High-speed visible light communication based on a III-nitride series-biased micro-LED array

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***Abstract*—Visible light communication (VLC) using III-nitride light-emitting diodes (LEDs) offers many advantages such as license-free operation, high spatial diversity and innate security. In particular, micro-LEDs (μLEDs) are strong candidates for VLC due to their high modulation bandwidths. However, the low optical power of a single μLED is a key factor limiting VLC performance. In this work, we report an optimized series-biased μLED array to achieve higher optical power while retaining high modulation bandwidth for high-speed VLC. An example array consisting of 3$\times$3 40 μm-in-diameter μLED elements is presented here. At a current density of 3200 A/cm^2 in direct-current operation, the optical power and small signal 6-dB electrical modulation bandwidth of a blue-emitting series-biased μLED array are over 18.0 mW and 285 MHz, respectively. The data transmission capabilities of this μLED array are demonstrated by using onoff-keying, pulse-amplitude modulation, and orthogonal frequency division multiplexing modulation formats over free space with the error-free data transmission rates of 1.95, 2.37 and 4.81 Gbps, respectively.**

***Index Terms*—Visible light communication, Series-biased micro-LED array.**

I. Introduction

VISIBLE light communication (VLC), which can be integrated into pre-existing lighting infrastructure, is an attractive technology. It opens up the wider licence-free, visible region of the electromagnetic spectrum for wireless communications and, thus, offers a promising alternative to the bandwidth limitation of the radio frequency (RF) spectrum. Furthermore, the spectral efficiency per unit area is also enhanced by VLC, which leads to high spatial diversity and innate security [1]. Light-emitting diodes (LEDs) based on III-nitride materials are very promising light sources for VLC systems due to their capabilities to efficiently generate light covering the whole visible spectrum and be modulated faster than conventional incandescent or fluorescent light sources. The typical 6-dB electrical modulation bandwidth (corresponding to 3-dB optical modulation bandwidth) of commercial III-nitride LEDs is in the range of 10-20 MHz [2], which is limited by the large resistance-capacitance (RC) time constant of the p-n junction in conventional broad-area LEDs. Through different modulation schemes such as parallel data transmission and equalization, the VLC data transmission rates based on these LEDs are in excess of 1 Gbps [3], [4]. A recorded data transmission rate up to 2.32 Gbps using commercial III-nitride LEDs has been reported recently [5].

In order to further increase the data transmission rate of VLC systems based on III-nitride LED light sources, much effort has been made to optimize the LED epitaxial structure and device configuration [6], [7]. In recent years, micro-LED (μLED) emitters, which have lateral dimensions of less than 100 μm, have emerged to enable high-speed VLC applications [8]. The smaller LED junction area of μLEDs leads to the small RC time constant and high operation current density [9]. These novel characteristics increase the 6-dB electrical bandwidth of μLEDs up to a few hundred MHz [10] and, thus, make them strong candidates for VLC systems. In early works, by using on-off keying (OOK) and orthogonal frequency division multiplexing (OFDM) modulation schemes, data transmission rates up to 1.7 Gbps [10] and 7.9 Gbps [11] have been achieved at the forward error correction (FEC) floor of 3.8×10^{-3}, applied to single μLEDs. However, the low optical power produced from a single μLED is considered as a main factor limiting wider use of this technology in VLC applications. According to the Shannon-Hartley theorem [12], the maximum data transmission rate, *D*, over a communication channel can be determined by $D = B\log_2(1 + S/N)$, where *B* is the channel bandwidth; *S* is the average received signal power over the bandwidth; *N* is the average power of the noise assumed to be white Gaussian; and *S*/*N* is the electrical signal-to-noise ratio (SNR). This theorem indicates that low signal power would result in a low SNR and, consequently, low data transmission rate over limited transmission distances. In [13], we employed a μLED array operating in a ‘ ganged ’ fashion to increase the optical power and, thus, signal power produced for VLC systems. However, in order to retain the high modulation bandwidth of this μLED array, each μLED element needed to be individually addressed by its own anode or cathode. This leads to a complex design, fabrication and integration process for both μLED array and driver circuit. Therefore, it is important to develop integrated μLED arrays with high optical

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power, high modulation bandwidth and a simple addressing scheme.

The series-biased LED arrays, which feature a monolithically-integrated configuration of multiple series-connected LED junctions, are considered to be reliable, compact and inexpensive light sources [14], [15], [16], [17], [18]. Compared with conventional broad-area LEDs, while retaining high optical power output, these LED arrays normally have a higher turn-on voltage and lower driving current under direct-current (DC) operation. Thanks to this high-voltage low-current operation mode, the series-biased LED arrays could mitigate the efficiency droop occurring in conventional III-nitride broad-area LEDs [18] and simplify the mains alternating current (AC)-to-DC driver design. Furthermore, the capacitance of the series-biased LED arrays should be theoretically smaller than the one of each individual LED element in the array due to the series-connection configuration. Thus, the series-biased LED arrays have great potential for VLC applications. For example, compared with a single LED with the same total emitting area, these arrays could be, in theory, modulated faster while producing similar optical power. On the other hand, compared with the individual LED elements in the array, while retaining the fast modulation speed, the optical power of these arrays is much higher. Recently, this hypothesis has been proved in [19], which demonstrates that, as the number of LED element-in-series increases, the modulation bandwidth and optical power increase at the same operation current density. However, to the best of our knowledge, there is as yet no work demonstrating the data rates of VLC applications based on the series-biased LED arrays.

In this paper, we report the design, fabrication, characterisation and VLC applications of III-nitride series-biased μLED arrays. An example array consisting of 3×3 40 μm-in-diameter μLED elements fabricated from a commercial blue LED wafer on sapphire is presented here. At 450 nm, over 18.0 mW optical power and 285 MHz 6-dB electrical bandwidth are achieved at 3200 A/cm^2 DC operating current density. We further demonstrate the free-space VLC application of this series-biased μLED array assuming OOK, pulse-amplitude modulation (PAM) and OFDM modulation formats. The error-free data rates of 1.95, 2.37 and 4.81 Gbps are achieved, respectively. The results shown in this work not only confirm the combined high optical power and high modulation bandwidth characteristics of series-biased μLED arrays, but also demonstrate their great potential for VLC applications.

II. Series-biased μLED array

A. Design and Fabrication

The series-biased μLED arrays were fabricated from commercial blue III-nitride LED wafers grown on c-plane (0001) sapphire with periodically patterned surfaces. The LED epitaxial structure consists of a 3.4 μm-thick undoped GaN buffer layer, a 2.6 μm-thick n-type GaN layer, eleven periods of InGaN (2.8 nm)/GaN (13.5 nm) quantum wells (QWs) emitting at 450 nm, a 30 nm-thick p-type AlGaN electron blocking layer and a 160 nm-thick p-type GaN topmost layer.

The series-biased μLED array presented here contains a 3×3 layout of μLED elements in a flip-chip configuration, each with a diameter of 40 μm (1256 μm^2 emitting area), on a 160 μm centre-to-centre pitch. Fig. 1(a) illustrates the simplified schematic structure of the series-biased μLED array, taking two adjacent μLED elements as an example, to highlight element-to-element electrical interconnections. The fabrication process of this series-biased μLED array is similar to that described in our recent work [20]. Firstly, the disk-shaped μLED elements are etched down to n-type GaN layer by Cl_2-based inductively coupled plasma (ICP) etching, Then, in order to fully isolate each μLED element from both p- and n-type GaN layers, GaN mesas, in a square shape with sides of 90 μm, are further etched down from n-type GaN layer to the sapphire substrate through a second ICP etch. Each μLED element is at the centre of its corresponding GaN mesa to guarantee a uniform current spreading. The spacing between GaN mesas is set as 70 μm to reduce light absorption by neighbouring μLED element and, thus, improve the optical power output of the array [21]. After these etching steps, a 100 nm Pd metal layer is evaporated on the p-type GaN surface, followed a thermal annealing in a N_2 ambient at 300 °C to form a quasi-ohmic contact to p-type GaN. The n-type metallization on GaN mesas is formed by Ti/Au (50 nm/200 nm) metal bilayer. After a plasma cleaning step by an O_2 plasma at 200 °C in plasma asher, a 300 nm-thick SiO_2 layer is deposited by plasma enhanced chemical vapour deposition as an insulating layer. Then, the SiO_2 on top of each μLED element and selected area on GaN mesas is removed for further metal interconnection. Finally, another Ti/Au metal bilayer is sputtered to interconnect μLED elements following series-connection configuration. In this optimised fabrication process, we employed a plasma ashing step to minimize the fabrication errors leading to the short-circuit issue [20]. Meanwhile, in order to eliminate the fab errors causing the open-circuit issue, the metal sputter step was employed to guarantee the conform metal deposition for μLED element interconnection. Fig. 1(b) is an optical image of the series-biased μLED array at a DC operating current density of 79.6 A/cm^2, corresponding to 1 mA operating current.

B. Electrical, Optical and Modulation Performance

Fig. 2(a) shows the current density versus voltage (*J-V*) and optical power versus current density (*L-J*) characteristics of the series-biased μLED array fabricated in this work. These characteristics were measured at the same time by placing a Si photodetector in close proximity to the polished sapphire substrate of the array, through scanning each data point under DC conditions. As shown, the turn-on voltage at 79.6 A/cm^2 (1 mA) of this array is 26.5 V, corresponding to about 2.94 V for each μLED element. This value is consistent with the theoretical turn-on voltage of blue-emitting LEDs, which is around 2.76 V, demonstrating a high-quality fabrication process we developed in this work. Meanwhile, this series-biased μLED array can be operated at a current density up to 3200 A/cm^2, and is able to produce an optical power over 18.0 mW before thermal rollover. Moreover, as the earlier

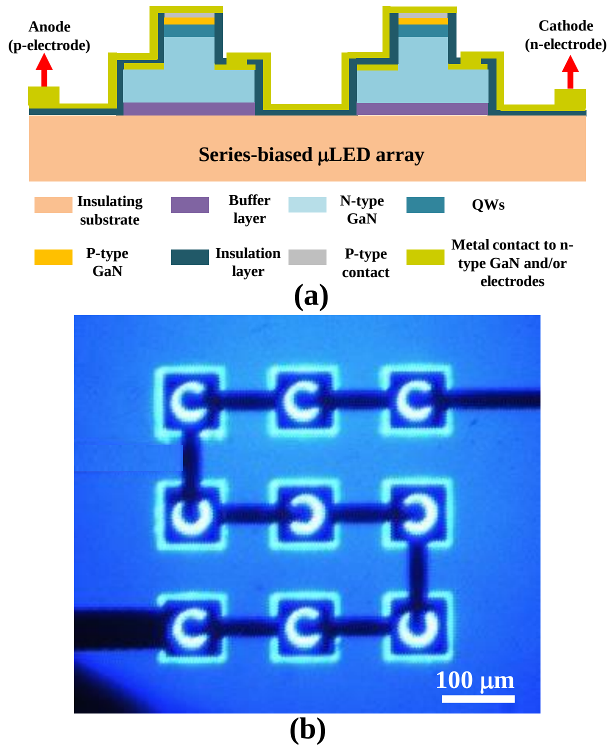

Fig. 1. (a) Simplified cross-sectional structure of a series-biased μLED array, taking two adjacent μLED elements as an example. Relative dimensions are not to scale. Part (b) shows an optical image of the operating array at a DC operating current density of 79.6 A/cm^2, corresponding to 1 mA operating current.

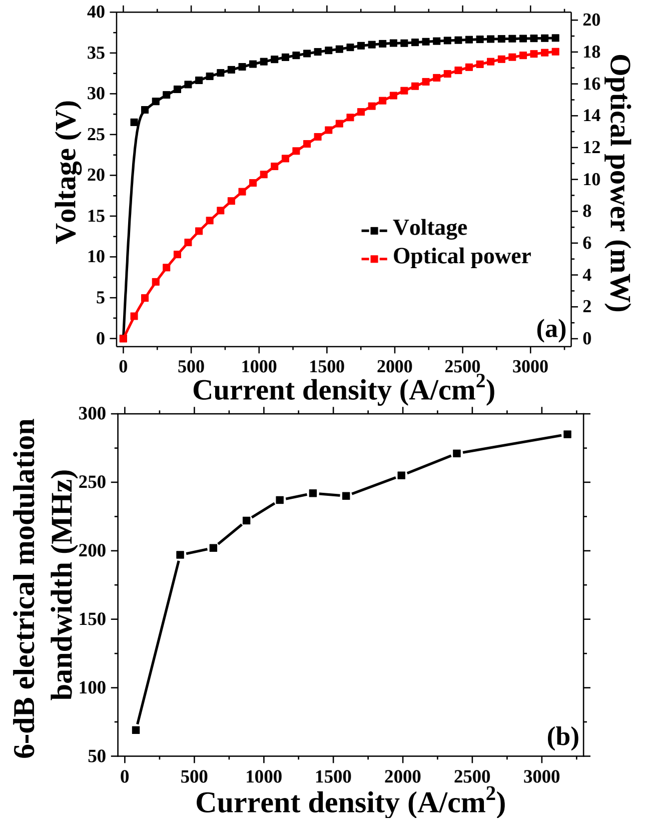

Fig. 2. (a) *J-V* and *L-J* characteristics of the series-biased μLED array; (b) 6-dB electrical bandwidth characteristic of the same series-biased μLED array.

work based on a single μLED emitter has shown [8], [9], this high operating current density leads to a shorter differential carrier lifetime and, thus, increases the modulation bandwidth. As illustrated in Fig. 2(b), the 6-dB electrical bandwidth of this array is in excess of 280 MHz at 3200 A/cm^2 operating current density. These 6-dB electrical modulation bandwidths were measured following the same method described in [8] and [22]. The series-biased μLED array was directly probed by a high-speed micro-probe and the input signal consists of a DC bias from a power supply combined with a small modulation voltage (few mV) from a network analyser. The modulated light was then received by a photodiode with a 3-dB electrical bandwidth of 1.4 GHz and sent to the network analyser. The optical power of this series-biased LED array consisting of 9 μLED elements is slightly lower than 9 times the optical power produced by a single μLED element with the similar size at the same operating current density as shown in [10]. This is mainly due to light absorption by neighbouring μLED elements [21] and heating effects in the series-biased μLED array. On the other hand, the modulation bandwidth of this array is even higher than the one of the single μLED element at the same operating current density. The observed higher modulation bandwidth of the series-biased μLED array is attributed to its lower capacitance due to the series-connection configuration, which is consistent with the one reported in [19]. We are currently working on the performance comparison between the single μLED elements, series-biased μLED array, parallel-biased μLED array and broad LEDs to systemically investigate the advantages of the series-biased μLED array for VLC applications and underlying physical mechanisms. Here, we also wish to emphasise that all the measurements of this series-biased LED array were performed on a bare chip without any thermal management. The maximum operating current density of the series-biased μLED array is strongly limited by its self-heating effect. Thus the results shown here only demonstrate the basic capability of series-biased LED arrays in terms of high optical power output and modulation bandwidth. Even higher values on both optical power and modulation bandwidth are expected when a heat sink is applied on the array.

III. VLC Applications

In this section, we present free-space data transmission results using the series-biased μLED array as a light source. The series-biased μLED array was modulated assuming OOK, *4*-PAM and OFDM modulation formats. The results shown here aim to demonstrate the capability of series-biased μLED arrays in VLC applications.

A. Experimental Setup

The experimental setup for the free-space VLC data communication used in this work was similar to that previously reported in [11]. Different waveforms generated in MATLAB® were supplied to an arbitrary waveform generator (AWG), which mapped them to analog signals. Keysight 81180B was used for OOK and PAM formats, and Keysight M8190A was for the OFDM formats. The output of the AWG was amplified with a high-power amplifier, SHF S126A, and a DC current density was added to the drive signal using a bias-T, Tektronix PSPL5575A. After extensive experiments to optimise the system performance, the modulation signal depths, V_{PP}, were set as 6.19 V for OOK and PAM, and 5.63 V for OFDM. The DC-bias current density, J_{DC}, was 1592.4 A/cm^2 for OOK and PAM, and 1074.8 A/cm^2 for the OFDM. The bias signal was applied to the series-biased μLED array using a high-speed micro-probe. Light emitted from the series-biased LED array was imaged onto a high-speed photodetector, Newport 1601FS-AC (3-dB electrical bandwidth of 1 GHz), using a high numerical aperture microscope objective, Newport M-40×. The distance between the series-biased μLED array and photo receiver was 0.3 m. The output signal of the photodetector was captured by a digital oscilloscope, MSO7104B for OOK and PAM, and DSA90804A for OFDM.

B. Free-space VLC Performance

For a general *M*-PAM modulation format with *M* constellation size and number of bits $k = log_2 M$, a set of $2k$ possible information symbols is mapped to a set of amplitudes $\{A_m, 1 \leq m \leq M\}$, where $A_m = 2m - 1 - M$ [23]. The set of amplitudes $\{A_m\}$ is referred to as transmitted symbols. During the experiment, the non-return-to-zero symbols are used for the OOK modulation format, which is equivalent to the *2*-PAM. The sets of OOK and *4*-PAM symbols are {-1, 1} and {-3, -1, 1, 3}, respectively. Fig. 3 compares the eye diagrams of transmitted (a) and received (b) signals assuming the OOK modulation format at 700 Mbps using the fabricated series-biased μLED array. As shown, even at this relative low data rate using a simple modulation format, the amplitude and temporal distortions caused by the communication channel can be observed (Fig. 3(b)). These distortions lead to intersymbol interference (ISI) [23], [24] and a higher bit error ratio (BER). In order to mitigate the ISI, a feedforward equalizer is employed. Specifically, a finite impulse response filter whose system function in z-domain is denoted as $H(z) = \sum_{l=0}^{L} b_l z^{-l}$ is used, where b_l is the filter coefficient and L is the number of filter taps. The number of used filter taps is set to $L = 9$ in this work which strikes a reasonable trade-off between computational complexity and performance enhancements given the line-of-sight channel, which is dominated by the direct, non-reflected signal component. To demonstrate the working mechanism of this equalizer, the histograms of transmitted and received symbols assuming OOK (Fig. 4(a)) and *4*-PAM (Fig. 4(b)) modulation formats at 2.1 Gbps are shown. Note that, uniformly distributed symbols are generated at the transmitter. However, the distribution of received symbols before equalizer is heavier in the negative side, which is mainly due to the ISI as discussed [23], [24]. The employed equalizer alleviates this phenomenon by estimating the received symbols. Generally, if the received symbol goes beyond a decision threshold, the estimated symbol from the equalizer will be decoded as its nearest neighbours. It leads to a narrower spread of received symbols and, therefore, the lower BER.

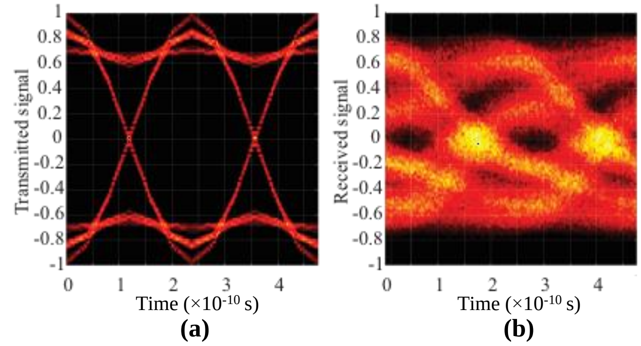

Fig. 3. Eye diagrams of (a) transmitted and (b) received signals assuming OOK modulation schemes at 700 Mbps without equalizer using the fabricated series-biased μLED array.

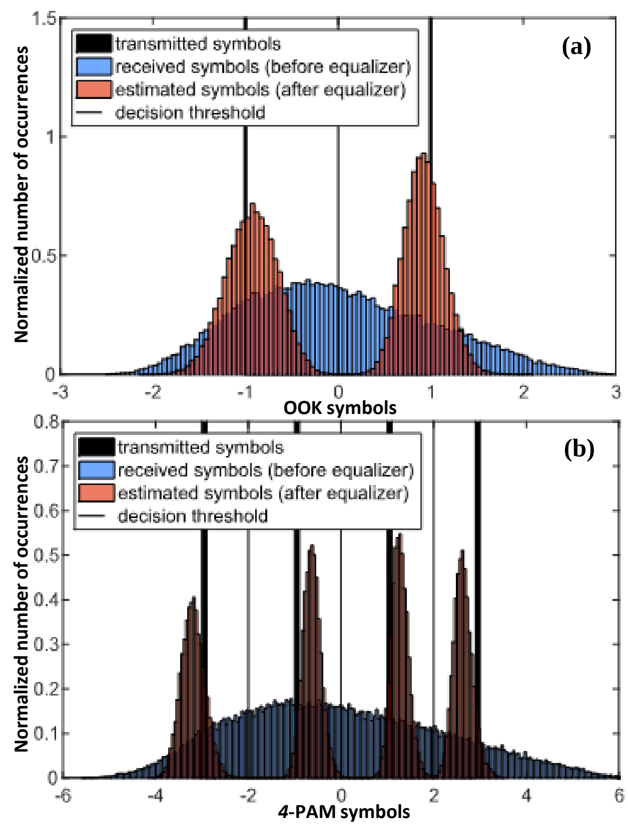

Fig. 4. Histograms of transmitted and received symbols assuming (a) OOK and (b) *4*-PAM modulation formats at 2.1 Gbps using the fabricated series-biased μLED array.

A drawback of single carrier modulation such as *M*-PAM is the computational complexity of the equalizer. A cost and computational effective solution is to use OFDM with a single tap equalizer in conjunction with a cyclic prefix which is at least as long as the largest multi-path component assumed to be between 3-10 ns. The number of subcarriers and hence the OFDM frame length will be chosen so that the spectrum efficiency loss is less than 5 %. Binary bits are modulated into M-ary quadrature amplitude modulation (*M*-QAM) symbols. Adaptive bit and energy loading is used to allow different constellation sizes to be loaded on the subcarriers based on

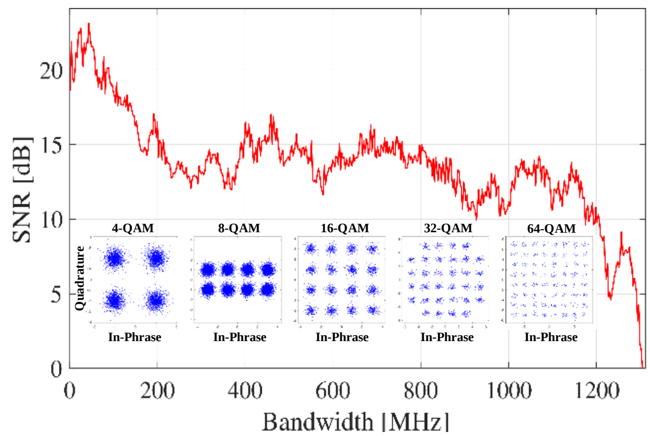

Fig. 5. SNR versus bandwidth achieved for OFDM using the fabricated series-biased μLED array at J_{DC} = 1074.8 A/cm^2 and V_{PP} = 5.63 V. The inserts are the M-QAM constellation symbols received at the photodetector after equalization for M = 4, 8, 16, 32, 64.

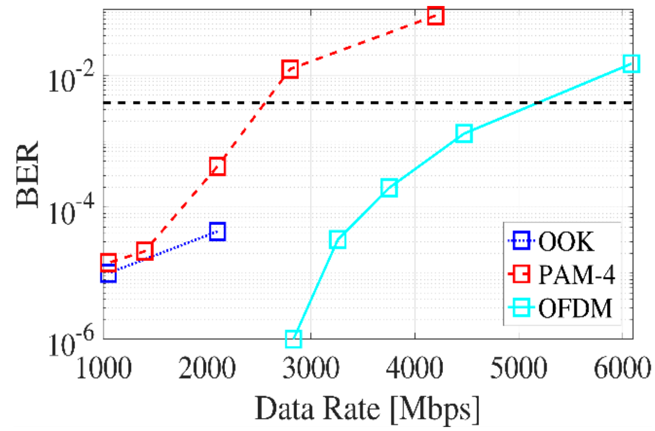

Fig. 6. BER versus data rate achieved using the fabricated series-biased μLED array as the transmitter assuming OOK, *4*-PAM and OFDM modulation formats, respectively.

the available SNR. This is done in consistency with our previous work [11]. A frame of N_{FFT}/2-1 QAM symbols is then multiplexed into NFFT subcarriers using inverse Fourier transformation (IFFT). Hermitian symmetry is imposed on the OFDM frame to guarantee a real-valued output. A DC bias is used to shift the negative OFDM samples into positive. The generated digital waveform is converted into analog by the AWG at a sampling frequency of 10.8 GSps. Root raised cosine is used with an oversampling factor of 4, which corresponds to a single-sided modulation bandwidth of 1.35 GHz. The fast Fourier transformation (FFT) is applied on the received signal and the received QAM symbols are equalized using the estimated channel. By using the fabricated series-biased μLED array, the recovered M-QAM constellations for $M = 4, 8, 16, 32, 64$ are shown as the inserts of Fig. 5. They demonstrate that the SNR is high enough to allow maximum likelihood decoder to distinguish the transmitted symbols. The SNR versus bandwidth of the series-biased μLED array at J_{DC} = 1074.8 A/cm^2 and V_{PP} = 5.63 V is shown in Fig. 5. The series-biased μLED array has shown an impressive SNR performance that is higher than 10 dB up to 1.2 GHz of bandwidth. This permits high speed data communications to be demonstrated.

Fig. 6 summarises the measured data transmission rates using the fabricated series-biased μLED array as the transmitter assuming OOK, *4*-PAM and OFDM modulation formats. As shown, the maximum data rates at the FEC floor of 3.8×10^{-3} are 2.1, 2.55, and 5.18 Gbps for OOK, *4*-PAM and OFDM with adaptive modulation formats, respectively. After applying a 7 % FEC overhead reduction, the error-free date rates of 1.95, 2.37 and 4.81 Gbps are achieved. To the best of our knowledge, this is the first work presenting the VLC performances using a series-biased μLED array as the transmitter. Compared with our previous work using a single μLED element as the transmitter [10], [11], these values are slightly lower. The pronounced self-heating effect of series-biased μLED arrays is considered as the main factor limiting the data rates we can achieved. Firstly, as we demonstrated in section II B, this effect imposes a restriction on the operating current density of the arrays. This leads to a lower J_{DC} applied on the array and, thus, a lower modulation bandwidth used in data communication measurements. Secondly, the linear region of the optical power versus voltage characteristic of the array are also narrowed by the self-heating effect. This results in a relative shallow V_{PP} set in the measurement, which degrades the SNR. Currently, we are working on applying a custom heat sink to the series-biased μLED arrays to alleviate this effect and, in turn, achieve higher data rates.

IV. CONCLUSION

We presented the design, fabrication and performance characterisation of III-nitride series-biased μLED arrays for VLC applications. An example array, which consists of 3×3 40 μm-in-diameter μLED elements, was fabricated from a commercial blue LED wafer on sapphire substrate. This series-biased μLED array shows the outstanding electrical, optical and modulation performance. At an operating current density of 3200 A/cm^2, over 18.0 mW optical power and a 6-dB electrical bandwidth of 285 MHz are achieved. We further demonstrated the free-space VLC application of this series-biased μLED array assuming OOK, PAM and OFDM modulation formats and achieved the error-free data rates of 1.95, 2.37 and 4.81 Gbps, respectively. All the data achieved in this work were measured from a bare chip and, thus, strongly limited by the self-heating effect from series-biased μLED arrays. We believe that, by integrating the array with heat sinks, the data rate would be further improved for both short- and long-distance VLC applications.

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