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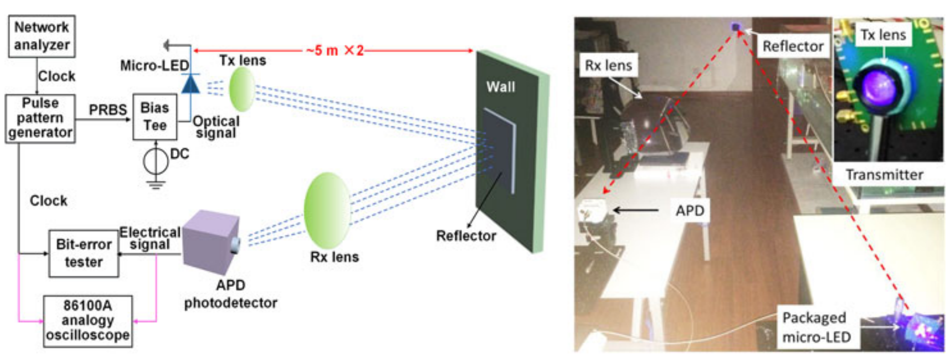


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# Gbps Long-Distance Real-Time Visible Light Communications Using a High-Bandwidth GaN-Based Micro-LED

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**Abstract:** In this investigation, we experimentally demonstrated a high-speed Gbps long-distance real-time visible light communication system based on non-return-to-zero on-off keying modulation by using a high-bandwidth Gallium nitride-based micro-LED with a modulation bandwidth of $\sim$230 MHz and a size of 40 $\mu$m $\times$ 40 $\mu$m. The maximum real-time data rate obtained is up to 1.3 Gbps at a 3 m free-space transmission distance with a bit-error rate (BER) of $3.4 \times 10^{-3}$ and 1 Gbps at a 10 m distance with a BER of $3.2 \times 10^{-3}$, both of which are underneath the forward error correction threshold of $3.8 \times 10^{-3}$ required for free-error operation. In addition, when the transmission distance is increased to 16 m in free space through reflecting the emission light beam by blue reflectors mounted on the wall, a data rate of 0.87 Gbps with a BER of $3.5 \times 10^{-3}$ is achieved successfully.

**Index Terms:** GaN, micro-LED, visible light communication, NRZ-OOK, real-time, high-speed, long-distance, free-space.

## 1. Introduction

Considerable progress has been made in Gallium nitride (GaN) based light-emitting diodes (LEDs) since their commercial introduction in the 1990s [1], which have been widely used in general lighting, traffic signal light, display etc [2]. Besides lighting application, additional applications are emerging including visible light communication (VLC) [3], [4], optogenetics [5], and micro-display [6], [7]. Recently, VLC has constantly gained attention in research and development worldwide [8]–[15]. VLC is an emerging optical wireless communication (OWC) technology using 400–800 THz visible spectrum, which has many advantages over radio frequency (RF) communication, e.g., unregulated bandwidth, high safety, high privacy, energy saving, no electromagnetic interference etc [16], [17]. Consequently, great efforts have been made to develop VLC based on LEDs, pursuing higher communication capacity including higher transmission speed, and/or longer distance.

There are many investigations [18]–[26] reported on increasing the overall transmission capacity of VLC system based on LEDs, which are mainly divided into two categories. First, the limited LED electrical-to-optical (E-O) modulation bandwidth was improved through using blue filter, adopting equalization technology, and optimizing the structure of LED chips [18]–[20]. Second, the bandwidth efficiency was enhanced under restricted modulation bandwidth through complex high-order modulation schemes [4], [21]–[26], significantly improving the communication capacity. However, complex arithmetic and hardware have to be implemented which increases the cost of the VLC system. Additionally, in most VLC systems, high-order modulation schemes were processed offline in lab environment. Thus, it is expected that high-speed long-distance real-time VLC should be achieved with low cost and complexity.

Therefore the study of real-time high-speed long-distance VLC based on LEDs using NRZ-OOK modulation scheme has become an important aspect of VLC system [15], [26]–[28]. Ref [15] presented a real-time data transmission speed of 750 Mbps at a free-space distance of 1.7 m with OOK modulation based on a monochromatic LED by employing post-equalization technology. Real-time data rate of 1.7 Gbps based on a micro-LED using OOK modulation was reported in 2016, nevertheless its free-space distance is only 0.5 m [26]. Furthermore, a data rate of 2.4 Gbps based on a micro-LED with OOK modulation was achieved, without giving the transmission distance [27]. The longest rea-time transmission distance is up to 110 m based on LEDs, but the data rate is only 160 Mbps [28]. In our previous work, real-time communication based on a micro-LED with OOK modulation was obtained at a data rate of 200 Mbps and a long underwater distance of 5.4 m [3]. Up to now, a real-time Gbps data transmission speed at long transmission distances (more than 3 m) of VLC system based on LEDs, in absence of employing sophisticated equalization, higher-order modulation and MIMO technologies, has not been extensively studied [15], [26]–[28].

In this work, we report the realization of a real-time VLC system with simple NRZ-OOK single carrier modulation scheme at a high data rate of Gbps and long distances over 3 m using a packaged 40 $\mu$m $\times$ 40 $\mu$m blue GaN-based micro-LED, whose modulation bandwidth is $\sim$230 MHz and center emission wavelength is $\sim$445 nm. In our VLC system, we used a high-bandwidth micro-LED to achieve high data transmission speed, a high-sensitivity APD to detect the low optical signal after long-distance transmission, and optimized optical antennas to transmit and collect the optical power. At a free-space distance of 3 m, the maximum data rate achieved is up to 1.3 Gbps. Using reflection mirrors fixed on the wall, the transmission distance is extended to 10 m by one reflection. The maximum transmission speed of 1 Gbps was acquired and the corresponding BER of $3.2 \times 10^{-3}$ satisfied the FEC required for the error-free operation. Furthermore, we extended the VLC link to 16 m in free space while maintaining a high data rate of 0.87 Gbps using GaN-based micro-LED. Through adopting simple NRZ-OOK modulation scheme without complex equalization and modulation technologies, the real-time high-speed long-distance VLC link we demonstrated is relatively simple and cost-effective, suitable for practical applications.

## 2. Experiments

### *2.1. Micro-LED Fabrication*

The blue GaN-based micro-LEDs proposed here were fabricated using commercial GaN-based epitaxial structure grown on a *c*-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The epitaxial layers consist of an *n*-GaN layer, an InGaN/GaN multiple quantum well (MQW), an AlGaN electronic blocking layer and a *p*-GaN layer. During micro-LED fabrication processes, Ni/Au metal layer was deposited as the current spreading layer, and then the dry etchings were employed to define mesas of different sizes through etching away the Ni/Au and the GaN layers down to the n-GaN layer. $SiO_2$ was deposited as the isolation layer by plasma-enhanced chemical vapour deposition (PECVD) and apertures on the micro-LED mesas were opened by wet etching. Finally, the Ti/Au was deposited as p-pads and n-contacts. The fabrication details are similar to our previous work [3]. The 2D schematic structure and microscope image of the micro-LED

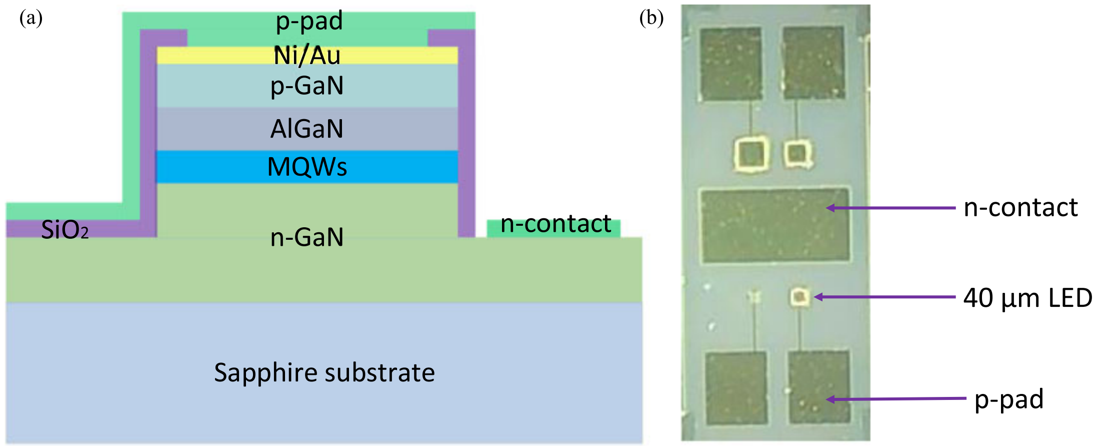


Fig. 1. (a) 2D schematic structure and (b) microscope image of a GaN-based micro-LED.

are shown in Fig. 1 and the size of the fabricated micro-LED in this work is 40 $\mu$m $\times$ 40 $\mu$m. The micro-LED device was bonded to a printed circuit board (PCB) for following tests.

### *2.2. Measurement Setup*

Fig. 2(a) illustrates the schematic diagram of the high-speed long-distance optical wireless communication link based on a micro-LED real-time VLC system with NRZ-OOK modulation scheme. At the transmitter side, the pseudo-random binary sequences (PRBS) with a pattern length of $2^7$-1 and a peak-to-peak voltage of 2 V were produced by a pulse pattern generator (PPG) module from an Anritsu MP1800 signal quality analyzer. The micro-LED was driven by the PRBS signal combined with a direct current (DC) from a Yokogawa GS610 current source via a bias-tee. An Agilent network analyzer (N5225A, 10 MHz-50 GHz) was used to generate a clock signal for the PPG. The light output from the micro-LED was collimated by a transmitter lens and focused by one or two receiver lenses (Tx and Rx lenses) and reflection mirrors were employed to extend the free-space transmission distance to 10 m and 16 m by increasing the reflection times. We used one or two Fresnel lenses depending on the requirements at different distances. The transmitter lens is a planoconvex lens with a diameter of $\sim$1.8 cm, and the receiver lenses are two Fresnel lenses with the same diameter of 30 cm and focal length of 60 cm. The used reflection mirror with a size of 10 cm $\times$ 10 cm was coated with 2-mm high-reflectivity $Ti_3O_5$ film to reflect the light beams. At the receiver side, the optical signal from the micro-LED was recorded and converted into electronic signal by a high-speed 1.4 GHz PIN photodetector or a high-sensitivity APD (MenloSystems APD210, 1 GHz). The frequency response was measured by an N5225A network analyzer (10 MHz–50 GHz) using the 1.4 GHz PIN photodetector to obtain E-O modulation. The high-sensitivity APD was used to test the BER by an error detector module from the MP1800 signal quality analyzer. The eye images were captured by an 86100A wide-bandwidth oscilloscope (14 GHz). The corresponding picture of the experiment setup is shown in Fig. 2(b), which indicates the distance between the transmitter and the receiver is 10 m by reflecting the light emission beam using high-reflectivity mirror installed on the wall. Here, we emphasize that long-distance real-time communication has been built through transmitting the signals and detecting the bit error rate (BER) simultaneously.

## 3. Results and Discussions

The modulation bandwidth of the communication system was extracted by characterizing the frequency response performance. Fig. 3 represents normalized frequency response curve of the micro-LED at a 35 mA DC injection current, and the corresponding light-output power is $\sim$0.8 mW. It can be seen that the $-3$ dB E-O modulation bandwidth is around 230 MHz without

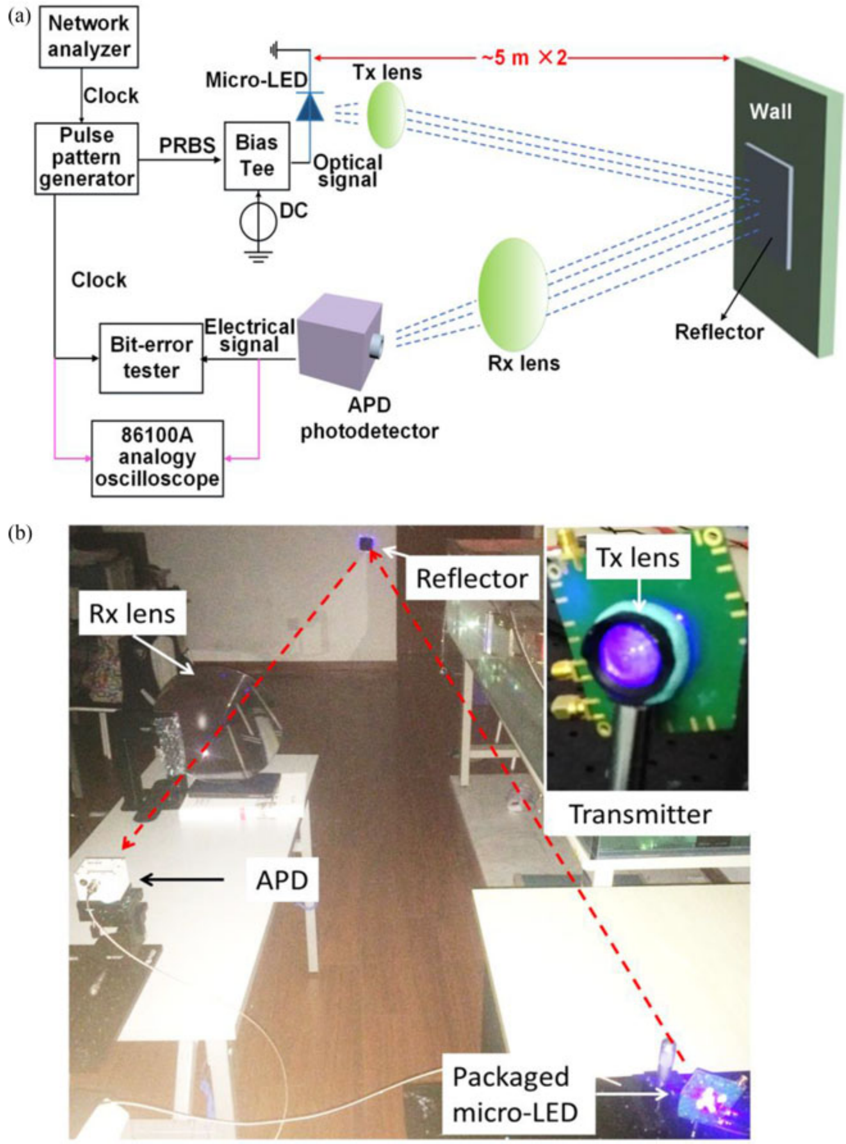


Fig. 2. (a) Schematic diagram of a real-time long-distance VLC system based on a micro-LED. (b) Photograph of experimental setup. The free space wireless optical link is around 10 m.

equalization technology. Such a high bandwidth of a packaged micro-LED will benefit the high-speed VLC significantly.

A BER measurement was employed to evaluate the communication performance of the micro-LED-based VLC system. The measured BER characteristics are shown in Fig. 4. Fig. 4(a) shows the BER as a function of data rate at an injection current of 35 mA and a transmission distance of 3 m. It can be seen that the real-time VLC system based on a GaN-based micro-LED we proposed performs well at a data rate below 0.9 Gbps, where the error-free data communication is realized. At the 1Gbps data rate, the BER is $2.4 \times 10^{-9}$, less than the FEC threshold of $3.8 \times 10^{-3}$ [29]. With the BER underneath the FEC limit, the highest achievable data transmission speed is up to 1.3 Gbps with a BER of $3.4 \times 10^{-3}$. Extending the link distance to 10 m using the high-reflectivity mirror reflecting the light beam, the measured BER versus data rate is shown in Fig. 4(b), demonstrating the data rate as high as 1 Gbps can be achieved with a BER of $3.2 \times 10^{-3}$ less than

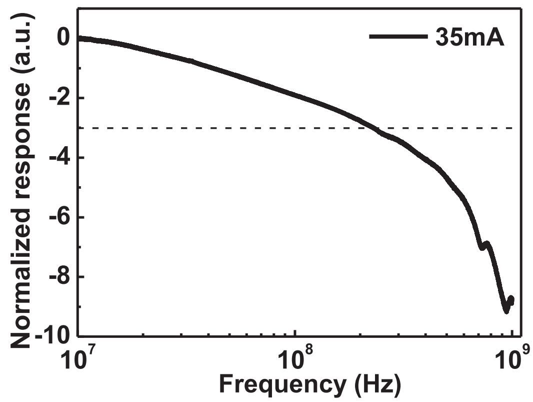


Fig. 3. Frequency response curve of the 40 $\mu$m $\times$ 40 $\mu$m micro-LED at an injection current of 35 mA. The dash line is to label the -3 dB band width.

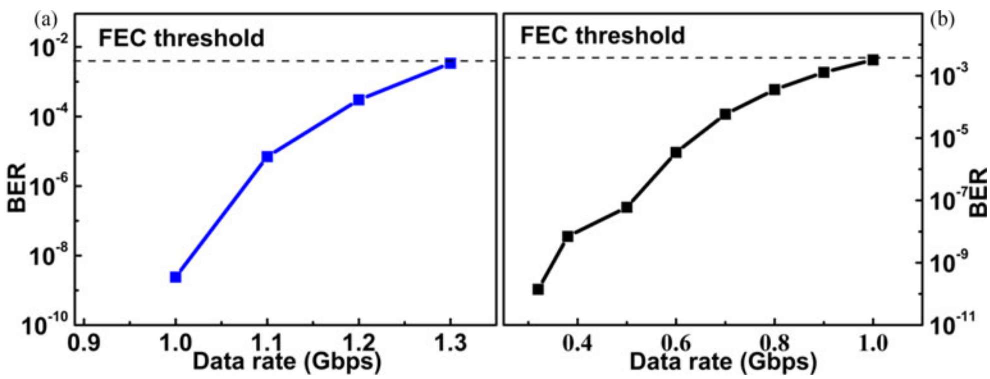


Fig. 4. BER curves as a function of data rate at an injection current of 35 mA and transmission distances of (a) 3 m and (b) 10 m. The FEC threshold is marked in dash line.

the FEC criteria. To the best of our knowledge, at such a communication distance from 3 m to 10 m, the data rate is higher than the reported values in the literature based on LEDs using a real-time OOK modulation scheme [3], [15]. These results demonstrate that VLC system based on a micro-LED is capable of realizing a real-time long-distance high-speed optical wireless communication in absence of equalization and multi-carrier modulation technologies and exhibits a higher performance.

The eye diagram also allows us to estimate the transmission performance of VLC system. Fig. 5 shows the eye diagrams at different data rates at transmission distances of 3 m and 10 m, respectively. Fig. 5(a) shows the eye diagrams at data rates of 0.8 Gbps (left), 1 Gbps (middle) and 1.3 Gbps (right), at a 3 m communication distance. Using the high-reflectivity mirror fixed on the wall, the light propagation distance was extended to be 10 m, and the eye diagrams captured at different data rates of 0.5 Gbps (left), 0.9 Gbps (middle) and 1 Gbps (right), are shown in Fig. 5(b). An "open eye" can be seen in Fig. 5(a) with data rates of 0.8 Gbps and 1 Gbps, and Fig. 5(b) with data rates of 0.5 Gps and 0.9 Gbps respectively, which allows a low BER (see Fig. 4). As the data rate is increased, the eye will close, which results in an increase in the BER, just as the right figures of Fig. 5(a) with the data rate of 1.3 Gbps and Fig. 5(b) with the data rate of 1 Gbps. Notwithstanding the relatively noisy eye diagram in right figures of Fig. 5(a) and (b), there is still distinction between high pulses and low pulses to resolve the "eyes" of the signal, and the measured BER is beneath the FEC threshold of $3.8 \times 10^{-3}$. The results of eye diagrams, given in Fig. 5, further indicate that the Gbps high-speed long-distance real-time VLC system has been achieved successfully.

To investigate the realizable communication distance and data transmission speed, we further extended the distance between the transmitter and the receiver to 16 m using two high-reflectivity

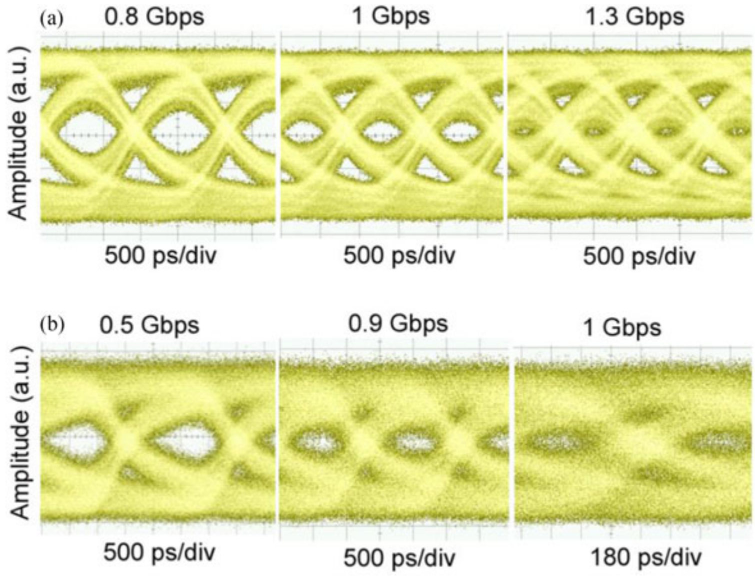


Fig. 5. Eye diagrams versus data rate at different transmission distances of (a) 3 m at data rates of 0.8 Gbps, 1 Gbps and 1.3 Gbps and (b) 10 m at data rates of 0.5 Gbps, 0.9 Gbps and 1 Gbps, from left to right.

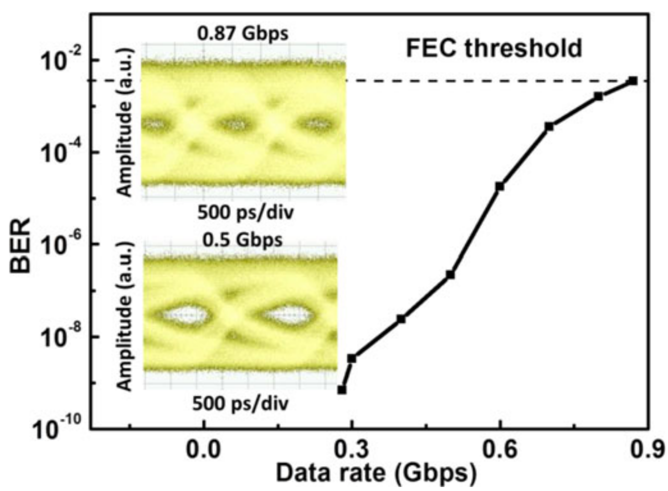


Fig. 6. Dependence of the BER on data rate measured at a 35 mA current and a 16 m free-space transmission distance. Inset: eye diagrams at data rates of 0.5 Gbps and 0.87 Gbps, respectively. The dash line is the FEC limit labeled.

mirrors reflecting the light emission of a micro-LED. Characteristics of the BER versus data rate at a 35 mA injection current are shown in Fig. 6. The achievable maximum transmission speed is up to 0.87 Gbps, and the corresponding BER of $3.5 \times 10^{-3}$ passes the FEC criteria. Meanwhile, the inset of Fig. 6 shows eye diagrams, which have open eyes when data rates are 0.5 Gbps and 0.87 Gbps. To the best of our knowledge, the real-time long-distance (16 m) VLC system based on LEDs, with OOK modulation scheme while retaining the high data rate (0.87 Gbps), was barely reported.

Finally, we summarize and analyze the overall communication performance of the high-speed long-distance real-time VLC system based on NRZ-OOK modulation scheme for the GaN-based micro-LED as shown in Fig. 7, which shows the measured maximum data rate and the corresponding received light output power versus transmission distance. It should be noted that the maximum data

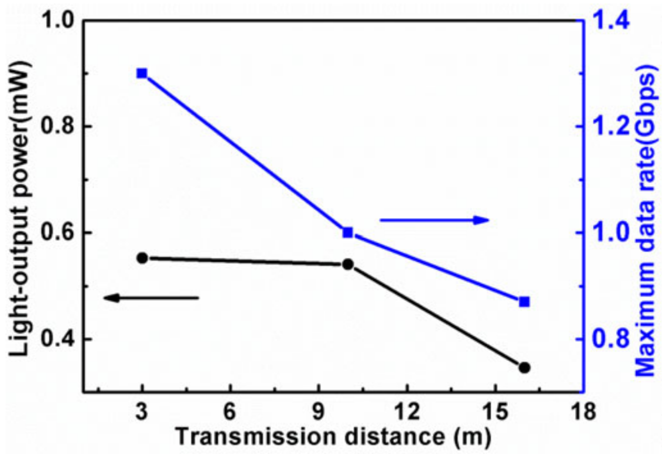


Fig. 7. Received light output power and the real-time maximum data rate as a function of transmission distance.

Table 1

Summary of Performance of VLC System Based on a Single LED

| Group | Type of LED | Transmitted Power (mW) | Available bandwidth (MHz) | Modulation Scheme | Real time | Data rate (Gbps) | BER | Distance (m) |
|---|---|---|---|---|---|---|---|---|
| M. Islim *et al.* [25] | Violet micro-LED | 2.3 | 655 | OFDM[a] | N[c] | 3.46 | Below FEC[e] | 5.25 |
| D. V. Dinh *et al.* [27] | Blue LED | 0.81 | 1000 | NRZ-OOK[b] | Y[d] | 2.4 | N/A[f] | N/A |
| J. Luo *et al.* [15] | Commercial LED | N/A | 370 | NRZ-OOK | Y | 0.75 | $6.64 \times 10^{-8}$ | 1.7 |
| P. Tian *et al.* [3] | Blue micro-LED | 1.1 | 160 | NRZ-OOK | Y | 0.2 | $3 \times 10^{-6}$ | 5.4 |
| Y. Chen *et al.* [28] | Commercial LED | 1000 | 2 | NRZ-OOK | Y | 0.16 | $10^{-3}$ | 110 |
| This work | Blue micro-LED | 0.8 | 230 | NRZ-OOK | Y | 1.3 | $3.4 \times 10^{-3}$ | 3 |
| | | | | | | 1 | $3.2 \times 10^{-3}$ | 10 |
| | | | | | | 0.87 | $3.5 \times 10^{-3}$ | 16 |

[a]OFDM represents orthogonal frequency-division multiplexing.
[b]NRZ-OOK represents non-return-to-zero on-off keying.
[c]N represents off-line communication.
[d]Y represents real time communication.
[e]FEC represents forward error correction threshold.
[f]N/A represents not applicable.

rate is 1.3 Gbps, 1 Gbps and 0.87 Gbps at the distances of 3 m, 10 m and 16 m, respectively. Note that extending the transmission distance to 16 m leads to a decrease of the received light output power and a reduction of the corresponding maximum data rate to 0.87 Gbps. The limitation stems from the expansion of light beam spot size on the receiver and the attenuation of the light output power at longer distances, as observed in most LED-based VLC systems [28]. In order to minimize the power lost in the system, we can choose special lens according to the light beam divergency, the special high-reflectivity mirror and adjust the optical lens position to decrease the transmission loss of the power and use more power efficiently. In general, the high-speed long-distance real-time VLC based on micro-LEDs achieved in our study is attributed to the superior properties of micro-LEDs including small size, high injection current density, short lifetime, high modulation bandwidth, the high-sensitivity receiver, and the optimization of the optical antennas.

Table 1 presents a comparison of the communication performance of VLC system based on a single LED proposed in previous studies [3], [15], [25], [27], [28]. It can be seen that the maximum data rate is up to 3.46 Gbps at a distance of 5.25 m based on a micro-LED with offline OFDM modulation [25]. For practical VLC applications, the complexity and cost of the system can be significantly increased using OFDM modulation. A maximum real-time data rate of 2.4 Gbps was reported by Dinh *et al.* but the transmission distance was not given [27]. A real-time long-distance VLC link of 110 m based on LEDs using pre-emphasis and post-equalization was proposed by Chen *et al.* with a relatively low data rate of 160 Mbps [28]. In our work, by using a single blue micro-LED based on NRZ-OOK modulation, the real time transmission data rate is up to 1.3 Gbps over a 3 m free-space distance and 1 Gbps over a 10 m distance. Moreover, the distance is extended to 16 m, maintaining a high data rate of 0.87 Gbps. This study provides the direction of real-time high-speed long-distance VLC based on LEDs.

## 4. Conclusion

In summary, we have investigated and experimentally demonstrated a high-speed long-distance real-time VLC link based on NRZ-OOK modulation scheme. High data rate of Gbps at distances from 3 m to 16 m has been achieved by using a high-bandwidth GaN-based blue micro-LED with a size of 40 $\mu$m $\times$ 40 $\mu$m and a peak wavelength of $\sim$445 nm. The maximum real-time data rate is up to 1.3 Gbps at a 3 m transmission distance and 1 Gbps at a 10 m transmission distance in free space. Moreover, when the free-space transmission distance is extended to 16 m, the data transmission speed of up to 0.87 Gbps was obtained. These results we proposed indicate that a GaN-based micro-LED can be used for real-time high data transmission speed of Gbps and long-distance optical wireless communications, and can be employed in practical applications. The high bandwidth of the micro-LED, high sensitivity APD, optimized optical antenna and operating conditions are the key elements in attaining real-time high-speed long-distance transmission performance in our study. To further improve communication data rate and transmission distance, further work on our VLC link will be done with equalization, multi-carrier modulation and MIMO technologies.

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