Underwater Wireless Optical Communications at 100 Mb/s Using Integrated Dual-Color Micro-LEDs

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***Abstract* — Integrated blue-violet and blue-green micro-LED arrays, fabricated via a transfer printing method, were employed to demonstrate wavelength division multiplexing underwater data transmission at 100 Mb/s over up to 9 attenuation lengths in a 1.5 m long water tank.**

***Keywords* — micro-LED, transfer printing, WDM, VLC, UWOC, turbid**

I. Introduction

The development of high-speed underwater wireless communication channels is of paramount importance for industrial, scientific, and military underwater activities [1], as tethered links can be impractical due to the challenging underwater environment. Underwater acoustics offer long range (tens of km), but suffer from high latency and limited data rates (tens of kb/s). Radio frequency communication are attenuated by seawater's conductivity resulting in data rates up to Mb/s for sub-meter ranges [2]. Optical devices operating at visible wavelengths, where water's lowest overall attenuation is exhibited, can enable high-speed transmission over tens of meters. For instance, Doniec *et al*. using an array of 18 light-emitting diodes (LEDs) demonstrated 25 Mb/s in 50 m of clear water [3]. Tian *et al*., presented 800 Mb/s over 0.6 m of clear tap water using a single micro-LED [4]. It is worth noting, however, that as water becomes more turbid the optical window of lowest loss tends to redshift [2], thus a wavelength-adaptable transmitter is greatly desirable.

We report here the deployment of micro-transfer printing (TP) enabled hybrid blue-violet and blue-green micro-LED arrays for underwater wireless optical communications (UWOC) using a single-photon avalanche diode (SPAD) array receiver. By having two different wavelengths integrated in the same transmitter chip, the option of tuning the optimum color depending on the water conditions is enabled. Furthermore, the two chips can potentially be integrated into the same package to give 3-color output. Data transmission rates of 50 Mb/s for each single color of micro-LED over 1.5 m of highly turbid water are demonstrated. When operating in a wavelength division multiplexing (WDM) mode, with the respective pairs of colors, a 100 Mb/s link is established in each case over up to 9 attenuation lengths.

II. Dual color micro-LED arrays fabrication

Blue-violet and blue-green micro-LED arrays were fabricated by TP a blue-micro-LED platelet onto the substrate of the violet and green micro-LED, respectively. The blue-violet array follows the same fabrication process as the blue-green array which is discussed in detail in [5].

Briefly, violet (405 nm) and green (510 nm) 20 µm diameter active area flip-chip micro-LEDs were fabricated from commercially available InGaN epistructures grown on c-plane sapphire by conventional photolithography techniques. Suspended flip-chip micro-LED platelets (6.5×10^{-5} cm^2 active area) were then fabricated from commercially available blue emitting (450 nm) InGaN epistructures grown on (111)-oriented silicon (Si). An elastomeric stamp was used to pick-up the blue micro-LED platelets from their Si substrate and print them onto the pre-prepared green and violet sapphire substrate micro-LED chips. The blue micro-LED platelet was then electrically insulated by parylene-C and addressed by Ti/Au (50/200 nm) metal tracks, following the process described in [5]. Fig. 1a) shows a plan view optical photograph of the resulting integrated blue-green micro-LED array (the blue-violet array shares the same layout). The micro-LEDs are individually anode-addressable sharing a common cathode. Fig. 1b) shows, by way of illustration, the blue-green device being simultaneously driven.

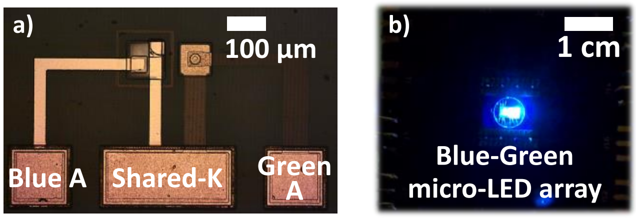

Fig. 1 – Plan view optical photographs of the blue-green micro-LED array a) magnified view; b) with both emitters simultaneously driven. Scale bars are shown inset.

III. Characterization and application

A. Micro-LEDs performance

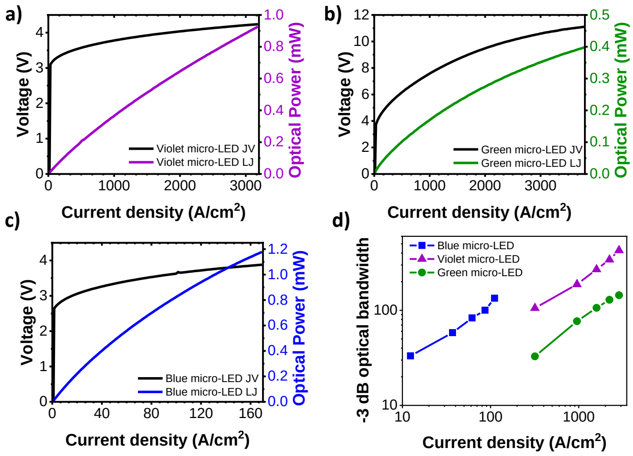

Fig. 2 – a), b) and c) current density-voltage (JV) and current density – optical power (LJ) curves of the violet, green, and blue micro-LED, respectively; d) micro-LEDs -3 dB optical bandwidth *vs* current density.

The individual electrical and optical performance of the chip-integrated violet, green, and blue micro-LEDs are shown in Fig. 2 a), b), and c) respectively. The through-sapphire directed optical power output shown in Fig. 2 was measured using a calibrated Si photodiode detector butt-coupled to the device. In these conditions, the maximum optical power achieved by the violet, green, and blue micro-LED are 0.9, 0.4 and 1.2 mW, respectively. All micro-LEDs exhibit a -3dB optical bandwidth above 100 MHz (Fig. 2 d)), which renders them highly suitable for data transmission.

B. UWOC Application

For the UWOC demonstration, an on-off keying (OOK) data signal was generated using a field-programmable gate array (FPGA, Opal Kelly XEM6310-LX45), modulating the micro-LED through a bias-tee. A sequence of length 2^{15} was transmitted, consisting of a wide synchronisation pulse and a pseudo-random bit sequence. The micro-LED emission was collected and collimated by a condenser lens (Thorlabs, ACL50832U-A), propagated through a 1.5 m long water tank and then focused onto the receiver by a 4-inch diameter Fresnel lens (Edmund, #46-614). The receiver is a 64 x 64 array of Si SPADs developed by the University of Edinburgh (details found in [6]) which operates as a digital silicon photo-multiplier. The photon counts are summed over a time window of 5 ns and the count values outputted through a digital-to-analog converter (DAC). The DAC signal was captured with an active oscilloscope probe and transferred to MATLAB® for offline processing to determine a bit-error ratio (BER). The turbidity of the water sample was varied by adding Maalox® antacid to tap water, a method widely used [7] to mimic different natural water analogs in a laboratory set-up. A block diagram of the experimental setup is shown in Fig. 3.

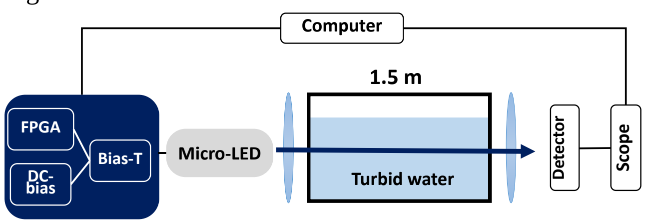

Fig. 3 – Block diagram of the experimental system.

The effect of increasing turbidity levels on the BER for individually driven micro-LEDs at the three wavelengths is shown in Fig. 4a). A 50 Mb\s communication channel, below the 3.8×10^{-3} forward error correction (FEC) threshold, is achieved for all the micro-LEDs for Maalox® concentration of 0.075 mL/L. For the blue and green micro-LEDs this concentration of Maalox® corresponds to a number of attenuation lengths (calculated following [8]) of 7.2 and 8.3, respectively. The operation of the integrated blue-violet and blue-green micro-LED arrays as respective dual wavelength WDM transmitters for underwater communication is shown in Fig. 4b). The blue and green micro-LED were operated simultaneously (as shown in Fig. 1b)) and each color carried a different data stream. In order to select which micro-LED was being detected bandpass filters (Laser 2000: blue FF01-445/20-25, green FF01-525-45/25) were placed in front of the detector. This results in a 100 Mb/s aggregate data rate link, below FEC, at a Maalox® concentration of 0.069 mL/L for the blue-green micro-LED array. The same measurements were repeated for the blue-violet micro-LED array, but with the use of a Laser 2000 FF01-392-23/25 bandpass filter for the violet micro-LED. In this case, a 100 Mb/s link, below FEC, at a Maalox® of 0.075 mL/L is achieved by the blue-violet micro-LED array. It should be noticed, that used data rates are limited by the driving method, and future work could reach an aggregate data rate of several hundred Mb/s with OOK.

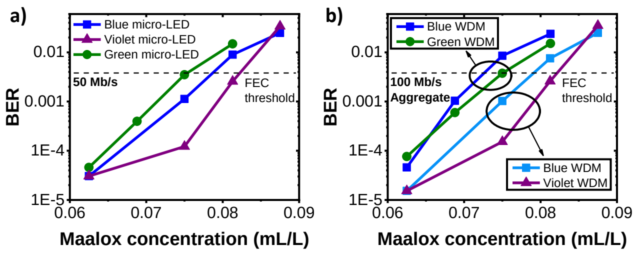

Fig. 4 – Bit-error-ratio *vs* Maalox® concentration a) for individually driven blue, violet and green micro-LEDs; b) Blue-green and blue-violet micro-LED arrays operated in wavelength division multiplexing mode.

IV. Conclusion

By micro-TP we have fabricated on-chip dual-color (respectively blue-violet and blue-green) micro-LED arrays. The potential of these devices as a UWOC transmitter in highly turbid underwater environments has been demonstrated with 100 Mb/s data rates achieved over multiple attenuation lengths using WDM and a SPAD-based receiver.

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