High-Speed Visible Light Communications Using Individual Pixels in a Micro Light-Emitting Diode Array

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***Abstract*—The high-frequency modulation of individual pixels in III–nitride-based micro-pixel light-emitting diode arrays, where each array consists of 16 × 16 individually addressable 72-μm-diameter pixels, are reported. The devices investigated have peak emission wavelengths at 370, 405, and 450 nm, respectively. The optical −3-dB modulation bandwidth of a typical pixel from the 450-nm-emitting device was found to be approximately 245 MHz. Data transmission at rates of up to 1 Gb/s is demonstrated from a single pixel emitting at 450 nm, using on–off keying nonreturn-to-zero modulation, with a bit-error ratio of less than 1×10^{-10}. Such devices have potential for free-space or fiber-coupled visible light communications.**

***Index Terms*—Bandwidth, GaN, micro light-emitting diodes (micro-LEDs), modulation, polymer optical fiber (POF), white light-emitting diode (LED).**

I. Introduction

CONTINUING advances in light-emitting diodes (LEDs) based on the AlInGaN alloy system have created the capability to efficiently generate light across the ultraviolet-blue-green part of the spectrum, allowing solid-state visible light sources to be commercialized for general purpose lighting, displays, and signaling applications. Visible light communications (VLC), in both fiber-based and free-space embodiments, is another potential application of AlInGaN LEDs which has attracted considerable recent interest. AlInGaN LEDs can exploit the lowest-loss transmission window that exists in polymer optical fiber (POF) around 520 nm. To this end, green-emitting GaN-based LEDs are demonstrated to have bandwidths of up to ≈330 MHz [1]. Free-space VLC that uses modulated white light (wavelength combined or color converted AlInGaN) LEDs to provide both general illumination and data transmission is an area of related interest, with bit rates of up to around 200 Mb/s demonstrated [2]. Although the resonant-cavity LED (RCLED) format of the device is in principle attractive for such applications due to its narrow linewidth and highly directional output, fabricating AlInGaN RCLEDs is challenging [3] owing to difficulties in producing microcavities in this alloy system. Therefore, it is important to explore the modulation characteristics of "conventional" AlInGaN LED structures in novel device formats. In this letter, we have investigated the potential of AlInGaN-based micro-pixellated LEDs ("micro-LEDs"), with peak emissions at 370, 405, and 450 nm, respectively, for use as optical data transmitters. These micro-LEDs each consist of a 16 × 16 array of individually addressable 72-μm-diameter pixels with a center-to-center pitch of 100 μm. The devices are shown to have bandwidths of up to 245 MHz per pixel. The transmission of error-free nonreturn-to-zero (NRZ) pseudorandom bit sequences (PRBS) at data rates of up to 1 Gb/s, using a 450-nm-emitting device, is also demonstrated. The comparatively straightforward fabrication process required for these devices means they are potentially simple and cheap light sources for VLC, and could be integrated with color-conversion materials [4], [5] for white VLC. In addition, their dimensions and micro-pixellated structure mean that a micro-LED array integrated with suitable complementary metal–oxide–semiconductor (CMOS) control electronics [6] could be used to transmit data over multiple POFs in a parallel fashion or, because the devices can also project images, as a communications "pico-projector."

II. Micro-LED Design and Performance

The micro-LED devices reported here were fabricated from commercially available epitaxial wafers grown on c-plane sapphire substrates and patterned by photolithography, further details of which can be found elsewhere [7]. The devices have peak emission at 370, 405, or 450 nm, with electroluminescence linewidth of approximately 15-nm full-width at half-maximum (FWHM). Each pixel in a device shares a common n-contact, and is addressed via an individual p-contact. The pixel-to-pixel electrical and optical performance showed good uniformity across the entire array [6], [7]. Due to the flip-chip format of these devices, light is extracted through the polished sapphire substrate. The current–voltage (I–V) and light output–current (L–I) curves measured from representative micro-LED pixels are shown in Fig. 1(a) and (b), respectively. Each micro-LED pixel was estimated to have an emission numerical aperture (NA) into air of 0.58.

III. Results and Discussion

A representative individual pixel from each array was electrically monitored by a ground–signal–ground probe. A direct cur-

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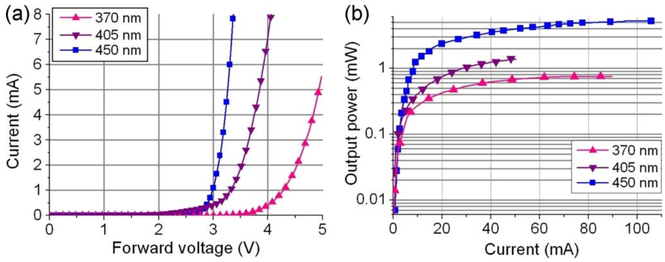

Fig. 1. Representative (a) I–V and (b) L–I curves for different peak emission micro-LED devices under dc operation.

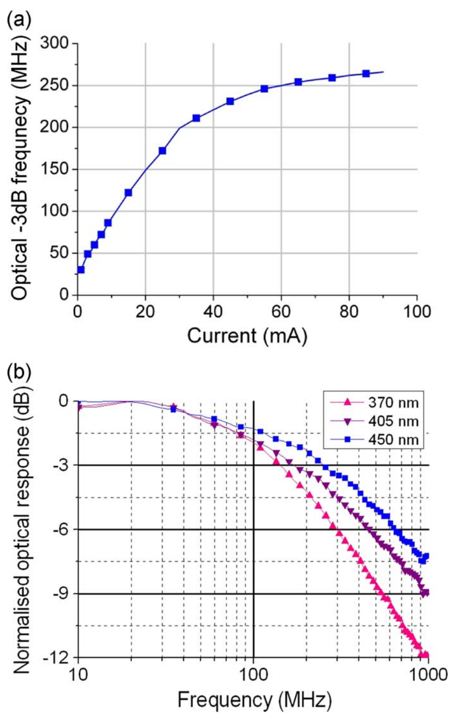

Fig. 2. (a) Bandwidth versus current for a representative 450-nm-emission pixel; (b) frequency response curves for micro-LED pixels of different peak emission wavelength, for an injected dc current of 20 mA.

rent (dc) bias was applied, and radio-frequency (RF) modulation and data were combined with this via a bias-tee. The light output of the pixel was collected by a 0.68 NA lens and imaged onto a high-speed silicon photodetector (Newport 818-BB-21A). The frequency response of each pixel was measured using a network analyzer. The modulated light was superimposed onto a large continuous-wave signal, which was blocked by the alternating current (ac)-coupled electrical amplifier. Eight pixels were sampled at random across a diagonal of a 450-nm emission array, and the maximum optical −3-dB modulation bandwidth (corresponding to the electrical −6-dB bandwidth) was found to be 245 MHz ± 10 MHz for all. The optical −3-dB bandwidth versus injected current characteristic of a representative 450-nm-emitting micro-LED pixel is shown in Fig. 2(a). Clearly, the optical bandwidth shows a dependence on the injected current. Initial analysis of the data suggests that, for low injection currents, the response of the device may be related to an increase in carrier lifetime at low carrier densities. The physical properties that ultimately limit the micro-LED bandwidth

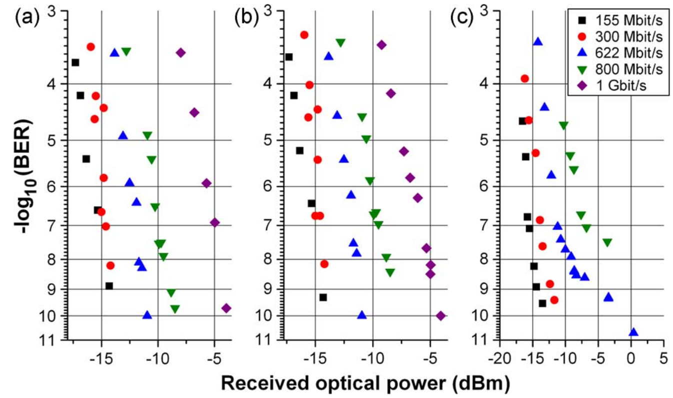

Fig. 3. BERs measured from a 450- nm-emitting micro-LED at various bit frequencies, micro-LED current $= 40$ mA. PRBS length of (a) $2^7 - 1$ bits, (b) $2^9 - 1$ bits, and (c) $2^{31} - 1$ bits.

are still under investigation and our findings will be reported in due course.

The frequency response of pixels in similar micro-LED devices having peak emissions at 370 and 405 nm, was also measured. A comparison of the frequency response of a pixel at each wavelength, for the same injected current of 20 mA, is shown in Fig. 2(b). An injected current of 20 mA was chosen in this case, as this is the highest dc current the 370-nm-emitting device can reliably sustain without heatsinking. The optical −3-dB modulation bandwidths for these devices were found to be approximately 100 MHz at 370 nm and 150 MHz at 405 nm. Devices emitting at these wavelengths are particularly suitable for pumping white light-emitting color conversion materials. Differing characteristic carrier lifetimes and series resistances are likely to be the properties that define the modulation bandwidth for devices of different peak emission, and a full investigation of these effects is currently underway.

Data transmission was carried out using a 450-nm-emitting device and a bit-error-ratio test system (BERT). Each micro-LED was driven directly from the BERT with an NRZ PRBS with peak-to-peak amplitude of 2 V. Short pattern lengths appropriate to the 8-B/10-B encoding used in some potential applications for these devices, such as Gigabit Ethernet and Fiber Channel, were used, i.e. ($2^7 - 1$, $2^9 - 1$ bits) as well as $2^{31} - 1$ bit pattern lengths suitable for telecommunications applications. Bit rates from 155 Mb/s to 1 Gb/s were investigated. Received bit-error ratios (BERs) were measured as a function of received optical power, and a digital sampling oscilloscope was used to measure eye diagrams and output bit patterns from each micro-LED pixel. Fig. 3 shows BERs versus received power, for various pattern lengths and bit rates. Error-free transmission, in this case indicated by observing no errors after transmission of 1×10^{10} bits, could be achieved for bit rates of up to 1 Gb/s for pattern lengths of $2^7 - 1$ and $2^9 - 1$ and 622 Mb/s for a pattern length of $2^{31} - 1$.

Bit rates of 1 Gb/s per pixel were achieved, although the high powers required and the fact that error-free operation could not be obtained for the longer pattern lengths indicates that the RF response of the pixels is limited at this high bit rate. However, it can be seen that a BER of 1×10^{-10} was achieved for pattern lengths of $2^7 - 1$ and $2^9 - 1$ at a bit rate of 622 Mb/s. Fig. 4 shows eye diagrams measured from a 450-nm-emitting micro-LED device at 155 and 622 Mb/s. At 155 Mb/s, an open eye is clearly

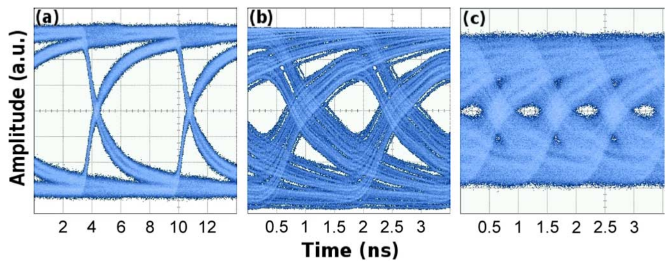

Fig. 4. Eye diagrams for a 450-nm-emitting pixel, dc current 40 mA, at (a) 155, (b) 622, and (c) 1000 Mb/s. Received optical power $\approx$ 1 mW (0 dBm).

shown for a pattern length of $2^7 - 1$ bits, although patterning effects are beginning to become apparent at 622 Mb/s. An extinction ratio (ER) of 0.74 dB was obtained under these conditions by comparing the magnitude of the output of the ac-coupled amplifier to the time averaged signal at its input, which was measured using a dc-coupled detector (ThorLabs DET200). From this value, we calculated that the system is subject to a power penalty relative to an ideal signal of $(\mathrm{ER} + 1)/(\mathrm{ER} - 1) = 11$ dB. This impaired performance is due to the 2-V p-p maximum output of the BERT being significantly lower than the dc bias applied to the device. While the sensitivity of the present setup is low, it is sufficient for our current purpose of measuring the high-frequency modulation performance of the micro-LEDs. The sensitivity could be improved in future by optimizing the components of the measurement system, for example by amplifying the output of the BERT to improve the ER.

These results demonstrate that micro-LED devices are capable of being modulated at high data rates, up to 1 Gb/s per pixel. This greatly exceeds the data rates required by present POF-based standards, such as the POF-based media oriented systems transport (MOST) 150-Mb/s standard [8], confirming that these devices provide a path towards future high-speed POF systems. To the best of our knowledge, this work represents the highest bandwidth reported for a blue-emitting LED fabricated in the AlInGaN alloy system. These micro-LEDs are amongst the simplest AlInGaN-based devices that have been proposed for VLC, as they are fabricated using standard epitaxial wafers and photolithographic techniques. This contrasts with AlInGaN RCLEDs [3], for example, which require the formation of a microcavity.

We anticipate that it should be possible to increase the bandwidth of the micro-LED pixels by using a pulse shaping circuit, and by optimizing the design of the micro-pixels in order to minimize parasitic resistances and capacitances. In addition, the micro-pixellated format of the device—here an array of 256 elements—potentially allows convenient coupling into POF arrays, so that a single micro-LED array device could transmit a high parallel data rate by modulating multiple pixels independently. Although multiple parallel pixel operation has not been demonstrated in this work, future plans include the demonstration of the potential of a CMOS-controlled micro-LED array [6] for high parallel data transmission rates. Furthermore, micro-LEDs have previously been successfully integrated with light-emitting organic polymer blends [4], and semiconductor nanocrystals [5] for color conversion. These materials have fluorescence lifetimes of the order of a few tens of nanoseconds for quantum dots, and a few nanoseconds, or less, for the polymer blends [4], while having photoluminescence quantum efficiencies. This offers a novel way of generating modulated white light for VLC, circumventing the restrictions imposed on the bandwidth of white LEDs that utilize conventional color-converting phosphors with long (microsecond regime) luminescent lifetimes.

IV. Conclusion

We have reported initial characterization of the modulation bandwidth of individual pixels in AlInGaN-based 16 $\times$ 16 micro-LED arrays, for devices having a peak emission at 370, 405, and 450 nm. At 450 nm, a typical individually addressed 72-μm-diameter pixel was found to have an average optical modulation bandwidth of approximately 245 MHz. This pixel was modulated with an NRZ data pattern, and error-free data transmission at up to 1 Gb/s was demonstrated, with a received optical output power of 1 mW. This demonstrates the potential of micro-LED arrays for use as optical data transmitters, which may be integrated with CMOS control electronics to provide a multi-element parallel data transmitter. These devices could be fabricated to exploit the low-loss transmission window in POF in the blue–green section of the spectrum, or integrated with organic or inorganic color conversion materials for the generation of modulated white light.

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