Wide illumination and communication angle visible light communication system based on low output impedance LED driver amplifier*

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The visible light communication (VLC) system employs large viewing divergence angle light-emitting diode (LED) to realize illumination and communication simultaneously, so the geometric loss of optical power may reach tens of decibels, moreover, considering the gain reduction of the LED at high frequency, signal power at the receiver will be too weak. To overcome these drawbacks, in this paper, a low output impedance power driver amplifier is presented to provide enough power to drive a medium power commercial LED used at the end of the optical transmitter. A 125 Mbit/s real-time communication with illumination and communication angle of 130° has been achieved at a distance of 3 m, the bit error rate (*BER*) is 3.13×10^{-11} at a divergence angle of LED of 0° and 1.21×10^{-6} at a communication angle of 130°. Experimental results indicated that this VLC system can be used for illumination and communication simultaneously.

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Visible light communication (VLC) technology takes light-emitting diodes (LEDs) as transmitter for both illumination and communication simultaneously[1,2]. The propose of VLC system based on orthogonal frequency-division multiplexing (OFDM) technology and wavelength division multiplexing (WDM) technology is considered as an important and promising approach to immensely improve the data rates of VLC systems[3-5]. VLC technology has gradually become a hot topic in the field of wireless communication in recent years.

At present, researches on VLC technology mainly focus on the direction of communication light source, modulation and demodulation technology and equalization circuit. In 2017, Liu et al successfully designed the long-distance VLC system of 1 Gbit/s by using the high-bandwidth micro LED on the basis of GAN developed by themselves[6]. In 2018, Zhang et al proposed a real-time VLC system of 1 Gbit/s on-off keying (OOK) data communication based on white LEDs using T-bridge cascaded pre-equalization circuit[7]. Xu et al proposed a real-time 262 Mbit/s VLC system based on the digital predistortion waveform shaping scheme combined with a blue filter[8]. In 2019, Mao et al designed a real-time CAP-VLC transceiver with the hybrid digital equalization[9]. In 2020, Tao et al presented a real-time OFDM-based VLC system with the utilization of a single InGaN/GaN multiquantum-wells LED[10]. And there is no report focused on the particularly designed LED power drive circuit. The VLC system employs large viewing divergence angle LED to realize illumination and communication simultaneously, so the geometric loss of optical power may reach tens of decibels. Moreover, considering the gain reduction of the LED at high frequency, signal power at the receiver will be too weak. High power LED drivers are required to produce enough signal power, but most of the reported research teams such as Xu[8] and Luo's[11] used the ZHL-6A power amplifier which has a maximum drive power of about 24 dBm and a output current of 200 mA in the 50 Ω system, considering the gain loss of the LED at high frequency and impedance mismatch, when it is used to drive the commercial LED, the modulation current will be small and the bandwidth

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will be compressed greatly. To overcome these drawbacks, this paper presents a low output impedance power driver amplifier comprised of AC and DC drive circuit which is designed to drive the Xlamp XB-D Royal Blue LED produced by Cree which has a maximum forward current of 1 A and minimum radiant flux of 1.38 W at 1 A. The DC drive part is used to improve low frequency response of the system and realize normal illumination and the AC drive part, with output power far beyond LED power, is designed to compensate the high frequency roll off of LED frequency response characteristics. Simulation and experimental results show that the low cut-off frequency of the drive circuit is as low as 0.02 MHz, the maximum signal amplification is 12.1 dB, the −3 dB upper cut-off frequency is 160 MHz, and the output resistance is less than 5 Ω. Based on this driver circuit, a 125 Mbit/s real-time VLC system with illumination and communication angle of 130° has been achieved at a distance of 3 m, and the bit error rate (*BER*) is 3.13×10^{-11} at the communication angle of 0° and 1.21×10^{-6} at the communication angle of 130° which is far below the forward error correction limit 3.8×10^{-3}. The above results indicated that this VLC system can be used for illumination and communication simultaneously with wide angle.

The diode is operated at a particular DC voltage bias point and the signal variations about this point are small, so we can develop a liner or small-signal model[12] as shown in Fig.1. The series resistor R_S models the voltage drop constituted by the electric field, which can accomplish the injection and extraction of charges. Thus the total voltage in Fig.1 is composed of two contributions:

$$V=V_S+V_A=R_SI_D+nV_T\ln(1+I_D/I_S), \tag{1}$$

where I_S is the reverse saturation current, n refers to the emission coefficient, and V_T=26 mV at room temperature. The concept of linearization implies the approximation of the exponential *I-V* characteristic in Eq.(1) through a tangent at the bias or Q-point V_Q. The tangent at this Q-point is the differential conductance G_d, which we can find as

$$G_d=\frac{1}{R_d}=\frac{dI_D}{dV_A}\bigg|_{V_A=V_Q}=\frac{I_Q+I_S}{nV_T}\ , \tag{2}$$

$$R_d=\frac{nV_T}{I_Q+I_S}\ . \tag{3}$$

Differential capacitance is shown in Eq.(4), in which τ_T is the transit time

$$C_d=\frac{I_S\tau_T}{nV_T}e^{V_Q/(nV_T)}\ . \tag{4}$$

To realize wide illumination and communication angle simultaneously, the geometric loss of the optical signal energy will be extremely large, so the large radiant flux LEDs are required. We choose Xlamp XB-D Royal Blue LED produced by Cree as the radiant device which has the maximum forward current of 1 A and the minimum radiant flux of 1.38 W at 1 A. To obtain the output resistance of Xlamp XB-D Royal Blue LED including series resistor R_S and junction resistor R_d at a particular DC bias current, the small-signal model of the diode can be used for the analysis. As given in SPICE model of Xlamp XB-D Royal Blue LED: R_S=0.277 228 085, $I_S=8.404\,96\times10^{-10}$ and n=5.887 227 779. The value of resistor R_d can be obtained by substituting the above parameters into Eq.(3). Assuming the DC bias current is set to I_O=100 mA, $V_A=V_Q$=3.058 4 V can be obtained according to Eq.(1) and the junction resistor R_d=0.382 7 Ω can be obtained according to Eq.(3).

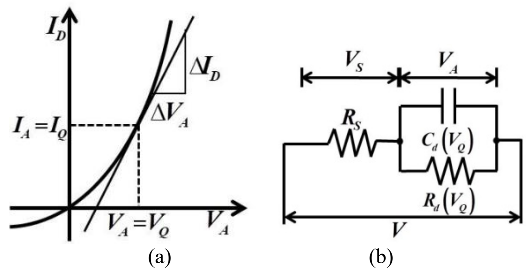

Fig.1 (a) Tangent approximation at Q-point; (b) Linear circuit model

The design requirements of LED power driver amplifier are mostly the same with those of ordinary power amplifier, however, the basic characteristics of LED need to be more considered in the circuit designing, such as, unidirectional conductivity, modulation characteristics and low impedance. The requirements in the circuit designing are as follows.

In general, the modulation bandwidth of LED would be wider if the DC bias current is relatively higher. Modulation bandwidth is an important index to measure the performance of system. According to Shannon-Hartley theorem and Nyquist theorem, the higher the modulation bandwidth is, the faster the data transfer rate of VLC system will be. For the VLC system, the frequency when the output optical power of LED dropped to half (−3 dB) of a certain referential low frequency value is the modulation bandwidth of LED, as expressed in f_{-3dB}[13]. The modulation bandwidth is inversely proportional to the response speed[14], and the modulation bandwidth can be found as

$$f_{-3dB}=\frac{\sqrt{3}}{2\pi\tau_c}\ . \tag{5}$$

The increase of the DC bias current of PN junction caused the increase of carrier concentration in the PN junction and the decrease in the carrier lifetime τ_c[15]. According to Eq.(5), the modulation bandwidth of LED became wider. Therefore, the LED power driver amplifier needs to provide a suitable DC bias current to ensure that the LED has a large modulation bandwidth and achieve normal lighting.

The modulation characteristics of LED are usually characterized by the optical power-current (*P-I*) curve is shown in Fig.2. The *P-I* characteristic curve of LED can be approximately linearly correlated. The current of LED consists of a DC bias current and a modulation current.

$$I(t)=I_b+I_m e^{j\omega_m t}\ ,\qquad(6)$$

where I_b is the DC bias current, I_m is the amplitude of modulation current, which is the difference between AC peak current and DC bias current, and ω_m is the modulation frequency. The optical modulation depth can be defined as

$$m=I_m/I_b.\qquad(7)$$

The optical modulation depth is used to indicate the relationship between the modulation current and the DC bias current. The higher the optical modulation depth is, the more easily the optical signals sent by the optical transmitter can be detected by the photoelectric detector, and the lower the consumed power in the optical receiving end will be[16]. Therefore, the LED power driver amplifier is required to have a large driving current to improve the optical modulation depth and make it easier for the photoelectric detector to detect the changing optical signals.

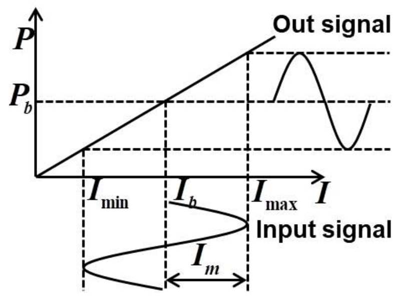

Fig.2 *P-I* characteristic curve of LED

The drive amplifier designed in this paper functions mainly to optimize the application scenario for compatible with the 100 Mbit/s optical fiber Ethernet, and its bandwidth requirements ranging is from 30 kHz to 87.5 MHz. Therefore, the operating frequency of the driver amplifier is at least 30 kHz to 87.5 MHz.

Maximum power transmission is guaranteed only when the output impedance of the signal source matches the load impendence[12]. The input and output impedance of all cascades of circuits are 50 Ω, so that the input impedance of the LED power driver amplifier should be 50 Ω. Because the output end of the circuit is directly connected to the LED, but the resistance of the LED is generally small, for example, the resistance of Xlamp XB-D Royal Blue LED is less than 1 Ω, and the output resistance of the drive circuit should be reduced as far as possible when designing the circuit to match the low resistance of the LED.

The circuit schematic diagram of the LED power driver amplifier used at the end of the optical transmitter as shown in Fig.3 is mainly composed of the DC drive circuit, the AC drive circuit and the voltage source. The output of the DC drive circuit is not directly connected to the LED, however, as part of the drain bias circuit, it is connected to the drain of the LDMOS. Choosing this way to connect the circuit not only ensure lighting normally, but also improve the low-frequency response of the circuit. The DC drive circuit which can be seen as a current source circuit was set as the drain bias circuit makes that the modulation signals fail to be shunted to the bias circuit and is loaded to the LED to the maximum extent.

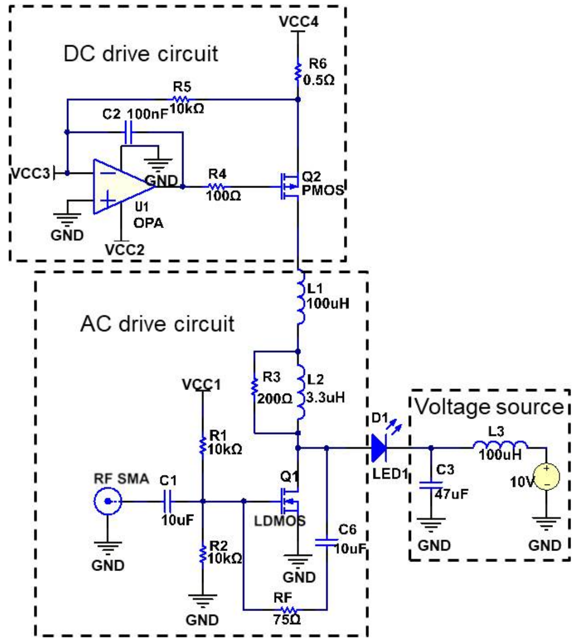

Fig.3 The circuit schematic diagram of the power driver amplifier

Assuming that the current source circuit is I_{out} and the static drain current of Q2 is I_D, then the DC bias current loaded to the LED, I_{DCB} can be expressed as

$$I_{DCB}= I_{out}- I_D.\qquad(8)$$

The photocurrent going through the LED will fluctuate up and down from I_{DCB}. Generally, if the cathode of the LED is directly connected to the ground, then the drain voltage V_{DS1} of Q1 will be very small due to the small equivalent resistance of the LED, which leads to the Q1 failed to work in the linear amplification region. Therefore, a voltage source circuit is designed to connect with the cathode of the LED to realize the purpose of increasing the value V_{DS1}. The feedback resistor RF and capacitor C6 are used to reduce the output resistance of the drive circuit, which can improve the load capacity of the drive and overcome the problem of unidirectional conduction of led to a certain extent. Although this design method reduced the amplification factor of the circuit, it has the advantages of simple circuit design, stable circuit and extending bandwidth compared with L, T and π matching networks.

To measure the performance of the independently designed power drive circuit, we used ADS2016 to simulate the drive circuit, and substituted the above calculated R_S and R_d into the simulation software. Without considering the influence of junction capacitor, the simulation curve of *S* parameter is shown in Fig.4(a). According to Fig.4(a), the low cut-off frequency of the drive circuit is as low as

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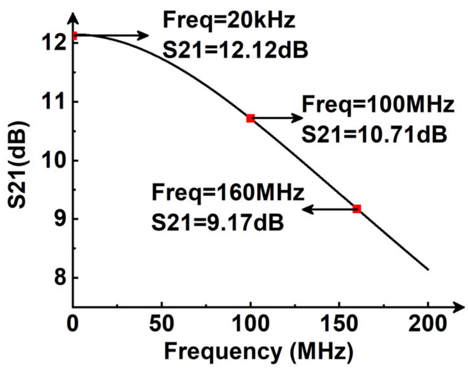
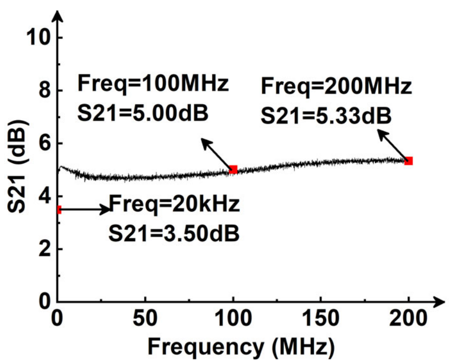
0.02 MHz, the maximum small signal amplification is about 12.1 dB, the −3 dB bandwidth is about 160 MHz. The measured *S* parameter and the output impedance of the drive circuit curves under 50 Ω load are shown in Fig.4(b) and (c), which show that under 50 Ω load, the low cut-off frequency can be as low as 20 kHz and the −3 dB bandwidth is less than 200 MHz. Because of the large loss of optical signal after long distance transmission, the signal-to-noise ratio (*SNR*) of the system is not high enough, so the noise caused a lot of burrs on the curve as shown in Fig.4(c). We can roughly judge that the output resistance of the drive circuit is less than 5 Ω, which is still much larger than that of the LED, still it is a significant improvement over the conventional output resistance of 50 Ω.

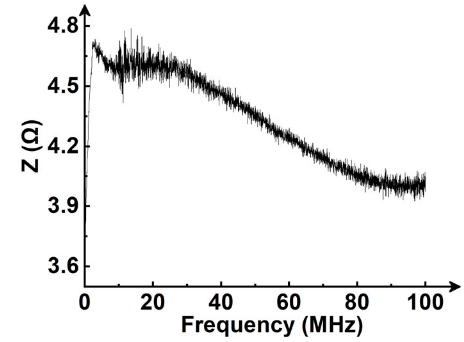
To directly measure the modulation current, we connected a 0.1 Ω resistor in series between the output end of the drive circuit and the anode of the LED. At the low frequency, the equivalent capacitance and inductance have little influence on the circuit, so by measuring the voltage at the both ends of the resistor, we can roughly estimate the modulation current of the LED. When the optical signal received by the receiving end is maximum distortionless at 1 MHz, the changing of the voltage at the both ends of the resistor is shown in Fig.4(d). Supposed that the voltage of the resistor near the output end of the drive circuit is $a(t)$, the voltage near the anode of the LED is $b(t)$ and the modulation current is $I(t)$, it can be concluded that the maximum modulation current of the LED is about 100 mA, and the optical modulation depth is about 25% according to Fig.4(d).



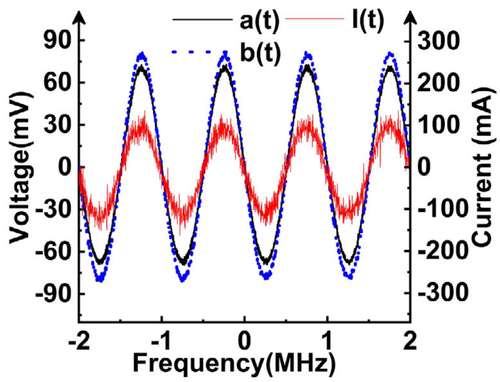
(a)



(b)



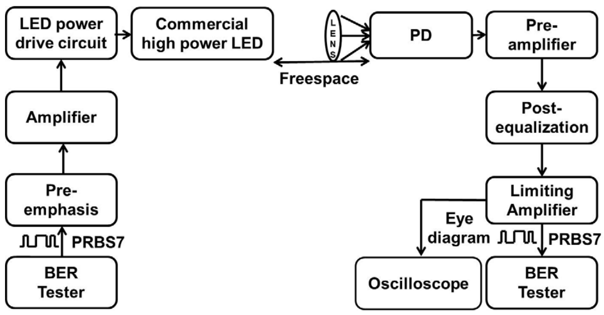
(c)



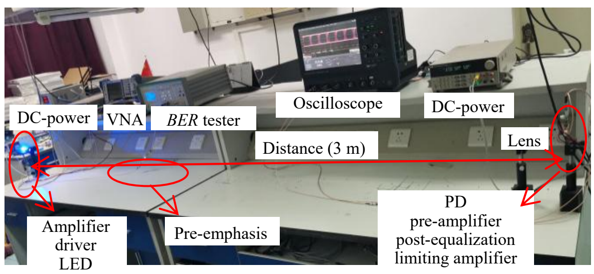
(d)

Fig.4 Performance parameters of LED power driver amplifier

A125 Mbit/s real-time VLC system set in the experiment is shown in Fig.5. This paper used Xlamp XB-D Royal Blue LED as the communication light source, and the DC bias current, I_{DCB} was set as 400 mA.



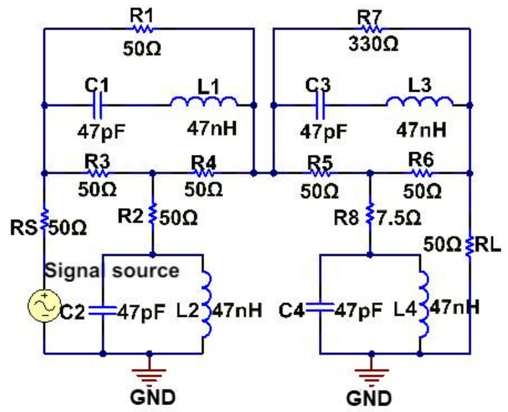
(a)



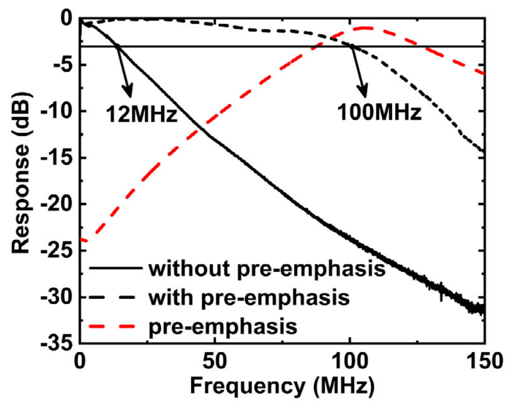
(b)

Fig.5 (a) The block diagram of our VLC system; (b) The VLC experimental link

As the high frequency response of the LED is poor, which directly influences the communication performance, a pre-emphasis circuit as shown in Fig.6(a) is designed to improve the frequency response. As shown in Fig.6(b), the frequency responses of pre-emphasis and LED-based VLC link with and without pre-emphasis show that the frequency response of the VLC system is poor without the pre-emphasis circuit, while it is improved with the pre-emphasis and the modulation bandwidth extended from 12 MHz to 100 MHz.



(a)



(b)

Fig.6 (a) The circuit schematic diagram of the pre-emphasis; (b) The frequency responses of pre-emphasis and LED-based VLC link with and without pre-emphasis

To evaluate the communication performance of the VLC system, we designed a measurement experiment of the *BER* and eye diagrams based on the system as shown in Fig.7. We used a *BER* tester (PSS BERT-S2500) as a signal generator to generate a pseudo-random binary sequence-7 (2^7-1) OOK-NRZ data stream whose maximum data rate is 125 Mbit/s, and added a variable attenuator to the signal output end of the *BER* tester to measure the modulation performance in different modulation currents. When the output end of the signal was connected with the *BER* tester, the *BER* can then be observed in real time, when it was connected with the oscilloscope (Waverunner 8404M 4 GHz), the communication eye diagrams can be observed. The optical power received by the photoelectric detector is related to the modulation current. For eye diagram, it can directly reflect the influence of inter symbol interference and noise on the performance of communication system. Due to noise and jitter, the blank area on the eye diagram will gradually decrease. At the same time, the line of the eye diagram becomes blurred, and for the blank area on the eye diagram, the distance on the horizontal axis is called eye width. Eye width can well reflect the stable time of the signal on the transmission line; similarly, for the blank area on the eye diagram, the distance on the vertical axis is called eye height. The eye height can well reflect the noise tolerance of the signal on the transmission line. As shown in Fig.7(a—c), when the communication distance is 3 m, the communication eye diagram and *BER* under different modulation currents are obtained. As shown in Fig.7(d—f), when the modulation current is 100 mA, the communication eye diagram and *BER* at different communication distances are obtained. By comparing Fig.7(a—c), we can find that when the communication distance is 3 m and the modulation current gradually decreases, the blank area on the eye diagram begins to decrease gradually. At this point, the lines of the eye diagram begin to blur. At the same time, the eye width becomes smaller and the communication quality becomes worse. As is shown in Fig.7(d—f), we can find that the lines of the eye diagram in Fig.7(f) are blurred compared with that of the eye diagrams in Fig.7(d) and Fig.7(e), and the 125 Mbit/s real-time VLC system established in the experiment can achieve a bit *BER* with zero at a distance of 2.5 m and a *BER* with 3.13×10^{-11} at a distance of 3 m, the results indicated that it has a good communication performance over a long distance.

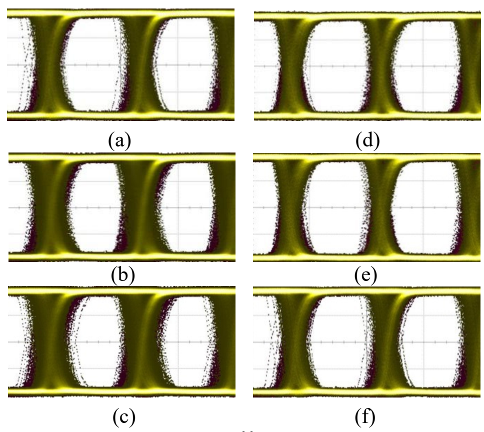
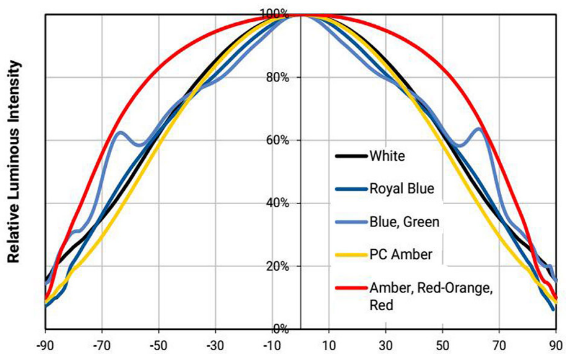
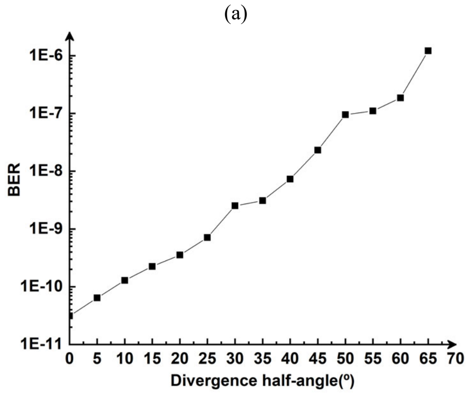


Fig.7 (a) *BER* with 3.13×10^{-11} under modulation current of 100 mA; (b) *BER* with 4.09×10^{-10} under modulation current of 90 mA; (c) *BER* with 4.29×10^{-9} under modulation current of 85 mA; (d) *BER* with zero at a distance of 2.5 m; (e) *BER* with zero at a distance of 2.7 m; (f) *BER* with 3.13×10^{-11} at a distance of 3 m

The relationship between the relative luminous intensity and the divergence angle of the Xlamp XBD LEDs is shown in Fig.8(a), which can be observed that the optical energy has a geometric loss with the increase of the divergence angle. When the photoelectric detector is placed under different divergence angles of LED, the optical power received by the photoelectric detector will decrease along with the increase of the divergence angle. Because the noise basically remains unchanged, the more optical power received by the optical receiver, the higher the *SNR* will be and the smaller the *BER* of the communication system will be. To confirm the feasibility that the real-time VLC system can be used for illumination and communication simultaneously within a wide communication angle, we tested the relationship between the divergence half-angle of LED and *BER* as shown in Fig.8(b). According to Fig.8(b), a *BER* with 1.21×10^{-6} which is far below the forward error correction limit 3.8×10^{-3} at a distance of 3 m at a communication angle of 130° can be achieved.



(a)



(b)

Fig.8 (a) The relationship between the relative luminous intensity and the light emitting angle; (b) The relationship curve of LED divergence half-angle and *BER*

In conclusion, this paper proposed a power driver amplifier combining AC and DC driver and achieved low output impedance though negative feedback based on the fundamental characteristics of LED. Since its output impedance is very low, more power will be loaded on the LED compared to an amplifier with an output impedance of 50 Ω. In this paper, a 125 Mbit/s real-time VLC system with illumination and communication angle of 130° has been achieved at a distance of 3 m, and was set up on basis of the presented drive circuit, achieving a bit *BER* of 3.13×10^{-11} at a divergence angle of 0° and 1.21×10^{-6} which is far below the forward error correction limit 3.8×10^{-3} at a divergence angle of 130°. The above results indicate that this VLC system can be used for illumination and communication simultaneously.

References

[1] Langer K D, L. Fernández del Rosal, Kottke C, Walewski J.W, Nerreter S, Habel K and Vučić J, Implementation of a 84 Mbit/s Visible-Light Link Based on Discrete-Multitone Modulation and LED Room Lighting, International Symposium on Communication Systems Networks and Digital Signal Processing IEEE, 528 (2010).

[2] Kwonhyung Lee, Hyuncheol Park and John R. Barry, IEEE Communications Letters **15**, 217 (2011).

[3] Vucic J, Kottke C, Habel K and Langer K D, 803 Mbit/s Visible Light WDM Link Based on DMT Modulation of a Single RGB LED Luminary, Optical Fiber Communication Conference and Exposition IEEE, 1 (2012).

[4] Cossu G, Khalid A M, Choudhury P, Corsini R and Ciaramella E, Optics Express **20**, B501 (2012).

[5] Wang Y, Tao L, Huang X, Shi J and Chi N, IEEE Photonics Journal **7**, 7904507 (2015).

[6] Liu X, Tian P, Wei Z, Yi S, Huang Y, Zhou X, Qiu Z, Hu L, Fang Z, Cong C, Zheng L and Liu R, IEEE Photonics Journal **9**, 7204909 (2017).

[7] Zhang H, Yang A, Feng L and Guo P, IEEE Photonics Journal **10**, 7901807 (2018).

[8] Xu W, Zhang M, Han D, Ghassemlooy Z, Luo P and Zhang Y, IEEE Photonics Journal **10**, 7903610 (2018).

[9] MaoY, Jin X, Pan W, Liu W, Jin M, Gong C and Xu Z, Optics Express **27**, 9382 (2019).

[10] Tao Z, Guan X, Wei Z, Liu N, Liu Y, Xu Y, Kang C, Kong M, Liu G and Ooi B, Microw. Opt. Technol. Lett. **62**, 1459 (2020).

[11] Luo J, Tang Y, Jia H, Zhu Q and Xue W, Chinese Optics Letters **14**, 120604 (2016).

[12] Ludwig R and Bretchko P, RF Circuit Design: Theory and Applications, Beijing: Publishing House of Electronics Industry, 235 (2000). (in Chinese)

[13] Li H, Chen X, Guo J, Tang D, Huang B and Chen H, Chinese Optics Letters **12**, 100604 (2014).

[14] Chi Nan, Key Components and Applications of LED Visible Light Communication, Beijing: Posts & Telecom Press, 95 (2015). (in Chinese)

[15] Song X, Wei Y, Zhao Z and Wang M, Infrared and Laser Engineering **46**, 172 (2017). (in Chinese)

[16] Cao J, Liang Z and Ma Z, Wireless Communication **2**, 7 (2012). (in Chinese)