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A High-Efficiency High Power Driver Circuit for Joint Illumination and Communication System With Phase Shift Pre-Emphasis Technology

XIUYU WANG[1], JILING TANG[1], XU ZHANG[2], SHENG XIE[1], XURUI MAO[2], AND HONGDA CHEN[2]

[1]School of Microelectronics, Tianjin University, Tianjin 300072, China
[2]State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Corresponding authors: Xu Zhang (zhangxu@semi.ac.cn) and Sheng Xie (xie_sheng06@tju.edu.cn)

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ABSTRACT This paper presents an improved white light-emitting-diode (LED) wireless transmitter for the Joint Illumination and Communication (JIC) System, which consists of two parts: the driver circuit and the pre-emphasis circuit. The main purpose of the driver circuit part is to solve the problem of dissipated power when sweeping the remaining carriers during the signal modulation of the high-efficiency, high-power and high-speed white LED driver. A push-pull structure driver with a current conduction angle less than 180 degrees is proposed, which is analogous to a Class C power amplification driver, thus avoiding the simultaneous existence of voltage and current on the driver circuit when the remaining carriers are swept out, and improves the efficiency of the LED driver. On this basis, the pre-emphasis circuit part adopts the phase shift technology to improve the data transmission rate, and the system efficiency has also been improved. Then, an improved class C push-pull structure white LED driver with phase shift pre-emphasis technology is formed. This novel driver and pre-emphasis technology achieve a system efficiency of 95.73% with a 10 W LED. The test results show that the system communication −3 dB bandwidth expanded from the original 8.3 MHz to 13.67 MHz, and the best-obtained transceiver baud rate is 25 Mbps at a distance of 1.3 m with BER of 1.63×10^{-4}. The test result verifies that the LED driver proposed in this paper is currently the highest figure of merit (FoM) for high power JIC systems.

INDEX TERMS Joint illumination and communication (JIC), high efficiency, high power, push-pull driver, phase shift, pre-emphasis, the figure of merit (FoM).

I. INTRODUCTION

Nowadays, high-power white light-emitting-diodes (LED) have gradually replaced traditional incandescent and fluorescent lamps as the main light source for lighting, because of their advantages such as energy saving, high efficiency, long life, and low cost. Besides, compared with traditional light sources, LED is a semiconductor device that can be switched at a faster speed. Therefore, LEDs have a wider modulation bandwidth and are more suitable for high-speed communication [1]–[4]. With the development of wired and wireless communications, in conjunction with the green development that is now admired globally, energy-saving communications have become the focus of the current development of communication technology. Especially, the joint illumination and visible light communication (JIC), whose energy consumption for data transmission comes from the lighting, can save the costs of infrastructure installment, and the transmission energy can be used for lighting in return, thus reducing more power consumption [2]. Therefore, JIC is now globally recognized as a promising green communication technology [5]–[9]. The development of visible light communication (VLC) technology in indoor illumination also has many advantages, such as strong confidentiality, no need to apply for radio frequency (RF) spectrum, and anti-RF interference [10]–[11]. For the JIC system, the redundant

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power consumption mainly lies in the power of the lighting equipment and the JIC driver. It is so important for the design of high-power LED drivers. Generally, the VLC technology of high-power LEDs has great development potential in the future and will attract more and more researchers from all over the world [1].

For the development of the coexistence of illumination and VLC technology, there are currently three major problems, cost, efficiency, and speed. To achieve a higher speed and effective JIC system, a trade-off is needed between these three factors [12], [13]. And in recent years many studies have been conducted on these issues. Researchers designed a control loop adaptive and binary shunt driver with 2 W LEDs, achieved a data transmission rate of 267 Kbps, and a system efficiency of 88.6% at a communication distance of 1.5 m [14]. However, the communication data transmission rate is only 267 Kbps, which is far from enough for JIC. To implement a high-speed VLC system, Zhou *et al.* proposed a two-level linear software equalizer and reached a VLC transmission rate of 2.32 Gbps based on a white 1 W LED with a 450 MHz bandwidth and a transmission distance of 1 m [15]. This method of software balance and compensation increased the costs for installation and maintenance, nevertheless. For larger power LEDs, the communication rate will be much slower, and there are few studies on high speed and high efficiency. However, due to the needs of factories, street lights, vehicles, and underwater applications, more powerful light sources are required to achieve JIC. In [16], Gong *et al.* designed a switched-mode W/GaN device driver with a white 8 W LED, which achieved a communication rate of 1 Mbps, the VLC system efficiency of 80.8%. Many researchers have also analyzed the system efficiency of the designed VLC driver. For example, a VLC system for a 2 W LED array used a baseband digital signal processing (DSP) unit and a DC-DC switching boost driver and achieved a data transmission rate of 266 Kbps with the system efficiency of 85% [17]. By using the average current mode control to design a dual-purpose offline LED driver, a data transmission rate of 2 Mbps, and a VLC system efficiency of 74.6% was achieved [18]. In these studies, although the efficiency of the transmitter system was considered and analyzed, the data transmission rate during communication was too low, and the system efficiency was not ideal, either. They cannot meet the requirements of the joint lighting and communication (JIC) system.

In response to these problems, Y. Wu *et al.* presented a high-power, high-efficiency, and high-rate white LED transmitter for VLC systems [19]. The design uses the Non-return-to-zero on-off keying (NRZ-OOK) modulation method. This modulation method is simple and low-cost and does not require any complicated hardware or software algorithms. Different from the traditional on-off modulation method, the signal of the LED is modulated by the push-pull structure driver in the bright-dim conversion. This method can make the LED is in a permanently bright state, and the reduction of the data transmission rate during signal modulation is avoided. It is more suitable for the coexistence of illumination and VLC [19]. However, in the transmitter proposed by Y. Wu *et al.*, there is an overlap of voltage and current when the remaining carriers are swept out during signal modulation, which is easy to cause a short circuit of the remaining carrier sweep-out structure. The overlap of voltage and current will also cause unnecessary power consumption. And their circuit structure also cannot be pre-emphasized. This paper will improve the circuit structure and propose an improved push-pull structure driver with a conduction angle of fewer than 180 degrees during signal modulation. It can reduce the dissipated power during the remaining carrier sweep-out circuit. And it avoids the simultaneous existence of voltage and current on the driving circuit when the remaining carriers are swept out and thus improves the efficiency of the driver. This is different from the class B push-pull structure which cannot be pre-emphasized. Instead, this method can provide phase-shift pre-emphasis technology, and forms an improved Class C GaN FET push-pull structure transmitter. This novel driver, together with the pre-emphasis circuit, could further improve the efficiency and bandwidth of the JIC system.

This paper is organized as follows: Firstly, we will introduce the improved LED push-pull driver structure for JIC. Secondly, we will provide a pre-emphasized circuit structure designed for the proposed driver. Finally, we present a conclusion and discuss the development and application prospects of this design.

II. IMPROVED LED PUSH-PULL DRIVER STRUCTURE FOR VLC

Figure 1 shows the circuit of a white LED communication transmitter proposed by the previous work, which mainly involves two parts. One part is a push-pull structure driver using two identical gallium nitride field-effect transistors (GaN FETs), and the other is a transmitter signal processing circuit [19]. Since the large LED junction capacitance, the remaining carriers cannot be released immediately when the signal causes the LED to change from bright and dim. Therefore, the remaining carrier sweep circuit designed by the signal control is needed to provide a release channel [20]–[22].

The circuit in Figure 1 is analogous to a Class B power amplifier in radio frequency (RF) communications [23]. The two GaN FETs are turned on within half a cycle, respectively, and the current conduction angle θ is 180 degrees as shown in Figure 2 (a). When the input data signal is "1", M1 is turned on, M2 is turned off, and the LED is in a bright state; when the input data signal is "0", M1 is turned off, M2 is turned on, and the LED is in a dim state. It ensures that both GaN FETs are used as switches, only in the on and off states. For the remaining carrier extraction circuit during the modulation process, the two GaN FETs are turned on within half a period respectively, and the current conduction angle θ is 180 degrees. There is an overlap of the voltage and current with the dim way signal when the remaining carriers

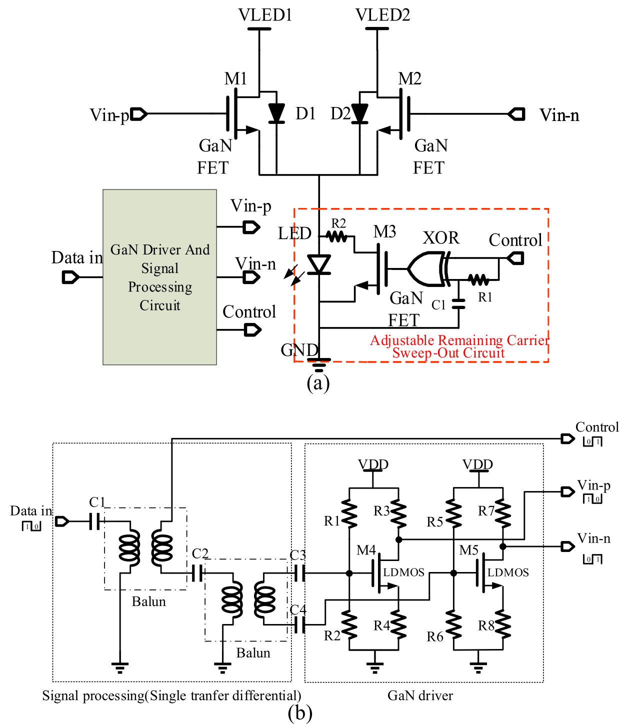

FIGURE 1. **White light LED communication transmitter [19]. (a) LED transmitter circuit schematic diagram; (b) Signal processing circuit schematic diagram.**

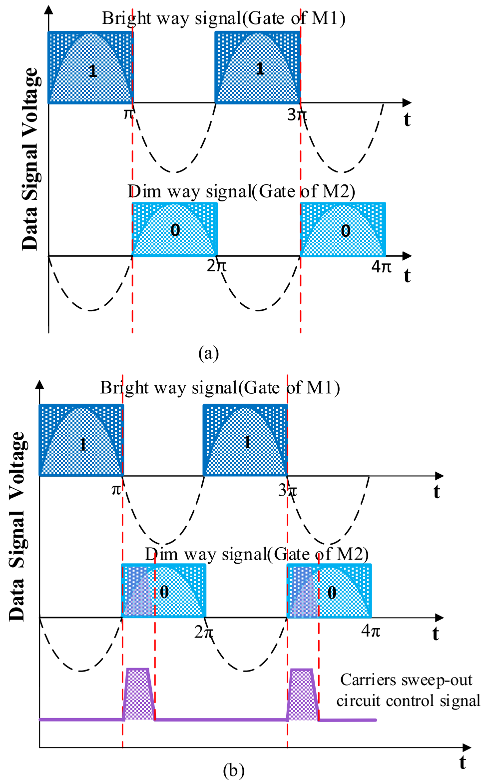

FIGURE 2. **Schematic diagram of the signal conduction angle of Class B driver. (a) Voltage change waveforms at the gates of M1 and M2; (b) The voltage change waveforms at the gates of M1 and M2 and the output of the remaining carriers sweep-out circuit. There is voltage overlap with the dim way signal when the remaining carriers are swept out.**

are swept out, as shown in Figure 2 (b). The overlap of the power during the remaining carrier being sweep-out will also cause unnecessary power loss, thus decreasing the system efficiency. So, a current-limiting resistor needs to be added to avoid the short circuit of the LED during the dark half-cycle of the signal.

To avoid the overlap of the carrier signal with the dim way signal during the sweeping of the remaining carriers, A scheme to make the signal conduction angle of the driver circuit less than 180 degrees is proposed in this paper. The driver circuit is analogous to the Class C power amplifier circuit in radio frequency (RF) communication [24]. We realize this by changing the static operating point voltage of the GaN FET pre-driver circuit in the signal processing circuit. In the signal processing circuit, the input signal is converted into two differential signals through a balun. One of them is used to control the adjustable remaining carriers sweep-out circuit in the push-pull structure driver, and the other is converted into two differential signals through the balun, then provided to two input ports of the push-pull structure driver circuit. The input signal power losses 6 dB after two balun conversions. To ensure that the two GaN FETs in the push-pull structure driver circuit can work normally in the switching state, the two differential signals at the input port of the push-pull structure need to have a sufficient voltage swing. The normal operating voltage of the 10 W LED used is about 3.3 V, and the GaN FET turn-on voltage V_{th} is about 1.4 V so that the GaN FET can be turned on in a suitable region, and the minimum voltage applied to its gate is 4.5 V. However, the signal voltage swing after conversion by the balun transformer is insufficient, and a pre-drive circuit is required to provide sufficient power for the drive circuit operating. Therefore, the common source amplifier composed of two LDMOS (M4, M5) emphasizes the high-frequency components makes the signal steeper so that the input signal has sufficient swing.

By changing the static operating point voltage V_Q of the common source amplifier composed of two LDMOS (M4, M5) to be less than the V_{th} of the GaN FET, only the part of the input signal in the driver circuit that is larger than the V_{th} can turn on the GaN FET. In this way, the signal conduction angle of the driver circuit can be adjusted to be less than 180 degrees, and when the signal makes the LED in a bright or dim state, the conduction angle of the GaN FET is less than half a period as shown in Figure 3 (b). It also avoids the overlap of the dim signal with the remaining carrier being swept out. as shown in Figure 3 (c), the voltage at the time of sweeping the remaining carriers does not overlap with the dim way signal voltage. The dissipated power will be eliminated, and the system efficiency will be improved [25], [26]. In the pre-driving circuit of the driver in Figure 3 (a), R1 and R2, R5 and R6 are the gate bias resistance of M4 and M5 respectively; R3 and R7 are the load resistance of the common source stage; R4 and R8 are source resistances, which control the static operating point of the amplifier circuit. The static

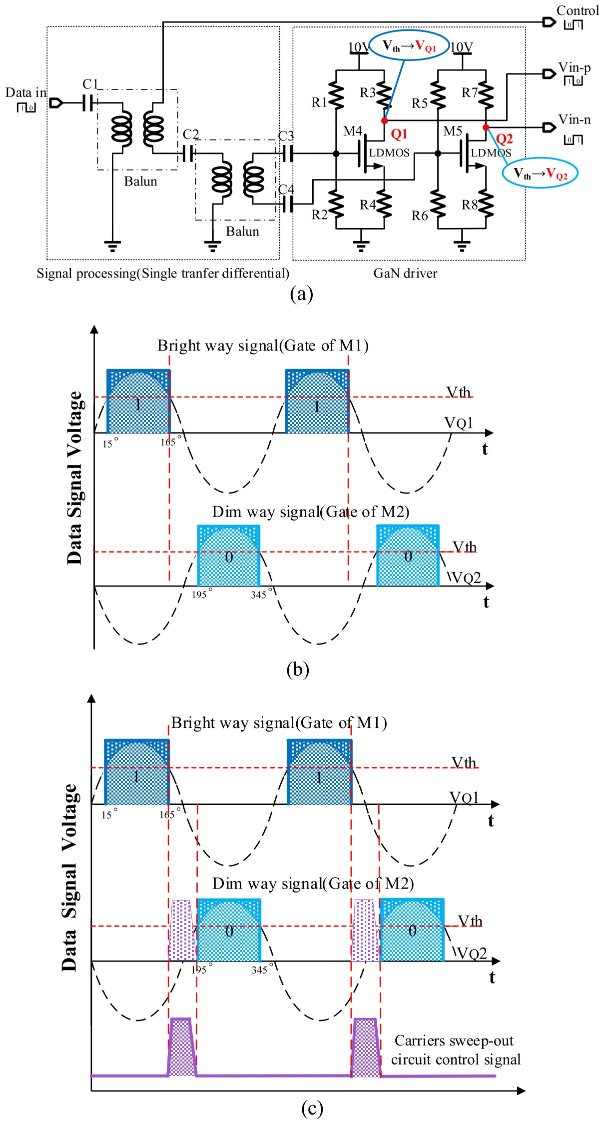

FIGURE 3. The signal current conduction angle diagram of the improved push-pull structure driver. (a) Signal processing circuit driving operating point circuit diagram [19]; (b) Voltage change waveforms at the gates of M1 and M2. The conduction angle of the bright and dim way signals is less than 180 degrees; (c) The voltage change waveforms at the gates of M1 and M2 and the output of the remaining carriers sweep-out circuit. The voltage at the time of sweeping the remaining carriers does not overlap with the dim way signal voltage.

operating point voltage is as follows:

$$I_{DQ} = \left(\frac{V_{GSQ}}{V_{GS(th)}} - 1\right)^2 \tag{1}$$

$$V_{GSQ} = \frac{R_2}{R_1 + R_2} \times 10V - I_{DQ}R_4 \tag{2}$$

III. PRE-EMPHASIS CIRCUIT FOR CLASS C PUSH-PULL STRUCTURE DRIVER

Based on the implementation of an improved push-pull structure driver circuit, a pre-emphasis technology that provides a phase shift to improve the modulation bandwidth and data transmission rate of the transmitter is proposed. Figure 4 shows the signal processing circuit of the pre-emphasis circuit. Based on the previous signal processing circuit, we perform the phase shift on the input signals of the bright and dim ways to achieve pre-emphasis.

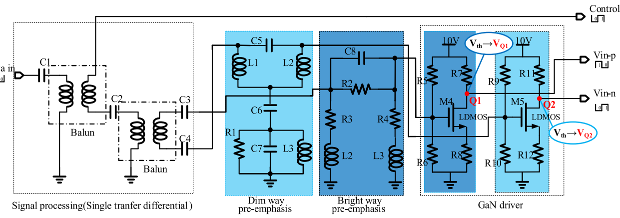

FIGURE 4. The signal processing circuit of the improved push-pull structure driver with phase shift pre-emphasis technology.

We propose to keep the phase of the signal unchanged in the low-frequency state. In the high-frequency state, let the signal of the input bright way and the signal of the input dim way shift forward and backward respectively by the appropriate phase, as shown in Figure 5. This can enable the signal to be more accurately modulated and increase the transmission rate of the data signal. When the input bright way signal is moved forward and the dim way signal is moved back by an appropriate phase, it can reduce the modulation error rate of the signal conversion from bright to dim, so the error code of the LED transmitter during modulation can be improved, and it also can avoid the superposition with the power during remaining carrier being swept out.

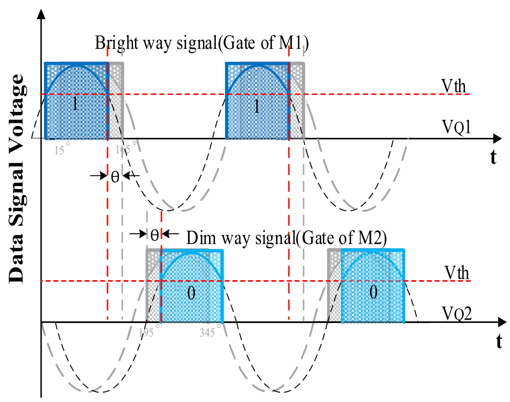

FIGURE 5. Schematic diagram of signal conduction angle of the improved driver after phase shift pre-emphasis. The bright way signal and the dim way signal move forward and backward by about 12 degrees, respectively.

For the pre-emphasis of the dim way signal, the typical all-pass network passive phase shift circuit is used, as shown in Figure 6 (a). For the need to shift the phase angle is less than 45 degrees, this all-pass passive phase shifter can shift the phase with a small-time error within the relative bandwidth of 10% to 20% [27],[28]. At the same time, it can achieve relatively good impedance matching. In Figure 7 the red curve shows the phase shift curve of the dim way. The red dotted line and solid line in Figure 8 are the frequency response S-parameter curves of the all-pass passive phase shifter.

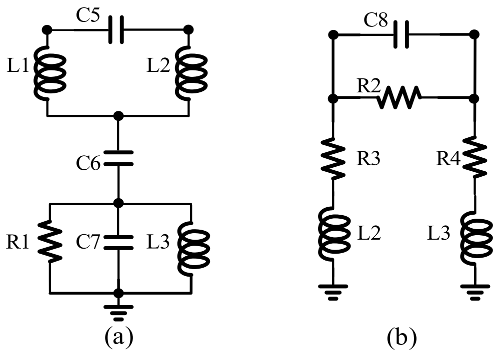

FIGURE 6. (a) All-pass passive phase-shift circuit; (b) All-pass phase-shift and π-type attenuation network combination circuit.

The optimal value of the inductor and capacitor that meets its phase requirements and impedance matching requirements can be expressed as:

$$C_6 = \frac{2}{\rho\omega_0 Z_0} \quad C_5 = \frac{1}{2\rho\omega_0 Z_0} \quad L_1 = \frac{Z_0}{\rho\omega_0} \tag{3}$$

$$C_7 = \frac{1}{Z_0\omega_0}\frac{2(\rho + 1/\rho)}{1 + (\rho - 1/\rho)^2} \tag{4}$$

$$L_2 = \frac{Z_0}{\omega_0^2}\frac{1 + (\rho - 1/\rho)^2}{2(\rho + 1/\rho)} \tag{5}$$

$$\rho = \frac{1}{\frac{1}{2\tan(\Delta\theta/2)} + \sqrt{1 + \frac{1}{4\tan^2(\Delta\theta/2)}}} \tag{6}$$

Among them, ω_0 is the center frequency, and Z_0 is the standard load impedance of 50 Ω.

According to the input signal requirements of the push-pull structure driver circuit, when the all-pass passive phase shifter is used for the pre-emphasis of the dim way signal, the signal will have a certain attenuation [29]. To make the input signal meet the requirements of the push-pull structure, the passive devices are used to form an all-pass phase-shifting dependent π-type attenuation network [30], [31]. Figure 6 (b) shows the all-pass phase-shift and π-type attenuation network combination circuit. Let the input signal of the bright way and the dim way input signal have the same power, and realize the phase shift of the bright way input signal. As shown in Figure 7 the blue curve for the phase shift curve in a bright way. The blue dotted line and solid line in Figure 8 are the frequency response S-parameter curves of the all-pass passive phase shifter. According to the amount of signal attenuation, the optimal value of each resistor and capacitor in the circuit can be expressed as:

$$R_3 = Z_0\frac{(U_o/U_i) + 1}{(U_o/U_i) - 1} \tag{7}$$

$$R_2 = Z_0\frac{(U_o/U_i)^2 - 1}{2(U_o/U_i)} \tag{8}$$

Z_0 is the standard load impedance of 50 Ω.

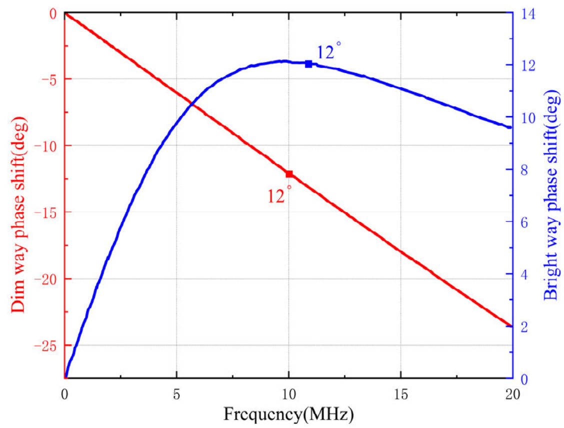

FIGURE 7. Changes in phase shift. The red curve is the dim way phase shift curve, and the blue curve is the bright way phase shift curve.

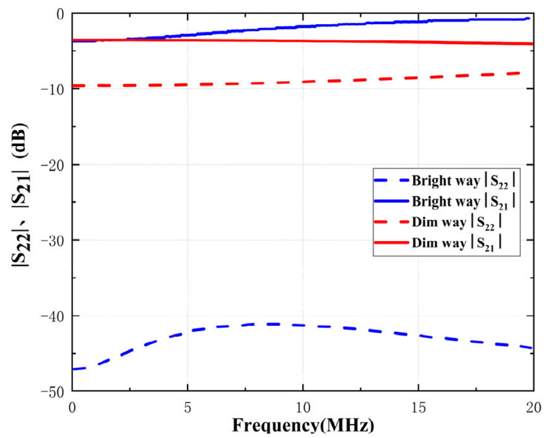

FIGURE 8. The frequency response curve of the phase shift pre-emphasis circuit.

IV. TESTING AND DISCUSSION

Figure 9 illustrates the photo of the proposed improved white LED push-pull structure transmitter module, which includes the driver circuit and the pre-emphasis circuit. It is composed of a push-pull GaN FET (EPC 8010), white 10 W LED (CREE XML2 U3), a freewheeling diode (SMP-320), an AND gate (SN74HC86N), and a balun (T-6T +KK81+). Figure 10 shows the test block diagram and the experimental operating platform. The block diagram of the visible light communication system is mainly the transmitting part and receiving part. The signal generator (Keysight 33600A) is used to generate a signal input to the transmitter, which is our proposed improved push-pull structure LED transmitter module. The light is collected through the lens(10mm), and the receiving part uses the high-speed avalanche photodiode (APD) module (HAMAMATSU C5658) to receive signals. And the oscilloscope (MSOX3034A) is used to analyze and process the received signal. The voltage waveform of the output signal is measured from the optical receiver in Figure 11.

In the experiment, we built the system according to the system block diagram and tested this VLC system. The current

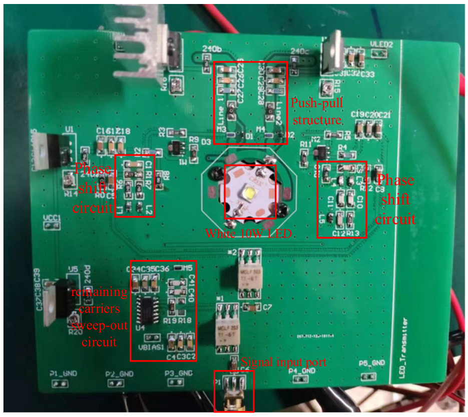

FIGURE 9. Visible light communication white LED transmitter module.

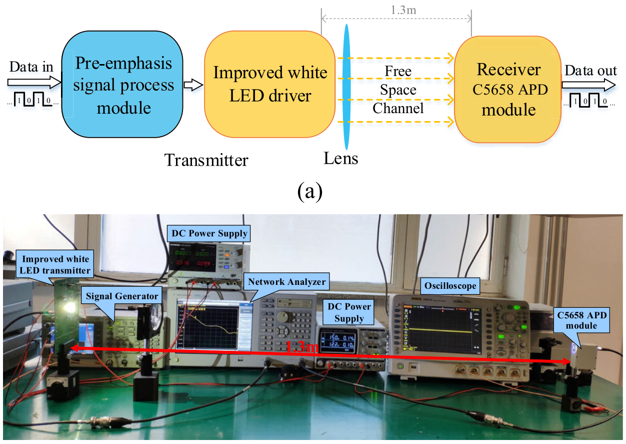

FIGURE 10. (a) VLC system block diagram; (b) Experimental operating platform for the VLC system.

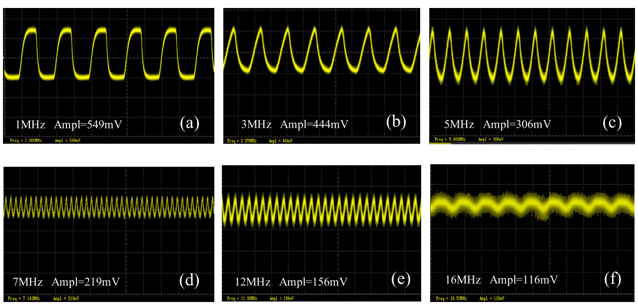

FIGURE 11. The voltage waveform of the output signal is measured from the optical receiver. (a) 1MHz; (b) 3MHz; (c) 5MHz; (d) 7MHz; (e) 12MHz; (f) 16MHz.

conduction angle in the driver has changed, and thus the signal conduction angle of the driver θ is less than 180 degrees. This will also be beneficial to the adjustable remaining carriers sweep-out circuit, and reducing the dissipation power of the driver. It can also improve the reliability of the remaining carriers sweep-out circuit. Then, the system efficiency of the driver will be further improved. The Figure 11 histogram is a comparison chart of the percentage of the dissipated power of the improved push-pull structure LED driver and the LED driver proposed by Y. Wu *et al.* except for the LED lamp power consumption in the LED driver. It can be seen that the power consumed in the remaining carrier sweep-out circuit and other parts has decreased significantly. In addition to the LED lamp power consumption, the percentage of power dissipated dropped from 6.83% to 4.27%. As shown in the pie chart of Figure 12, the system power efficiency percentage of the improved driver proposed in this paper reaches 95.73% with 10W LED.

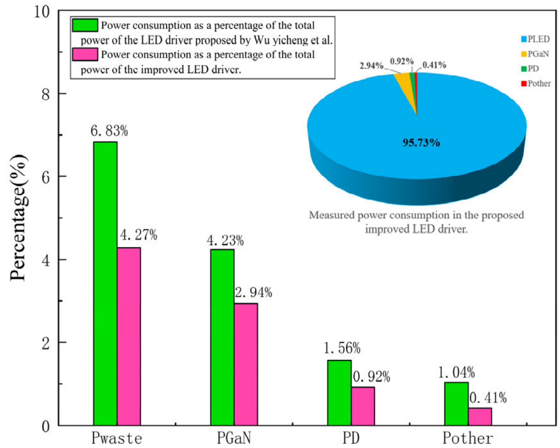

FIGURE 12. Comparison chart of the percentage of the dissipated power of LED driver except for the LED lamp power consumption and power consumption as a percentage of total system power. Pwaste: power dissipated of LED driver except for the LED lamp power consumption; PLED: power dissipation in the LED; PD: power dissipation of freewheeling diode; PGaN: power dissipation of GaN FET.

The system electro-optical-electrical (EOE) frequency response is tested by the network analyzer (Agilent E5071B). The input end of the improved LED driver is connected to the Port1 of the network analyzer, in which the signal power of 14.5 dBm is input. The high-speed avalanche photodiode (APD) module (HAMAMATSU C5658) of the receiving part is connected to the Port2 of the network analyzer [32]. As shown in Figure 13, It shows that the white light 10W LED lamp has a −3 dB bandwidth of 3.9 MHz. For the improved class C push-pull structure LED driver with phase shift pre-emphasis technology, the modulation bandwidth is obtained with further improvement, the −3 dB bandwidth was increased from the original 8.3 MHz to 13.67 MHz.

Next, we also evaluated the data transmission performance of this system. Figure 14 shows the experimental operation platform. The pseudorandom binary sequence signals were generated first in MATLAB. These signals were loaded into an arbitrary waveform generator (Agilent, M8190A), via a U disk, and adopt PAM2 modulation mode to output 14.5 dBm signal of AWG as the input of LED transmitter. Then, at the receiver, the detected signals were captured by a digital signal oscilloscope (Agilent MSO9254A). Finally, the captured signals were transmitted to the computer

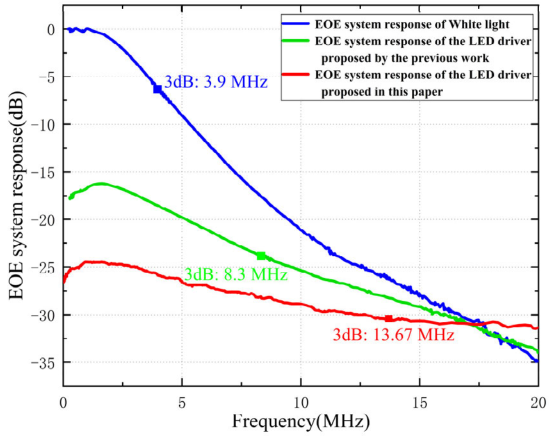

FIGURE 13. Comparison diagram of measured EOE system frequency response of White light, the LED driver proposed by the previous work [19] and the improved LED driver proposed in this paper.

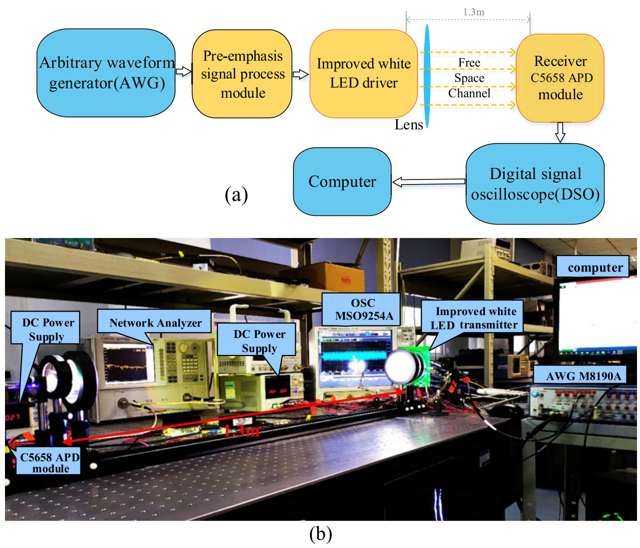

FIGURE 14. (a) Experimental setup to measure both BER at different data rates and the eye diagram of the VLC system; (b) Experimental operating platform for the VLC system.

via a U disk for offline processing, including bit synchronization and calculation of BERs and eye diagrams [33]. Figure 15 shows the measurement results of the system bit error rate. Among them, the measurement rate of the improved push-pull structure LED driver with phase shift pre-emphasis technology reached 27 Mbps with BER of 3.26×10^{-3}, at a communication distance of 1.3 m, which was below the FEC limit of 3.8×10^{-3}. The experimental results show that the data transmission rate of class C improved push-pull structure white LED driver with phase shift pre-emphasized technology has been greatly improved.

To analyze the performance index of the LED driver used in the JIC system, we define the Figure of Merit (FoM) of the LED driver to describe. The higher the FoM value, the more suitable the LED driver is for the JIC system. Without losing

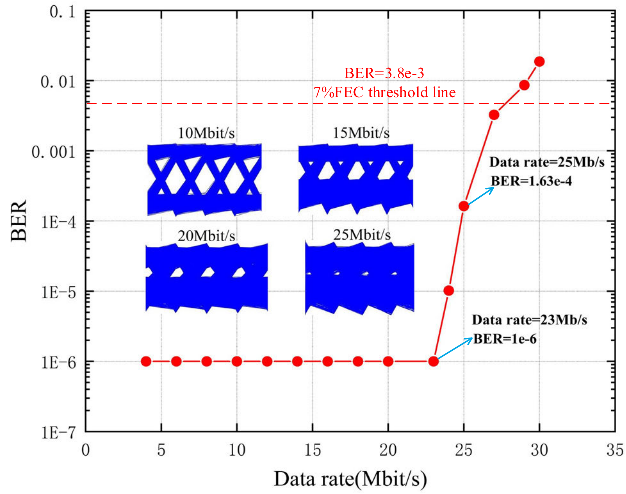

FIGURE 15. The measured BER at the different data rates. Insert: Eye diagrams of the VLC system at 10 Mbit/s, 15 Mbit/s, 20 Mbit/s, and 25 Mbit/s.

generality, the performance metrics for a JIC transmitter can be described by the FoM shown in (equation) as follows:

$$\mathrm{FoM} = P_{LED}\,(W)\,\eta^2 R_b\,(Mbps) \tag{9}$$

where P_{LED} is the injection power of a driver circuit in the JIC system. η is the efficiency of the driver circuit and the square term indicates that η influence both LED's output power and system power efficiency. R_b (Mbps) is the max data transmission rate in which the BER values are below the FEC threshold of 1×10^{-3} for the JIC system. The FoM reflects the performance of the LED driver of the JIC system. The communication distance of the system can be adjusted through the size of the lens diameter, so the effective formula of the FoM does not include the communication distance.

TABLE 1. Comparison between the proposed design and state-of-the-art works.

	This work	[19]	[16]	[18]	[14]	[17]
FoM	225.6	112.4	5.9	5.6	0.4	0.2
Efficiency	95.7%	93%	85.8%	74.6%	88.6%	85%
Max.Date rate	≤27 Mbps	≤13 Mbps	≤1 Mbps	≤2 Mbps	≤267 Kbps	≤266 Kbps
P_{LED}	10 W	10 W	8 W	5 W	2 W	2 W
Architecture	Phase shift pre-emphasis Technology	Switched-mode with push-pull structure	Switched-mode w/GaN device	Dual-Purpose Offline LED Driver	Control-loop adapting driver	Switching boost LED driver

After the definition of FoM, Table 1 outlines the performance of this work and other prior published state-of-the-art JIC driver systems. The driver circuit in this work has demonstrated a higher or comparable output power and power efficiency with a higher data transmission rate when compared with the other respectable state-of-the-arts.

V. CONCLUSION

Through the improved push-pull structure LED driver, the signal conduction angle of the driver circuit is less than 180 degrees. A high-efficiency, high-power, and high-speed white LED transmitter with the novel class C GaN FET push-pull structure driver circuit and pre-emphasis circuit is formed, which has a higher data transmission rate and system efficiency. And the superposition of the power consumption during the sweeping of the remaining carriers and the modulation of the dim way signal is avoided, thus reducing the dissipation power of the driver and a system efficiency of 95.73%. The phase shift pre-emphasis technology is provided on this driver, and the system communication -3 dB bandwidth has been increased from the original 8.3 MHz to 13.67 MHz, and the data transmission rate reached 25 Mbps at a distance of 1.3 m with BER of 1.63×10^{-4}. The transmitter module we proposed can be applied to white LED communication systems with high efficiency, high power, high speed, low cost, and low complexity. It also provides a broader application prospect for vehicle telematics and efficient UWOC systems.

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XIUYU WANG received the Ph.D. degree in microelectronics and solid-state electronics from Tianjin University, Tianjin, China.

He is currently an Associate Professor with the Department of Electronics Science and Technology, Tianjin University. His main research interests include semiconductor gas sensors, CMOS image sensors, and CMOS analog integrated circuits.

JILING TANG received the B.S. degree from the Tianjin University of Technology, Tianjin, China. He is currently pursuing the master's degree with Tianjin University, Tianjin.

His current research interests include visible light communication, underwater wireless optical communication, and hardware pre-emphasis technology.

XU ZHANG received the B.S. degree from the South China University of Technology and the Ph.D. degree from the Chinese Academy of Sciences.

He is currently an Associate Professor with the Institute of Semiconductors, Chinese Academy of Sciences. His main research interests include ICs and microsystems for implantable neuromodulation, high-reliability integration technology for automotive electronic components, and flexible tactile sensor and interface.

SHENG XIE received the B.S. degree in physics from Hebei Normal University, Shijiazhuang, China, and the Ph.D. degree in condensed state physics from Xiamen University, Xiamen, China.

He is currently an Associate Professor with Tianjin University, Tianjin, China. His current research interests include semiconductor photodetectors, high-speed optical receiver, and CMOS analog integrated circuits.

XURUI MAO received the B.S. and M.S. degrees from Tianjin University and the Ph.D. degree from the University of Chinese Academy of Sciences.

He is currently an Associate Professor with the Institute of Semiconductors, Chinese Academy of Sciences. His main research interests include novel nanoelectronic devices, intelligent sensors, and integrated microelectromechanical systems especially on visual and tactile sensory devices and systems.

HONGDA CHEN received the B.S., M.S., and Ph.D. degrees from Tianjin University, Tianjin, China, in 1982, 1990, and 1996, respectively.

He is currently a Professor with the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China. His current research interests include the fundamentals of semiconductor devices, optoelectronic devices and integration technology, visible light communication, and system-on-chip for biomedical applications.