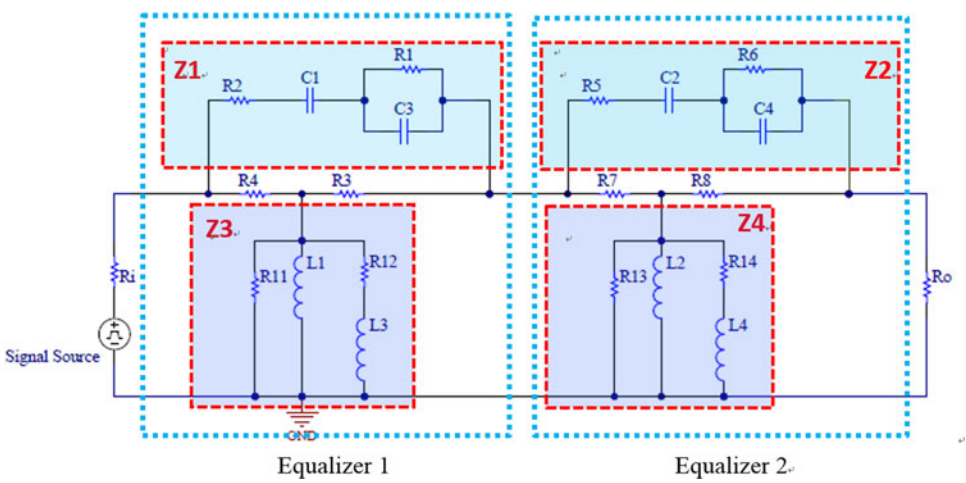
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Gb/s Real-Time Visible Light Communication System Based on White LEDs Using T-Bridge Cascaded Pre-Equalization Circuit

Volume 10, Number 2, April 2018

Haiqi Zhang
Aiying Yang
Lihui Feng
Peng Guo



DOI: 10.1109/JPHOT.2018.2812759
1943-0655 © 2018 IEEE

Gb/s Real-Time Visible Light Communication System Based on White LEDs Using T-Bridge Cascaded Pre-Equalization Circuit

Haiqi Zhang, Aiying Yang, Lihui Feng, and Peng Guo

School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China

DOI:10.1109/JPHOT.2018.2812759
1943-0655 © 2018 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Manuscript received January 19, 2018; revised February 26, 2018; accepted March 2, 2018. Date of publication March 6, 2018; date of current version March 26, 2018. This work was supported by National Natural Science Foundation of China under Grant 61475094 and Grant 61675025. Corresponding authors: A. Yang (e-mail: yangaiying@bit.edu.cn).

Abstract: We demonstrate a Gb/s real-time visible light communication (VLC) system based on NRZ-OOK by a phosphorescent white light-emitting diode (LED). We propose an equalizer employed by an RC series-parallel connection cascade circuit based on the T-bridge structure. With the proposed circuit, the 3-dB bandwidth of the VLC system can be extended from 1 to 520 MHz. The Bit Error Ratio (BER) of the system was 7.36×10^{-4}, and the data rate was 1 Gb/s at a distance of 1.5 m. To the best of our knowledge, this is the highest real-time data rate and 3-dB bandwidth achieved based on a white LED.

Index Terms: Visible light communication, T-bridge structure, cascaded pre-equalization circuit.

1. Introduction

A visible light communication (VLC) system based on a phosphorescent white LED has been a promising and emerging communication technology owing to its low power consumption and high security [1]. Compared with an RGB LED, a phosphorescent white LED has many advantages, such as low cost, high market penetration, and lower complexity. Because the response of the phosphor is very slow, the bandwidth of a white LED is only a few megahertz, thus limiting its applications in high-speed communications [2]. To improve the data rate of a VLC system, researchers have proposed many methods, such as adding a blue filter to eliminate the slow response of the phosphorescent component [3], using different modulation techniques such as Wavelength Division Multiplexing(WDM) [4], Orthogonal Frequency Division Multiplexing [5], and Discrete Multi-Tone(DMT) [6] or employing equalization technology [7].

In [8], Le-Minh proposed a pre-equalization circuit and realized 100-Mb/s, Non-Return to Zero On-Off Keying (NRZ-OOK) data transmission with a 3-dB bandwidth of 50 MHz. In [9], Chow improved the bandwidth of a VLC system using an RLC equalizer and achieved a data rate of 84.44 Mb/s-190 Mb/s without a blue filter. In [10], Li achieved 550 Mb/s real-time data transmission based on a white LED at the short distance of 0.6 m. The highest data rate ever achieved was 750 Mb/s (red LED) and the VLC link was accomplished by an RGB LED with a distance of 1.7 m [11]. In [12], Chi achieved a data rate of 1.6 Gb/s using a cascaded pre-equalization circuit based

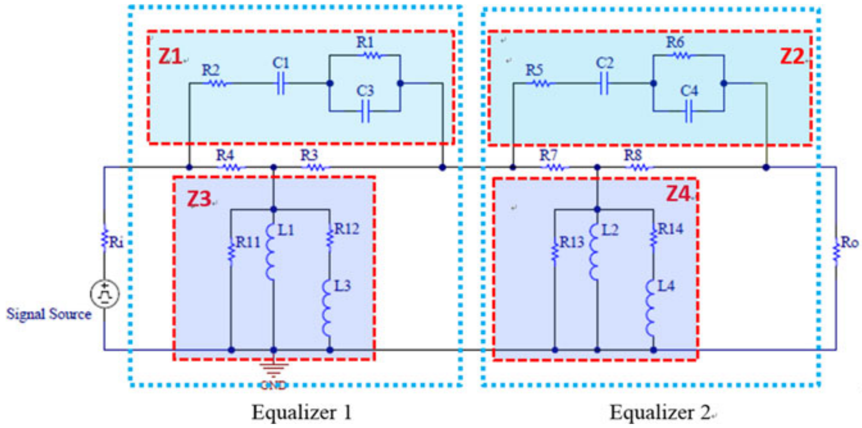


Fig. 1. Schematic of cascaded T-bridge equalization circuit.

on a white LED; the system was off-line, and the modulation format was 16 Quadrature Amplitude Modulation Orthogonal Frequency Division Multiplexing (16QAM-OFDM). Equalization technology is widely used in all of the above-mentioned works, but the data rate of real-time VLC system is less than 1 Gb/s.

Ordinary RC parallel or cascaded RC parallel circuits could effectively extend the 3-dB bandwidth below 100 MHz. An RC equalization circuit based on a transistor exhibits good performance in the signal-noise-ratio (SNR) since the power of the signal is amplified by the transistor, but it is seriously impacted by the frequency of the input signal. The stability of the transistor will decrease and even introduce noise as the frequency increases. Compared with common RC equalization circuits and active equalizers, an RC-based T-bridge passive equalizer exhibits constant characteristic impedance and stable high frequency response, especially when the signal is several hundred or several thousand megahertz.

In this paper, we first propose a novel pre-equalizer comprised of an RC series-parallel cascade circuit based on T-bridge structure. With the proposed pre-equalizer, we experimentally demonstrate a real-time VLC system with a 1-Gb/s data rate based on NRZ-OOK modulation at a distance of 1.5 m. The BER of the system is 7.36×10^{-4} below the forward error correction (FEC) limit of 3.8×10^{-3}, and the 3-dB bandwidth is extended from 1 MHz to 520 MHz with a commercially available phosphorescent white LED. To the best of our knowledge, this is the highest data rate and 3-dB bandwidth ever achieved using a commercially available phosphorescent white LED in real-time VLC systems.

2. Proposed Cascaded T-Bridge Pre-Equalization Circuit

Fig. 1 shows the proposed cascaded T-bridge pre-equalization circuit. Ri is the input resistance, which we consider the resistance of the amplifier (50 Ω). R0 is the load resistance, which is the internal impedance of the BERT, also 50 Ω. Z1 is the equivalent impedance of R1, C1, R2, and C2. Z2, Z3, and Z4 are the respective circuits corresponding to the equivalent impedance. In order to ensure impedance matching with the input and the load of the output, we set R3 = R4 = R7 = R8 = R0 = 50 Ω. In the T-bridge circuit, the product $Z1 \times Z3$ must be equal to the $R0^2$ [13]. Z1 and Z3 can be expressed, respectively, by

$$\frac{1}{\frac{R_2}{R_0} + \frac{1}{j\omega C_1 R_0} + \frac{R_1}{j\omega C_3 R_0 R_1 + R_0}} \tag{1}$$

and

$$\frac{R_{1_1} \times j\omega L_1 \times (R_{1_2} + j\omega L_3)}{R_{1_1} + j\omega L_1 + R_{1_2} + j\omega L_3} \tag{2}$$

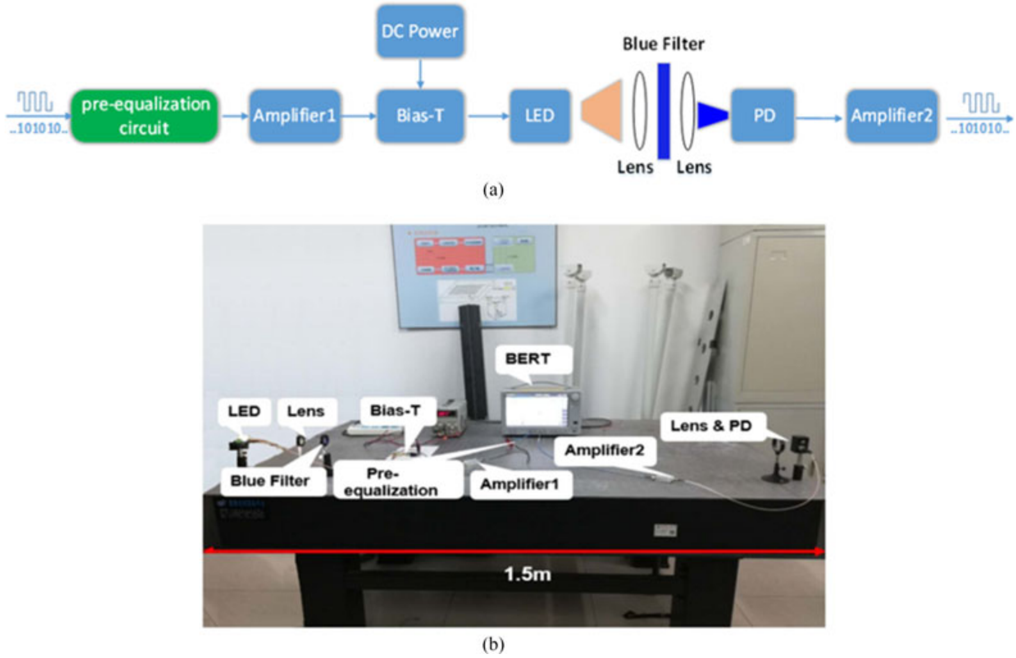


Fig. 2. (a) The block diagram of our VLC system and (b) the VLC experimental link.

where ω is the angular frequency. To maintain the impedance stability of the cascade circuit, we set R1 = R2 = R5 = R6, C1 = C2 = C3 = C4, R11 = R12 = R13 = R14, and L1 = L2 = L3 = L4. The frequency response of Equalizer 1 is

$$H_1 = \frac{1}{\frac{R_2}{R_0} + \frac{1}{j\omega C_1 R_0} + \frac{R_1}{j\omega C_3 R_0 R_1 + R_0}} \tag{3}$$

Similarly, the frequency response of Equalizer 2 is

$$H_2 = \frac{1}{\frac{R_5}{R_0} + \frac{1}{j\omega C_2 R_0} + \frac{R_6}{j\omega C_4 R_0 R_6 + R_0}} \tag{4}$$

The frequency response of the cascade equalizer is

$$H = H_1 \times H_2 \tag{5}$$

3. Experimental System and Results

Fig. 2 shows the experimental VLC system. The signal is first produced by BERT(MP2100A, Anritsu, Japan) and then processed by the proposed equalizer and amplified by Amplifier 1 (1–1300 MHz, 25 dB). The signal is then modulated to the LED (720-LUWCQARNPNRHPJR1, OSRAM Licht AG, Germany) by the Bias-T . We use a lens at both the transmitter and receiver to increase the receiving power for the Photodiode (818-BB-21A, Newport Corp., USA) with a small diameter of 0.40 mm. The blue filter removes the slow-responding phosphor component. After photoelectric conversion, the weak signal is amplified by the low-input, high-gain amplifier, Amplifier 2 (1–2000 MHz, 64 dB). The experiments to measure 3-dB bandwidth and BER were both completed at a distance of 1.5 m.

In order to select the appropriate value for the equalizer, we performed many simulations to explore the impact of resistance and capacitance on the bridge-T cascade circuit. In Fig. 3(a), we first set R1 = R2 = R3 = R4 = 5 Ω and change the values of C1, C2, C3, and C4, and R11 = R12 = R13 = R14 = 500 Ω according to [12]. In Fig. 3(b), we change the value of the resistance and hold the capacitance value to 5 pF, and also change R11, R12, R13, and R14 based on the

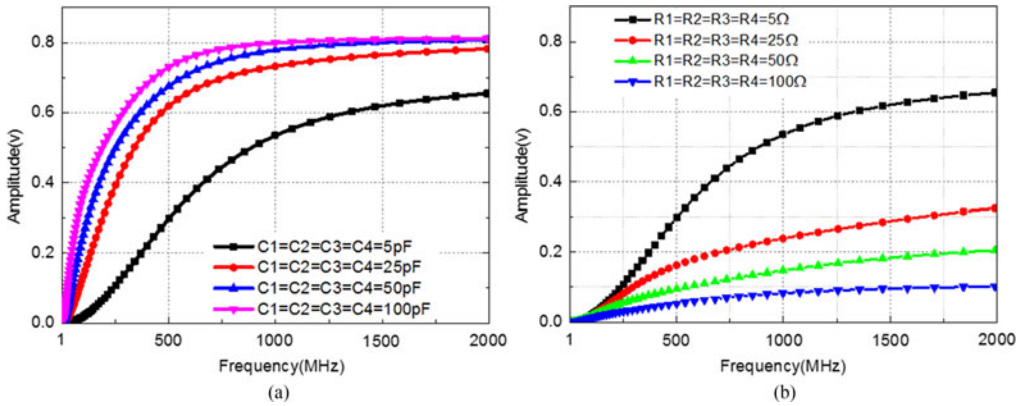


Fig. 3. Response of bridge-T cascade circuit with (a) different capacitances (R1 = R2 = R3 = R4 = 5 Ω) and (b) different resistances (C1 = C2 = C3 = C4 = 5 pF).

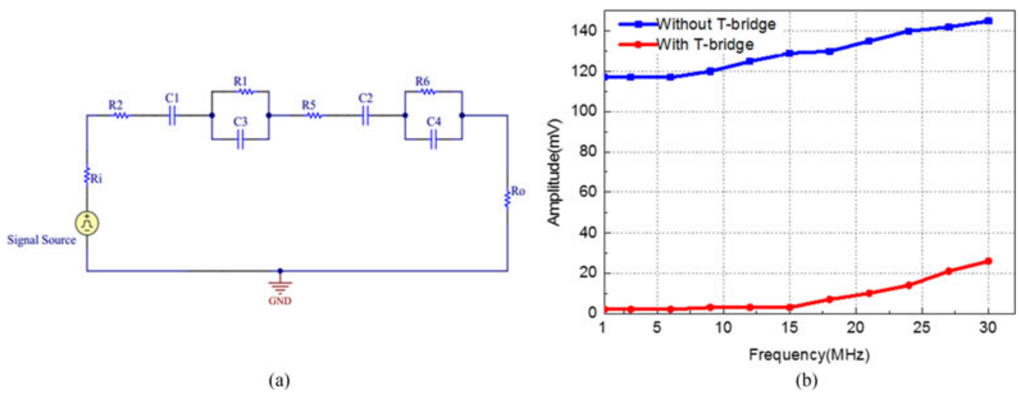


Fig. 4. (a) Cascade circuit without a T-bridge and (b) measurement result with and without a T-bridge with the frequency below 30 MHz.

equation in [13]. We found that the frequency range of the equalizer was determined by the values of the capacitance and resistance, and that we can determine the slope of the response curve of the equalizer by comparing Fig. 3(a) and (b). Note, further, that the amplitude of the output is almost the same below a certain frequency according to Fig. 3.

The T-bridge circuit will strongly attenuate the low-frequency signals, so it necessary to confirm the attenuation range for the 3-dB bandwidth measurement. To expand the 3-dB bandwidth as much as possible, we set 1 MHz as the start frequency and completed the experiment to explore the influence caused by the T-bridge circuit structure on the 3-dB bandwidth measurement.

Fig. 4(b) shows the frequency response of the cascade equalizer with and without a T-bridge. In this experiment, we set R1 = R2 = R3 = R4 = 5 Ω and C1 = C2 = C3 = C4 = 5 pF. The low-frequency signal below 15 MHz was very weak with the T-bridge, so we can consider the signal to be completely filtered by the circuit for the inherent noise of the oscilloscope. However, in another experiment, the signal amplitude in the same frequency range is beyond 100 mV for the cascade circuit without a T-bridge. In order to maximize the 3-dB bandwidth, we used the circuit shown in Fig. 4(a) to expand the 3-dB bandwidth of the VLC link.

We then measured the 3-dB bandwidth of the LED for the white and blue components of the light. In this experiment, we set the start frequency as 1 MHz. Fig. 5(a) shows that the 3-dB bandwidth of white light is 4 MHz and the blue component of the light is 14 MHz. In order to ensure the accuracy of the results, we took several measurements of the 3-dB bandwidth. The proposed equalizer is based on the response of the blue component of the white LED. Z1 and Z3 have a significant influence on the equalizer, and determine the high-frequency response characteristics, while Z2

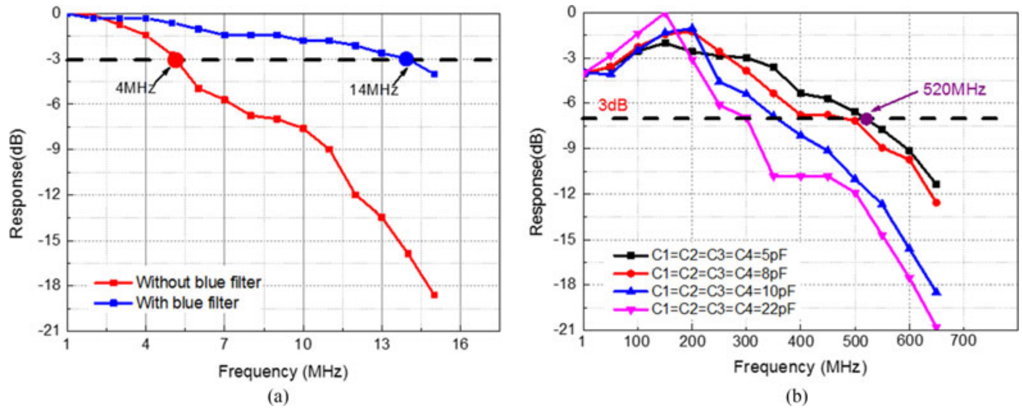


Fig. 5. 3-dB bandwidth (a) of white LED with and without blue filter and (b) of VLC link for different capacitances.

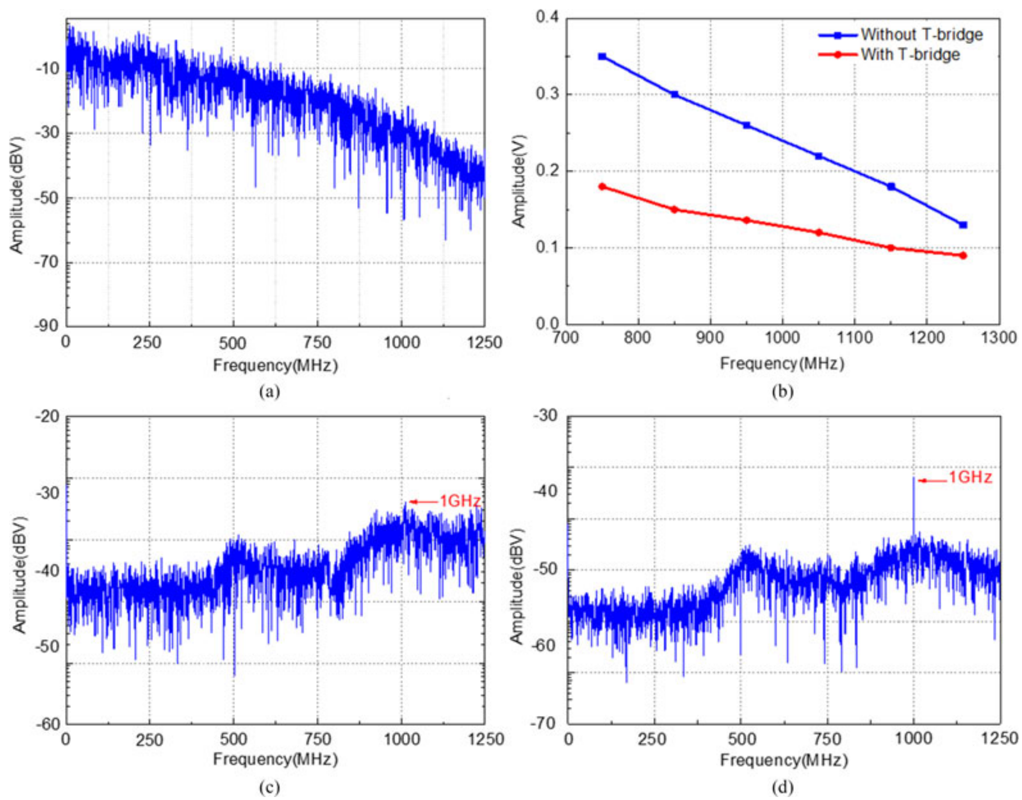


Fig. 6. (a) Noise of VLC link, (b) characteristics of different circuit structures, (c) VLC system response with the cascade circuit without a T-bridge, and (d) VLC system response with the cascade circuit with a T-bridge.

and Z4 enhanced the stability of the equalizer. We must first confirm the parameters Z1 and Z3. Considering the ease of design and impedance mutation, we set C1 = C2 = C3 = C4 and R1 = R2 = R5 = R6. We performed many experiments in choosing the values of C1 and R1. The value of C1 has a significant influence on the VLC system frequency range; the smaller the value of C1, the higher the frequency range that we can choose, but the amplitude of the output signal will be smaller. The value of R1 determines the equilibrium of the equalizer and the slope of the response curve of the VLC system.

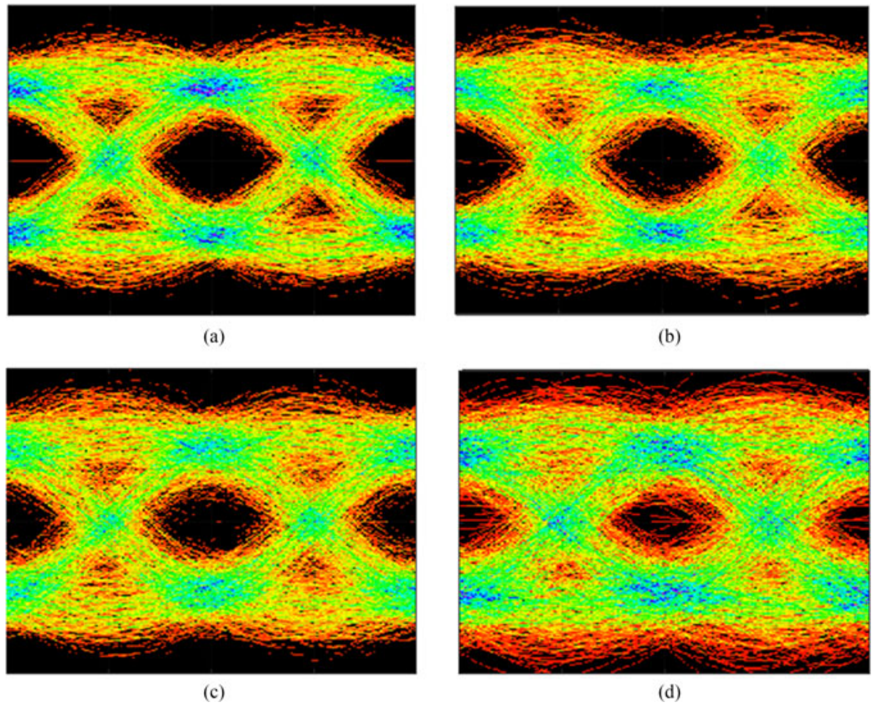


Fig. 7. BER of the VLC link with different frequencies (a) 3.92×10^{-7} at 700 MHz, (b) 2.38×10^{-6} at 800 MHz, (c) 6.59×10^{-5} at 900 MHz, (d) 7.36×10^{-4} at 1 GHz.

We first set R1 = R2 = R3 = R4 = 5 Ω based on Fig. 3(b) and then choose appropriate capacitance values according to the frequency range of the input signal. According to Fig. 3(a), the capacitance value should be set below 25 pF, so we select values of 5, 8, 10, and 22 pF, and compare the results. Considering the input range of the amplifier, we did not select a value of C1 less than 5 pF. Fig. 5(b) shows the response of the cascade circuits under different conditions. The results show that the bandwidth of the VLC system is 520 MHz when C1 = 5 pF.

We measured the frequency range of the noise from the system to choose a suitable equalizer. Fig. 6(a) shows the measurement results. In order to compare the high-frequency characteristics of different circuit structures, we set the input range from 750 to 1250 MHz and measured the amplitude using an oscilloscope (DPO7254, Tektronix, USA). In the experiment, we set R1 = R2 = R3 = R4 = 5 Ω and C1 = C2 = C3 = C4=5 pF. The results are shown in Fig. 6(b). Compared with the circuit without a T-bridge, the proposed equalizer has a stable high-frequency characteristic in that the absolute value of the red curve's slope is far less than that of the blue's slope. We used the sinusoidal signal as the input of the VLC system a frequency of 1000 MHz. Fig. 6(c) and (d) are the oscilloscope results. We found that the signal in the transmitting end processed by the equalizer without a T-bridge cannot be distinguished. In contrast, the signal processed by the equalizer with a T-bridge can be clearly received. Therefore, we used the equalizer with the T-bridge in the BER measurements even though the amplitude of the signal is far below the amplitude in Fig. 6(c).

In the experimental measurements of the BER, we used the pseudo-random binary sequence (PRBS)-7 (2^7-1) NRZ-OOK data as the input signal, with a peak-to-peak voltage swing of 100 mV. In the 3-dB measurement experiment, we confirmed that the VLC system 3-dB bandwidth can be extended from 1 to 520 MHz with a blue filter when C1 = 5 pF and R1 = 5 Ω. We set R11 = R12 = R13 = R14 = 500 Ω for the equation $Z1 \times Z3 = Z2 \times Z4 = R0^2$. We obtained different bit error rates with the input signal frequency from 700 MHz to 1 GHz. The results of the BER measurements are shown in Fig. 7. The BER is 7.36×10^{-4} with an input signal of 1 GHz when C1 = C2 = C3 = C4 = 5 pF. Generally, BER is improved by smaller capacitance values owing to its high-frequency characteristics.

The limiting factor in our experiment is the PD response and the noise from the transmission channel and amplifier in the receiver. The PD response is very weak at a frequency of 1 GHz, which caused difficulty in receiving the high-frequency signal. Multiple focusings were performed in the experiment to maximize the receiving power, since the active area of the PD is too small. Another factor is the noise from the VLC link. The signal power received is very small and easy covered by low-frequency noise, even in natural light, and the experiment conducted in the dark. The PCB design and layout of the equalizer can be optimized to be close to the response curve shown in Fig. 3. In the future, we plan to continue to optimize circuit performance and reduce the system noise, apply the other modulation format such as OFDM [14], and try to design a wider-bandwidth PD to enhance the 3-dB bandwidth and data rate of real-time VLC systems.

4. Conclusions

In this paper, we proposed a cascaded T-bridge pre-equalization circuit for use in indoor real-time and high-speed VLC links based on OOK-NRZ modulation. We used a blue filter in the experiment, and the 3-dB bandwidth of a VLC system was extended from 14 MHz to 520 MHz with a single commercially available phosphorescent white LED. The data rate achieved was 1 Gb/s with a BER of 7.36×10^{-4} at a distance of 1.5 m. The proposed pre-emphasis equalizer significantly improved the 3-dB bandwidth and achieved high-speed data transmission in a real-time VLC link. To the best of our knowledge, 1 Gb/s is the highest data rate ever achieved in a real-time VLC system based on a single commercially available phosphorescent white LED.

References

[1] T. Komine and M. Nakagawa, “Integrated system of white led visible-light communication and power-line communication,” *IEEE Trans. Consumer Electron.*, vol. 49, no. 1, pp. 71–79, Feb. 2003.
[2] D. O’Brien, L. Zeng, H. Le-Minh, G. Faulkner, J. W. Walewski, and S. Randel, “Visible light communications: Challenges and possibilities,” in *Proc. IEEE 19th Int. Symp. Pers. Indoor Mobile Radio Commun.*, 2008, pp. 1–5.
[3] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using led lights,” *IEEE Trans. Consumer Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.
[4] W. Y. Lin *et al.*, “10m/500 MBPS WDM visible light communication systems,” *Opt. Exp.*, vol. 20, no. 9, p. 9919, 2012.
[5] H. Elgala, R. Mesleh, H. Haas, and B. Pricope, “OFDM visible light wireless communication based on white leds,” in *Proc. IEEE 65th Veh. Technol. Conf.*, 2007, pp. 2185–2189.
[6] J. Y. Sung, C. W. Chow, and C. H. Yeh, “Dimming-discrete-multi-tone (DMT) for simultaneous color control and high speed visible light communication,” *Opt. Exp.*, vol. 22, no. 7, pp. 7538–43, 2014.
[7] L. Zeng, D. O’Brien, H. Le-Minh, K. Lee, D. Jung, and Y. Oh, “Improvement of date rate by using equalization in an indoor visible light communication system,” in *Proc. IEEE Int. Conf. Circuits Syst. Commun.*, 2008, pp. 678–682.
[8] H. L. Minh *et al.*, “100-Mb/s NRZ visible light communications using a postequalized white led,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 15, pp. 1063–1065, Aug. 2009.
[9] C. H. Yeh, C. W. Chow, H. Y. Chen, J. Chen, and Y. L. Liu, “Adaptive 84.44-190 Mbit/s phosphor-led wireless communication utilizing no blue filter at practical transmission distance,” *Opt. Exp.*, vol. 22, no. 8, pp. 9783–9788, 2014.
[10] H. Li, X. Chen, J. Guo, and H. Chen, “A 550 mbit/s real-time visible light communication system based on phosphorescent white light led for practical high-speed low-complexity application,” *Opt. Exp.*, vol. 22, no. 22, pp. 27203–27213, 2014.
[11] H. J. Q. Z. Jiabin Luo, Yi Tang, and W. Xue, “750 Mb/s monochromatic led-based real-time visible light communication system employing a low-complexity cascaded post-equalizer,” *Chin. Opt. Lett*, no. 12, pp. 55–59, 2016.
[12] X. Huang, Z. Wang, J. Shi, Y. Wang, and N. Chi, “1.6 gbit/s phosphorescent white led based VLC transmission using a cascaded pre-equalization circuit and a differential outputs pin receiver,” *Opt. Exp.*, vol. 23, no. 17, pp. 22 034–22042, 2015.
[13] O. J. Zobel, “Distortion correction in electrical circuits with constant resistance recurrent networks,” *Bell Labs Tech. J.*, vol. 7, no. 3, pp. 438–534, 2013.
[14] R. Deng, J. He, Z. Zhou, J. Shi, M. Hou, and L. Chen, “Experimental demonstration of software-configurable asynchronous real-time OFDM signal transmission in a hybrid fiber-vllc system,” *IEEE Photon. J.*, vol. 9, no. 1, Feb. 2017, Art. no. 7801008.