Ultrafast Perovskite Color Conversion of Blue Laser Diode for White-Lighting Optical Wireless Link

Yi-Chien Wu (1)(2), Chih-Hsien Cheng (1)(5), Hao-Chung Kuo (3), Jr-Hau He (4), Gong-Ru Lin (1)(2)

(1) Graduate Institute of Photonics and Optoelectronics, and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan R.O.C., grlin@ntu.edu.tw.
(2) NTU-Tektronix Joint Research Center, National Taiwan University, Taipei, Taiwan R.O.C..
(3) Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan R.O.C..
(4) Department of Materials Science and Engineering, City University of Hong Kong, Kowloon, Hong Kong SAR 999077, China.
(5) Research Center for Advanced Science and Technology, University of Tokyo, Tokyo 153-0041, Japan.

Abstract *The ultrathin perovskite paper enables the color-converted white-lighting of an 80-mW blue laser diode without severely compromising its encoding bandwidth to demonstrate a 9-Gbit/s 8-QAM-OFDM optical wireless data link over 0.3-m free-space after waveform pre-leveling.*

Introduction

Optical Wireless or visible light communication (OWC or VLC) link using visible light-emitting diodes (LEDs) or laser diodes (LDs) accompanied with white lighting for light-fidelity (Li-Fi) has recently attracted much attention due to its capability of network coverage with microwave wireless links. Various scenarios of the lighting OWC have been combined with display panels, traffic signs, and ubiquitous lighting modules to provide multi-functional smart optical hardwares with superiorities of electromagnetic immunity and directional security. However, the lower modulation bandwidth of LEDs inevitably limits the OWC/VLC data capacity. Hence the LDs with broader bandwidth and higher efficiency gradually take over the LEDs for latter development nowadays. In 2015, Chi et al. preliminarily proposed the QAM-OFDM encoded 450-nm GaN blue LD for OWC at 9 Gbps. Later on, the same group used the BLD and yellow phosphor for white lighting at CCT of 5217K and indoor OWC at 5.2 Gbps. Chun et al. converted the BLD light with remote phosphor to generate 7092K cold white light OWC at 6.52 Gbps at 0.35 m. Dursun et al. proposed the perovskite nanocrystal with a short luminescent lifetime of 7 ns for white-lighting OWC at 2 Gbps in 2016. In view of previous works, the raw data rate of the perovskite color converted BLD white-light source seldom exceeds over 5 Gbps. In this work, an ultrathin perovskite paper is employed to convert a 450-nm BLD beam for the desktop white-lighting OWC over 0.3 m. After analysing the color coordinates, CCT, and illuminance for lighting performance, the biasing and encoding parameters of the BLD are optimized to provide the highest data rate for the back-to-back and free-space OWC data links. By performing the power pre-leveling of the QAM-OFDM data in the frequency domain, the ultrathin perovskite paper enables the color-converted white lighting without compromising the encoding bandwidth of the BLD for 8/16-QAM OFDM data transmission.

Experimental Setup

The experimental setup of the white-light transmission system composed of a BLD and perovskite was shown in Fig.1. This white-light transmission system could be divided into two parts. One is the pure point-to-point BLD based transmission in 30-cm free space and another is the BLD+perovskite based white-light transmission in 30-cm. In the beginning, the homemade Matlab program was used to construct the OFDM data format with an FFT size of 512, which was loaded into the arbitrary waveform generator (AWG, Keysight M8195A) with a sampling rate of 16 Gs/s to generate the electrical data stream. The electrical QAM-OFDM data stream was amplified by a preamplifier (Tektronix, 5866) with a gain of 24 dB. Then, a bias tee was set to combine with the

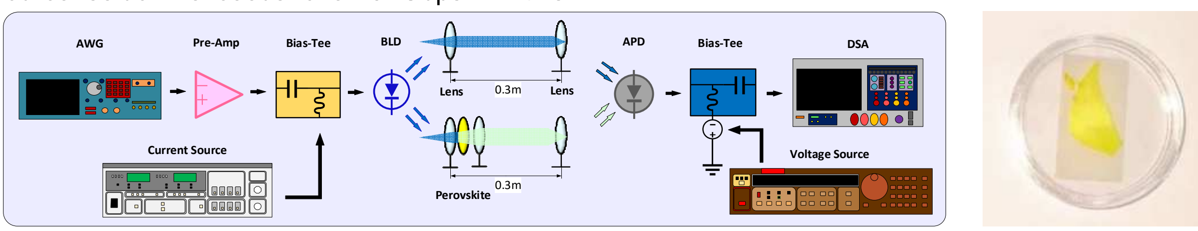

Fig. 1: The experimental setup for color-converting communication and the photograph of the perovskite

corresponding DC bias current DC and the amplified electrical QAM OFDM data stream for direct modulating the BLD. To focus the dispersed BLD beam into a parallel beam, a flat-convex lens with a focal length of 2.5 mm was placed at the front of the BLD. After the 0.3-m free-space transmission, another plane convex lens with a focal length of 5 cm was utilized to refocus the parallel beam into an avalanche photodiode.

In the white-light transmission system, the perovskite was placed behind the focused BLD beam via a front flat-convex lens to perform the color conversion. Then, the second plano-convex lens with a focal length of 5 cm was set behind the perovskite to focus the white-light beam. After the 0.3-m free-space propagation, a plane convex lens was used to refocus to be detected by the APD. At the receiving end, another bias-tee was employed to separate the DC bias and the received data stream. The received QAM OFDM data stream passed through a limiter and a DC block to isolate the DC component and transmitted to a real-time digital oscilloscope to pick up the waveform in the time domain. Finally, the received QAM OFDM data stream was demodulated via a homemade MATLAB program.

Results and Discussions

The power-current (P-I) and voltage-current (V-I) responses of the BLD are shown in Fig. 2(a). In Fig. 2(a), the threshold current of the BLD is measured as 22.5 mA with a corresponding slope efficiency of 1.06 W/A above the threshold current. The maximal output power of the BLD before saturation was obtained as 135 mW at the biased current of 150 mA. Furthermore, the linear resistance of the BLD can be evaluated as 10.1 Ω by using the V-I response. Fig. 2(b) exhibits the slope efficiency and the differential resistance obtained from the P-I and V-I curves of the BLD. The differential resistance (dV/dI) of the BLD was gradually decreased around 26 Ω above the threshold. The optimal differential resistance of the BLD for the direct modulation is chosen as 19 Ω (I_{BLD}=45 mA), and the corresponding reflection coefficient (Γ) for BLD is calculated as -0.45. Moreover, the related voltage standing wave ratios (VSWR) were 49 and the return loss ($\eta_{RL}=-20\log10(|\Gamma|)$) is obtained as 6.94 dB. To find out the operating current range to perform the linear modulation, the slope efficiency (dP/dI) was calculated by differentiating the P-I curve. The slope efficiency of the BLD is slowly decreased with a slope of -0.0003 W/A by increasing the bias current, as shown in Fig. 2(b). Fig. 2(c) displays the Committee International del1'Eclairage chromatic coordinates (CIE) and spot size of the BLD+perovskite based white light. The maximal illuminance of 18.9 lx is observed at the center of the light spot at 0.3 m. In addition, the CIE of the BLD+perovskite based white light was also measured as (0.1636, 0.0203).

Fig. 3(a) illustrates the analog modulation frequency response of the BLD within and without the perovskite at different bias currents. Raising bias currents effectively stretches the flattened response and increases the up-shifted relaxation oscillation frequency for the pure BLD. After passing through the perovskite color converter, the divergence caused by perovskite reduces the optical power and further affects the transmission capacity. In Fig. 3(a), the modulation throughput was extremely attenuated about 17 dB after applying the perovskite as a color converter. Furthermore, the frequency response of the BLD+perovskite based white light is the same as that of the BLD even though the perovskite induces the huge loss. It indicates that the lifetime of the perovskite is much smaller than that of the BLD. However, the over-driven bias current can induce the clipping effect to decline the frequency response. Fig. 3(b) reveals the received BERs of 3 GHz 16-QAM OFDM data stream carried by a BLD at different bias currents. With enlarging the BLD bias from 55 mA to 65 mA, the received BERs reduces from 3.9×10^{-3} to 2.6×10^{-3}. The received BER is further degraded to 6.0×10^{-3} when the bias current is operated beyond 75 mA. Therefore, the optimized bias current of the BLD is selected as 75 mA. In principle, the pre-leveling method uses a rising exponential function to perform the signal optimization. The BER performances of the 16-QAM QAM OFDM data carried by BLD with and without a pre-leveling at different modulation bandwidths are shown in

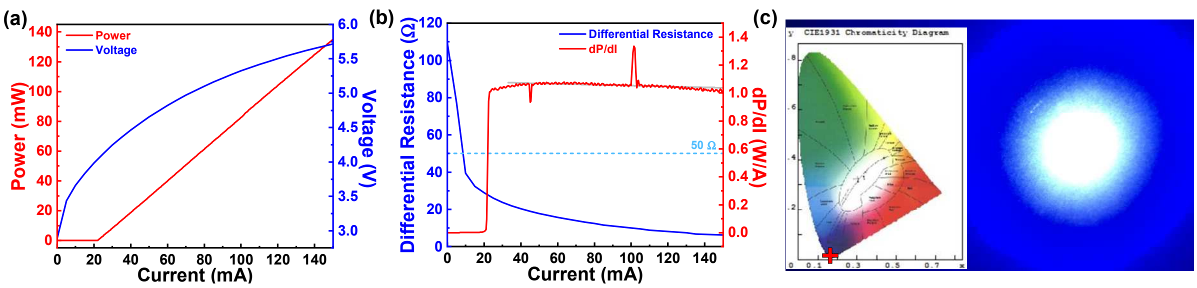

Fig. 2: (a) The P-I and V-I and (b) dP/dI and dV/dI curves of the 80-mW BLD; (c) The CIE and light spot of the BLD+perovskite

Fig.

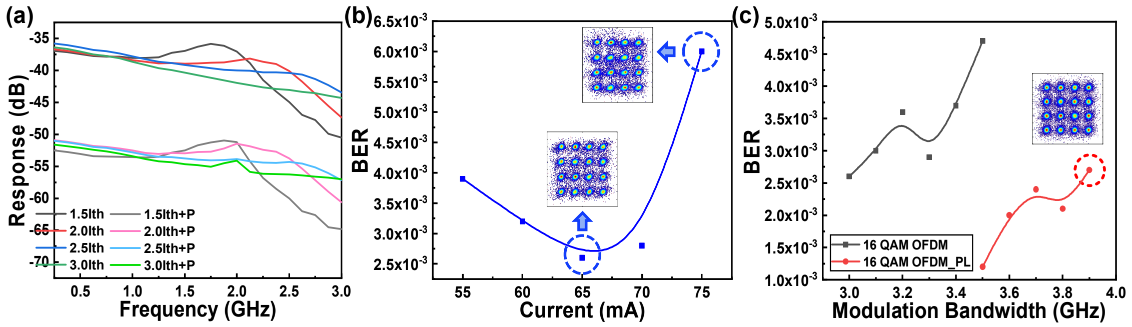

Fig. 3: (a) The frequency response of the BLD and BLD+perovskite mixed white light. (b) The BERs of the 16-QAM OFDM data carried by BLD at different bias currents. (c) The BERs of the OFDM data carried by BLD with/without a pre-leveling at different modulation bandwidths

3(c). Without the pre-leveling, the modulation bandwidth of the 16-QAM QAM OFDM data is increased from 3 GHz to 3.5 GHz with the corresponding BER degrading from 2.6 $\times 10^{-3}$ to 4.7×10^{-3}, which does not meet the BER standard of 3.8 $\times 10^{-3}$ by the FEC criterion. After the pre-leveling to optimize, the modulation bandwidth can be increased from 3.5 GHz to 3.9 GHz and the improved BER value increases from 1.2×10^{-3} to 2.7×10^{-3}. Without pre-leveling, the proposed 13.6 Gbps data rate of 16-QAM OFDM over 0.3-m propagation could be achieved by using 80 mW BLD with an optimized P-I slope. By pre-upgrading 16-QAM OFDM subcarriers, the data capacity could be further expanded to 15.6 Gbps with an EVM of 16.6454 %, an SNR of 15.5741 dB, and an FEC qualified BER of 2.7×10^{-3}. In addition, the PAPR at the probability of 0.1 is evaluated as 9.2 dB.

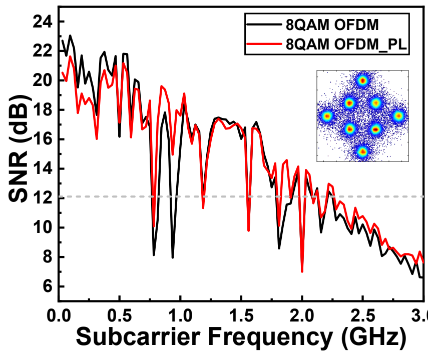

Fig. 4: SNR spectra of the 3-GHz 8-QAM OFDM data carried by BLD+perovskite mixed white light with/without a pre-leveling.

By adhering the perovskite in the front of the BLD, the white-light source can be produced by mixing the excited green-yellow light with diverged blue light. Because of the scattering and absorption induced by the perovskite film, the SNR is much smaller than that of the pure BLD based transmission. Hence, the filtered 8-QAM OFDM data is employed to achieve the maximal transmission capacity, and the optimized pre-leveling slope has to be modified as well. With using the pre-leveling slope of 0.2 dB/GHz, the SNR of the filtered 8-QAM OFDM data is measured as 11.9 dB with a corresponding BER of 4.3×10^{-3}, which indicates that the power throughput at the high-frequency region is hard to fully compensate. However, when the pre-leveling slope enlarges above 0.5 dB/GHz, the data power carried by the low-frequency subcarriers will be seriously sacrificed to degrade the BER of 4.9×10^{-3} and SNR of 11.74. Therefore, the optimized pre-leveling slope is selected as 0.4 dB/GHz. Fig. 4 shows the SNR of the 3-GHz 8-QAM OFDM data carried by the BLD+perovskite mixed white light with and without pre-leveling shown in Fig. 4. The 8-QAM OFDM data carried by the BLD+perovskite mixed white light can obtain an EVM of 23.76%, an SNR of 12.48 dB, and a BER of 2.5×10^{-3} at a total data rate of 9 Gbps.

Conclusion

The ultrathin perovskite paper encapsulated 80-mW BLD enables the color-converted white-lighting and the desktop optical wireless communication, which achieves a breakthrough on the encodable data rate by using the QAM-OFDM format after power pre-levering. In comparison with the 16-QAM OFDM encoded BLD back-to-back transmission at an allowable data rate of 15.6 Gbps, the perovskite color-converted BLD white-light slightly reduces the encodable bandwidth to nearly 3 GHz for 8-QAM OFDM transmission at 9 Gbps due to divergent lighting and power dissipation.

References

[1] Y.-C. Chi *et al.*, “450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM,” Opt. Express 23, 13051-13059 (2015).

[2] H. Chun, *et al.*, "Visible Light Communication using Laser Diode based Remote Phosphor Technique," IEEE Communication Workshop (ICCW), London (2015).

[3] Y.-C. Chi, *et al.*, “Phosphorous diffuser diverged blue laser diode for indoor lighting and communication,” Sci. Rep 5, 1–9 (2015).

[4] I. Dursun, *et al.*, “Perovskite Nanocrystals as a Color Converter for Visible Light,” ACS Photon., vol. 3, pp.

1150-1156 (2016).