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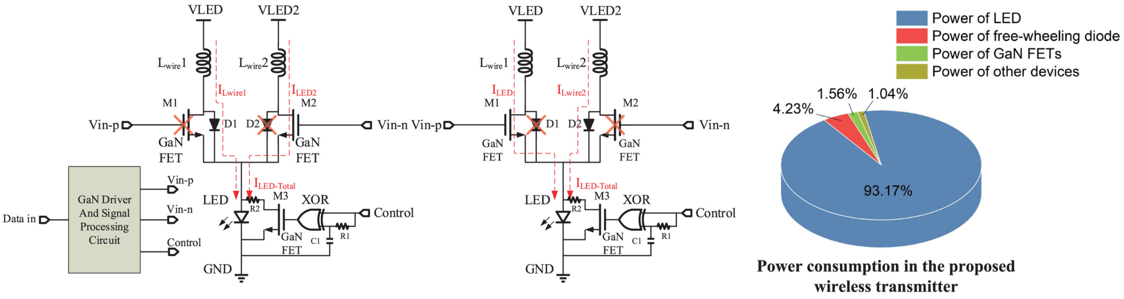

Power consumption in the proposed wireless transmitter

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GaN FET Push–Pull Driver Circuit Enabling Power Light Emitting Diode to be a High-Efficiency, High-Speed Wireless Transmitter

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Abstract: A high-power, high-efficiency, and high-speed white light-emitting-diode (LED) wireless transmitter is presented in this paper. This transmitter system consists of a gallium nitride field effect transistor (GaN FET) driver with push–pull structure, freewheeling circuit, and remaining carriers sweep-out circuit based on a phosphorescent white LED. A novel push–pull circuit structure with intensity modulation is used to increase the efficiency of the proposed transmitter to 94.2% at 12 Mb/s theoretical baud rate. Generally speaking, LED transmission speed is restricted by the remaining carriers in the junction capacitance. In this paper, we introduce an improved adjustable carrier sweep-out circuit to resolve this problem. High-frequency components in the signal are preemphasized by adding parallel freewheeling diodes between the drain and source of the GaN drivers. Test results show that the power efficiency is 93.17% with -3 dB bandwidth at 8.3 MHz. The results also show that the architecture proposed in this paper allows the baud rate of the transmitter to reach 10 Mb/s with bit error rate below 10^{-5}, which meets the IEEE 802.11 b requirements at distances farther than 1 m.

Index Terms: Wireless optical communication, white light-emitting-diode (LED), high-power, high-efficiency, push–pull driver.

1. Introduction

Light-emitting-diodes (LED) have gradually become mainstream for lighting applications due to their low energy consumption, high efficiency, and long lifetime [1], [2]. In addition, compared with a conventional illuminator like an incandescent lamp and or fluorescent lamp, LEDs can switch at MHz frequencies, which makes them more attractive in the field of joint illumination communication (JIC) [3].

White LED can be used in high speed communication thanks to their low complexity, and a growing number of researchers remain focused on this technology. At present, white LED communication systems based on 1 W LED have provided data rates of 2.32 Gbps by employing Orthogonal Frequency Division Multiplexing (OFDM) modulation [4]. However, only a few researchers have considered power efficiency and actual illumination power of an LED driver. For instance, a high-speed VLC system provides 233 MHz of bandwidth, but the power output from the LED is only a few watts and the efficiency of the transmitter system is less than 50% [5]. Recently, a high power white LED communication system provided efficiency of 81.5%, but the baud rate of this transmitter was only 1 Mbps [1]. Therefore, a high power, high efficiency, and high speed LED driver circuit is in great demand in white LED communication [6]–[8].

Non-return-to-zero on-off keying (NRZ-OOK) modulation is a suitable switching method in white LED drivers thanks to its low-complexity and high-efficiency. The LED will switch on and off in this way. However, the large junction capacitance will greatly limit the LED switching speed, especially for high-power LEDs. As a result, a higher frequency data signal cannot be achieved [9]–[13]. Moreover, if the transmission rate is too low, there will be a long 0 or long 1, resulting in visual discomfort. Therefore, allowing the LED to transfer between bright and dim is not only good for boosting the baud rate of the system, but also good for indoor illumination. Based on this method, Honglei Li et al. demonstrated a system with 460 Mbps baud rate [5]. However, in Lis system, the power transistor works in the saturation region. This caused the efficiency of the LED driver to decrease significantly, because when a driver FET operating in saturation region, nearly half of the power dissipates in the drain and source, and therefore, the LED driver cannot provide high efficiency [14].

In this paper, we propose a high power, high efficiency LED driver architecture. First, we introduce this novel push-pull architecture to improve the efficiency and baud rate. Second, we propose an improved adjustable sweep-out circuit for increasing data transmission rate and maintaining high-efficiency. Third, we propose using a freewheeling circuit in the proposed module in order to further improve the baud rate. We then present test results showing that our proposed white LED transmitter could provide 10 Mbps baud rate, which meets the IEEE 802.11b standard. The system efficiency is 93.17% at this rate. Finally, we present conclusions and discuss the possible applications for this driver circuit.

2. Design Of New GaN FET Power LED Driver

2.1 Dual Level Push-Pull Driver Structure

The proposed high power, high efficiency LED driver with push-pull structure is shown in Fig. 1(a). This device is different from traditional LED drivers, where the LED is connected to the drain electrode. We connect the LED to the source electrode. The LED is driven and intensity modulation is provided with two push-pull GaN FETs (M_1, M_2). The GaN FETs provide high output power to the LED driver. Higher switching frequency can also be achieved due to high switching speed and low switching loss of the GaN FET. A push-pull driver with intensity modulation operates as follows. Data is converted to two differential signals and amplified to an adequate voltage swing by passing the signal through a GaN driver and signal processing circuit, which is then input to the push-pull GaN driver. A schematic of the GaN driver and signal processing circuit is shown in Fig. 1(b). The intensity emitted from the LED depends on V_{LED} and V_{LED2}. M_1 is ON and M_2 is OFF when the input data is “1”.Due to V_{LED} is greater than V_{LED2}, the LED is bright. Conversely, M_1 is OFF and M_2 is ON when the input data is “0”, and the LED is dim. We can ensure the two GaN FETs are only on or off and decrease the power loss in the GaN FET, which is why our proposed circuit can maintain high efficiency with intensity modulation. The simulated transient waveforms of the LED terminal voltage and drain-source voltage of the GaN FETs (M_1, M_2) are shown in Fig. 2. In order to analyze the efficiency of the LED driver, we define η as the ratio between the power dissipated by the LED and the total dissipated power:

$$\eta = \frac{\bar{P}_{LED}}{\bar{P}_{Total}} = \frac{V_{LED} \times I_{LED}}{V_{LED} \times I_{LED} + V_{GaN} \times I_{GaN}} \tag{1}$$

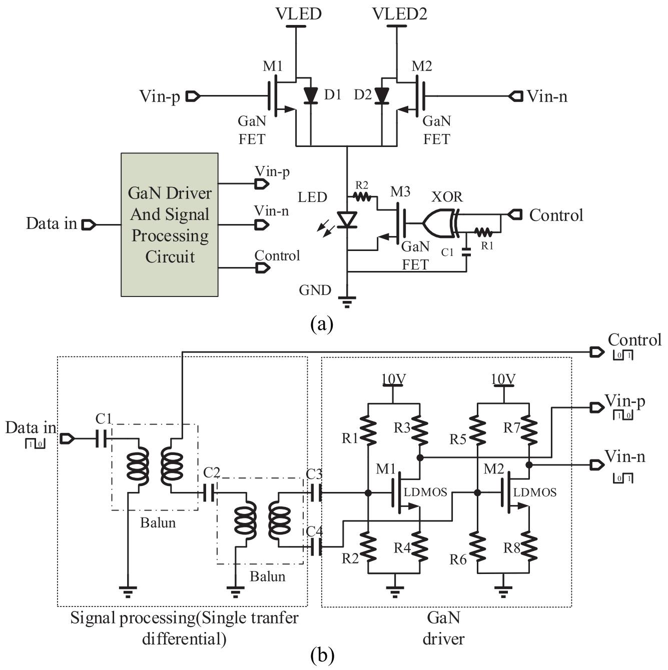


Fig. 1. Proposed white LED communication transmitter. (a) Overall configuration of the proposed LED transmitter architecture. (b) Internal architecture of the GaN driver and signal processing circuit.

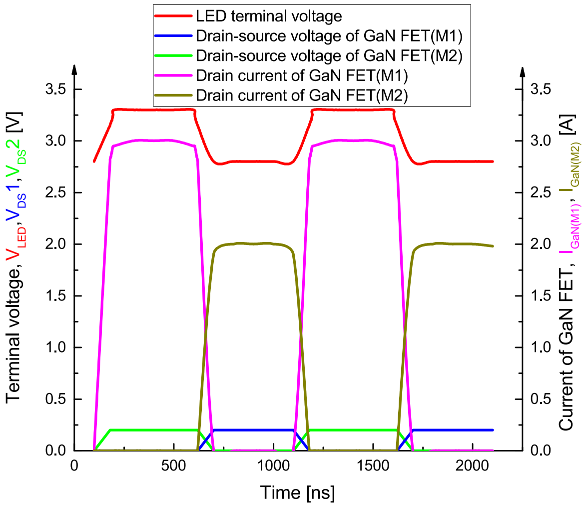


Fig. 2. Transient LED terminal voltage and the drain-source voltage waveforms of the GaN FETs (M_1, M_2). No current flows through the GaN FET when there is a voltage drop between the drain and source, and vice versa.

Eq. (1) defines the power budget in the driver when $I_{LED} = I_{GaN}$. The power efficiency ratio η can vary from 0 to 1. The product of V_{GaN} and I_{GaN} is the average power consumed by the GaN FET, which depends on operating state of the GaN FET. When the GaN FET is in on/off state, the dissipated power of the GaN FET is smaller than in the saturation region and the efficiency of the system will be higher.

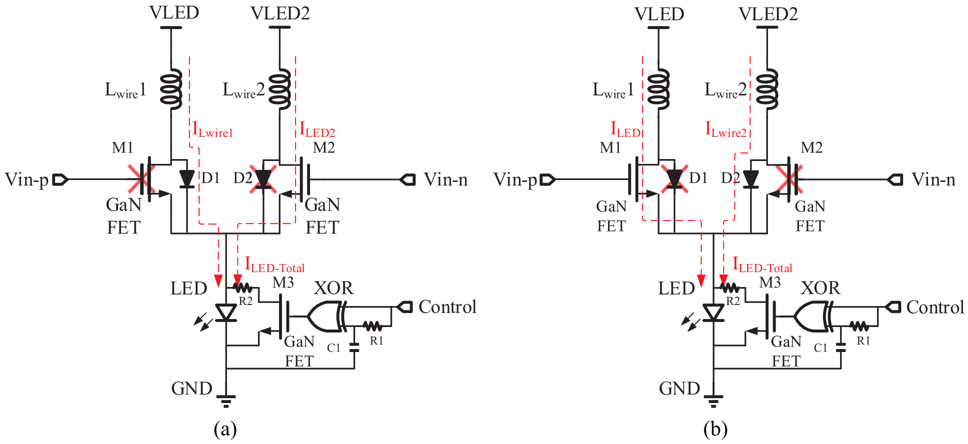


Fig. 3. Current flow in the proposed LED driver. (a) Operating principle of the freewheeling circuit when the LED switches from bright to dim (M_1 is OFF, M_2 is ON). (b) Operating principle of the freewheeling circuit when the LED switches from dim to bright (M_1 is ON, M_2 is OFF).

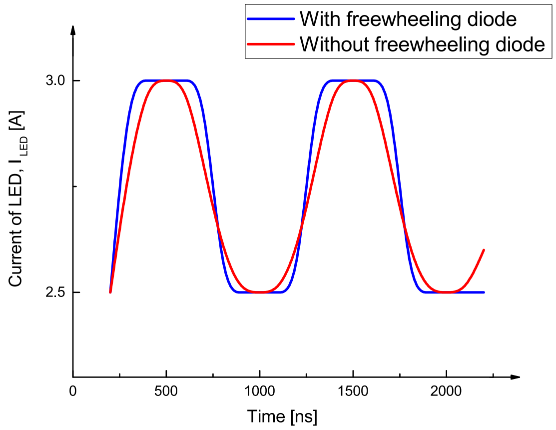
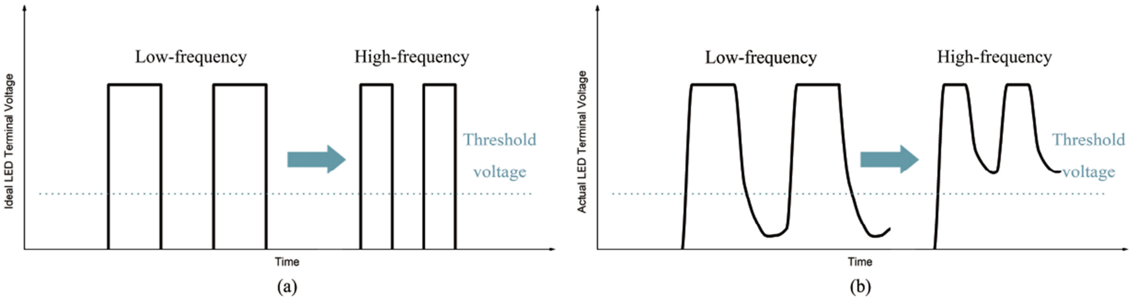


Fig. 4. Current waveforms in the LED with and without the freewheeling diode.

2.2 Freewheeling Circuit

As the proposed LED driver has dual voltage supply (V_{LED}, V_{LED2}), we must consider isolation between two voltage sources. As shown in Fig. 1(a), two freewheeling diodes (D_1, D_2) are connected in parallel to the drain-source pole of the GaN FET (M_1, M_2). Moreover, the power output from the LED in this paper is 10 W and the operating current is rather large (1 to 3 A). The small inductance of the printed circuit board (PCB) can also have a significant impact on the performance of the circuit. The wire inductance (L_{Wire1}, L_{Wire2}) of the PCB is shown in Fig. 3; these two inductors will generate reverse currents when M_1 and M_2 switch at high speeds. As shown in Fig. 3(a), D_1 is ON and D_2 is OFF when M_1 is OFF and M_2 is ON. The induced wire current (I_{Lwire1}) has the same direction as the decreased current generated by L_{wire1}, and this current will flow through D_1. The total current ($I_{LED-total}$) flowing through the LED is the sum of the induced current (I_{Lwire1}) and the drain current (I_{LED2}) in M_2. Therefore, the high frequency component of the signal is emphasized, and its loss in the LED will not distort the waveform. This will not lead to higher bit error rate (BER) and will limit the speed of white LED communication system. The improved waveforms provided by the freewheeling circuit are shown in Fig. 4.



(a) (b)

Fig. 5. Diagrams conceptualizing modulation speed limitation due to remaining carriers. (a) Idea LED terminal voltage waveforms. (b) Actual LED terminal voltage waveforms.

2.3 Adjustable Remaining Carrier Sweep-Out Circuit

The junction capacitance in a high power LED is much larger than in a low power LED. The remaining carriers in the junction cannot be released immediately when the LED changes from bright to dim. This will lead to insufficient switching between bright and dim luminance. Fig. 5 shows how the remaining carriers limit the modulation speed. The current in the LED will not fall low enough with increasing baud rate, causing the amplitude of the modulation signal to be unable to distinguish between 0 and 1. This increases the BER.

Consequently, we designed an improved remaining carriers sweep-out circuit for the proposed LED transmitter, as shown in Fig. 1(a). In this circuit, a GaN FET (M_3) is connected in parallel with the LED. M_3 is switched on at the edge when the LED switches from bright to dim. As a result, current flows through the LED is by passed by M_3, and the remaining carriers are swept out rapidly. It is also necessary to prevent obvious flicker in the LED output. Therefore, M_3 must be switched on as soon as the LED changes from bright to dim and will then be switched off immediately. In order to realize this function, we must capture the rising edge of the signal, and this edge is used to control whether M_3 is ON or OFF. The rising edge of the signal can be captured by R_1, C_1 and high speed XOR gate. This circuit is shown in Fig. 1(a). Its working principle is as follows: the signal controlling the dim state of the LED is divided into two channels, one of which is directly input to the XOR gate, while the other is input to the XOR gate after passing through an RC filter. This results in an RC time delay between the two inputs at the XOR gate, and the output of the XOR gate is 1. After an RC time delay, the two inputs of the XOR gate are identical, and the output of the XOR gate is 0. The simulated voltage waveforms at the gates of M_1 and M_2 and the output port of the XOR gate are shown in Fig. 6. The time constant of the RC circuit is

$$\tau = R_1 C_1 \tag{2}$$

and the response function of the RC circuit is

$$V_{C1}(t) = V_S(t) - V_S(t) e^{\frac{-t}{\tau}} \tag{3}$$

where $V_S(t)$ and $V_{C1}(t)$ are the transient voltage of the input and $C1$, respectively. Thus, the captured time of the remaining carriers sweep-out circuit can be controlled by adjusting the value of $R1C1$ at various baud rates. Although the carriers sweep-out circuit can effectively improve the baud rate, the voltage drop across $R2$ will decrease the efficiency of the circuit when the sweep-out circuit operates. Therefore, there is a trade-off between efficiency and speed.

3. Test and Discussion

The proposed LED transmitter module is shown in Fig. 7. Its discrete components consist of a GaN FET (EPC 8010), freewheeling diode (Alpha SMP-1320), XOR gate (Texas Instrument SN74HC86N), and BALUN circuit (Mini Circuits T1-6T+KK81+). The experimental white LED

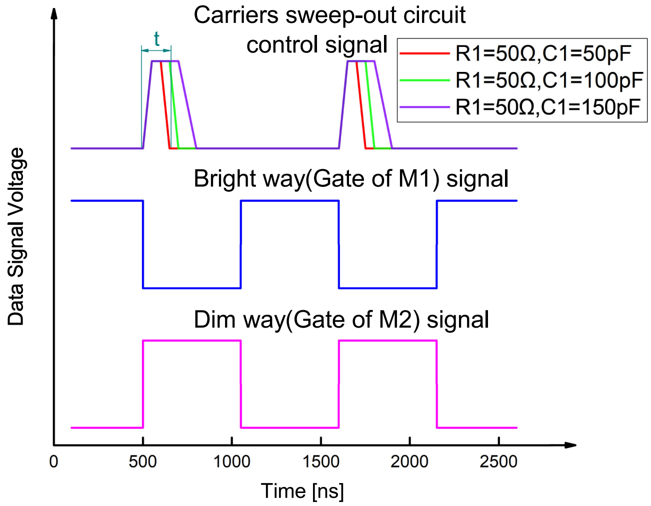


Fig. 6. Voltage waveforms at the gates of $M1$ and $M2$ and at the output from the XOR gate. Different carriers sweep-out circuit control signals for $R_1 = 50\ \Omega$, $C_1 = 50$ pF; $R_1 = 50\ \Omega$, $C_1 = 100$ pF; $R_1 = 50\ \Omega$, $C_1 = 150$ pF.

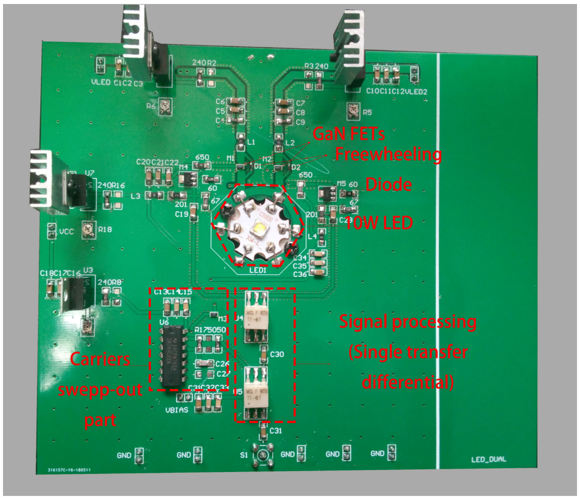
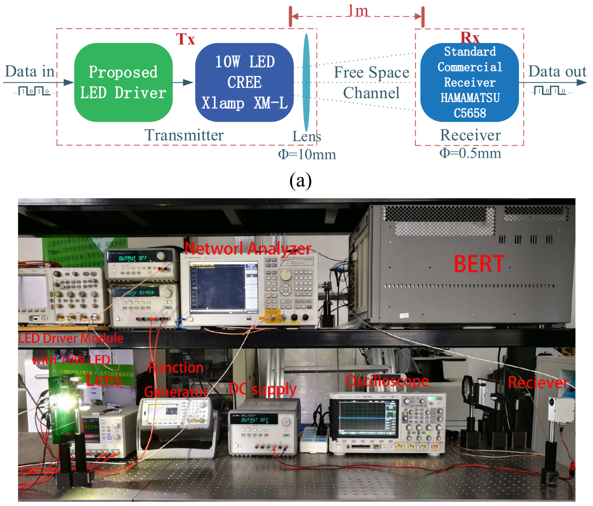


Fig. 7. Proposed LED transmitter module, which includes a signal processing circuit, improved adjustable carriers sweep-out circuit, LED driver circuit with push-pull structure, and freewheeling diode.

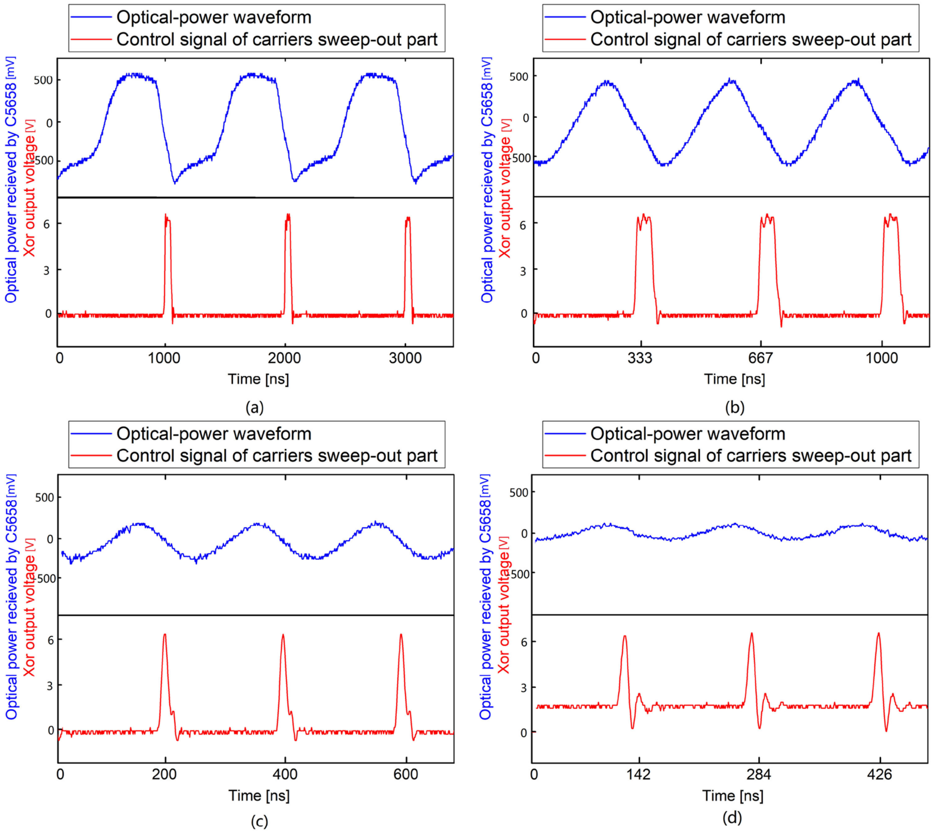
communication system and verification platform are shown in Fig. 8. A signal from a function generator (Keysight 33600A) was input to the proposed wireless transmitter and was set to a 10 W LED (CREE XLamp XM-L). A standard commercial receiver (HAMAMATSU C5658) was used to convert the output optical signal back to an electrical signal. This electrical signal was analyzed with an oscilloscope (Agilent MSOX3034A). The radius of the lens near the transmitter is 10 mm. It should be pointed out that no other lenses were used at the receiver end, and the radius of the lens (0.5 mm) is compatible with mobile terminals. The waveforms received at the receiver and the inner control signal in the remaining carriers sweep-out circuit are shown in Fig. 9. The experiment results show that the remaining carriers sweep-out circuit functions as designed when the LED changes from bright to dim (i.e., the data signal changes from 1 to 0). Using the test voltages in each part of the circuit when driven with a 5 MHz square wave, the power consumed by the LED transmitter can be calculated using Eq. (1). Fig. 10 shows that the novel push-pull structure causes the power efficiency ratio η to reach 93.17%.



(a)

(b)

Fig. 8. (a) Experimental setup of the white LED communication system. The data signal generated from the function generator is transmitted through proposed transmitter and received by the receiver module. (b) Verification platform for the white LED communication system, which includes the proposed wireless transmitter, commercial receiver module, function generator, network analyzer, oscilloscope, and BERT.



(a)

(b)

(c)

(d)

Fig. 9. Measured output voltage waveform from the optical receiver and the XOR gate. (a) 1 MHz, (b) 3 MHz, (c) 5 MHz, and (d) 7 MHz. All waveforms were measured with an Agilent MSOX3034A oscilloscope.

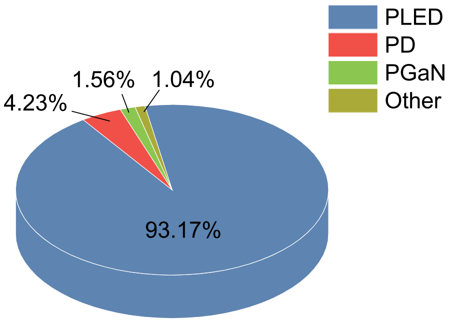


Fig. 10. Measured power consumption in the proposed LED driver. PLED: power dissipation in the 10 W LED; PD: power dissipation of freewheeling diode; PGaN: power dissipation of GaN FET.

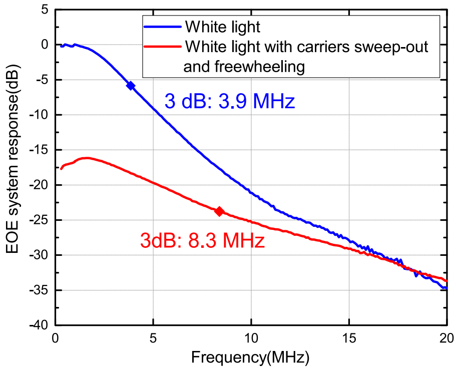


Fig. 11. Measured EOE system frequency response with and without the remaining carriers sweep-out and freewheeling circuits. The decreased response at low frequency is caused by inner AC coupling in the receiver.

In addition, we performed a measurement of the electro-optical-electrical (EOE) channel frequency in the white LED communication system with an Agilent E5071B network analyzer. Fig. 11 shows the frequency response of the EOE system with and without the remaining carriers sweep-out and freewheeling circuits. The optical receiver converts the optical signal to an electrical signal. The receiver converts the changing light intensity to a changing current and then outputs the power signal. Therefore, the -6 dB bandwidth of the EOE system is equivalent to the -3 dB bandwidth of the LED transmitter. We can see that the -3 dB bandwidth of the 10 W white LED is 3.9 MHz. The carriers sweep-out and freewheeling parts increase the magnitude of the high frequency components. In this way, the -3 dB bandwidth of the transmitter system could be extended to 8.3 MHz.

A bit error rate test (BERT) system (Agilent 81250) was used to evaluate the data transmission performance of the communication system and measure the BER as a function of data rate. a pseudo-random binary sequence with a peak-to-peak voltage of 0.15 V was used as the input to the LED driver module. The BER measurements are shown in Fig. 12. The communication system provides 10 Mbps data rate with 3.4×10^{-6} BER. Compared to the case without any transmission rate boosting technology, the proposed LED transmitter increases the transmission rate to 10 Mbps, which meets the IEEE 802.11b standard. The high illumination level from the 10 W LED provides a high data rate at 1 m distance.

A comparison between the proposed design and devices reported in prior publications is tabulated in Table 1. The proposed driver circuit architecture provides higher power, higher efficiency, and higher data rate than prior circuits. This white LED communication technique can be directly applied to indoor illumination without extra power dissipation.

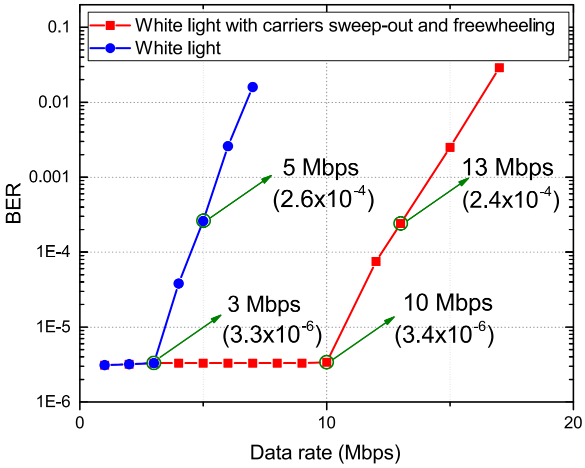


Fig. 12. Measured BER vs. transmission data rate (white with and without carriers sweep-out handling). BER values below 10^{-6} are truncated to this threshold.

TABLE 1
Comparison Between the Proposed Design and Prior Results

	Data rate	Power of LED	Efficiency	Architecture
This work	10 Mbps	10 W	93%	Switched-mode with push-pull structure
Ref. [1]	1 Mbps	8 W	81.5%	Switched-mode GaN device
Ref. [13]	2 Mbps	5 W	88.6% (with no data and dimming), 74.6% (transmit data)	Shunt switch in parallel to LED
Ref. [3]	267 Kbps	2 W	85%	Control-loop adapting and binary shunting

4. Conclusion

The high power LED transmitter with push-pull structure we proposed provides high efficiency and high speed data transmission. We effectively improved the driver by utilizing GaN power devices, resulting in improved power efficiency by transforming the conventional single drain driving LED driver to a dual level driver with push-pull architecture. In addition, the white light transceiver system we built provides a higher data rate through the use of an improved remaining carriers sweep-out circuit and freewheeling diode, which provides similar pre-emphasis function. The proposed LED driver circuit could extend the -3 dB bandwidth from 3.9 to 8.3 MHz, which allows OOK-NRZ data transmission up to 10 Mbps with BER below 10^{-5} at a distance of 1 m without any additional lens at the receiver. Our device could be applied in high-speed, high-efficiency, and low-complexity white LED communication systems. Our high efficiency white LED communication system based on a 10W LED with 10 Mbps baud rate opens up much broader prospects for application in street lamp broadcast communication, vehicle telematics, and high-speed underwater communication.

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