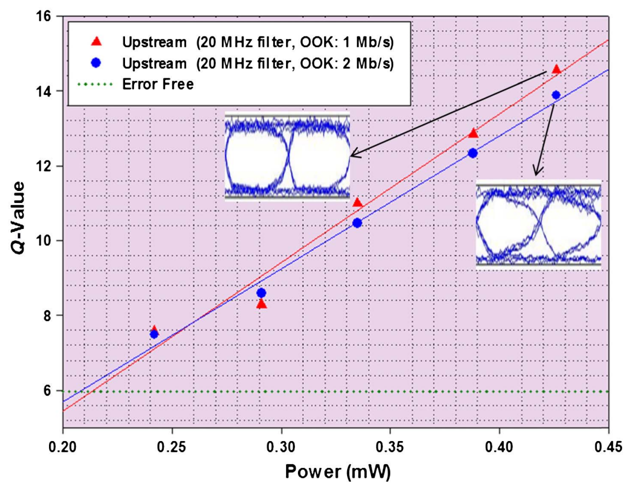

Fig. 9. Measured Q-value of the remodulated upstream OOK signal (red points: 1 Mbit/s, blue points: 2 Mbit/s) against different received optical powers when different LPFs are used.

Figure 9 shows the Q-value measurement of the upstream remodulated OOK signal at data rates of 2 and 1 Mbit/s. As the LD sources are located at the CO, the laser wavelength and temperature managements at the cost-sensitive client side are not needed. The results show that very low received optical power is needed to detect the upstream remodulated OOK signal; hence this facilitates the deployment of the signal remodulation VLC system. Error free (BER $< 10^{-9}$) transmission is observed when the received optical power at PD is >0.24 mW.

4. CONCLUSION

In this work, we proposed and experimentally demonstrated a recorded 20.231 Gbit/s (R: 11.023 Gbit/s; G: 4.618 Gbit/s; B: 4.59 Gbit/s) 1-m bidirectional tricolor RGB LD-based VLC system supporting signal remodulation. As the LD sources are located at the CO, the laser wavelength and temperature managements at the cost-sensitive client side are not needed. The cross talks introduced by adjacent color channels in the RGB LD-based transmissions were evaluated. 2 Mbit/s remodulated error-free OOK upstream signal was achieved. The data rate was limited by the AOM available; higher upstream data rates are possible. This work is the first demonstration of >20 Gbit/s VLC signal transmission with the support of upstream remodulation.

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