# Micro-light-emitting-diode array with dual functions of visible light communication and illumination*

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We demonstrate high-speed blue $4 \times 4$ micro-light-emitting-diode (LED) arrays with 14 light-emitting units (two light-emitting units are used as the positive and negative electrodes for power supply, respectively) comprising multiple quantum wells formed of GaN epitaxial layers grown on a sapphire substrate, and experimentally test their applicability for being used as VLC transmitters and illuminations. The micro-LED arrays provide a maximum $-3$-dB frequency response of 60.5 MHz with a smooth frequency curve from 1 MHz to 500 MHz for an optical output power of 165 mW at an injection current of 30 mA, which, to our knowledge, is the highest response frequency ever reported for blue GaN-based LEDs operating at that level of optical output power. The relationship between the frequency and size of the device single pixel diameter reveals the relationship between the response frequency and diffusion capacitance of the device.

**Keywords:** light-emitting devices, optical communications, diffusion capacitance

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## 1. Introduction

Light-emitting-diodes (LEDs) are key transmitter components for light fidelity (Li–Fi) communication networks by using plastic optical fibers (POFs)[1] or visible light communication (VLC) systems due to their relatively low complexity and low cost, and market dominance. They have incomparable advantages in particular environments, such as underwater communication, traffic safety data transmission, indoor environments,[2] and secure communication, and potential applications in implementing wireless communications in environments where radio communication is impossible.[3,4] The use of diverse structures and materials for visible-light LEDs has received considerable attention, and the study of their performances has made significant progress.[5,6] Appropriate device size, the employment of advanced epitaxial materials, and optimum pixel arrangement are the areas of concern in VLC chip development. Micro-LEDs, which are high-density micrometer-sized LED arrays, have aroused the considerable interest in being used as transmitter devices in VLC systems[7] because the structure not only offers numerous benefits such as low power consumption, small size, and long life, but also provides the rapid response conditions required by communication systems. Shi *et al.*[8,9] demonstrated linear cascade arrays of GaN-based LEDs, which were modulated by using a resonant driving technique, resulting in an overall bandwidth of 90 MHz. Arrays of four LEDs provided around four times the optical output power of a single LED, with a maximum output power near 20 mW. McKendry *et al.*[10] evaluated a series of micro-LEDs with different pixel diameters, and concluded that micro-LED pixels with smaller areas generally provide higher modulation bandwidths than those with larger areas, which was attributed to the ability of small-area pixels to be driven at higher current densities. The high-frequency modulation of individual pixels in $8 \times 8$ arrays of III-nitride-based micro-pixellated LEDs, where the pixel diameters ranged from 14 μm to 84 μm, were reported. The arrays were driven with a complementary metal–oxide–semiconductor (CMOS) driver array chip, which allowed for simple computer control of the individual micro-LED pixels. The highest optical $-3$-dB modulation bandwidth from these LED devices was shown to be in excess of 400 MHz, and a maximum output power of about 5 mW was obtained. Liao *et al.*[11] reported on high-speed GaN-based green LEDs with an aperture diameter of 75 μm, and obtained a maximum optical $-3$-dB modulation bandwidth of 463 MHz at a current of 50 mA. The LED device exhibited a relatively high optical output power of 1.6 mW. For enhancing the diffusion velocity of electrons, a new conductive material was utilized as a top transparent conductive layer. Liao *et al.*[12] later reported on high-speed GaN-based blue LEDs with an aperture diameter of 75 μm, which exhibited a $-3$-dB modulation bandwidth of 225.4 MHz and an optical output power of 1.6 mW. The researchers employed

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InSnO/Ga-doped Zn oxide (ITO/GZO) or a GZO contact layer deposited by sputtering as a current-spreading layer to enhance the optical output powers of GaN/InGaN LEDs.

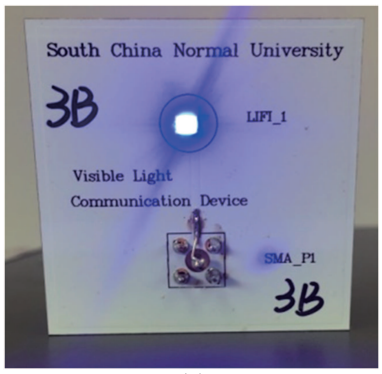
Device dimension has also been shown to play a key role in providing optimal LED transmitter device performance. While the decreased size allows for higher frequency operation, the smaller size also leads to a decreased optical output power.[13] In addition, because the sidewall heat radiation is increased with pixel size decreasing, the ohmic contact and the PN junction can be destroyed by over-heating, resulting in overall device failure.[14] Different device structures have also been reported in previous studies, such as heterojunction bipolar LEDs (HBLEDs), which have been utilized as a high-speed LED structure.[14] This device structure allows the distribution of electrons to be altered during the device working cycle, and, owing to the increased operational frequency of the device, a high-speed −3-dB bandwidth of greater than 1 GHz can be obtained. As the size decreases, the current density increases; Walter *et al.*[15] demonstrated a large frequency modulation bandwidth of 524 MHz at a current density of 10 kA/cm$^2$

In this paper, we demonstrate high-speed blue $4 \times 4$ micro-LED arrays (two light-emitting units are used as the positive and negative electrodes for power supply) comprising multiple quantum wells (MQWs) formed of GaN epitaxial layers grown on a sapphire substrate, and experimentally test their applicability for being used as VLC transmitters. The proposed transmitter device (14 light emitting units) achieves a maximum −3-dB frequency response of 60.5 MHz without driver or modulation circuit, and a smooth frequency curve from 1 MHz to 500 MHz is obtained for an optical output power of 11.7 mW for each single unit, and reaches 165 mW for whole chip at an injection current of 30 mA with an active area diameter of 60 μm for single light emitting unit, which, to our knowledge, is the highest bandwidth ever reported for blue GaN-based LEDs operating at that level of optical output power. As is well known, the optical output power has a significant practical influence on transmitter device performance in a VLC system. We also demonstrate that LEDs with smaller mesa areas generally exhibit higher modulation bandwidths than LEDs with large mesa areas, which is attributed to their ability to be driven at higher current density. The bandwidth is set to be 250 MHz in our experiment. Therefore, an aggregate data rate of 1.375 Gbit/s is successfully demonstrated by using bit and power loading orthogonal frequency division multiplexing (OFDM) with the bit error rate (BER) of $3.3 \times 10^{-3}$ under the forward-error-correction (FEC) limit of $3.8 \times 10^{-3}$.

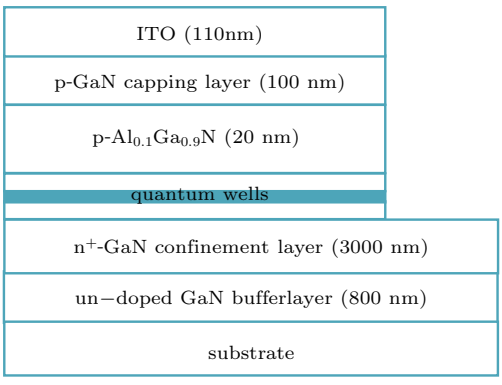
## 2. Experiment

### 2.1. Device preparation

Four groups of blue LEDs with different unit mesa diameters were fabricated, where each LED consisted of $4 \times 4$ micro-LED arrays (two light-emitting units are used as the positive and negative electrodes for power supply respectively). These units were connected in series to ensure a high output power. Figure 1 shows the LED transmitter device mounted on a circuit board. As the size of a single device unit decreases, a high density of current will cause heat to increase. In the design of the device, the spacing between the individual devices in the lighting area was increased to 60 μm, and copper substrate was used in the working circuit board for enhancing the cooling effect. The epitaxial layers of the LEDs wafers were grown by metal–organic chemical vapor deposition (MOCVD). To ensure high response and high brightness, these layers were: 1) an 800-nm thick undoped GaN buffer layer, 2) a 3000-nm thick n$^+$-GaN confinement layer, 3) an MQW active region consisting of fourteen 3-nm thick $In_{0.25}Ga_{0.75}N$ quantum wells separated by thirteen GaN barrier layers, specifically, a GaN barrier layer is sandwiched between the two adjacent $In_{0.25}Ga_{0.75}N$ quantum wells, 4) a 20-nm thick p-$Al_{0.1}Ga_{0.9}N$ confinement layer, 5) a 100-nm thick p-GaN capping layer, and 6) a 110-nm thick ITO film deposited by magnetron sputtering. After conducting epitaxial growth, the LED devices were fabricated using standard processing techniques, including sample cleaning, photolithography and metallization, lapping, polishing, scribing, and bonding. In the photolithography process, the wafer was divided into a $4 \times 4$ array of pixels of equal size (with sizes varying from 60 μm to 120 μm), and a multilayer




(a)




(b)

**Fig. 1.** (color online) (a) The LED transmitter device mounted on a circuit board, and (b) schematic diagram of visible light communication LEDs.

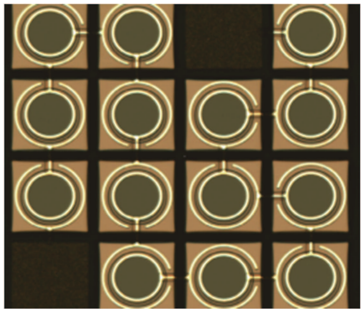


**Fig. 2.** (color online) $4 \times 4$ high-speed light fidelity communication light-emitting diode structure image after metal wire has been deposited on p-GaN prior to the silicon oxide passivation layer deposition, observed by optical microscopy, and two dark square areas are the position of the metal wire.

metal conductive coating consisting of Cr/Al/Cr/Ti/Al with respective thickness values of 20/2000/250/450/20000 nm was applied. Connected between pixels is a conductive metal wire. Prior to depositing a metal wire, a $SiO_2$ layer was deposited on the area where the metal wire must pass through a deep erosion channel to ensure that the wire properly connects two neighboring pixels. To accelerate the current distributions of the N and P poles, and thereby accelerate the frequency response characteristics of the device, we employed circular electrodes, which can improve the efficiency of current diffusion and shorten the spontaneous recombination time. Figure 2 shows an optical microscopy image of a portion of a $4 \times 4$ micro-LED array designed for high-speed Li–Fi communication after conductive metal wire deposition on the p-GaN capping layer, but prior to $SiO_2$ passivation layer deposition. The two dark square areas are the positions of the metal wire. Simulations have shown that circular p-electrodes can effectively improve the current distribution inside the device, and it was useful for improving the frequency response of the device.

### 2.2. Measurement system

The experimental system and procedure are shown in Fig. 3. The LED optical data transmission performance testing was conducted as follows. The input signal was first generated using a Tektronix 7122C arbitrary waveform generator (AWG). The generated signal was subsequently passed through an amplifier for the purpose of increasing the modulation depth of each LED pixel, which was under a DC bias provided by a Keithley 2420 source meter (SMU) instrument. The amplified signal was then superimposed onto the DC bias current of each pixel via a Pulsar BT-52-400S Bias Tee. The maximum operating voltage of the amplifier (Coaxial ZHL-32A) is 24 V. In this experiment, the input signal voltage is 0.3 V. It is also found that the signal inputs with different voltages and the response frequencies are the same. The Bias-Tee output was directly supplied to each blue LED pixel. Light from the blue micro-LED array was imaged onto a Newport 818-BB-21A high-speed photo-detector consisting of an avalanche photodiode (APD), and the transmitted signal was obtained using a high numerical aperture (NA) Tektronix DSO 73304D oscilloscope. The received signal was then displayed and analyzed via a computer using MATLAB software.

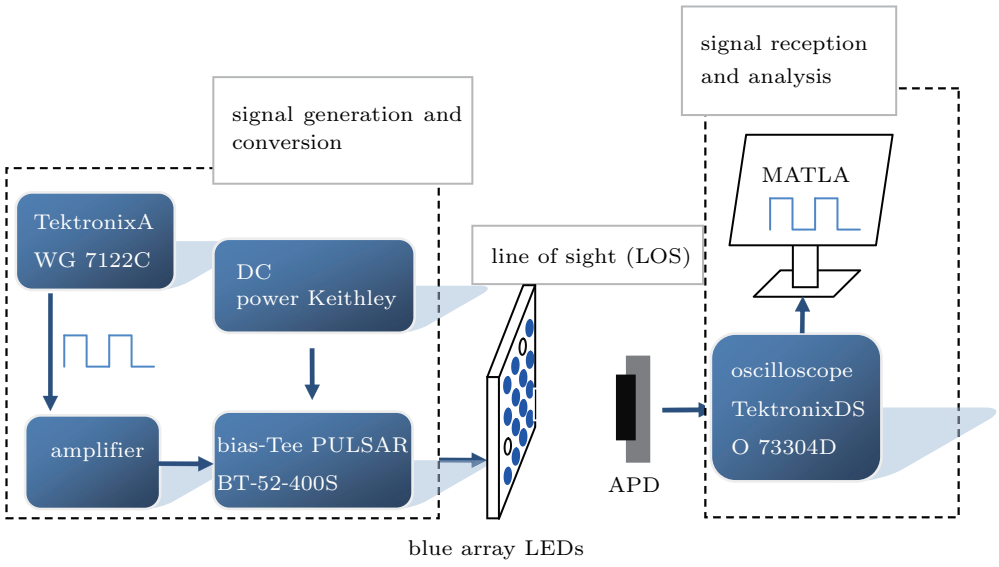



**Fig. 3.** (color online) Experimental setup of the VLC-LED measurement system composed of an arbitrary waveform generator (AWG), a bias tee to overlay the amplified signal with the DC bias current provided by a source meter (SMU) instrument, and an avalanche photodiode (APD) as a high-speed photo-detector.

## 3. Results and discussion

As is well known, the frequency response of an LED is mainly limited by its diffusion capacitance[16] and carrier lifetime, and the number of injected carriers in the active region of the device; of course, there are links between these three factors. For all sizes of LEDs, the corresponding frequency response increases significantly as the injected current increases, which results in carriers lifetime shortening. In addition, the

injected carrier density in the active region increases with increasing current injection.

$$f_{-3\ \mathrm{dB}}=\frac{1}{2\pi\tau}\sqrt{\frac{BJ}{qd}}, \tag{1}$$

where $B$ is the bimolecular coefficient, $J$ the injected current density, $q$ the elementary charge d the thickness of the active region, and $\tau$ the carrier lifetime.

In addition to the effect of carrier lifetime, the capacitance is also an important factor limiting LED bandwidth. In the LED device, the capacitance is divided into parasitic capacitance and diffusion capacitance, in which the diffusion capacitance and carrier life are related to each other.

The diffusion capacitance

$$C_{\mathrm{D}}=\frac{qI}{kT}\tau, \tag{2}$$

where $I$ is the current of the device, $q$ is the elementary charge, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $\tau$ is the carrier lifetime.

The device parasitic capacitance is

$$C_{\mathrm{T}}=A\frac{\varepsilon_{\mathrm{s}}}{\chi}, \tag{3}$$

where $A$ is the junction area, $C_{\mathrm{T}}$ is dependent on the characteristics of the device $\varepsilon_{\mathrm{s}}$ the dielectric constant of the semiconductor, $\chi$ is the depletion layer width related to the bias of the p–n junction.

Therefore, the current density of the device, carrier life, the device diffusion capacitance, and the device response frequency have a direct relationship.

Figure 4 shows the $I$–$V$ characteristics of LEDs with mesa diameters ranging from 60 μm to 120 μm. From the $I$–$V$ characteristics, it can be observed that the smaller diameter mesa areas tend to have higher turn-on voltages and work voltages than their larger counterparts, which may be attributed to the relatively great laser dry-etching induced damage and/or poor p-contact quality.

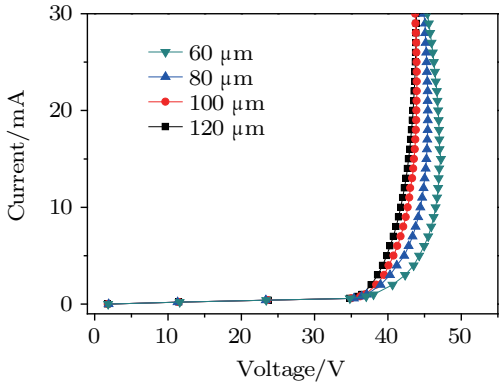



**Fig. 4.** (color online) $I$–$V$ characteristics of LEDs with different mesa diameters.

Figure 5 shows the optical output power of LED arrays as a function of the forward current ($L$–$I$) measured at room temperature for the LEDs with different mesa diameters. The optical output power values measured by HAAS-2000 (EVERFINE) at a 30-mA injection current are 356, 305, 275, and 165 mW for the LEDs with mesa diameters of 120, 100, 80, and 60 μm, respectively. We see that the output power of the device decreases as the device dimension decreases because the effective area of the LED device decreases. The device luminous efficiency decreases mainly due to the current density increasing caused by the droop effect of the device. In order to reduce the influence of this effect on the device, in the experiment a ring electrode is used as shown in Fig. 6, so that the current distribution in the device is in equilibrium.

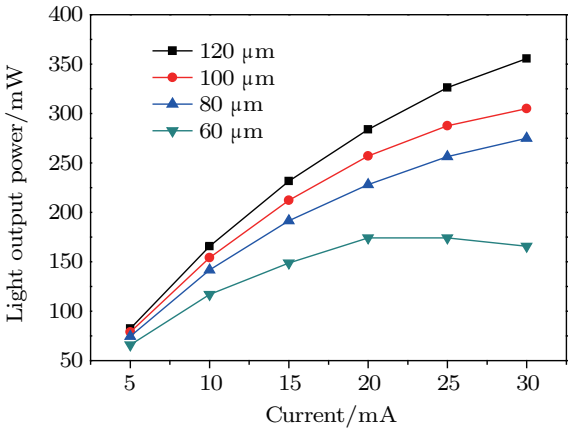



**Fig. 5.** (color online) Optical output powers of LEDs with different mesa diameters.

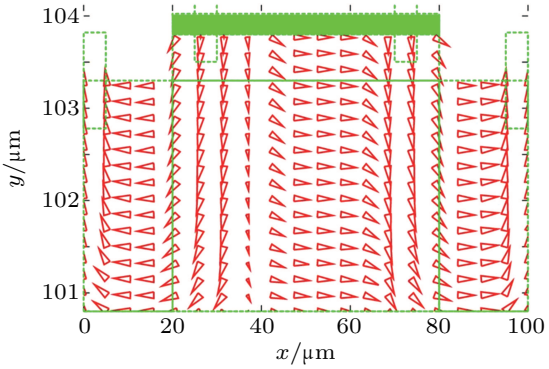



**Fig. 6.** (color online) Current distribution in cross-section of the ring electrode device.

Figure 7 shows the room-temperature electroluminescence (EL) spectra of the LED with a 60-μm mesa diameter under various injection currents. Each of the LEDs investigated provides a peak emission wavelength of around 450 nm. A slight red shift is observed with increasing injection current due to the quantum confined Stark effect (QCSE) in the MQW layer. As discussed previously, the sidewall heat radiation increases with reducing pixel size, and the ohmic contact and the PN junction may be destroyed due to excessive heating. In addition, an increasing junction temperature will lead to more of the active layer and stronger non-carrier leakage radiation. Finally, an increasing junction temperature also affects the EL spectrum of the LED.

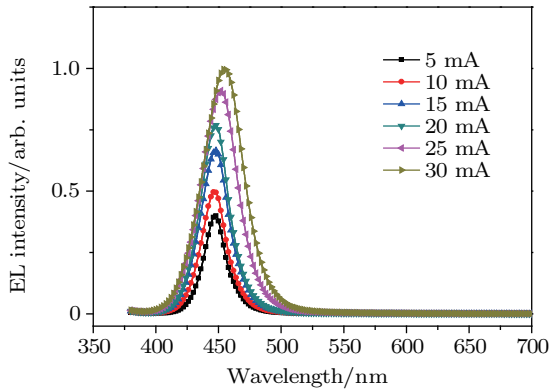



**Fig. 7.** (color online) Room-temperature electroluminescence (EL) spectra under various injection currents for an LED with a mesa diameter of 60 μm.

Figure 8 shows the frequency response of the LED with a mesa diameter of 60 μm at different injection currents. For injection currents of 5 mA, 10 mA, 15 mA, 20 mA, 25 mA, and 30 mA, the values of $f_{-3\ \mathrm{dB}}$ obtained are 25 MHz, 43.7 MHz, 51.2 MHz, 55.1 MHz, 58.3 MHz, and 60.5 MHz, respectively. With increasing current density in LED device, $\tau$ decreases, and hence, $f_{-3\ \mathrm{dB}}$ increases. From the measured values of $f_{-3\ \mathrm{dB}}$, it can be concluded that $f_{-3\ \mathrm{dB}}$ is proportional to the square root of the current density and we see that $f_{-3\ \mathrm{dB}}$ and $\tau$ exhibit an inversely proportional relationship. According to Eq. (2), for the device current increasing, the capacitance and current which are proportional to the response frequency should also increase proportionally, but the experimental results indicate that when the current increases, the response frequency increases only to a certain extent, especially when the current increases to a certain value such as 20mA. When the current continues to increase to a certain percentage, the response frequency has a smaller increase, so it can be found that the current grows to a certain extent, the device diffusion capacitance has a significant effect on device frequency.

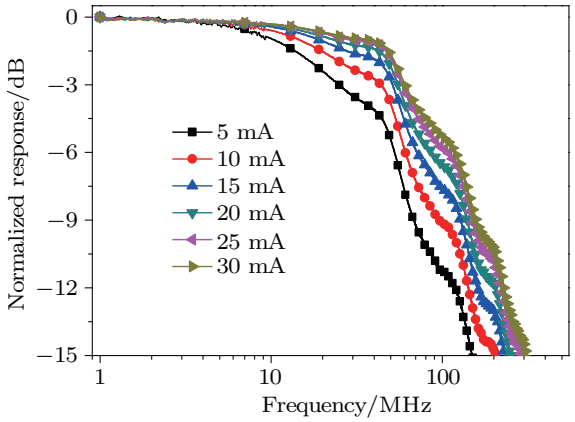



**Fig. 8.** (color online) Frequency response measured at different injection currents for an LED with a mesa diameter of 60 μm.

Figure 9 shows the frequency responses in linear and logarithmic graphs (the inset) measured at an injection current of 20 mA for LEDs with mesa diameters ranging from 60 μm to 120 μm. For mesa diameters of 60, 80, 100, and 120 μm, the values of $f_{-3\ \mathrm{dB}}$ obtained are 55.1, 42.2, 24.8, and 18.4 MHz, respectively. The maximum −3-dB response frequency curves obtained from the devices are smooth, which are suitable for the application to high-speed VLC systems.

According to Eq. (1), with other factors unchanged, only changing the area of the device, that is, only changing the current density, current per unit area, the frequency ratio of the four devices should be 20:15:12:10. As a result of the test, the response frequency of the four devices is approximately 30:23:13:10 in the same current condition. The difference between them is greater than the difference between the calculated results according to Eq. (1), so we can confirm that the relationship between the frequency and size of the device single pixel diameter reveals the relationship between the response frequency and diffusion capacitance of the device.

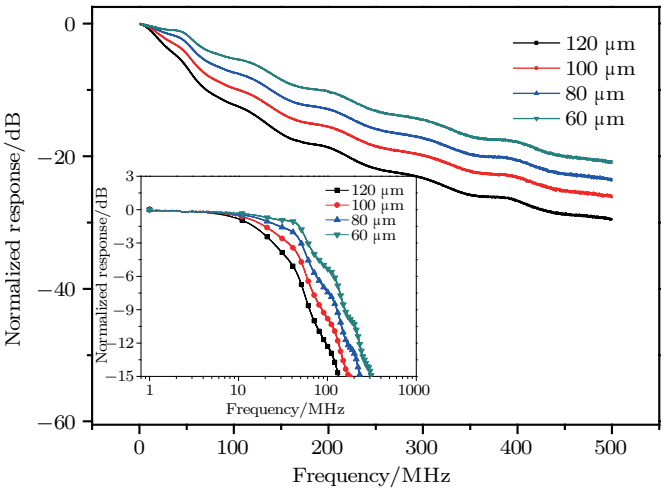



**Fig. 9.** (color online) Frequency response curves measured at an injection current of 20 mA for LEDs with different mesa diameters. The inset presents the values of $f_{-3\ \mathrm{dB}}$ and the current density obtained at an injection current of 20 mA for different LED pixel diameters.

## 4. Conclusions and perspectives

In this paper, we demonstrate high-speed blue micro-LED arrays comprising MQWs formed of GaN epitaxial layers grown on a sapphire substrate, and experimentally test their applicability for being used as VLC transmitters and illuminations. The device with 14 pixels achieves a maximum −3-dB frequency response of 60.5 MHz and a smooth response frequency curve from 1 MHz to 500 MHz for an optical output power of 165 mW at an injection current 30 mA. The device performance verifies its applicability to high-speed VLC systems. To the best of our knowledge, the proposed device provides the highest −3-dB frequency response and modulation bandwidth in all ever reported blue GaN-based LEDs operating at that level of optical output power. Smaller mesa area LEDs generally exhibit higher modulation bandwidths than larger mesa area LEDs, which is attributed to their ability to be driven at higher current densities, and the effect of the diffusion capacitor plays an important role in the response frequency of the device. We conclude that the relationship be-

tween the frequency and size of the device (i.e., single pixel diameter) reveals the relationship between the response frequency and diffusion capacitance of the device.

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