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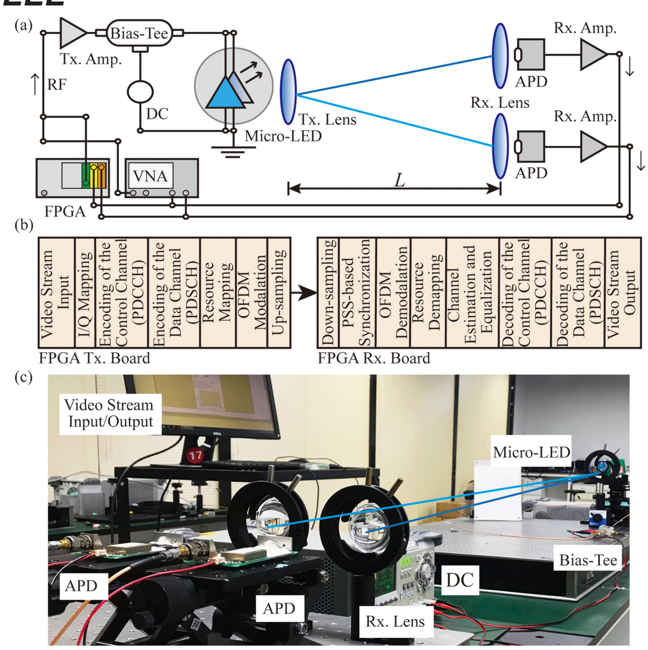


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# Real-Time Multi-User Video Optical Wireless Transmission Based on a Parallel Micro-LEDs Bulb

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**Abstract:** In this work, we experimentally achieved a real-time video optical wireless transmission which can broadcast two users in different positions, simultaneously. Firstly, a single-pixel 50-$\mu$m micro-LED is designed and fabricated on a GaN-based wafer and then two micro-LED chips are connected as parallel form in a single bulb. The transceiver based on two FPGA boards is used to generate quadrature amplitude modulation-orthogonal frequency division multiplexed (QAM-OFDM) signals and measure the communication performance of the VLC system. The low-power micro-LEDs bulb emits 0.8 mW optical power through two optical paths at 20 mA driving current, and the modulation bandwidths for two users' access are 90 MHz and 73 MHz, respectively. In this two-user real-time video transmission system, the total data rate exceeds 105.54 Mbps without naked eye discernable distortion over 2-m free-space distance. Different from traditional point-to-point links, this work demonstrates the possibility of flexible high-speed multi-user real-time video optical wireless transmission based on a parallel micro-LEDs bulb.

**Index Terms:** Visible light communication (VLC), multi-user communication, parallel micro-LEDs, FPGA transceiver.

## 1. Introduction

Visible light communication (VLC) is a kind of optical wireless communication (OWC), also known as light fidelity (Li-Fi), that uses high-speed modulated visible light which cannot be observed by the naked eye from lighting equipment. Li-Fi can simultaneously realize the functions of illumination and communication with low power consumption, good confidentiality, no electromagnetic interference (EMI), no frequency licensing, and many other advantages. It is an ideal indoor high-speed wireless access technology for the current commercial wireless communication field [1], [2]. The increasing demand for high security and confidentiality for business data has attracted more and more attention from research institutions and commercial companies [3]. However, the commonly used commercial white light-emitting diodes (LEDs) for solid-state lighting (SSL) are composed of blue-emitting broad-area LEDs and yellow-emitting phosphor which suffer from low modulation bandwidth [4]. Micro-size LEDs (micro-LEDs) based on III-nitride semiconductors have higher modulation bandwidth which provides a promising solution for high-capacity VLC [5], [6]. Towards next-generation VLC system for practical deployment, the use of field programmable gate arrays (FPGAs) for real-time data stream transmission is significant for live broadcast, optical Internet of thing (OIoT), multi-user access, and unmanned aerial vehicle (UAV) communication [7].

On the one hand, with the emergence of upcoming applications such as holographic communication, e-health, and virtual reality, the demand for high-speed real-time video transmission has increased. In addition, due to relatively low cost and small size, FPGA used for direct modulation can facilitate the implementation of real-time video transmission systems. In recent years, real-time VLC systems based on laser diode (LD) have been extensively studied in underwater scenarios. By utilizing quadrature amplitude modulation (QAM) modulated blue LD and FPGA, a 1.45-Gbps real-time VLC system over a 4.8-m underwater channel was proposed in [8], and a 50 Mbps underwater wireless optical communication (UWOC) system over 3-m point-to-point links was demonstrated in [9]. For reducing the complexity of systems, H. M. Oubei *et al.* adopted on-off keying non-return-to-zero (NRZ-OOK) modulation scheme to achieve 2.3-Gbps transmission over a 7-m underwater link by using 520-nm LD [10]. Besides, in order to simultaneously realize the function of communication and illumination underwater, red, green, and blue LDs (RGB-LDs) are used to generate white light in [11]. Although VLC systems based on LDs have longer transmission distance and higher modulation bandwidth, the LDs need more cost than LEDs and have safety issues for human eyes. In [12] and [13], commercial LEDs were used for real-time video transmission systems, which enabled 37 Mbps transmission over 1.5 m and 25 Mbps transmission over 10 m, respectively. Furthermore, a 66-m real-time differential phase shift keying (DPSK) VLC system based on FPGA with red LED was proposed in [14], which can achieve data rate of 10 Mbps with a BER below 1e-5. However, the low modulation bandwidth of LED limits the data rate of real-time VLC systems. To increase the bandwidth of systems, micro-LEDs have been adopted in real-time VLC systems, where the Gbps long-distance transmission was accomplished through free space in [15] and hundreds of Mbits/s underwater transmission was demonstrated in [16]. But these studies did not provide the modulation and demodulation schemes for real-time video transmission, and most research works focused on point-to-point transmission without considering the user number. Therefore, the high-speed real-time video broadcast transmission VLC system is still pending urgently, and the structure design of the micro-LED-based transmitter can be a potential solution for the issue.

On the other hand, for distinguishing different users, conventional multiple access technologies including time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) have been proposed. Recently, orthogonal frequency division multiple access (OFDMA), non-orthogonal multiple access (NOMA), and sparse coded multiple access (SCMA) are also adopted for multi-user VLC system. These multiple access methods not only increase the user number but also expand network scale [17]–[22]. For example, L. Zhang *et al.* used NOMA in a multiple LDs-based underwater optical wireless communication (UOWC) system based on wavelength division multiplexing (WDM) and polarization division multiplexing (PDM), achieving a data rate of 18.75 Gbps for 8 users [20]. Using non-Hermitian symmetry orthogonal frequency division multiplexing (OFDM) scheme and successive interference cancellation (SIC) algorithms, the problems of transmission distance and coverage of multi-users NOMA VLC system are proposed and investigated [21]. J. Shi *et al.* used a combination of OFDMA and NOMA as a solution to increase the number of users in VLC system [22]. Generally, these proposed multi-user VLC systems adopt point-to-point hardware configurations and differentiate various users by software-defined digital signal processing (DSP). However, for multi-user VLC communication, it is obvious that different users will be at different positions. Software-defined multiple access technologies cannot fundamentally solve the problem of multi-user VLC. Therefore, how to change the configuration of the VLC transmitter is a key step to achieve multi-user

TABLE 1
Summary of Performance of The Existing Real-time VLC Systems

| Year | Reference | Transmitter | BW[1] (MHz) | Modulation format | Data rate (Mbps) | BER[2] | Distance (m) |
|---|---|---|---|---|---|---|---|
| 2013 | [12] | Commercial Phosphor LED | 12 | 16-QAM | 37 | <FEC[4] | 1.5 |
| 2015 | [8] | FPGA + Bule LD | - | 64-QAM-OFDM[5] | 1450 | $9.1 \times 10^{-4}$ | 4.8 |
| 2015 | [10] | Single Mode Pigtailed LD + BERT[3] | 1200 | NRZ-OOK | 2300 | $2.33 \times 10^{-4}$ | 7 |
| 2017 | [15] | Blue Micro-LED + BERT | 230 | NRZ-OOK | 1300<br>1000<br>870 | $3.4 \times 10^{-3}$<br>$3.2 \times 10^{-3}$<br>$3.5 \times 10^{-3}$ | 3<br>10<br>16 |
| 2017 | [16] | Blue Micro-LED+ BERT | 160 | NRZ-OOK | 800<br>200 | $1.3 \times 10^{-3}$<br>$3.0 \times 10^{-3}$ | 0.6<br>5.4 |
| 2018 | [11] | RGB-LDs + BERT | 1400 | OOK+WDM | 3200<br>3400<br>3100 | $3.6 \times 10^{-3}$<br>$3.5 \times 10^{-3}$<br>$3.7 \times 10^{-3}$ | 2.3 |
| 2018 | [13] | Commercial blue LED +FPGA | 13 | NRZ-OOK | 25 | $1.0 \times 10^{-4}$ | 10 |
| 2019 | [9] | 450 nm Yellow LD + FPGA | >100 | 16-QAM-OFDM | 50 | $7.11 \times 10^{-4}$ | 3 |
| 2019 | [14] | Red LED + FPGA | - | DPSK | 10 | $<1.0 \times 10^{-5}$ | 66 |
| 2021 | Our work | Parallel Micro-LEDs + FPGA | 90<br>75 | QAM-OFDM | 105.54 | <FEC | 2 |

[1]BW: Bandwidth;
[2]BER: Bit-error-rate;
[3]BERT: Bit-error-rate tester;
[4]FEC: Forward error correction;
[5]QAM-OFDM: Quadrature amplitude modulation-orthogonal frequency division multiplexed (QAM-OFDM).

communication and video transmission. The hardware architecture of ingle-input multiple-output (SIMO) or multiple-input multiple-output (MIMO) VLC systems are a better solution for multiple users [23]. In addition, some high-speed blue or green micro-LEDs designs can further provide a higher capacity access. For example, Z. Wei *et al.* proposed a 4 Gbps VLC system based on single layer quantum dot blue micro-LED and OFDM scheme, and S. W. H. Chen *et al.* fabricated a high-bandwidth green micro-LED using semipolar (20-21) InGaN/GaN material [24], [25].

In this work, we firstly established a real-time multi-user video transmission system based on a parallel micro-LEDs bulb and two FPGA transceiver boards. In order to change the normal configuration of the traditional point-to-point VLC link, a parallel micro-LEDs bulb is proposed and used to broadcast for two users at different positions. Experiments confirm that the parallel micro-LEDs-based VLC system can provide two links with 90 MHz and 73 MHz modulation bandwidth for two independent users which can support data rates of 52.65 Mbps and 52.59 Mbps using 64-QAM-OFDM signal format, respectively. This work demonstrates the potential and broad application prospects of the parallel micro-LEDs-based VLC in the next generation of high-speed multi-user VLC in crowded indoor environment.

## 2. Devices and VLC System Setup

### *2.1 Fabrication and Packaging Design*

In this section, the design, fabrication and packaging of the proposed micro-LED will be introduced. Based on a GaN-based epitaxial wafer grown on a standard 2-inch *c*-plane sapphire substrate, a micro-LED array is fabricated using metal-organic vapor phase epitaxy (MOVPE, AIXTRON 2000HT). Schematic diagram of the cross section of the proposed micro-LED is shown in Fig. 1.

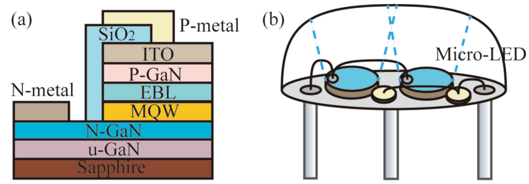


Fig. 1. The structure schematic diagrams of (a) a single-pixel blue micro-LED and (b) the package of the parallel micro-LEDs bulb.

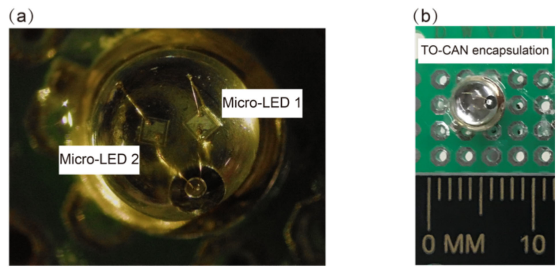


Fig. 2. (a) The microscopic photo and (b) the scaled photo of a package of the parallel micro-LEDs bulb.

According to the structure schematic from the bottom to the top, the GaN-based epitaxial structure includes a sapphire substrate, an unintentionally-dopped GaN (u-GaN) layer, a N-GaN layer, an InGaN/GaN multiple quantum well (MQW), an electron blocking layer (EBL), a P-GaN layer, and an indium tin oxide (ITO) layer. Here, the ITO layer would be a current spreading layer and ohmic contact layer, simultaneously. P-metal and N-metal is used to contact and drive micro-LED illuminations as the anode and cathode. In addition, the mesa sidewall is wrapped and passivated by a layer of silicon dioxide ($SiO_2$). Finally, the micro-LED arrays are grown and cut apart as a single pixel for the following transistor outline (TO) package. Fig. 1(b) shows the package of the proposed parallel micro-LEDs bulb with two independent 50-$\mu$m GaN-based micro-LED chips for the following dual-users VLC system and real-time video transmission.

Fig. 2(a) is the microscopic photo of the parallel micro-LED and Fig. 2(b) is an image of the outer package. Here we use the TO-CAN form encapsulation as shown in Fig. 1(b) and Fig. 2(b). The size of the proposed parallel micro-LEDs bulb is about 5 mm in diameter. Two micro-LEDs with the same diameter are connected in parallel in a single lamp. When using this proposed device for VLC, it can transmit same signal to different locations, which means two users at different locations can be broadcast, simultaneously. This design outperforms the traditional single-pixel micro-LED-based point-to-point VLC system [15], [16], [20], [22].

### 2.2. FPGA-Based Real-Time Optical Transmission System

The schematic diagram of the experimental system is shown in Fig. 3(a), which is composed of micro-LED-based transmitter, dual-APD-based receiver, and FPGA boards measuring equipment. A direct current (DC) regulated power supply (DP832, RIGOL) is used to supply the bias current to the micro-LED at the transmitter. The signal generated by the FPGA Tx. board is superimposed on the bias current and then transmitted to the micro-LED by a T-type bias circuit (ZFBT-6GW+, Mini-Circuits) to drive its luminance. The two-path light emitted by micro-LED converges through the plane-convex lens and then diverges in space. After 2-m transmission, two high-speed avalanche photodiodes (APD, $<$100 MHz) with a 1.0-mm photosensitive diameter convert the optical signal into an electrical signal, and then transmit the electrical signal to two home-made amplifiers ($<$100 MHz) via a coaxial cable. A vector network analyzer (VNA, N5227A, Agilent, 10 MHz-67 GHz) and two FPGA test boards are used to test the system bandwidth and communication performance, respectively.

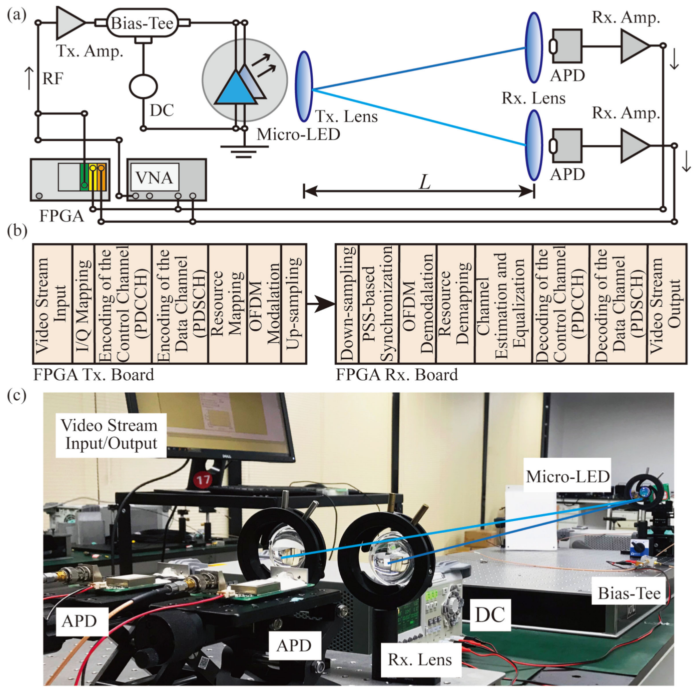


Fig. 3. (a) Schematic diagram of experimental setup for two-user video optical wireless transmission. (b) The real-time signal processing flow in FPGA boards of transmitter and receiver and (c) the picture of the VLC system setup.

To use the LTE Application Framework for multi-user video VLC transmission, two RF capable devices, a National Instruments (NI) PXIe-8880 system, a PXIe-1092 PXI Express equipment, two NI PXIe-7975R modules with an attached NI 5792 adapter modules with 200 MHz bandwidth are adopted. The two devices can be connected to one host computer and the testing loopback is connected. Then, the design software framework provides some application interface for long-term evolution (LTE) developing and customizing. Fig. 3(b) presents the DSP flow in the FPGA transceiver boards which is designed with reference to the LTE-framework. The input video stream is modulated by I/Q mapping into a QAM signal format. The modulated QAM signal is encoded using encoding of the control channel (PDCCH) and encoding of the data channel (PDSCH), and then the resource mapping is implemented, sequentially. Then the encoded signal is modulated by OFDM and finally up-sampled to the radio frequency (RF) pre-amplifier. In this way, the video signal is generated by the FPGA Tx. board and loaded onto the light intensity of the micro-LED transmitter. The receiving RF post-amplifier transmits the received signal to the FPGA. After the signal is down-sampled, a series of processing will be implemented, including synchronization, OFDM de-modulation, resource de-mapping, channel estimation, and equalization. Subsequently, the channel decoding will take place including decoding of the control channel and decoding of the data channel. Finally, the de-modulated OFDM signal further decomposes the QAM mapping and forms the video stream output. In addition, Fig. 3(c) shows the photo of the dual-user communication VLC system with two optical paths based on a parallel micro-LEDs bulb.

## 3. Results and Discussions

### *3.1 Optical and Electronic Characteristics of the Parallel Micro-Leds Bulb*

The current *versus* voltage (*I-V*) and optical power *versus* current (*L-I*) relations of the proposed parallel micro-LEDs bulb are shown in Fig. 4 and Fig. 5. The threshold voltage of the proposed bulb is 2.87 V, corresponding to driving current value of 1.1 mA, which is lower than the single-pixel

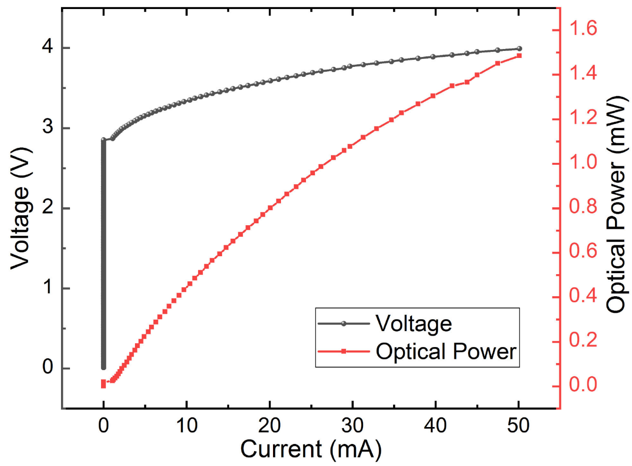


Fig. 4. *I-V* and *L-I* properties of the parallel micro-LEDs bulb.

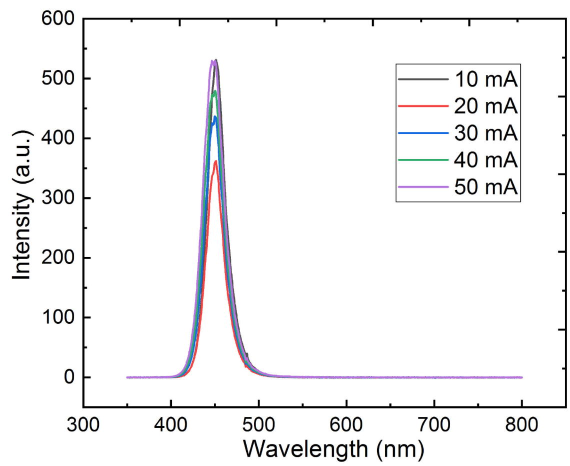


Fig. 5. Optical spectra of the parallel micro-LEDs bulb under various operating currents at room-temperature.

micro-LED owing to the decrease of series resistance. This means that two micro-LEDs in parallel reduce the impedance of the entire bulb. The measured *I-V* properties of the designed parallel micro-LEDs bulb is linear with the driving current from 1.1 mA to 50 mA, corresponding to emitting optical power from 0 mW to 1.48 mW. Fig. 5 is the measured optical spectra from 10 mA to 50 mA at room-temperature, where the wavelength is 451 nm at the driven current of 10 mA and shifts to 450 nm at the driven current of 50 mA.

### *3.2 The Bandwidth and Link Loss of Multi-User VLC System*

As shown in Fig. 6(a) and Fig. 6(b), the normalized frequency responses of two independent links are plotted under different driving currents of the transmitter. With the driving current increases from 0.8 mA to 20.5 mA, the modulation bandwidths of the two parallel micro-LEDs also increase. Due to the packaging of two micro-LED chips, the modulation bandwidth characteristics of the two parallel micro-LEDs are similar but not exactly the same. To distinguish the two parallel micro-LEDs, we assign them to user 1 and user 2, respectively. For the micro-LED for user 1, the modulation bandwidth increases from 29 MHz at 0.8 mA to 90 MHz at 20.5 mA. As for the other micro-LED for user 2, the maximum modulation bandwidth reaches 73 MHz at 20.5 mA. Fig. 6(c) presents the extracted −3 dB modulation bandwidths of two parallel micro-LEDs under

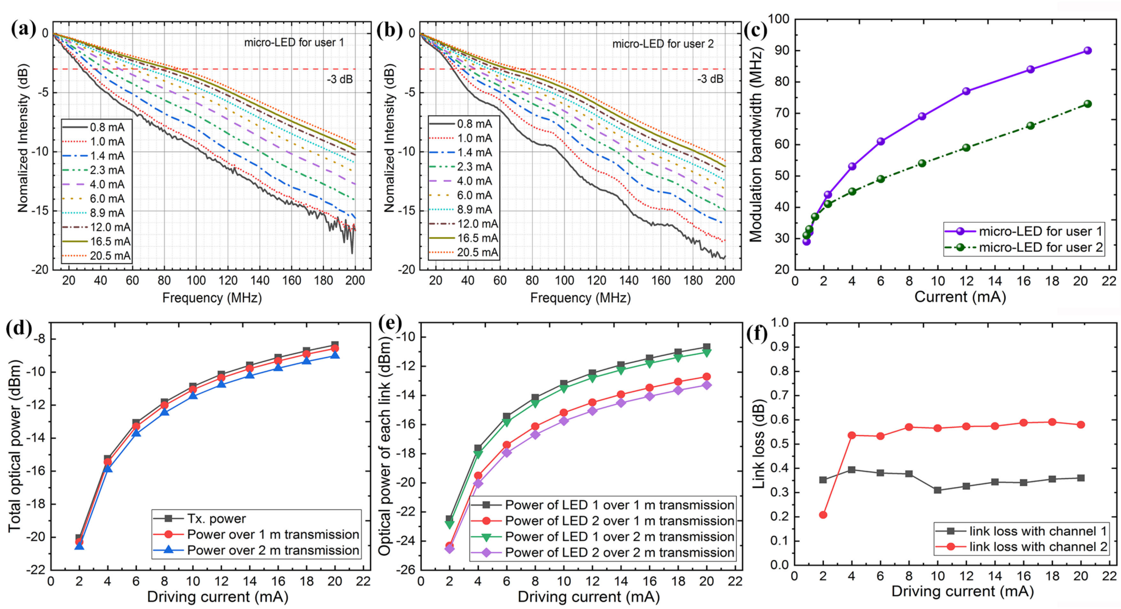


Fig. 6. Normalized frequency responses of the (a) link for user 1 and (b) the link for user 2. (c) Comparisons of extracted −3 dB modulation bandwidths of two links. (d) The comparison of total optical power at the transmitter, over 1-m and 2-m transmission. (e) The optical power of discrete link at different transmission distance and (f) the link loss from 1-m to 2-m transmission.

various driving currents. The bandwidth values shown here are much lower than the actual E-O bandwidth of the 50-$\mu$m micro-LED because the modulation bandwidth of the receiver module limits the modulation bandwidth of the entire VLC system. The modulation bandwidths of APD module and home-made post-amplifier are just several tens of MHz. However, this bandwidth is sufficient for building this flexible multi-user VLC system. In addition, for the video optical wireless transmission, the FPGA transceiver is based on the LTE-framework which causes the data rates of the generated QAM-OFDM signal to match the modulation bandwidth of the entire multi-user VLC system. Fig. 6(d) and Fig. 6(e) show the total and discrete optical power change with the injection current increasing from 2 mA to 20 mA. Relatively, the optical power gain of user 1 is about $\sim$2 dB more than that of user 2. Fig. 6(e) shows the optical power values measured at 1 m and 2 m from the transmitter of two links, and Fig. 6(f) is the link losses with two links distance increasing from 1 m to 2 m, respectively. As shown in the Fig. 6(f), the link losses of two user are stable at $\sim$0.57 dB and $\sim$0.35 dB.

### 3.3 Video Transmission Performances of Two Users

In this VLC experimental setup, instead of pursuing high-rate transmission, we pursue a reliable video optical wireless transmission scheme which can simultaneously broadcast for multiple users based on the proposed parallel micro-LED. Therefore, this experiment designs a stable transmission scheme with reference to the framework of LTE. Two FPGA boards are used for real-time testing experiment. To analyze the transmitted signal performance, the signal power spectrum of the transceiver and the constellation diagram demodulated by the receiver can be monitored in real time at the upper machine. In our VLC experiments, QPSK-OFDM, 16-QAM-OFDM, and 64-QAM-OFDM with various data rates are adopted and their communication performances are compared by observing the quality of video transmission after 2-m free space. The measured power spectra of the RF LTE signals of 16-QAM-OFDM are depicted in Fig. 7 at the transmitter side and receiver side of two links. The Tx. RF power is about -8 dBm and the Rx. RF power is about -15 dBm

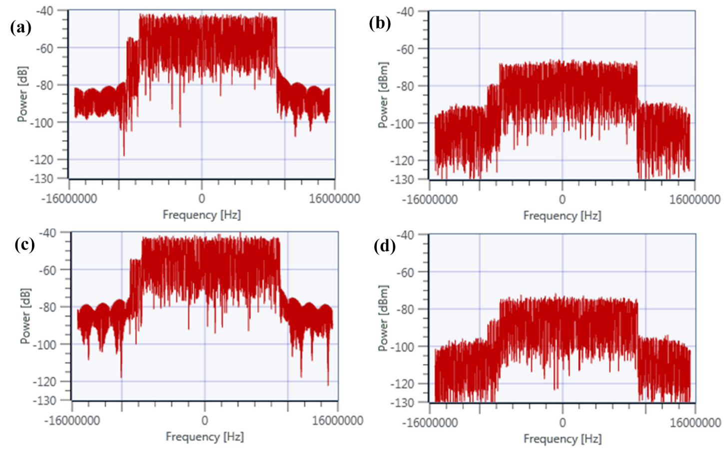


Fig. 7. The power spectra of two links with 16-QAM-OFDM scheme: The power spectra of the (a) transmitted signal and (b) received signal of user 1; the power spectra of the (c) transmitted signal and (d) received signal of user 2, respectively.

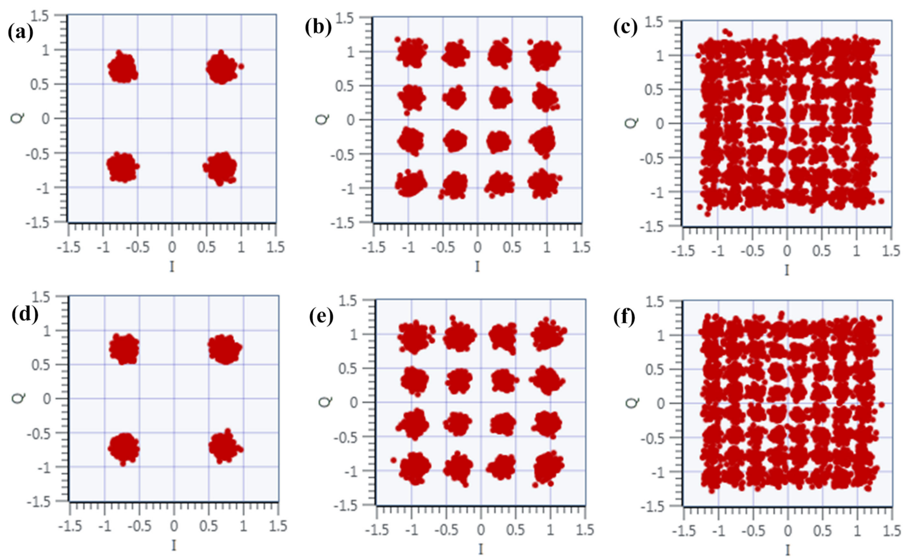


Fig. 8. The received signal constellation diagram of two links with different modulation formats: (a) QPSK-OFDM, (b) 16-QAM-OFDM, and (c) 64-QAM-OFDM for user 1; (d) QPSK-OFDM, (e) 16-QAM-OFDM, and (f) 64-QAM-OFDM for user 2, respectively.

for all the modulation formats. As shown in the constellation diagram of Fig. 8, the communication performances of two parallel micro-LEDs for different users are similar. For the micro-LED for user 1, the data rates can reach 14.6 Mbps, 29.17 Mbps, and 52.65 Mbps with QPSK-OFDM, 16-QAM-OFDM, and 64-QAM-OFDM at 20 mA driving current, respectively. The corresponding signal to interference plus noise ratios (SINRs) of modulation formats are 24.29 dB, 24.56 dB, and 24.19 dB. For the other micro-LED for user 2, the data rates are 14,64 Mbps, 28.25 Mbps, and 52.59 Mbps and the SINRs are 24.22 dB, 22.54 dB, and 24.04 dB with the modulation formats of QPSK-OFDM, 16-QAM-OFDM, and 64-QAM-OFDM, respectively. The constellation diagrams are distinguishable with a relatively low block error rate (BLER). Fig. 9 presents the real-time image of the comparison between transmitting video and receiving video over 2-m optical link of the user 1 and user 2, respectively. Fig. 9(c) and Fig. 9(f) also present the BLER and their corresponding SINR adopting 16-QAM-OFDM modulation format. The BLERs of two users are almost to zero.

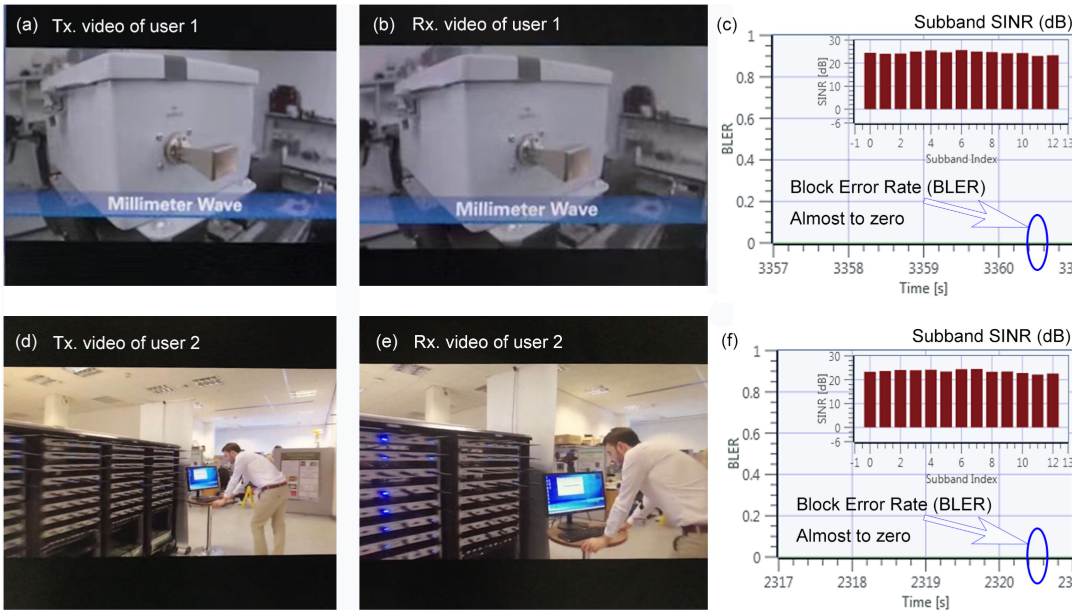


Fig. 9. Real-time image comparison between transmitting video and receiving video of user 1 (a) and (b), and user 2 (d) and (e) with the modulation format of 16-QAM-OFDM. (c) and (f) is the BLER and their corresponding SINR, respectively.

TABLE 2

Performance of Real-Time VLC System Based on the Proposed Parallel Micro-LEDs Bulb

| Performance | Value |
|---|---|
| RF Power of Tx. FPGA board | -8 dBm |
| RF Power of Rx. FPGA board | -15 dBm |
| Simultaneous supporting number of users | 2 |
| Max. modulation bandwidth of user 1 | 90 MHz |
| Max. modulation bandwidth of user 2 | 73 MHz |
| Max. real-time transmission data rate of user 1 | 52.65 Mbps |
| Max. real-time transmission data rate of user 2 | 52.59 Mbps |
| Max. total data rate | 105.54 Mbps |
| Time delay | ~2 s |

Both videos for two users can be clearly restored with a time delay of about 2 s. Table 2 shows the detailed parameters of the proposed real-time multi-user video transmission VLC system.

We have implemented a flexible multi-user real-time video optical wireless transmission system based on LTE-framework in FPGA transceiver by designing the transmitter micro-LED light source and receiver module. The real-time broadcasting for two users at different indoor positions is successfully realized under low power consumption of 0.8 mW. The advantage of low power consumption is beneficial to the future integration of VLC light source in consumer electronic terminal. However, there are also clear limits to this VLC system. First of all, the packaging of our micro-LED bulbs still needs to be further optimized. Although the two micro-led chips have the same diameter, the electrical characteristics and bandwidth performances are different. More single-pixel micro-LEDs can be set in parallel to broadcast towards more users. Parallel micro-LED chips will reduce the overall transmitter impedance compared with single pixel, while the mQAM-OFDM modulation scheme adopted by the VLC system has a relatively high peak to average power ratio (PAPR), resulting the transmitter is easy to be damaged. As a result, the micro-LED transmitter operates at a relatively low drive current. In addition, the power coupling and bandwidth enhancement inside transmitter can be optimized through a better design of impedance matching. As for the receiver of the VLC system, the APD can be further integrated with the home-made post-amplifier and a designed module with higher bandwidth can then be adopted. Finally, the signal processing in FPGA transceiver boards can be further redesigned to increase the maximum data rate, which is now limited to a few standard values by the current LTE-framework.

## 4. Conclusion

A flexible multi-user real-time video optical wireless transmission system based on FPGA with LTE-framework is proposed in this paper. Firstly, two 50-$\mu$m micro-LEDs are connected in parallel in a single bulb for simultaneous support to two users in different locations. Then FPGA broads with LTE-framework are used to modulate and demodulate video information. With a low power consumption of 0.8 mW, the total data rate of video transmission reaches more than 100 Mbps by using 64-QAM-OFDM modulation format. These designs and results can help build up a high-speed real-time video transmission system for multiple users, which can facilitate the practical deployment of VLC.

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