Miniature R/G/V-LDs+Y-LED Mixed White-Lighting Module with High-Lux and High-CRI for 20-Gbps Li-Fi

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Abstract: Miniature white-lighting beam mixed by R/G/V-LDs+Y-LED module with high illuminance of 12800 lux, high color-rendering-index of >60 is demonstrated for vehicle light fidelity or distant optical wireless lighting transmission at data rate beyond 20 Gbps.

OCIS codes: (250.5960) Semiconductor lasers; (060.4510) Optical communications; (140.7300) Visible lasers; (140.0140) Lasers and laser optics; (060.4080) Modulation

1. Introduction

Versatile lighting modules based on visible LEDs and LDs have been configured to achieve the dual-purpose distant white lighting and optical wireless transmission scenarios for free-space and under-water applications. Such a visible lighting communication (VLC) or lighting fidelity (Li-Fi) was emerged as an exceptional candidate in the optical wireless communication (OWC) family, as it features better security and higher capacity than present wireless-fidelity (Wi-Fi) for data broadcast. To extend this supplementary solution from local to distant access networks and to fulfill the rapidly increasing demand on high-speed OWC link in free-space environments, high-power visible LDs with larger power efficiency and broader modulation bandwidth has gradually taken over LEDs to perform white-lighting with using either the phosphor adhered blue/violet LD or the tri-color mixed LD solution [1-3]. Even though, the former solution usually consumes more LD power for color conversion such that its transmission speed is severely degraded by preserving the white lighting performance, whereas the latter one with either red/blue/green (RGB) or red/blue/violet (R/G/V) tri-color LD mixed solution still suffers from its low color rendering index (CRI), large beam collimating and wavelength demultiplexing losses. Another obstacle is that most LDs enlarge their emission power to facilitate distant lighting at the cost of reduced modulation bandwidth. In this work, the high-power R/G/V-LDs+Y-LED module is packaged in a miniature four-color beam combiner for high-speed VLC and OWC applications. The emission power, the modulation bandwidth and the color rendering index (CRI) of the R/G/V-LDs mixed beam are comprised one another for performing high-lux, high-speed and high-CRI white lighting. The Y-LED with broad yellow emission spectrum is added to compensate the narrow spectral linewidth provided by the R/G/V-LDs for improving the CRI performance. The performances including illuminance, divergent angle, CCT/CRI and digital QAM-OFDM transmission for such a minimized high-power R/G/V/Y mixed white-lighting module is with visible wavelength division multiplexing functionality is analyzed in detail.

2. Experimental Setup

The high-power R/G/V/Y white-lighting module with its miniature size of W×L×H = 6×5.4×2 cm^3 and the digital QAM-OFDM transmission setup are shown in Fig. 1. To collimate the divergent beams for obtaining achromatic lighting spot, four anti-reflective coated glass lens collimators were packaged at the output ports of R/G/V LDs and Y-LED. The green light was firstly reflected by a prism mirror, and the other three color lights were individually reflected by related dichroic mirror combiners. Afterwards, a frosted glass diffuser was employed to diverge the mixed white light with suppressed chromatic aberration. The R/G/V/Y module was temperature controlled at 25^{o}C to stabilize their transmission performance.

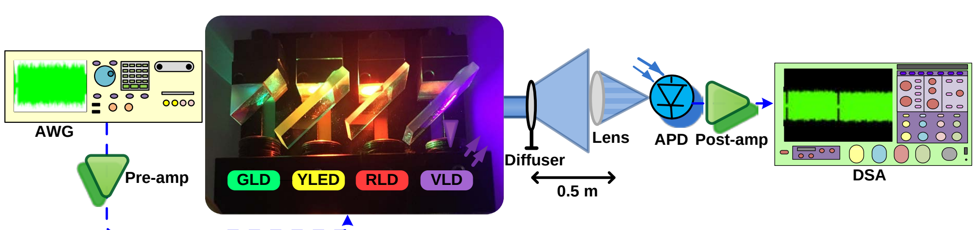

Fig. 1. The photograph of the miniature R/G/V/Y module and the experimental setup for white-lighting communication.

Different sets of the 16-QAM OFDM data streams for OWC transmission were generated from Tektronix 70001A arbitrary waveform generator and combined with DC bias current to encode the R/G/V LDs individually. After free-space transmitting through 0.5 m, another plano-convex lens was used to refocus the divergent white-light beam for receiving by an avalanche photodiode. The received data waveform was post-amplified and captured by Tektronix 71604C digital serial analyzer and decoded by a homemade MATLAB program. The high-power Y-LED was not used for data transmission because of its extremely low modulation bandwidth. A colorimeter (OKTEK, GL-2) was employed to analyze the CCT, CRI and CIE coordinate, and a lux meter (TECPEL, 530) was used to analyze the illuminance and divergence of the miniature R/G/V/Y mixed white lighting module.

3. Results and Discussion

To adjust the CCT and CRI of the R/G/V/Y four-color mixed high-power and high-CRI white-light, the wavelengths of the colored lights were selected as 638-nm for red, 520-nm for green, 405-nm for violet and 595-nm for yellow. The emission spectra of these high power R/G/V LDs and yellow LED are shown in Fig. 2(a). The red, green and violet light beams are with their peak wavelengths at 638 nm, 519 nm and 405 nm and related linewidth of 4.2 nm, 5.6 nm and 2.8 nm, respectively. On the other hand, the high-power yellow LED, which reveals the peak wavelength at 595 nm and the full width at half maximum (FWHM) of 26 nm, is only employed for upgrading the CRI performance of the R/G/V/Y white-lighting module because of the broadband spontaneous emission and low modulation bandwidth of the LED. One prism mirror and three dichroic beam combiners are employed to collimate the colored light beams. The dichroic combiner 1 placed in front of the Y-LED combines the transmitted green light from G-LD with the reflected yellow light. Dichroic mirror 2 placed in front of the R-LD combines the collimated green and yellow light with the reflected red light. The dichroic mirror 3 placed in front of the V-LD mixes the collimated G+Y+R beams with the reflected violet beam eventually. The CCT and CRI are tunable via the bias adjustment of LD and LED. With appropriate on the R/G/V current, the general white-lighting demand can be satisfied with the CRI up-scaled to >60 under the CCT of >5000 K at CIE coordinate of (0.34, 0.44), as shown in Fig. 2(b). Under such adjustment,

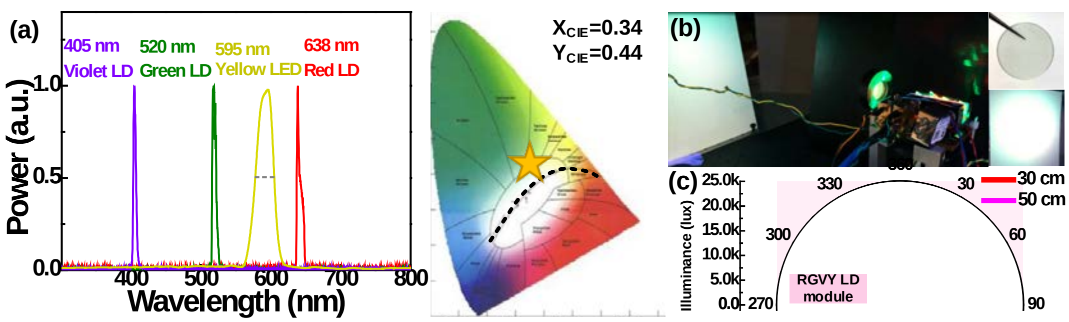

Fig. 2. (a) Optical and CIE spectra of the R/G/V LDs and yellow LED. (b) The photographs of the miniature R/G/V/Y mixed white-lighting module and its lighting spot on white paper. (c) The angle-dependent illuminance distribution of the R/G/V/Y mixed white-light module.

Fig. 2(c) shows the white-lighting spot obtained with R/G/V LD biased at 345/345/180 mA and Y-LED biased at 3.2V. To completely suppress the color aberration of the R/G/V-LD+Y-LED mixed white light spot due to the beam collimation, a frosted glass (FG) diffuser with single-side roughened surface is employed to uniformly diffuse the glare light from the miniature R/G/V/Y module, as shown in the right upper part of Fig. 2(c). Moreover, the divergent beam of mixed white-light illuminated on a white A4 paper located away from a distance of 0.5 m is also shown in Fig. 2(c), indicating that the miniature high-power R/G/V/Y+FG white-lighting module can provide uniform and clean white lighting spot without any dazzling speckle. To discuss the application possibility of the R/G/V/Y+FG module, the distance dependent illuminance and angular distribution profiles is compared in the lower part of Fig. 2(c). With using the FG diffuser to uniformly diffuse the mixed and collimated R/G/V-LD+Y-LED beams, the illuminance of nearly 40000 lux is observed at a distance of 15 cm. When extending the distance to 30 cm, the illuminance of the high-power R/G/V/Y module is decreased to 25000 lux. Further lengthening the lighting distance to 50 cm causes the high-power R/G/V/Y module decayed its illuminance to 12500 lux. When checking the angular distribution profile, the high-power R/G/V/Y module displays a divergent angle of >50^o at 30 cm and >60^o at 50 cm in horizontal axis. Although the miniature R/G/V/Y mixed white light beam exhibits a slightly high directionality in this case, its radiant angle can be further expanded via appropriate defocusing design.

Figure 3(a) shows the analog modulation frequency response of the high-power R/G/V LDs individually optimized with adjusting their DC bias currents. As a result, the -3 dB and -6 dB bandwidths of the red LD are with 2.05 GHz and 2.25 GHz when biasing at 350 mA, and the related relaxation oscillation peak is observed at 1.5 GHz. The frequency response of the green LD driven at DC bias of 345 mA only exhibits the -3 dB and -6 dB bandwidths of 1.27 GHz and 1.31 GHz with corresponding relaxation oscillation peak of 1 GHz. The violet LD exhibits -3 dB and -6 dB bandwidths of 0.65 GHz and 1.35 GHz under a DC bias of 180 mA. Nevertheless, the violet LD also reveals the most flattened modulation throughput among all LDs used in this work. To maximize the data transmission capacity, the bias currents of the R/G/V LDs and the sampling rate of the QAM-OFDM data need to be adjusted individually. By taking the R-LD as an example for the digital 16-QAM OFDM data transmission performance analysis, the upper part of Fig. 3(b) shows the optimization with raising the R-LD current from 335 to 345 mA, which observes the lowest EVM of 16.7% and BER of 2.8×10^{-3} for the received 16-QAM OFDM covering a data bandwidth of 2 GHz. The over-biased R-LD inevitably enlarges its EVM with degrading BER.

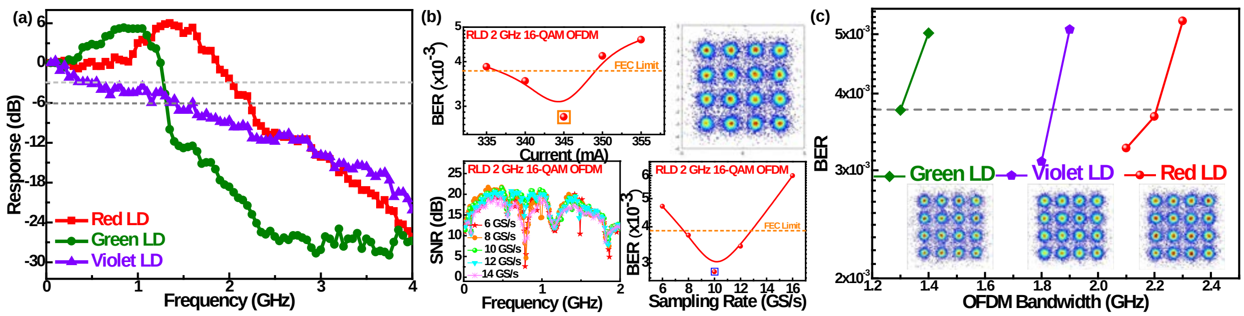

Fig. 3. (a) Analog modulation responses of the red LD, green LD and violet LD with each optimized bias current. (b) BER versus bias current, constellation plot, and SNR spectra and BER under different sampling rates for 16-QAM OFDM data carried by R-LD. (c) Bandwidth dependent BERs of the 16-QAM OFDM data carried by R/G/V LDs before and after pre-leveling optimization.

On the other hand, the sampling rate of the synthesized data stream for encoding the R-LD also needs optimization. This is performed by characterizing the sampling-rate dependent subcarrier SNR spectrum and decoding BER of the R-LD respectively shown in the lower left and right parts of Fig. 3(b). With an over sampling rate of 10 GS/s, the R-LD carried 16-QAM OFDM with a data bandwidth of 2 GHz can optimize its receiving SNR to 15.5 dB with corresponding BER of $2.8\text{x}10^{-3}$. Over sampling up to 16 GS/s degrades the SNR to 14.2 dB with corresponding BER degraded to $8.1\text{x}10^{-3}$. To maximize the data transmission capacity, the bias currents of the R/G/V LDs and the sampling rate of the QAM-OFDM data need to be adjusted individually. Afterwards, the BER of the delivered 16-QAM OFDM data individually modulated on R/G/V LDs with different data bandwidths are exhibited in Fig. 3(c). With executing spectral power pre-leveling optimization, the decoding BER of the 2.2-GHz 16-QAM OFDM with its data rate up to 8.8 Gbps carried by the R-LD greatly reduces from $6.2\text{x}10^{-3}$ to $3.7\text{x}10^{-3}$. Similar BER improvement for the G-LD delivered data before and after pre-leveling reveals that its encoding bandwidth can be expanded to 1.3 GHz for 5.2-Gbps 16-QAM OFDM with the qualified BER at $3.7\text{x}10^{-3}$ after pre-leveling optimization. Finally, the VLD can carry the 16-QAM OFDM at 7.2 Gbps after power pre-leveling with a bandwidth penalty reducing by only 0.1 GHz. To sum up, the maximal data rate transmitted by the R/G/V LDs can improve to 2.2/1.3/1.8 GHz individually, and the total data rate of the high-lux and high-CRI R/G/V/Y white-lighting module can be increased beyond 20 Gbps.

4. Conclusion

A miniature high-power R/G/V-LDs+Y-LED module is packaged with its volume of only W×L×H = $6\times5.4\times2$ cm^3, which performs the four-color mixed white lighting with high illuminance of 40000 lux and high CRI of >60, and enables the visible wavelength division multiplexing based optical wireless communication link. The bias current optimization of the R/G/V-LD+Y-LED module provides a total output power of 328 mW, which can supply an illuminance of >12500 lux after illuminating over a distance 0.5 m with a divergent angle of >60^o. After pre-leveling optimization, the miniature R/G/V-LDs+Y-LED module can achieve a total transmission data rate beyond 20 Gbps.

5. References

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