Micro-LED Based Double-Sided Emission Display and Cross-Medium Communication

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***Abstract*—GaN micro-LEDs have been spotlighted as promising candidates for high-speed optical communication, which may become important components in 6G communication blueprint. To achieve a superior network covering sea, land and air for 6G communication, we demonstrated cross-medium communication based on an 80 μm double-sided emission micro-LED array. The high enough light output power radiated from both sides of the green micro-LED enabled interference-free signal transmission in different media. Data rates of 1.55 Gbps over the 3 m free-space link and 1.11 Gbps over the 3.4 m underwater link could be achieved simultaneously. Furthermore, parallel-connected micro-LEDs were utilized to demonstrate the feasibility of pattern display and communication, and expected to achieve longer communication distances in media such as underwater channels.**

***Index Terms*—Cross-medium communication, underwater communication, double-sided emission, micro-LED.**

I. Introduction

GAN micro-LEDs have attracted much attention in high-resolution display and high-speed optical wireless communication (OWC) beyond lighting [1], [2]. Conventional GaN-based broad-area LEDs have large RC time constant and long carrier lifetime, resulting in low system bandwidth and data rate, especially in the green region due to their larger built-in piezoelectric polarization [3]. Micro-LED as a promising candidate enables a high bandwidth over 1.5 GHz [4] and data rate exceeding 10 Gbps [5] due to its low carrier lifetime at higher current density. Many studies have been carried out towards free-space optical (FSO) communication based on micro-LED, but there has been a paucity of research on the underwater wireless optical communication (UWOC) [6]–[8]. Although blue micro-LED has been widely used in UWOC due to the low absorption of blue light in pure water, green micro-LED could achieve a lower light loss in certain waters such as coastal water [9], and the application of green micro-LED in UWOC can lay the foundation for underwater WDM communication to improve the system data rate [10]. Furthermore, the upcoming 6G communication is expected to integrate space/air/underwater networks to realize a superior communication network coverage, which will be potentially realized by various applications of micro-LED in FSO communication, UWOC and outer space communication [5], [6], [11]. The direct connection of the air-to-water link based on OWC requires the optical signal to cross the interface between the two media, light reflection at the interface and the shape of the water surface caused by fluctuations will bring some challenges. Multiple beamformed LED light sources can boost optical signal coverage and are expected to establish robust air-to-water communication links [12]. Therefore, our proposed double-sided emission micro-LED array could play an important role in 6G network by integrating air/underwater OWC networks because it can transmit light in both directions at the air-water interface to avoid medium crossing. In addition, the parallel configuration of the green micro-LED array can enhance the light output power (LOP) and achieve longer transmission distance, allows some pixels to continue to work while others fail, thus maintaining uninterrupted communication, and has the potential of underwater display or as a point indicator for underwater robot docking in an underwater environment with low visibility [13].

In this paper, we proposed a cross-medium communication system based on an 80 μm green double-sided emission micro-LED array, which can emit light on double sides and realize communication in both free-space and underwater channels simultaneously. We have also tried to show the feasibility of compatibility between display and communication. We have achieved a data rate of 1.55 Gbps over a 3 m FSO link using 16-ary quadrature amplitude modulation orthogonal frequency division multiplexing (16-QAM-OFDM) based on the back-side emitting. For the UWOC system based on the front-side emitting, a data rate of 1.11 Gbps was obtained through a 3.4 m water tank. This is the first time to propose the concept of cross-medium communication between free-space and underwater channel using a single micro-LED chip, which also fills the gap of green micro-LED in UWOC research and is expected to be a promising candidate for 6G integration communication with space/air/underwater channels.

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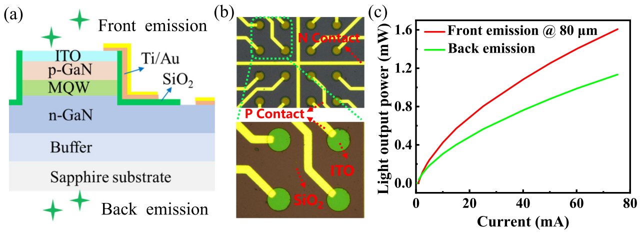

Fig. 1. (a) Structure schematic diagram and (b) microscope images of the double-sided emission micro-LED. (c) P-I characteristics of an 80 μm green micro-LED for the front and back emission.

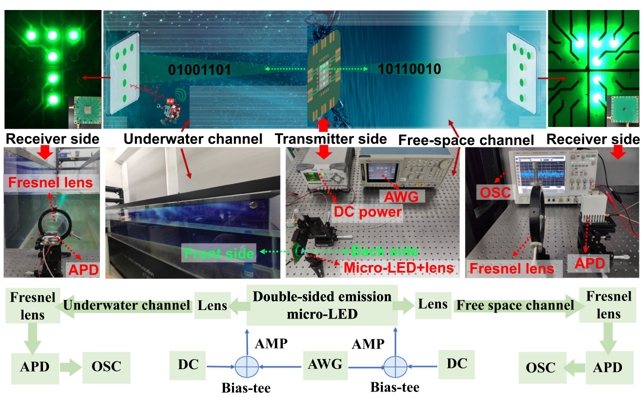

Fig. 2. Schematic diagrams and experimental setup photos of the cross-medium communication system including the transmitter, receivers, 3 m free-space channel and 3.4 m underwater channel. The inserts in the upper left and right are the optical microscope images of the letter 'T' formed by micro-LED array viewed from both sides.

II. Experimental Details

The epitaxial structure of green micro-LED array used for both UWOC and FSO communication is shown in Fig. 1(a). The fabrication process involves deposition of ITO (300 nm) on top of the p-GaN, patterned lithography, dry etching to n-GaN layer by inductively coupled plasma etching and annealing under nitrogen at 550 °C for a good Ohmic contact. SiO_2 (300 nm) as an electrical isolation layer was deposited by plasma-enhanced chemical vapor deposition. Ti/Au (50 nm/200 nm) was deposited by magnetron sputtering and acted as p- and n-contacts to address each pixel individually. Fig. 1(b) shows that there is only a small overlap between the p contact and the ITO layer to ensure that the light can be emitted from both front and back sapphire substrate sides. The micro-LED array with an emission peak wavelength of 510 nm at the voltage of 5 V was then bonded onto the printed circuit board (PCB). The characteristic of LOP versus current (P-I) measured by placing the optical power meter (Thorlabs PM100D) close to the PCB packaged micro-LED is presented in Fig. 1(c). The LOPs at the current of 50 mA are 1.254 mW for the front side and 0.882 mW for the back side, respectively.

The schematic diagrams and experimental setup photos of the cross-medium communication system based on the green double-sided emission micro-LED are shown in Fig. 2. The pictures inserted in the upper left and right are the patterns of the letter 'T' formed by the micro-LED array connected by wire bonding. The pattern can be clearly seen from both sides, indicating that the device has the ability of double-sided display. We used the light emitted from the front side and the back side for UWOC and FSO communication, respectively. At the transmitter side, the micro-LED was driven by a direct current (DC) source (Keithley 2614B) combined with the OFDM signal through a bias-tee (Mini-circuit ZFBT-6GW). The OFDM signal was output by an arbitrary waveform generator (AWG, Tektronix AWG710B) and then pre-amplified by an amplifier (AMP, Mini-Circuits ZHL-6A-S+) to obtain a suitable modulation depth for the micro-LED. The light emitted by the micro-LED was collimated by a lens with a diameter of 1 in and a numerical aperture of 0.79. A water tank with a length of 3.4 m filled with tap water was used to simulate the underwater channel. At the receiver side of the UWOC system, the collimated beam was focused into a high-sensitivity APD (Hamamatsu C12702-11) by a Fresnel lens with a diameter of 4 in and then converted into electrical signal, which was captured by an oscilloscope (OSC, Agilent DSA90604A). The FSO system is similar to the UWOC system with a channel distance of 3 m in free space, and a high-speed 1 GHz APD (Hamamatsu C5658) was used to further increase the data rate. The −3 dB bandwidth of the micro-LED is extracted from its frequency response curve, which is measured by a vector network analyzer (VNA, PicoVNA 106) [14].

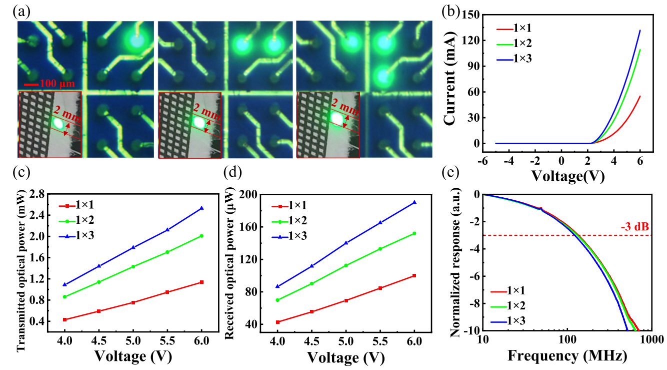

Fig. 3. (a) Optical microscope images of various parallel micro-LEDs including 1, 2 and 3 pixels. The insert pictures are the pixel spots between equally spaced lines at the receiver side. (b) Current versus voltage curves for various parallel micro-LEDs. (c) Light output power at the transmitter side versus voltage for various parallel micro-LEDs. (d) Light output power at the receiver side versus voltage for various parallel micro-LEDs. (e) Frequency responses for various parallel micro-LEDs.

III. Results and Discussion

We utilized a different number of pixels for light emission including 1, 2 and 3 pixels in parallel, as shown in Fig. 3(a). The current versus voltage (I-V) characteristics of the three groups of micro-LEDs are shown in Fig. 3(b). The series resistances of the devices decreases as the number of pixels increases due to the parallel connection, and are calculated by dV/dI at the driving voltage of 5 V as 46.29 Ω, 24.19 Ω, and 21.11 Ω for 1, 2 and 3 pixels in parallel, respectively. The series resistance does not decrease uniformly with increasing number of pixels due to differences between micro-LED pixels and the introduction of

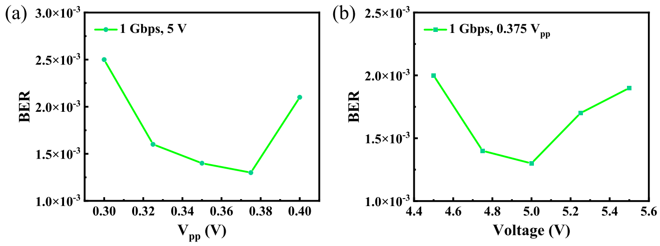

Fig. 4. BER of a single green-light micro-LED with 1 Gbps data rate for underwater communication at (a) different peak-to-peak voltages and (b) operating voltages.

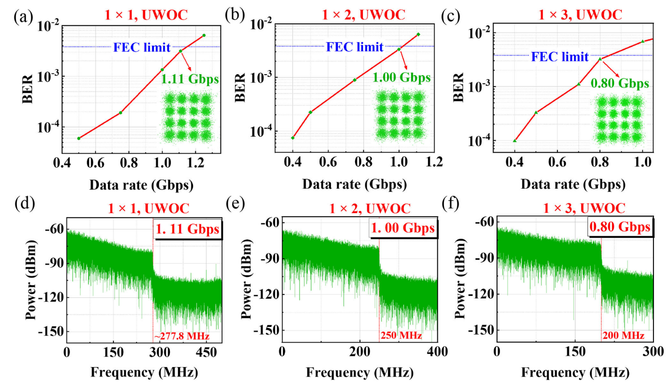

Fig. 5. BER versus data rate for underwater communication with (a) 1 pixel, (b) 2 pixels, and (c) 3 pixels in parallel connection, inserts are the corresponding constellation diagrams. The power spectra of OFDM signal at the highest date rate of (d) 1.1 Gbps for 1 pixel, (e) 1.0 Gbps for 2 pixels and (f) 0.8 Gbps for 3 pixels communication.

parasitic resistance when connecting the pixels by wire bonding, causing the drive current to increase non-linearly with the number of pixels. The LOPs at the transmitter side and receiver side of the UWOC system are shown in Fig. 3(c) and (d). The transmitted LOP of 3 pixels at 5 V is about 1.79 mW, which is about 2.35 times that of a single pixel, less than the expected 3 times. This is mainly due to the non-linear increase of the current and more serious thermal effect. And the received LOP of 3 pixels after 3.4 m underwater transmission is about 140 μW, which decreases to 2 times that of a single pixel. This may be caused by the large pixel pitch of 3 pixels, and the diverging light at the receiver side is not completely collected by the lens, resulting in more light loss and larger light spot as shown in Fig. 3(a). The frequency responses of different number of pixels at the same driving voltage of 5 V are shown in Fig. 3(e), the extracted -3 dB optical modulation bandwidths of 1, 2 and 3 pixels are 135.2, 131.3, and 122.1 MHz, respectively. The good linear relationship between the parallel capacitance value and the number of pixels has been proven [15]. Combining the calculated parallel resistance, the decreased RC limited bandwidth as the number of pixels increases can be obtained. However, the carrier lifetime is the main limitation of the modulation bandwidth compared with RC time constant for micro-LED [3], so the bandwidth difference is small for different parallel numbers of pixels.

To improve the transmission data rate, the operating voltage of the micro-LEDs and the peak-to-peak voltage (V_{PP}) of the QAM-OFDM signal need to be optimized individually. For underwater communication utilized a single micro-LED, the bit error ratio (BER) as a function of the V_{PP} under a fixed transmission data rate of 1 Gbps and operating voltage of 5 V is shown in Fig. 4(a), and the corresponding BER is the lowest at the V_{PP} of 0.375 V, which is the initial V_{PP} value output by AWG and would be amplified by the amplifier. Then fixing the V_{PP} at 0.375 V, the BERs under different operating voltages were obtained as shown in Fig. 4(b). The optimum operating voltage is 5 V with the lowest BER. The communication performances of both free-space and underwater channel were all tested under the operating condition with the driving voltage of 5 V and the V_{PP} value of 0.375 V due to the small difference in the optimal operating conditions.

In this work, 16-QAM-OFDM modulation was utilized considering the signal-to-noise ratio (SNR) of the proposed system, and the relevant parameters of OFDM signal are set as follows: the subcarrier number is 512 and the symbol length is 2048, and two 1/16 symbol lengths are set as the cyclic prefix (CP) and the pilot sequence, respectively. The OFDM schematic diagram and calculation method of data rate can refer to our previous work [16]. BERs versus data rate of the UWOC system with various parallel micro-LEDs were obtained as shown in Fig. 5(a), (b), and (c) by changing the sampling frequency of AWG corresponding to various OFDM signal bandwidths. The highest data rates of 1, 2 and 3 pixels are 1.11, 1, and 0.8 Gbps over a 3.4-m water link with the BERs below the FEC limit (3.8×10^{-3}), respectively, and the inserts are the corresponding constellation diagrams. Fig. 5(d), (e), and (f) show the power spectra of OFDM signal with cut-off frequencies around 277.8, 250 and 200 MHz, respectively. Multi-pixel parallel communication can effectively increase the received LOP, so it is expected to increase the communication data rate under the same transmission distance compared to single-pixel communication [17]. However, in this study, the highest data rate that can be achieved decreases as the number of pixels increases. This result may be attributed to the multipath effect of multiple pixels in the micro-LED array used for long-distance transmission in water, resulting in inter-symbol interference (ISI) and thus reducing SNR [18]. In addition, the increased heating effect caused by multi-pixel parallel connection may also reduce communication performance [19]. While green micro-LED has been proposed in high-speed FSO communication, few works explored its potential application in UWOC. Based on the proposed communication system, our green micro-LED could obtain a high data rate over a relatively long underwater distance, compared with Table I.

To evaluate the communication distance that can be achieved by different parallel numbers of pixels with different received LOPs, we considered the loss of light at the interface between air, glass and water, and calculated the attenuation coefficient of green light in tap water based on the optical power at the transmitter and receiver sides with and without water. The value of the attenuation coefficient in this experiment is 0.148 m^{-1}, which is similar to the reported attenuation coefficient about 0.1 m^{-1} for green light in pure water [9]. Through the attenuation

TABLE I
PERFORMANCE SUMMARY OF UWOC SYSTEM BASED ON MICRO-LED

Group	Optical source	Bandwidth (MHz)	Modulation Format	Data Rate (Gbps)	Distance
Tian et al. [20]	Blue micro-LED	230	NRZ-OOK	0.933/0.8	2.3 m Tap/2.3 m Maalox
Tian et al. [6]	Blue micro-LED	160	NRZ-OOK	0.8	0.6 m Tap
Wei et al. [8]	QD blue micro-LED	1000	NRZ-OOK	2	1m Air+2 m Tap
Arvanitakis et al. [7]	Series blue micro-LED array	338.5	QAM-OFDM	4.92/2.34/1.32	1.5 m Tap /3 m Ocean/4.5 m Ocean
Carreira et al. [21]	Green micro-LED	above 100	NRZ-OOK	0.05	1.5 m Maalox
This work	Green micro-LED	122.1	16-QAM-OFDM	1.11+1.55	3.4 m Tap+3 m Air

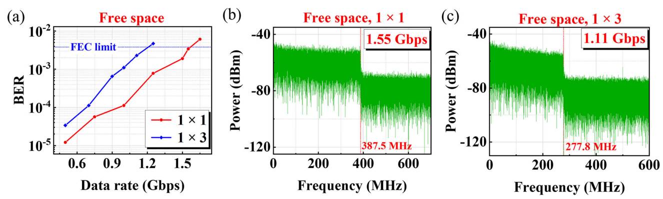

Fig. 6. (a) BER versus data rate for FSO communication with 1 pixel and 3 pixels in parallel. The power spectra of OFDM signal at the date rate of (b) 1.55 Gbps for 1 pixel and (c) 1.11 Gbps for 3 pixels communication.

coefficient of green light in water, the optical power at the receiver side with different distances can be calculated, and combined with our previous work [6], the achievable transmission distance and the corresponding data rate change can be roughly estimated. Since the LOP of 3 parallel pixels at the receiver side is about twice that of a single pixel, the communication distance of 3 parallel pixels can be expected to be about 5 m longer than that of a single pixel according to Bill-Lambert law without considering the effect of SNR degradation caused by multi-pixel crosstalk. More pixels in parallel are expected to achieve a longer communication distance, but at the cost of a loss of data rate. The performance degradation in bandwidth and data rate can be reduced or even eliminated by better consideration of packaging and impedance matching in future work. In addition, the use of parallel micro-LED arrays to enhance the LOP is also expected to alleviate the degradation of communication performance in more challenging water environments. And the relationship among LOP, data rate, and BER could be further investigated in the future.

While the front side of the micro-LED array emits light for underwater communication, the back side can also emit light for free-space communication, thus enabling cross-media double-sided communication. The double-sided communication method can provide an interesting idea for the architecture of a full-dimensional communication network including free-space and underwater communication, which is expected to meet the needs of 6G communication to expand communication network integrating land, sea and air. Similar to the underwater communication test, BERs versus data rate for free-space communication system with various parallel micro-LEDs were obtained as shown in Fig. 6(a), a maximum data rate of 1.55 Gbps can be obtained over a 3 m free-space link with a BER of 3.4×10^{-3} using a single pixel, and 1.11 Gbps can be obtained with a BER of 2.3×10^{-3} using 3 parallel pixels. And the corresponding power spectrum diagrams are shown in Fig. 6(b) and (c). We also found that blocking the light or stopping the communication on one side hardly affected the communication performance on the other side. Furthermore, we may take advantages of micro-LED for integrating RGB micro-LEDs to realize full-color micro-LED display and cross-medium communication in our future work.

IV. CONCLUSION

We experimentally demonstrated the cross-medium communication based on a single green micro-LED. A data rate of 1.55 Gbps over a 3 m free-space link and a data rate of 1.11 Gbps over a 3.4 m underwater link could be achieved simultaneously using 16-QAM-OFDM modulation. To the best of our knowledge, few researches employ green micro-LED for high-speed underwater communication, and this is the first time for cross-medium communication achieved successfully using a single green micro-LED chip. In addition, the micro-LED array can also realize pattern display and extend the communication distance by connecting pixels in parallel. These results make the OWC system based on the green micro-LED expected to play an important role in the future 6G communication field, to realize the requirements of full coverage of underwater and free-space. Moreover, the communication data rate and distance are expected to be further improved by device and modulation optimization such as suitable packaging and impedance matching in the future.

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