GaN-based Series Hybrid LED Array: A Dual-function Light Source with Illumination and High-speed Visible Light Communication Capabilities

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***Abstract*—We propose and demonstrate a GaN-based series-driven hybrid light emitting diode (SH-LED) device in which broad-area and micro-LED components are interconnected for simultaneous illumination and high-speed visible light communication (VLC) applications. Through theoretical analysis based on an equivalent electrical circuit model and characterization from a fabricated exemplar device with blue emission, it is shown that SH-LEDs combine the advantages of broad-area and micro-LED components by offering high direct-current (DC) optical power output and a fast frequency response. The application of this device to VLC is demonstrated through both the point-to-point and 9° divergence-angle coverage systems at 3 m transmission distance adopting a DC-biased optical-orthogonal frequency-division multiplexing modulation scheme. Compared with a point-to-point system using a single micro-LED, that our initial demonstrator SH-LED achieves the same data transmission rate of 3.39 Gbps at forward error correction (FEC) floor of 3.8×10^{-3}, but the received DC optical power is improved by over 3 times. For the area coverage system, up to 1.56 Gbps data transmission rates at a FEC floor of 3.8×10^{-3} are accomplished by using this device, associated with over 4 times higher received DC optical power compared with that using a single micro-LED.**

***Index Terms*—Visible light communication, Series hybrid LED.**

I. INTRODUCTION

THE migration of wireless communication techniques into the unregulated visible light spectrum between 375-780 nm for data transmission is considered to be a promising approach to address the radio-frequency (RF) spectrum crunch [1]. Thanks to its inherent advantages such as improved spectral efficiency, innate security and less susceptibility to electromagnetic interference, visible light communication (VLC) technology exhibits great potential in short-distance wireless access, especially for the indoor environment [2]. Moreover, VLC technology can also be embedded into existing solid-state lighting (SSL) systems, which makes the VLC transmitters capable of being used for illumination and communication simultaneously for energy saving and novel functionality [3].

In SSL systems, GaN-based commercial blue light emitting diodes (LEDs) are commonly used which photo-excite a yellow phosphor for white light illumination. Compared with the conventional incandescent or fluorescent light sources, LEDs possess advantages such as higher power efficiency and faster modulation speed. However, due to the large resistance-capacitance (RC) time constant of the p-n junction, the modulation bandwidth of broad-area (typically 0.1-1 mm^2) LEDs (BA-LEDs), which is in the range of 10-20 MHz at -6 dB [4], is insufficient to support high-speed VLC with Gbps data rate. Therefore, different approaches such as pre-equalization, post-equalization and high-order modulation have been demonstrated to enable higher modulation bandwidth of LEDs [5]. In addition to these methods, micro-LEDs, which are with active area dimension less than 100 μm, are considered as promising light sources with high-bandwidth characteristics to enable high-speed communication. The small junction area of micro-LEDs makes these devices operating in a high current density regime with low RC effects. Consequently, modulation bandwidths of up to several hundred MHz at -6 dB can be achieved by the single micro-LEDs with different emission wavelengths covering from violet to green spectral range [6], [7], [8], [9], [10], [11]. By assuming direct current-biased optical (DCO)-orthogonal frequency division multiplexing (OFDM) modulation scheme, the data transmission rates up to 7.91 Gbps [6], 5.37 Gbps [8] and 4.65 Gbps [10] have been accomplished at the forward error correction (FEC) floor of 3.8×10^{-3} using a single micro-LED with the violet, blue and green emissions, respectively. Meanwhile, the GaN-based micro-LEDs can also be used as the photodetectors to sense short-wavelength signals and, in turn, gain the signal-to-noise ratio (SNR) in VLC systems [12], [13].

However, the small junction area of micro-LEDs results in a considerably lower light output power (LOP) than their

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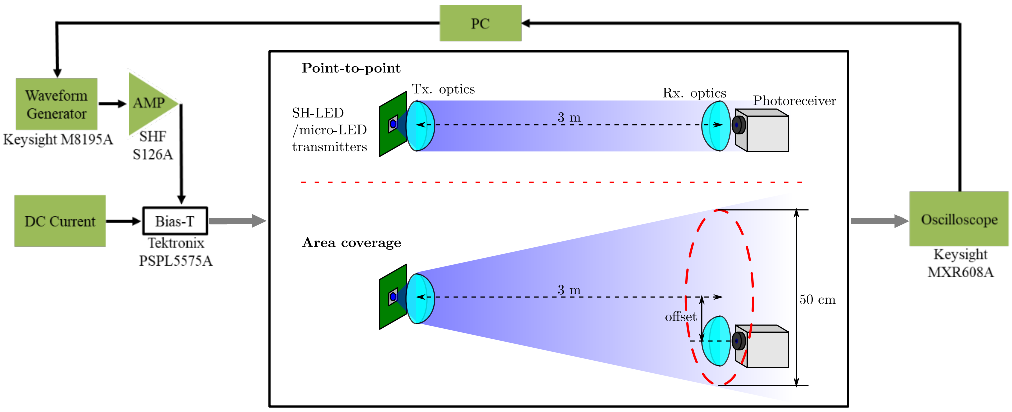

Fig. 5. Schematic block diagram of the setup used for point-to-point and area coverage VLC measurements.

distortion resulting from the voltage-optical power behavior of LEDs strongly depends on the chip size, which is well consistent with the results observed in this work.

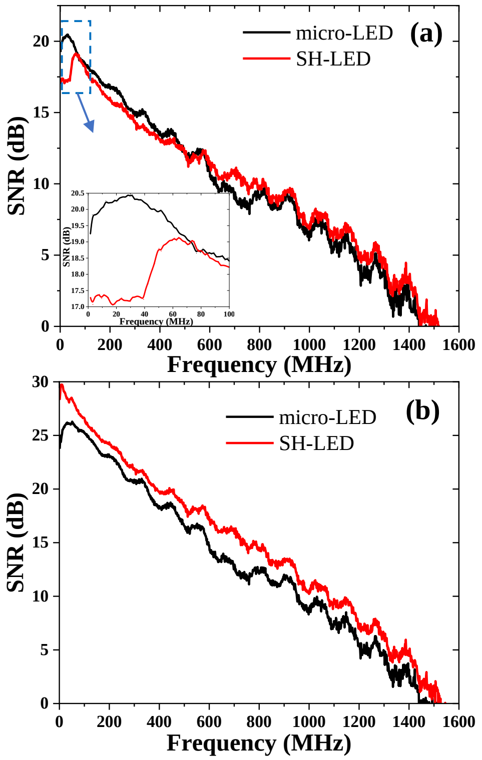

Fig. 6. (a) SNR versus frequency for the free-space point-to-point VLC systems using SH-LED and micro-LED with a 3 m data transmission distance, the inset shows the detailed SNR performance in the first 100 MHz; (b) SNR under the sole effect of receiver noise versus frequency for the same VLC systems shown in part (a).

Fig.7 illustrates the measured data transmission rates against bit error rate (BER) for the VLC systems using SH-LED and micro-LED, respectively. As shown, although the SH-LED presents slightly worse SNR performance in the low frequency region, the achieved data transmission rates are generally identical for VLC systems using different LEDs due to the similar frequency characteristics and optical-power dynamic region contributed from the micro-LED. Up to 3.39 Gbps data transmission rate is accomplished at the forward error correction (FEC) floor of 3.8×10^{-3} for both systems. Meanwhile, the received DC LOP at the receiver part after lens focusing is measured as 1.30 mW for the system using SH-LED, which is over 3 times higher than the one measured for the system using the micro-LED. These results are well consistent with the analyses in section II indicating that the system with SH-LED fully exploits the advantages from its BA-LED component on the DC LOP and micro-LED component on the frequency response, respectively. This characteristic makes this innovative device a promising candidate as the light source for systems requiring both high DC optical power illumination and high-speed communications, such as light-fidelity (LiFi) applications.

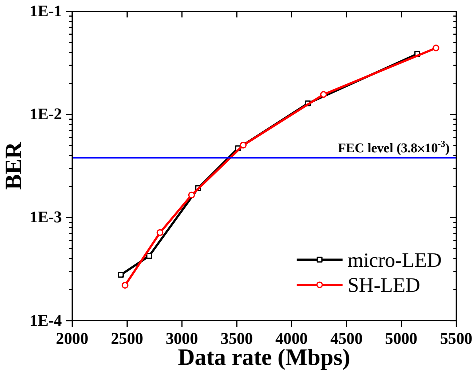

Fig. 7. Measured data transmission rates against BER for the free-space point-to-point VLC systems using SH-LED and micro-LED with a 3 m data transmission distance.

B. Area coverage VLC system

As described above, a VLC system covering an illumination region with a 50 cm diameter at 3 m center-to-center distance has been implemented to characterise the performance of different LEDs under a scenario highly relevant for LiFi applications. Fig.8(a) summarises the achieved data rates at FEC floor of 3.8×10^{-3} at different offsets (the distance between the measurement point and the center of the illuminated region) for the area coverage VLC systems using SH-LED and micro-LED, respectively. In order to avoid the influence of stray light,

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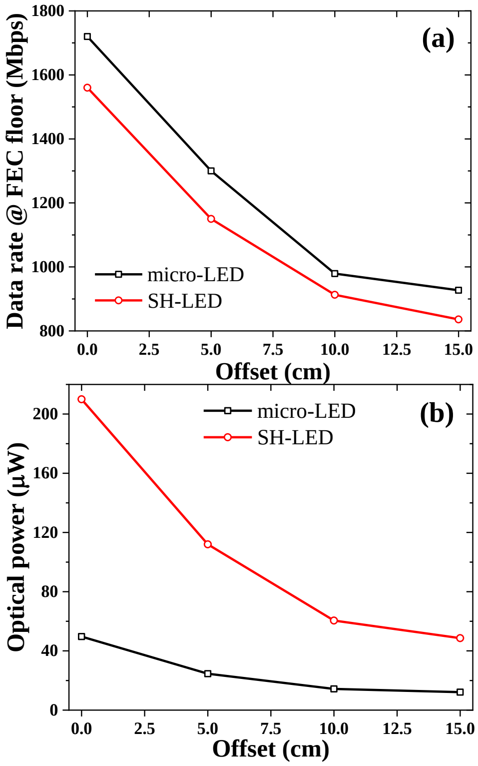

Fig. 8. Measured (a) data transmission rates at the FEC floor of 3.8×10^{-3} and (b) DC LOP at different offsets for the free-space area coverage VLC systems using SH-LED and micro-LED, respectively, with a 9° divergence angle and 3 m center-to-center distance.

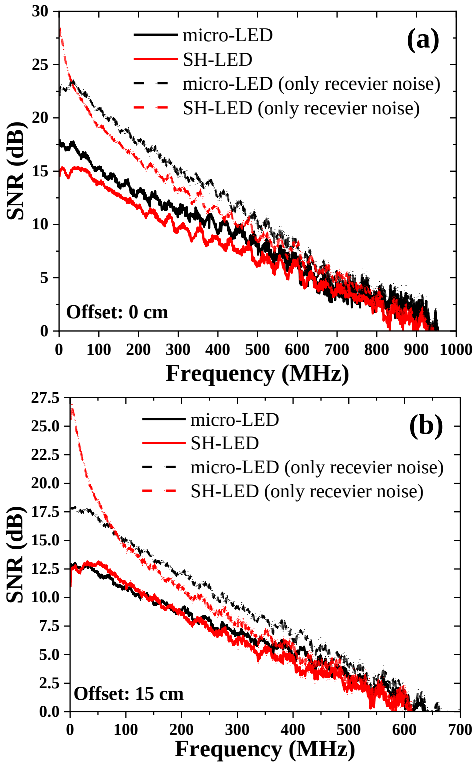

Fig. 9. SNR versus frequency for the free-space area coverage VLC systems using SH-LED and micro-LED at the offsets of (a) 0 cm and (b) 15 cm. The dash curves in each part represent the SNRs estimated under the sole effect of receiver noises for different LEDs at the same offset.

the corresponding lateral offsets for the data shown here are limited to 15 cm though the actual radius of the coverage area is 25 cm. Thanks to the concentric design employed for the SH-LED, the achieved data rates at the FEC floor of 3.8×10^{-3} for both systems follow the same trend in lower data rates at larger offsets. As shown in Fig.8(b), the irradiance intensities of both systems follow a Gaussian distribution, which results in a lower DC LOP received at larger offsets and, in turn, lower data rates. For the system using SH-LED, up to 1.56, 1.15, 0.91, and 0.84 Gbps data rates, respectively, are accomplished at offsets of 0, 5, 10, and 15 cm. These values are around 9% lower compared with the ones achieved by the system using the micro-LED at the same offsets. When comparing DC LOP, the system using the SH-LED presents about 4 times higher values than the one using the micro-LED at the same offsets. These results confirm the innovative characteristics of SH-LED with high DC LOP and wider frequency region utility contributed from its different-size components. Meanwhile, the promising illumination and communication performance achieved by the area coverage system using the SH-LED further demonstrates the great potential of SH-LED for LiFi applications. As discussed in section IV, we are carrying out optimization works on the device design, including LED component size selection and configuration modification, to further improve the device performance on both illumination and communication applications.

In order to investigate the differences in the data transmission rates achieved by SH-LED and micro-LED in area coverage VLC systems, the SNR curves of both LEDs at the offsets of 0 and 15 cm are shown in Fig.9(a) and (b), respectively. The corresponding SNR curves under the sole effect of receiver noise are also included in the figures as dashed plots for comparison purposes. As shown, at both offsets, the observed differences in the low frequency region between the SNR curves under different estimations are similar to the results shown in Fig.6. Thus, we could attribute the degraded SNR performance of the SH-LED in the low frequency region to the severe nonlinear distortions from its BA-LED component. On the other hand, compared with the micro-LED, the SH-LED presents lower SNR values at higher frequencies under both estimations. The relatively small modulation signal power applied on the SH-LED, which is mainly limited by the high-power amplifier used in this work, is considered as the main factor leading to this phenomenon. In our previous work, it has been demonstrated that the SNR performance at high frequencies can be significantly improved by the large signal swing thanks to the increased modulation signal power [6]. Due to the high path loss in the coverage VLC measurements, a large modulation signal power should be used for obtaining the optimized SNR performance and, in turn, highest data transmission rates, especially for the SH-LED employing series-connection configurations. However, the 3 dB compression point of the used amplifier limits the maximum modulation signal power applied on SH-LED. It has been found in our experiments that further increases in the V_{PP} from AWG for SH-LED do not lead to the improvements in the achieved SNR. This results in a considerable small modulation signal power and, in turn, lower SNR values at high frequencies for the SH-LED. It is expected that the higher data transmission rates for the system using an SH-LED, which are similar to those achieved by the system using a micro-LED, should be accomplished when a high-performance amplifier is employed.

VI. CONCLUSION

In this work, we propose an innovative GaN-based SH-LED concept, which employs a series configuration to interconnect the conventional BA-LED and micro-LED components together in a single chip, as a promising light source for high-speed VLC systems with illumination capabilities. Compared with the conventional LED devices, this SH-LED offers several advantages such as flexible design strategy, high fabrication yield, simple addressing method and moderate driving requirement. The performance of this SH-LED was investigated through the theoretical analysis based on an equivalent electrical circuit and experimental characterization from a fabricated example demonstrator device with blue emission. The results indicate that, thanks to the contributions from its different-size components, the SH-LED possesses the combined benefits of high DC LOP for illumination and wide modulation bandwidth for communications. In order to demonstrate its applications in VLC, this SH-LED is further employed as a transmitter in point-to-point and area coverage demonstrator communication systems with a 3 m center-to-center distance. Compared with the systems using a reference micro-LED, those using the SH-LED achieve not only similar data transmission rates but also higher DC LOP. Utilizing a DCO-OFDM modulation format, up to 3.39 and 1.56 Gbps respective data transmission rates at a FEC floor of 3.8×10^{-3} are accomplished by the SH-LED in point-to-point and area coverage VLC systems, associated with over 3 and 4 times higher received DC LOP, respectively, compared with the systems using a micro-LED. Further improvements are expected by optimizing this design.

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