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High Bandwidth GaN-Based Micro-LEDs for Multi-Gb/s Visible Light Communications

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***Abstract*— Gallium-nitride (GaN)-based light-emitting diodes (LEDs) are highly efficient sources for general purpose illumination. Visible light communications (VLC) uses these sources to supplement existing wireless communications by offering a large, licence-free region of optical spectrum. Here, we report on progress in the development of micro-scale GaN LEDs (micro-LEDs), optimized for VLC. These blue-emitting micro-LEDs are shown to have very high electrical-to-optical modulation bandwidths, exceeding 800 MHz. The data transmission capabilities of the micro-LEDs are illustrated by demonstrations using ON–OFF-keying, pulse-amplitude modulation, and orthogonal frequency division multiplexing modulation schemes to transmit data over free space at the rates of 1.7, 3.4, and 5 Gb/s, respectively.**

***Index Terms*— Bandwidth, micro light-emitting diodes, GaN, optical communication, visible-light communication, OFDM, PAM.**

I. INTRODUCTION

VISIBLE light communications (VLC) is an emerging technology that has significant potential to supplement existing radio frequency (RF) based wireless communications. VLC opens up a large, licence-free, visible region of the electromagnetic spectrum for wireless communications, and can in principle be integrated into, and work alongside, pre-existing lighting infrastructure. Gallium nitride (GaN) light-emitting diodes (LEDs) are attractive light sources for use in VLC systems. They can be used to generate light across the visible spectrum, including white light, and being semiconductor-based they can be modulated significantly faster than conventional incandescent or fluorescent light sources, as well as being amenable to integration with drive electronics. LED-based VLC typically uses off-the-shelf LEDs, which generally have modest electrical-to-optical modulation bandwidths of the order of 10-20 MHz, although the use of complex modulation schemes, parallel data transmission and equalisation can allow data transmission rates in excess of 1 Gbps [1], [2]. There have been efforts made to develop novel LED epitaxial structure and devices optimised for VLC [3], [4]. For example by reducing the LED active area, and thereby decreasing capacitance and increasing current density, we have previously reported modulation bandwidths in excess of 400 MHz [5]. Such LEDs, with dimensions of 100 × 100 μm^2 or less, have been used to demonstrate 3 Gbps transmission over free-space [6] and 5 Gbps along a polymer optical fibre (POF) [7]. In this work, we report further advancement of these micro-LED sources. A significant increase in the modulation bandwidth, now exceeding 800 MHz has been obtained. Using single pixels from individually-addressable arrays of these LEDs, with a nominal peak emission wavelength of 450 nm, we demonstrate data transmission over free-space using on-off keying (OOK), pulse-amplitude modulation (PAM) and orthogonal frequency division multiplexing (OFDM) modulation schemes at data rates of 1.7, 3.4 and 5 Gbps, respectively. These modulation bandwidths and data transmission rates represent, to the best of our knowledge, the highest yet reported for GaN LEDs.

II. DEVICES

Two segmented geometries of micro-LEDs were fabricated for this work which we designate A and B, with active areas of 435 and 1369 μm^2, respectively. These areas are equivalent to disk shape micro-LEDs with diameters of 24 μm for LED A and 42 μm for LED B. Fig. 1 shows large concentric arrays of these LEDs designed primarily for use with POF. The chosen micro-LEDs are single elements of these arrays, as shown in Fig. 1 (a) for LED A and Fig. 1 (b) for LED B.

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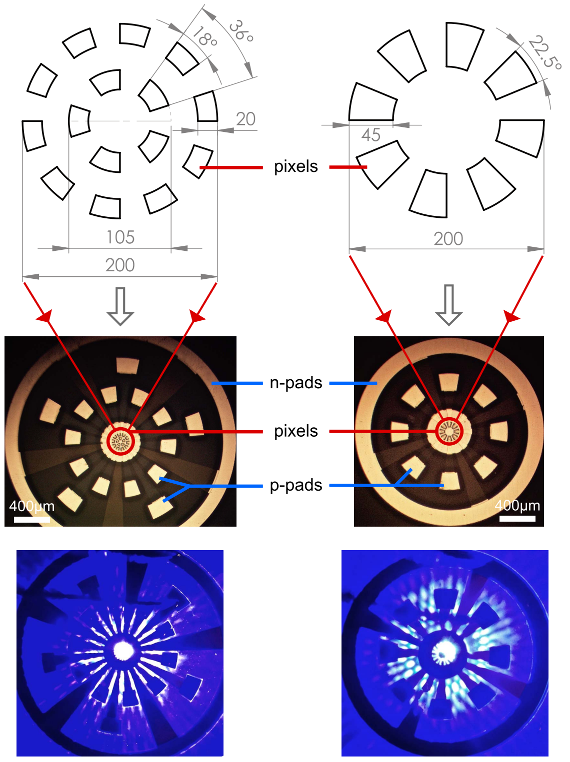


(a) (b)

Fig. 1. Micro-LED designs in concentric multiple element geometries. LED A is a single element of (a) and LED B is a single element of (b), dimensions are given in micrometers. The upper diagrams correspond to the pixels which are located at center of the photographs.

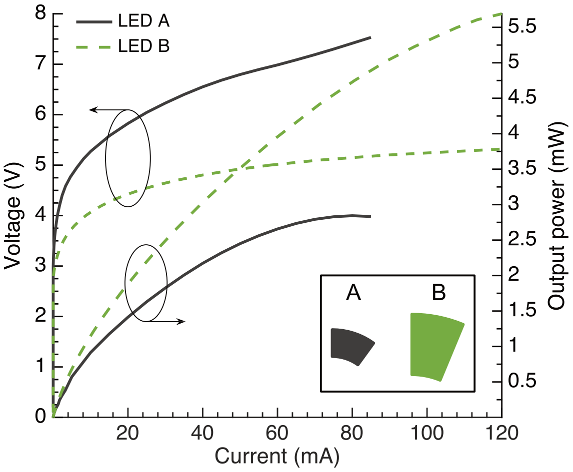


Fig. 2. Voltage-current-optical power characteristics of LED A and B with respective maximum optical power densities of 655 and 415 W/cm^2 at current densities of 19.5 and 8.7 kA/cm^2, respectively. Inset shows the relative size and shape of the micro-LEDs.

A direct comparison of relative size and shape of LED A and B can be found in the inset of Fig. 2.

The micro-LEDs had flip-chip configurations (substrate emitting) and were fabricated from a commercial 450 nm GaN-based LED wafer grown on a c-plane sapphire substrate. Basic details of the fabrication process for these devices can be found in our previous reports [5]. However, here we have changed the p-contact metal and etching depth. We use palladium (Pd) for the p-contact, thermally annealed to form a metal contact with high reflectivity ($>$ 50%) and low contact resistance [8]. In addition, the mesa is etched down to the sapphire substrate, confining the n-GaN to match the LED active area, thus reducing the capacitance of each pixel.

These two changes in fabrication combined with a change of LED shape and layout are the key factors to which we attribute the improvements in performance that are shown in the following sections. Note that the chips are not on a heat-sink.

III. PERFORMANCE

A. I-V and L-I Characteristics

Fig. 2 presents the current-voltage (I-V) and output power-current (L-I) characteristics of the micro-LEDs. The DC current densities are up to 19.5 kA/cm^2 for device A and 8.7 kA/cm^2 for device B. The optical power is 2.7 mW for LED A and 5.7 mW for LED B, corresponding to optical power densities of 655 W/cm^2 and 415 W/cm^2 for LED A and B, respectively. This corresponds to an increase in optical power of three times compared with our previous reports for devices of comparable size [5]. We note that these powers are measured in the forward direction only, without an integrating sphere.

The high current density capability is characteristic of flip-chip micro-LEDs and is attributed to improved thermal management and reduced current crowding [9]. Higher series resistance is common for small active areas and increases with the decrease of area [10], [11]. In these devices the improved p-contact with Pd results in a lower contact resistance in comparison to our previous report using Ni/Au [5]. The lower resistance reduces the Joule heating, thus contributing to a lower junction temperature. In addition, the shape of the pixel is designed to increase the surface-to-active-area ratio, which enables a more efficient thermal dissipation. As such, in comparison with our previous report for equivalent areas, these devices show an increase by a factor of 2 in the current densities at which the roll-over point occurs [5].

B. Modulation Bandwidth

The small signal electrical-to-optical (E-O) modulation bandwidth was measured in similar fashion to our previous reports [5], [12], [13]. The micro-LEDs were directly probed on chip using a high-speed micro-probe. The input signal consists of a constant bias current from a power supply combined with a small modulation voltage (few mV) from a network analyser. The modulated light is then received by a high-speed photodiode (bandwidth = 1.4 GHz) and sent to the network analyser.

Fig. 3 presents the (E-O) bandwidth as a function of the injected current density for LEDs A and B. These devices achieve high current densities as described in III A, enabling modulation bandwidths up to $\approx$830 MHz for LED A and 400 MHz for LED B. We have previously shown that increasing the current densities in the active region decreases the differential carrier lifetime [5], [14]. The differential carrier

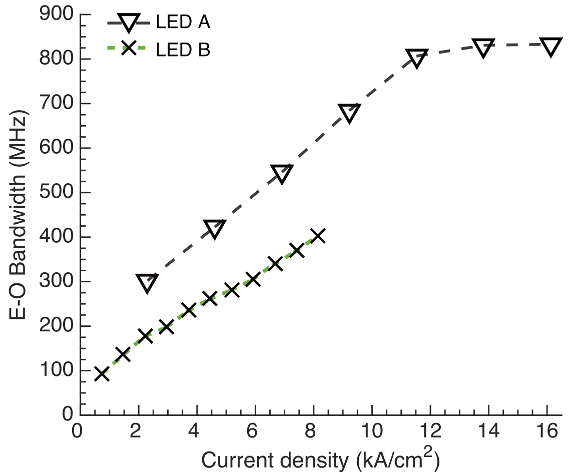


Fig. 3. E-O bandwidth as function of the injected current density for micro-LEDs A and B. The maximum bandwidths are 833 MHz and 397 MHz, respectively. Note that these current densities correspond to a DC bias range of 10–70 mA for LED A and 10–110 mA for B.

lifetimes are calculated here to be 0.19 ns (at 19.5 $kA/cm2$) for LED A and 0.40 ns (at 8.7 $kA/cm2$) for B, which we attribute to a combined effect of high carrier densities. As a comparison, the micro-LEDs reported in [5] had differential carrier lifetimes down to 0.37 ns at $< 10\,kA/cm2$, which suggests that the high current densities possible from LED A, in particular, are key in enabling the high modulation bandwidths shown here. Lower capacitance due to the etch process down to the substrate may have also reduced parasitic capacitance that might otherwise have affected the modulation response of the LEDs.

In addition, at the same injected current densities the observed bandwidths are higher for LED A than B. This effect differs from our previous reports with 450 nm devices [5]. This difference may be attributed to improved current spreading across the active area of the small pixel and an associated reduction in the junction temperature [15]. Furthermore, temperature differences at the same current densities may contribute to this effect.

IV. DATA TRANSMISSION

The next two sections present free-space data transmission with OOK, PAM and DC biased optical OFDM (DCO-OFDM) modulation formats.

A. OOK

Free-space data transmission using OOK was performed over an optical link distance of approximately 0.5 m using a bit-error ratio test (BERT) system. The various LED chips were directly probed as in section III B with a high-speed micro-probe and the light focused onto the photodiode (Femto HSA-X-S-1G4-SI, bandwidth of 1.4 GHz). Data rates ranging from 155 Mbps up to 1.7 Gbps were investigated for the different devices. In Fig. 4 the BER for LED A versus received optical power is shown for data rates from 1 Gbps to 1.7 Gbps.

A BER of 10^{-9} was achieved for 1.7 Gbps at a received optical power of -6 dBm. Note that no equalisation was applied here and at 1.7 Gbps the system is limited by the bandwidth of the photodetector (1.4 GHz).

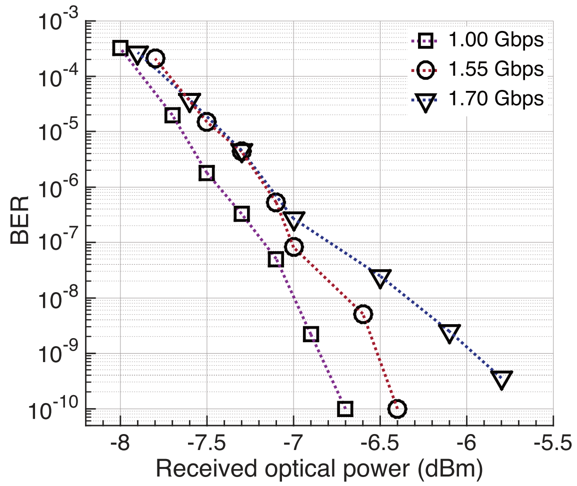


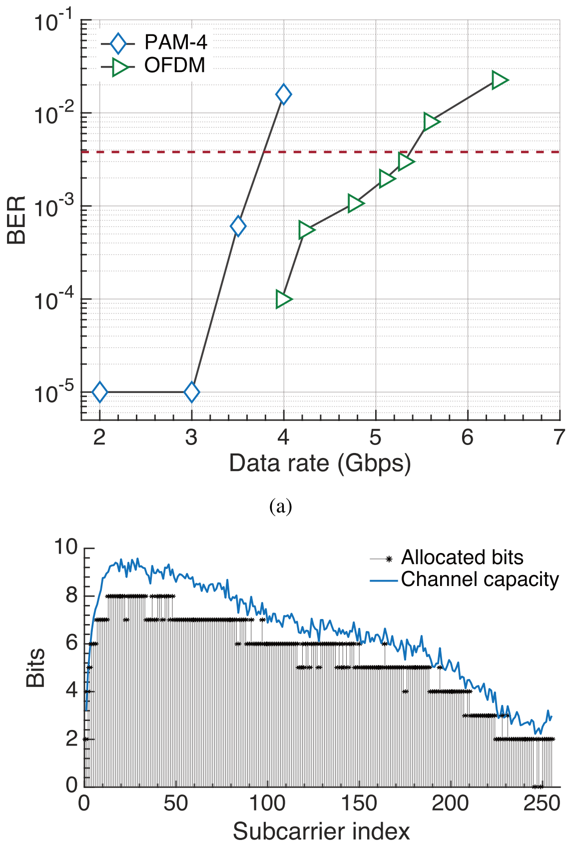
Fig. 4. Bit-error-rate as function of received optical power for LED A in free-space with OOK.

B. PAM and OFDM

This section describes the maximum data rates achieved using PAM and OFDM schemes. The experimental set-up was similar to that previously reported [6]. An analogue signal (OFDM or PAM) from an arbitrary waveform generator (AWG, Keysight 81180B) was combined with a 5 V DC bias, using a bias-tee. The output from the micro-LED was collimated and imaged onto a Si photodetector (New Focus 1601, bandwidth of 1 GHz) using a singlet aspheric lens. The micro-LED and photodetector were in this case approximately 0.75 m apart. The received signal was captured by a digital oscilloscope (Keysight, MSO8104A) and processed offline in MATLAB®.

A PAM-L signal was generated using a pseudo-random bit sequence (PRBS) of $2^{14} - 1$ and transmitted via the micro-LED. Due to the limited bandwidth of the micro-LED, an adaptive decision feedback equaliser (DFE) was adopted at the receiver. The data rate versus BER for a PAM-4 scheme is shown in Fig. 5 (a). The achievable data rate below the forward error correction (FEC) floor of 3.8×10^{-3} is ~3.8 Gbps, which corresponds to a net data rate of 3.5 Gbps, after applying a 7% FEC overhead reduction. Higher order PAM schemes were also tested, however the data rates achieved were below this value. Although OOK offered BER of 10^{-5} at 3 Gbps with a DFE, it was not possible to test higher data rates due to the limited sampling rate of the AWG.

The spectrally efficient DCO-OFDM scheme was also tested for the same link setup. DCO-OFDM signal generation and decoding is described in detail in [6] and we have adopted a similar approach. The DCO-OFDM parameters used for the experiments were: Fast Fourier Transform (FFT) size of $N_{fft} = 512$; cyclic prefix length = 5; clipping level = $\pm 4\sigma$, where σ is the standard deviation of the time-domain OFDM signal. Fig. 5 (a) presents the data rate versus BER for DCO-OFDM and PAM-4 schemes. Fig. 5 (b) presents the



(a)

(b)

Fig. 5. In (a) is the BER as function of the data rate for LED B in free-space with PAM-4 and DCO-OFDM. In (b) is the bit loading per subcarrier index for the OFDM signal.

adaptive bit loading for the DCO-OFDM. Also shown in the figure are the allocated bits for different subcarriers. A maximum data rate of 5.37 Gbps was achieved at a FEC BER floor of 3.8×10^{-3}. Taking into account the 7% FEC overhead, the data becomes 5 Gbps. This compares to 3 Gbps over 5 cm reported in [6], and represents, to the best of the authors' knowledge, the fastest single link wireless VLC data rate demonstrated using a single wavelength.

V. CONCLUSION

We present two new micro-LED designs for VLC and polymer optical fibre systems. We demonstrate record modulation bandwidths and data transmission with both PAM and OFDM. The devices sustain very high current densities producing higher optical power densities than comparable commercial devices while retaining multi-mW optical powers. Bandwidths in excess of 800 MHz were obtained and data rates of 3.5 Gbps using PAM-4 and 5 Gbps using adaptive DCO-OFDM. At this stage in our own studies, the performance achieved by these micro-LEDs is attributed to three factors: deep etch of the mesa down to substrate; improved metallisation of the Pd p-contact and the shaping of the active area. The individual contributions of these factors are part of on-going work to be reported shortly. Other future investigations include the influence of design in the thermal and bandwidth performance, and its impacts on the radiative and non-radiative recombination.

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