Low Cost and Large Bandwidth Visible Light Communication System Design

Ziming Zhang1,a, Xichen Wang1,b, Qian Wu 1,c, Yuanqin Liu1,d

1Liangjiang International College, Chongqing University of Technology, Chongqing, China

a2907241459@qq.com; bwangxichen@cqut.edu.cn

cwuqian@2019.cqut.edu.cn; dyuanqinliu@163.com

Abstract—Aiming at the problem of insufficient bandwidth of transmitter and receiver of low-cost visible light communication system, this article applies novel equalization circuits to separately expand the bandwidth of LED and transimpedance amplifier circuit to 114MHz and 95.7MHz. In addition, signal-to-noise ratio and bit error rate of the system are also analyzed by a line of sight model and the feasibility of the designed system is confirmed.

1. Introduction

Visible-Light-Communication (VLC) is an emerging technology based on white LED. The advantage of visible light communication is that there is no electromagnetic field interference, so white LED visible light communication can be adopted in an environment which sensitive to electromagnetic field. However, the limited modulation bandwidth of LED has been limiting the development of visible light communication. Therefore, many researchers are dedicated to this research.

The LED equalization technology was proposed in 2008, which increased the LED modulation bandwidth from 15Mbps to 75Mbps [1]. Afterwards, scholars demonstrated that the maximum transmission speed of the VLC system based on OOK-NRZ modulation is 477 Mbit/s through pre-emphasis [2]. Moreover, With the emergence of RGB white LEDs, a transmission rate of 662 Mbps has been achieved [3]. In addition, researchers introduce the LED VLC system to underwater work, using a single-stage T-bridge equalizer to upgrade the −3 dB bandwidth and −6 dB bandwidth of the underwater optical wireless communication (VL /UOWC) system to 700 MHz and 900 MHz [4]. In order to further improve the LED transmission rate, researchers proposed a two-stage linear software equalizer for high-speed visible light communication systems. The experimental results show that the system achieves 2.32 Gbit/s VLC transmission rate through equalization technology [5].

However, the cost of obtaining high bandwidth in the above papers is to increase the complexity and cost of the equalization circuit. Aiming at the problem, this paper designs the equalizing circuit of the transmitting end and receiving end of the system to realize a low-complexity VLC system. By adopting a new equalization circuit, the bandwidth of the designed system has been significantly improved compared with similar systems in reference [6].
2. TRANSMITTER EQUALIZATION CIRCUIT DESIGN

2.1. LED 3dB bandwidth measurement

The function generator produces a single-frequency sinusoidal signal as the power source, and the LED output voltage under different sinusoidal signals is measured in turn. Figure 1 is LED 3dB bandwidth test circuit.

Figure 2 shows that the LED 3dB bandwidth is about 7MHz.

2.2. LED equalization circuit design

The 3dB bandwidth of 7MHz cannot meet the transmission rate requirements of VLC, so an equalization circuit is needed to broaden its 3dB bandwidth.

Reference [6], the method adopted is introducing a system that is opposite to the LED spectrum characteristics. However, only introducing a high-pass filter composed of resistors and capacitors will not work, because resistors and capacitors are passive components, which will attenuate the output. Therefore, a voltage amplifier circuit composed of an operational amplifier (OPA) is introduced after the high-pass filter circuit to compensate the loss of passive devices. The first-order active high-pass filter circuit is shown in Figure 3.
$R_s$ introduces the signal, the resistors $R_2$, $R_1$ and the capacitor C form a first-order passive high-pass filter. The operational amplifier and resistors $R_4$ and $R_5$ form a voltage negative feedback. The transfer function of the equalizer is shown in equation (1).

$$H(S) = \frac{1 + \frac{R_2}{R_s}}{R_2 + \frac{(1 + R_2CS)R_s}{R_s + (1 + R_2CS)}}$$ \hspace{1cm} (1)

Introducing this method into the LED used in this experiment, the spectrum response of the circuit after equalization is shown in Figure 4. In the simulation, the method used is that fix the value of $R_s$, observe the output signal Bode plot of the operational amplifier by changing the value of the capacitor C, and the output needs to meet two requirements. First one is stability, the output Bode plot without protrusion (the gain difference between two points nearby in the passband not exceed 0.2dB). Second one is maximum bandwidth. When the 3dB of the LED and the first-order active high-pass filter are the same, bandwidth and stability are trade-off. The attenuation introduced by the passive high-pass filter is about -15.6dB, and the system gains 5.26dB after adding the operational amplifier. The compensated 3dB bandwidth is 45.7MHz.

**Figure 4.** First-order active high-pass filter circuit equalization effect

From the frequency spectrum in the above figure, it can be seen that the active high-pass filter with only one pole does not meet the requirement of 100MHz modulation bandwidth, so this paper designs a higher-order active high-pass filter circuit. Introduce two branches with different cut-off frequencies and gains at the inverting input terminal to compensate the LED's intermediate frequency response and high frequency response to achieve a flat 3dB bandwidth curve. The circuit diagram is shown in Figure 5.

**Figure 5.** Second-order active high-pass filter circuit.
In the figure, \( R_7, C_1 \) and \( R_8, C_2 \) determine two different corner frequencies. The equivalent impedance of \( R_7, C_1, R_8, C_2 \) and the feedback resistance \( R_0 \) constitute a negative feedback voltage amplifier circuit. The value of the resistance and capacitance is shown in Table 1.

### TABLE 1. PARAMETERS AND VALUES IN THE CIRCUIT

| Parameters | \( R_7 \) | \( R_8 \) | \( R_0 \) |
|-----------|----------|----------|----------|
| Values    | 100 Ω    | 300 Ω    | 1000 Ω   |
| Parameters| \( C_1 \) | \( C_2 \) | \( R_{10} \) |
| Values    | 24pF     | 13.6pF   | 1000 Ω   |

Second-order active high-pass filter transfer function.

\[
G = \frac{R_{10}}{\sqrt{R_7^2 + S^2C_1^2} / \sqrt{R_8^2 + S^2C_2^2}}
\]  

(2)

The test result of the equalizer is shown in Figure 6. The abscissa in the figure is sine wave frequency and the ordinate represent the spectrum response of the LED, the spectrum response of the second-order high-pass filter equalization circuit, and the spectrum response of the circuit output signal after equalization.

![Equalizer frequency response](image)

**Figure 6.** Second-order active high-pass filter compensation effect.

After the high frequency compensation of the second-order active high-pass filter, the modulation bandwidth of the LED can be extended to 114MHz, which is 2.5 times compared with the first-order active filter (45.7MHz).

**LED VISIBLE LIGHT COMMUNICATION RECEIVER CIRCUIT**

### 3. VLC receiver circuit design

At the receiver, a trans-impedance amplifier (TIA) is used to convert the photocurrent generated by the photodiode into a voltage signal and amplify it. The equivalent circuit of the TIA is shown in Figure 7.
3.1. TIA self-oscillation suppression

The transimpedance gain will produce 40dB/decade attenuation at the intersection point \( f_i \), \( A_{sd} \) and \( \beta \) separately provide 20dB roll-off attenuation. Every 20dB of attenuation rate will introduce a 90° phase shift, so here is 180° phase shift. In addition, the OPA introduce another 180° phase shift because of negative feedback. Moreover, at the intersection point, the open loop gain \( A_{sd} \) is equal to the reciprocal of the feedback factor \( \beta \), so the self-oscillation take place.

\[
A\beta = 1 \\
\phi_o = 2n\pi
\]

(3)

\[
\frac{1}{\beta} = 1 + R_f C_s = 1 + \frac{1}{2\pi f_{zf}}
\]

(4)

Where \( f_{zf} \) is the zero of the feedback factor, \( R_f \) is the feedback resistance of the TIA, \( C_s \) is equivalent input capacitance of the TIA, and \( f_c \) is the cutoff frequency of the OPA. The solution to the oscillation is selecting an appropriate feedback capacitor to change the phase difference between input and output (a phase difference of 45° can compromise the stability and bandwidth of the TIA). The principle is that introduce a zero to cancel the pole of the feedback factor.

The transfer function of the feedback factor before introducing the feedback capacitor \( C_f \):

\[
\beta = \frac{X_{zf}}{R_f + X_{zf}} = \frac{1}{1 + R_f C_s S}
\]

(5)

The transfer function of the feedback factor after introducing the feedback capacitor \( C_f \):

\[
\beta = \frac{1 + R_f C_f S}{1 + R_f (C_f + C_s) S}
\]

(6)

When the phase difference is 45°, the feedback capacitor needs to satisfy:

\[
C_f = \sqrt{\frac{C_s}{2\pi R_f f_i}}
\]

(7)

\[
C_s = C_D + C_{sd} + C_{cm}
\]

(8)
$C_D$ is the equivalent junction capacitance of the photodiode, and $C_{id}$, $C_{icm}$ are the differential and common mode input capacitance of OPA, the relationship between $A_{id}$ curve and $1/\beta$ curve before and after phase compensation is shown in the Figure 8.

![Figure 8. $A_{id}$ curve and $1/\beta$ curve before and after phase compensation.](image)

parameters of TIA circuit are shown in Table 2.

**TABLE 2. TIA PARAMETERS AND VALUES.**

| Parameters | GBP | $A_{id}$ | $C_{icm}$ | $C_{id}$ |
|------------|-----|----------|-----------|----------|
| Values     | 3.9GHz | 98dB | 1.7pF | 2pF |
| Parameters | $R_f$ | $C_f$ | $C_D$ | VCC/VEE |
| Values     | 0.2 $M\Omega$ | 0.133pF | 13pF | +5V/-5V |

By calculation, $C_f$ is 0.133pF. The output voltage transfer function of the TIA circuit is:

$$e_o = i_p Z_f.$$  

$$Z_f = \frac{R_f}{1 + R_f C_f S}.$$  

$i_p$ is the photocurrent generated by the photodiode, and $S$ is Laplace transform factor. The spectrum response of TIA is shown in Figure 9.

![Figure 9. TIA spectrum response.](image)

Figure 9 shows that the effective 3dB bandwidth of TIA is 5.985MHz.
3.2. TIA equalization

The TIA circuit is a low-pass filter. In order to increase its bandwidth, we use a high-pass filter to compensate. The circuit diagram is shown in Figure 10.

![TIA equalization circuit](image)

Figure 10. TIA equalization circuit.

The parameters of each device in the equalization circuit are shown in Table 3.

| Parameters | $R_{11}$ | $R_{12}$ | $C_3$ | VCC/VEE |
|------------|----------|----------|-------|---------|
| Values     | 5 Ω      | 100 Ω    | 1nF   | +5V/-5V |

The transfer function of the high-pass filter is:

$$T_{HPF} = \frac{R_1 (1 + R_1 C_3 S)}{R_2 + R_3 (1 + R_2 C_3 S)}$$

The transfer function after equalization is:

$$T = Z_s T_{HPF}.$$  \hspace{1cm} (12)

The receiving bandwidth of the equalized TIA circuit is about 95.7MHz, and its spectrum response is shown in Figure 11.

![Equalized TIA spectrum response](image)

Figure 11. Equalized TIA spectrum response.
4. System performance evaluation

4.1 Visible light communication channel model
In the VLC system, LED is used as a light source, and its radiation model is similar to the Lambertian model. The light emitted by the LED propagates in the free space following the inverse square of the distance.

\[
H_{\text{LOS}} = \frac{(m+1)\cos^m(\phi)A}{2\pi d^2}\cos(\psi).
\]  

(13)

Where A is the photoelectric area of the photodetector, d is the transmission distance, \( \psi \) is the incident angle of the photodetector( \( 0 \leq \psi \leq \psi_f \) ), \( \phi \) is the radiation angle of the LED, and \( \psi_f \) is the half angle of the receiver’s field of view (FOV).

The noise that affects the circuit at the receiving end is mainly divided into two categories. Firstly, thermal noise introduced by the feedback resistor.

\[
I_{\text{th}}^2 = 4KT\frac{\Delta f}{R_f}.
\]  

(14)

Where K is Boltzmann’s constant, T is the Kelvin temperature, and \( \Delta f \) is the width of the TIA passband.

Secondly, the shot noise generated by the irregular emission of electrons at the receiver.

\[
I_{\text{shot}}^2 = 2qI\Delta f.
\]  

(15)

The total receive noise is:

\[
I_{\text{total}}^2 = I_{\text{th}}^2 + I_{\text{shot}}^2.
\]  

(16)

4.2 System signal-to-noise ratio and bit error rate
The position of the LED is in the center of the upper plane, as shown in Figure 12. Only LOS (line of sight) is considered during the test, and the impact of reflection is not considered. Space size \( 5m \times 5m \times 3m \).

![LED and PD distribution diagram.](image)

Figure 12. LED and PD distribution diagram.

The signal-to-noise ratio (SNR) at receiver side is:
\[ \text{SNR} = \frac{I_p^2}{I_{nc}^2 + I_{shot}^2}. \]  

(17)

When applied OOK-NRZ modulation, the relationship between the received signal-to-noise ratio and the bit error rate is \(^7\):

\[ \text{BER} = \frac{1}{2} \exp(-\frac{\text{SNR}}{4}). \]  

(18)

Figure 13 depicts the signal-to-noise ratio and bit error rate of the receiver under different LED luminous powers (PD right below the LED).

![Figure 13. SNR and BER under different LED optical power(W).](image1)

Figure 14 depicts the signal-to-noise ratio and bit error rate of the receiver, which LED power is taken in dBm.

![Figure 14. SNR and BER under different LED optical power(dBm).](image2)

5. CONCLUSION

This paper designed a simple VLC system, low cost and suitable for various scenarios. An equalization circuit based on a second-order active high-pass filter is used to increase the LED bandwidth. At the receiver side, a high-pass filter compensation is adopted to realize a 95.7MHz receiver bandwidth. Finally, by establishing an effective numerical model, the performance of the
system was evaluated, also, the feasibility of the low-cost 100Mbps visible light communication system was verified.

REFERENCES

[1] Zeng L, Minh H, O'Brien D, et al. Equalisation for high-speed Visible Light Communications using white-LEDs[C]// Communication Systems, Networks and Digital Signal Processing, 2008. CNSDSP 2008. 6th International Symposium on. IEEE, 2008.

[2] Fujimoto N, Mochizuki H. 477 Mbit/s visible light transmission based on OOK-NRZ modulation using a single commercially available visible LED and a practical LED driver with a pre-emphasis circuit[C]// Optical Fiber Communication Conference & Exposition & the National Fiber Optic Engineers Conference. IEEE, 2013.

[3] Fujimoto N, Mochizuki H. 477 Mbit/s visible light transmission based on OOK-NRZ modulation using a single commercially available visible LED and a practical LED driver with a pre-emphasis circuit[C]// Optical Fiber Communication Conference & Exposition & the National Fiber Optic Engineers Conference. IEEE, 2013.

[4] Zhang Z, Lai Y, Lv J, et al. Over 700 MHz –3 dB Bandwidth UOWC System Based on Blue HV-LED With T-Bridge Pre-Equalizer[J]. Photonics Journal IEEE, pp. 11(3):1-12, 2019.

[5] Zhou Y, Zhao J, Zhang M, et al. 2.32 Gbit/s phosphorescent white LED visible light communication aided by two-staged linear software equalizer[C]// 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP). IEEE, 2016.

[6] Stratil T, Koudelka P, Martinek R, et al. Active Pre-Equalizer for Broadband over Visible Light[J]. Advances in Electrical and Electronic Engineering, pp. 15(3), 2017.

[7] Zhang H, Cao L. Modern communication principle and technology. Xian: Xidian University Press, pp. 188-191, 2013.