A 550 Mbit/s real-time visible light communication system based on phosphorescent white light LED for practical high-speed low-complexity application

Honglei Li, Xiongbin Chen,* Junqing Guo, and Hongda Chen

State Key Laboratory of Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, 100083, China

**chenxiongbin@semi.ac.cn*

Abstract: In this paper, we first experimentally demonstrate a 550 Mbit/s real-time visible light communication (VLC) system based on nonreturn-to-zero on-off keying (NRZ-OOK) modulation of a commercial phosphorescent white light LED. The 3-dB modulation bandwidth of such devices is only a few megahertz. We proposed an analog pre-emphasis circuit based on NPN transistors and an active post-equalization circuit based on an amplifier to enhance the 3-dB bandwidth of VLC link. Utilizing our proposed pre-emphasis and post-equalization circuits, the 3-dB bandwidth of VLC link could be extended from 3 to 233 MHz with blue-filter, to the best of our knowledge, which is the highest ever achieved in VLC systems reported. The achieved data rate was 550 Mbit/s at the distance of 60 cm and the resultant bit-error-ratio (BER) was 2.6×10^{-9}. When the VLC link operated at 160 cm, the data rate was 480 Mbit/s with 2.3×10^{-7} of BER. Our proposed VLC system is a good solution for high-speed low-complexity application.

OCIS codes: (060.4510) Optical communications; (060.2605) Free-space optical communication.

References and links

1. K.-D. Langer, J. Vucic, C. Kottke, L. F. del Rosal, S. Nerreter, and J. Walewski, “Advances and prospects in high-speed information broadcast using phosphorescent white light LEDs, ” in *Proceedings of International Conference on Transparent Optical Networks (ICTON)* (2009), pp. 90–95.
2. J. Grubor, S. C. J. Lee, K.-D. Langer, T. Koonen, and J. W. Walewski, “Wireless high-Speed data transmission with phosphorescent white-Light LEDs,” in *Proceedings of European Conference on Optical Communication (ECOC)* (2007).
3. H. Le-Minh, D. C. O’Brien, G. Faulkner, L. Zeng, K. Lee, K. Lee, D. Jung, and Y. Oh, “80 Mbit/s visible light communications using pre-equalized white LED,” in *Proceedings of European Conference on Optical Communication (ECOC)* (2008).
4. H. Le-Minh, D. C. O’Brien, G. Faulkner, L. Zeng, K. Lee, K. Lee, D. Jung, and Y. Oh, “High-speed visible light communications using multiple-resonant equalization,” IEEE Photon. Technol. Lett. **20**(14), 1243–1245 (2008).
5. N. Fujimoto and H. Mochizuki, “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,” in *Proceedings of OFC Collocated National Fiber Optic Engineers Conference (OFC/NFOEC)* (2013).
6. C. H. Yeh, Y. L. Liu, and C. W. Chow, “Real-time white-light phosphor-LED visible light communication (VLC) with compact size,” Opt. Express **21**(22), 26192–26197 (2013).
7. H. Le-Minh, D. C. O’Brien, G. Faulkner, L. Zeng, K. Lee, K. Lee, D. Jung, Y. Oh, and E. T. Won, “100-Mb/s NRZ visible light communications using a post-equalized white LED,” IEEE Photon. Technol. Lett. **21**(15), 1063–1065 (2009).
8. H. Li, X. Chen, B. Huang, D. Tang, and H. Chen, “High bandwidth visible light communications based on a post-equalization circuit,” IEEE Photon. Technol. Lett. **26**(2), 119–122 (2014).

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014

9. C. H. Yeh, C. W. Chow, Y. F. Liu, and P. Y. Huang, "Simple digital FIR equalizer design for improving the phosphor LED modulation bandwidth in visible light communication," Opt. Quantum Electron. **45**(8), 901–905 (2013).
10. T. Kishi, H. Tanaka, Y. Umeda, and O. Takyu, "A high-speed driver that sweeps out remaining carriers for visible light communications," J. Lightwave Technol. **32**(2), 239–249 (2014).
11. J. Vucic, C. Kottke, S. Nerreter, A. Buttner, K. D. Langer, and J. W. Walewski, "513 Mbit/s visible light communications link based on DMT-modulation of a white LED," J. Lightwave Technol. **28**(24), 3512–3518 (2010).
12. A. H. Azhar, T. A. Tran, and D. O'brien, "A Gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications," IEEE Photon. Technol. Lett. **25**(2), 171–174 (2013).
13. G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 Gbit/s visible optical wireless transmission based on RGB LED," Opt. Express **20**(26), B501–B506 (2012).
14. C. W. Chow, C. H. Yeh, Y. F. Liu, P. Y. Huang, and Y. Liu, "Adaptive scheme for maintaining the performance of the in-home white-LED visible light wireless communications using OFDM," Opt. Commun. **292**, 49–52 (2013).
15. N. Chi, Y. Wang, Y. Wang, X. Huang, and X. Lu, "Ultra-high-speed single red–green–blue light-emitting diode-based visible light communication system utilizing advanced modulation formats," Chin. Opt. Lett. **12**(1), 010605 (2014).
16. Y. Wang, Y. Wang, N. Chi, J. Yu, and H. Shang, "Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED," Opt. Express **21**(1), 1203–1208 (2013).
17. 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. Express **22**(8), 9783–9788 (2014).
18. 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. Express **22**(7), 7538–7543 (2014).
19. E. Fred Schubert, *Light-Emitting Diodes* (Cambridge University, 2003).
20. S. Zhang, S. Watson, J. J. D. Mckendry, D. Massoubre, A. Cogman, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, "1.5Gbit/s multi-channel visible light communications using CMOS-controlled GaN-based LEDs," J. Lightwave Technol. **31**(8), 1211–1216 (2013).
21. D. Tsonev, H. Chun, S. Rajbhandari, J. J. D. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. E. Kelly, G. Faulkner, M. D. Dawson, H. Haas, and D. O'Brien, "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μLED," IEEE Photon. Technol. Lett. **26**(7), 637–640 (2014).

1. Introduction

White light-emitting diodes (LEDs) can be used for illumination and communications simultaneously, which are ideal sources for free-space optical wireless communication. Visible light communication (VLC) based on white LEDs is a promising technology, attracting many researchers to study on it [1].

Due to lower complexity, lower cost and market dominance, phosphorescent white LEDs are more attractive for VLC, compared with triple-chip RGB type LEDs. Despite the bandwidths of these devices are only typically a few megahertz, blue-filtering [2], pre-equalization [3–6], post-equalization [7–9] and sweeping out remaining carriers [10] have been reported to enhance bandwidths and data rates of VLC system. Furthermore, spectrally efficient modulation techniques [11–18] such as discrete multitone modulation (DMT), multiple-input multiple-output (MIMO) and wavelength division multiplexing (WDM) and so on also can be used to realize high speed VLC system.

In [3], H. L. Minh et al first report pre-equalizer composed by three amplifiers (BUFF634T), resistors and capacitors, the pre-equalized bandwidth was 45 MHz and data rate was 80Mbit/s. In [4], H. L. Minh et al proposed multiple-resonant equalization to enhance bandwidth of 16 LED arrays to 25 MHz, then 40 Mb/s could be achieved. In [5], N. Fujimoto et al proposed a practical LED driver with pre-emphasis circuit, the pre-emphasis circuit improved the 3-dB bandwidth of RGB LED (Red LED) from 6.2 MHz to 91MHz, and 160MHz bandwidth achieved by using peaking characteristics of operational amplifier, then 477 Mbit/s could be achieved under the distance of 40 cm when only red LED was modulated and Green and Blue LEDs are OFF. In [6] and [17], C. W. Chow et al used RLC pre-equalization circuit to improve the bandwidth of VLC system, which acquired good results. In [7], H. L. Minh et al first use simple analog RC-based post-equalizer to improve the bandwidth of VLC link to 50 MHz, and 100 Mbit/s could be achieved. All the works above they have done have promoted the development of VLC pre-equalization and post-equalization technology and speeded up the industrialization of high-speed VLC application.

In this paper, we first experimentally demonstrate a 550 Mbit/s real-time VLC system based on NRZ-OOK modulation of a commercial phosphorescent white light LED. The resultant BER was 2.6×10^{-9}, which is much less than forward-error-correction (FEC) limit 3.8×10^{-3}. We proposed an analog pre-emphasis circuit based on NPN transistors and an active post-equalization circuit based on an amplifier to enhance the 3-dB bandwidth of VLC link. We designed two new effective equalizers and made the equalization further development. Utilizing our proposed pre-emphasis and post-equalization circuits, the 3-dB bandwidth of VLC link could be extended from 3 to 233 MHz with blue filter, to the best of our knowledge, which is the highest ever achieved in VLC systems reported. When the VLC link operated at 160 cm, the data rate was 480 Mbit/s with 2.3×10^{-7} of BER.

We adopt the simplest NRZ-OOK modulation, and use optimal analog pre-equalizer and post-equalizer we designed, a 550 Mbit/s real-time VLC link could be realized. The works we did were the development of VLC pre-emphasis and post-equalization technology. The approach to realize high-speed VLC link is easy and low-cost without complex arithmetic and hardware. Our VLC link was a good solution for high-speed low-complexity VLC application.

2. Proposed VLC pre-emphasis and post-equalization circuit

Generally, VLC pre-emphasis and post-equalization circuits were applied to improve the 3-dB bandwidth of VLC link. However, the performance of equalizers in [3–7] is limited by their simple architecture, for example, RC-based equalizer is passive equalizer that could decrease sensitivity of receiver. We improved VLC equalization approach and proposed new effective equalizers including an analog pre-emphasis circuit based on NPN transistors and an active post-equalization circuit based on an amplifier.

2.1 Proposed VLC pre-emphasis circuit

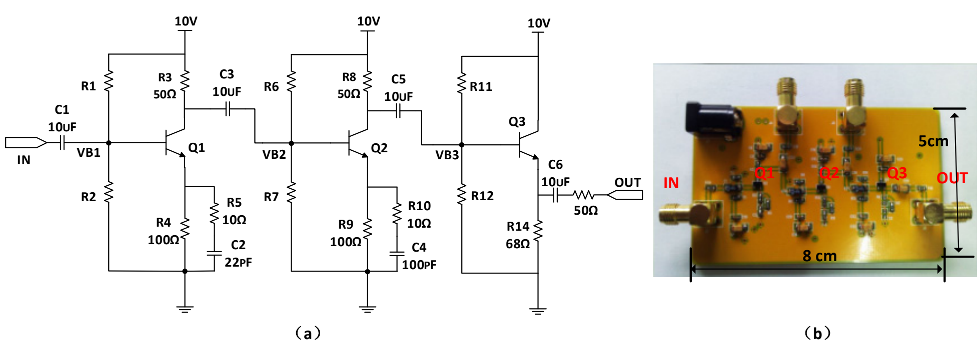

Fig. 1. (a) VLC pre-emphasis circuit using wideband NPN transistors. Q1and Q2: BFR520; Q3: BFR540. (b) Designed pre-emphasis circuit module.

In Fig. 1(a), we present the pre-emphasis circuit that we designed. Figure 1(b) shows the pre-emphasis circuit module that we designed with 6 cm × 8 cm size. The circuit adopted wideband NPN transistors with transition frequency of 9 GHz. The circuit contains three stages amplify circuit. The first and second stage are common emitter amplify circuit, whose output impedance is large and drive capability is weak. In order to enhance the output driving ability, an emitter follower was used in the third stage, whose output impedance is small. The pre-emphasis is mainly relative with the first and second stage amplifies circuit.

In the first stage amplifier, for example, ac voltage magnification could be expressed by

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014

$$\mathrm{A_{v1}}(\mathrm{j}\omega) = \frac{\mathrm{R_3}}{\mathrm{R_4} // (R_5 + \frac{1}{j\omega C_2})} = \frac{R_3}{R_4}(1 + \frac{R_4}{R_5(1 + \frac{1}{j\omega R_5 C_2})}) \tag{1}$$

The magnitude of first stage amplifier response is

$$\left|\mathrm{A_{v1}}(\mathrm{j}\omega)\right| = \frac{R_3}{R_4}(1 + \frac{\omega R_4 C_2}{\sqrt{1 + \omega^2 R_5^2 C_2^2}}) \tag{2}$$

Note that $\frac{R_3}{R_4}$ is the dc coefficient of the first stage amplifier ($\omega = 0$). The 3-dB point above the $\frac{R_3}{R_4}$ is computed as

$$\omega_{3-\mathrm{dB}} \approx \frac{0.414}{C_2\sqrt{R_4^2 - 0.172 R_5^2}} \tag{3}$$

In experiment, we need get large compensation for high frequency operation, thus R_5 is much smaller than R_4, then

$$\omega_{3-\mathrm{dB}} \approx \frac{0.414}{\mathrm{C_2 R_4}} \tag{4}$$

From Eqs. (2) and (4), we can calculate the magnitude response of the first stage amplifier. The second stage amplifier is same with the first one. The reason why we used the second stage amplifier is that the pre-emphasis circuit could compensate for two different high frequency points and much more easily to control the range of signal amplitude and slope of pre-emphasis curve. At the same time, the second stage amplifier could make the phase of signal output of pre-emphasis circuit same with the phase of input signal. Meanwhile, it is necessary to set proper static operating point of each transistor.

The structure of pre-emphasis circuit that we proposed was different from pre-equalization circuit of [3–7]. We adopt two cascade pre-emphasis amplifiers to control the range of signal amplitude and slope of pre-emphasis curve, thus it will be more easily to compensate LED response. In the experiment, we firstly read the 3-dB frequency point from the LED response without pre-emphasis compensation, secondly estimate the values of R_4 and C_2, through the Eq. (4), then we set the value of R_5 and static operating point of each transistor, we have to optimize the parameters and improve the performance of the pre-emphasis circuit again and again, finally we find out the optimal values of components used in the pre-emphasis circuit. Typical values of key parameters was shown in Fig. 1(a).

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014

2.2 Proposed VLC post-equalization circuit

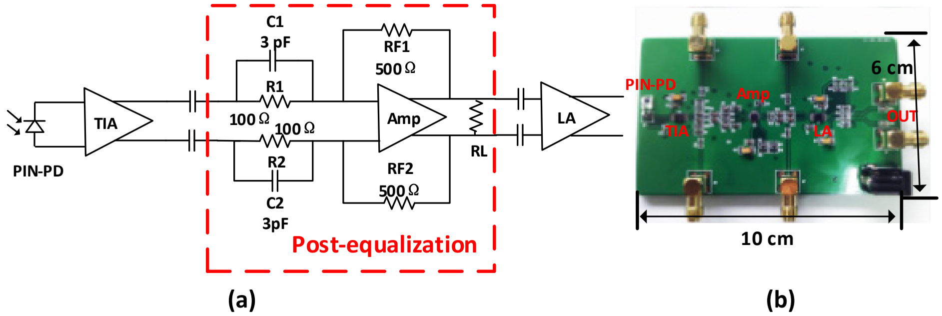

Fig. 2. (a) VLC post-equalization circuit. (b) Optical receiver module with post-equalization circuit designed.

The post-equalization circuit was shown in Fig. 2(a). This is an active post-equalizer, such post-equalization circuit was not only used in single ended amplifier but also applied to differential amplifier. Both amplifiers must be voltage feedback amplifier. Optical receiver module with post-equalization and 6 cm × 10 cm size we designed was shown in Fig. 2(b), the differential amplifier ADA4937-1 was used to design the post-equalizer. The frequency response of active post-equalizer is expressed by

$$H_A(j\omega) = \frac{RF_1}{R_1 // (\frac{1}{j\omega C_1})} = \frac{RF_1}{R_1}(1 + j\omega R_1 C_1) \tag{5}$$

The magnitude of the equalizer response is

$$|H_A(j\omega)| = \frac{RF_1}{R_1}\sqrt{1+\omega^2 R_1^{\,2} C_1^{\,2}} \tag{6}$$

When the C_2 is 0 pF, the amplifier DC gain is $\frac{RF_1}{R_1}$, while the C_2 is taken into consideration, the frequency response of equalizer is related with it. The 3-dB point above the DC gain is

$$\omega_{3-dB} = \frac{1}{R_1 C_1} \tag{7}$$

From Eq. (7), we can see that when the R_1 and 3-dB frequency point are known, the value of C_1 could be calculated. However, this is only an ideal model, which only explain the principle of such active post-equalizer. In the experiment, we calculate the value of C_1 firstly, then experiment again and again to find out the optimal value of C_1. If the value of C_1 were too big, it would affect the stability of amplifier due to large compensation for higher frequency. To achieve the best results and take into account the stability of the amplifier, 3pF was chosen for C_1 and C_2 in the post-equalization circuit. The proposed active post-equalizer would not affect the sensitivity of receiver, and it is simple ingenious design.

3. Experiment and results

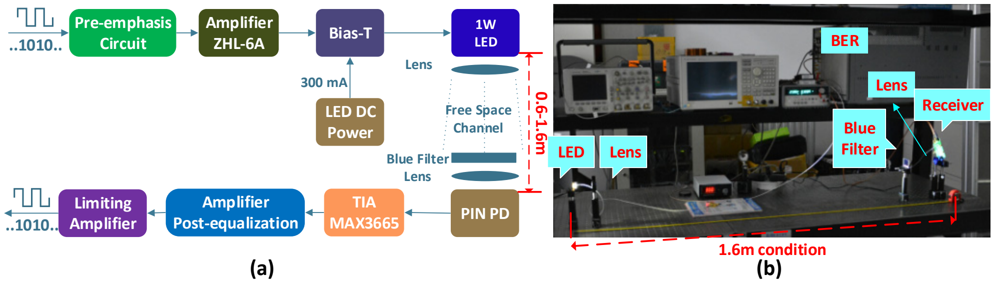

Fig. 3. (a) Experimental setup of phosphor-LED VLC system. TIA: trans-impedance amplifier; PD: photodiode. (b) VLC experimental link (Media 1).

The experimental setup is reported in Fig. 3(a). The signal was processed firstly by a pre-emphasis circuit that we designed, then amplified by the amplifier (ZHL-6A) with the purpose to increase the LED modulation depth, and superimposed onto the LED bias current via a Bias-T (Aeroflex 8810). The output of Bias-T was directly supplied to a commercially available phosphorescent white LED (OSRAM LUW W5AM). A 15° full opening angle lens was fixed to make sure the light transmits along the regular direction. An optical short-pass filter with a cutoff wavelength of 500 nm and an optical convex lens (5 cm focal length) was mounted in front of the PIN photodiode (HAMAMATSU S10784). An trans-impedance amplifier (TIA) MAX3665 (8KΩ gain, 470MHz bandwidth) was used to amplify electrical current signal of photodiode (PD), then a differential amplifier (ADA4937-1) circuit with post-equalization boosted the signal level up to the operation range of the error bit-error-ratio (BER) tester (Agilent 81250). The receiver also consists a wideband limiting amplifier (MAX3768) with a gain of 55 dB, which could provide low voltage positive emitter-coupled logic (LVPECL) output interface.

Figure 3(b) shows the VLC experimental link. Two convex lenses were used to focus the light and make the light transmit according to a certain direction. The blue filter could be placed anywhere between LED and receiver, it also should be fixed in line with LED, receiver and two lenses. The PIN photodiode should be placed at the focus of convex lens that near to the receiver. The distance between LED and receiver could be extended to from 60 cm to 160 cm. Figure 3(b) shows VLC link with 160 cm distance of an illumination level of ~300 lux with a single 1W white LED.

We firstly performed a measurement of the frequency response of white light, blue light and yellow component which is shown in Fig. 4(a). We define the 3-dB bandwidth as the 3-dB frequency point where the power of spectral response reduced by 3 dB compared with low-frequency reference value [19]. In order to ensure the preciseness and accuracy of the experiment, we set the response of frequency point at 1 MHz as the low-frequency reference value in all the 3-dB bandwidth measurements in this paper. The 3-dB bandwidth of white light response is only 3 MHz, whereas the blue component response is 12MHz. The 3-dB bandwidth of yellow component is approximately 3 MHz, which is consistent with white light response. As frequency increases, the response of yellow component decreases rapidly, white light response is close to blue light response.

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014

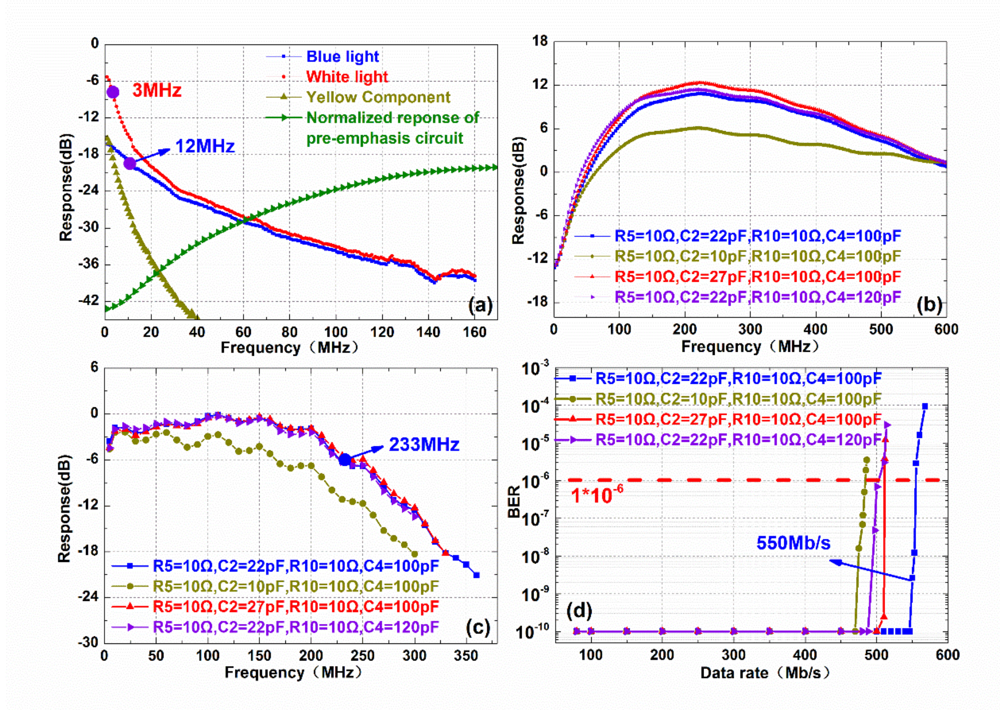

Fig. 4. (a) EOE system frequency response of blue light, white light, yellow component and normalized response of pre-emphasis circuit. (b) Frequency response of pre-emphasis circuit with different cases. (c) EOE system frequency response with different cases of pre-emphasis circuit and under a certain value 3 pF of post-equalization capacitor. (d) BER versus transmission data rate with different cases of pre-emphasis circuit and under a certain value 3 pF of post-equalization capacitor. BER below 10^{-10} is truncated to this threshold. Different cases for (a), (b) and (c) include $R_5 = 10\ \Omega$, $C_2 = 22$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 100$ pF; $R_5 = 10\ \Omega$, $C_2 = 10$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 100$ pF; $R_5 = 10\ \Omega$, $C_2 = 27$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 100$ pF and $R_5 = 10\ \Omega$, $C_2 = 22$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 120$pF. All the measurements of (a), (c) and (d) are at the distance of 60 cm.

In order to characterize the performance of pre-emphasis circuit, we did a great deal experiments on changing the values of key parameters such as R_5, C_2, R_{10} and C_4. Figure 4(b) shows the frequency response of pre-emphasis circuit with typical four cases. Its output magnitude could changes from −13 dB to 10.8 dB when the frequency range from 1 to 238MHz. The pre-emphasis amplifier is a nonlinear amplify circuit. Utilizing two cascade pre-emphasis circuit, the range of signal amplitude could be more than 23 dB change. We also can see that the slope of pre-emphasis curve could be easily controlled by choosing proper values of related key parameters.

Here, we will analysis how we choose the values of these key parameters of pre-emphasis in the experiment. We first set the values of R_4 as 100Ω according to the static operation point of NPN transistor.R_5 is much smaller than R_4, it changes little to the corner frequency of pre-emphasis circuit on the basis of Eq. (3), but it affects the amplitude of pre-emphasis curve significantly according to Eq. (2). We set the value of R_5 as 10Ω, according to the experiment. When it was set 10Ω, the compensation amplitude of pre-emphasis circuit would be fit to the blue light response of VLC link under the frequency changing from 1 to 160 MHz just as shown in Fig. 4(a). The pre-emphasis circuit has two cascade pre-emphasis amplifier. We utilized the first stage of pre-emphasis circuit to compensate higher frequency region and used the second stage of pre-emphasis circuit to compensate lower frequency region. Then we calculate the values of C_2 and C_4 according to Eq. (4). It is noteworthy that these estimated values are 3-dB frequency point above the DC point in theory, this model could provide the estimate values but not very accurate values. We have to experiment on changing the values of C_2 and C_4. All the works of experiment on changing these parameters were extensive, we will give four typical groups of these values to evaluate the performance of VLC link with equalizers we designed just as Figs. 4(b)–4(d) shown.

Secondly, we performed a measurement of 3-dB bandwidth of VLC system with pre-emphasis and post-equalization circuits. The post-equalization capacitors C_1 and C_2 were set to 3 pF, we just changed key parameters of pre-emphasis circuit such as R_5, C_2, R_{10} and C_4. The magnitude of the channel's frequency response was measured by varying the frequency of a small-signal sine wave (−15 dB) provided by the analog signal generator (Agilent N5181A), and directly monitoring the receive amplitude at the oscilloscope. Figure 4(c) presents the electro-optical-electrical (EOE) channel frequency response with different cases of pre-emphasis circuit. The response of low-frequency reference point at 1MHz is −3.5 dB, and the response of 233MHz point is about −6.5 dB which is 3 dB penalty. With blue-filtering, pre-emphasis and post-equalization circuits, the system 3-dB bandwidth could be extended from 3 to 233 MHz just as Figs. 4(a) and 4(c) shown. We can see that the pre-emphasis equalizer and post-equalizer was effective to enhance the 3-dB bandwidth of VLC system.

Then, we performed BER measurements as a function of data rate with different cases of changing the key parameters of pre-emphasis circuit and maintain the value 3 pF of post-equalization capacitor unchanged. A pseudo random binary sequence (PRBS)-9 (2^9-1) OOK-NRZ data stream with a peak-to-peak voltage swing of 80 mV is used to modulate the emitted light. We have made our best effort to find that the condition of $R_5 = 10\ \Omega$, $C_2 = 22$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 100$ pF is better than the other conditions, but it doesn't mean the best in experiment. Figure 4(d) shows the measured data rate achieved could be 550 Mbit/s, the resulting BER is 2.6×10^{-9}, much less than FEC limit 3.8×10^{-3}. In generally, data rate achieved is not only related with the 3-dB bandwidth of VLC link, but also has a relationship with signal amplitude of receiver. The channel attenuation follows closely the 3-dB frequency of 233 MHz, the remaining elements in the system are guaranteed to have a higher transmission bandwidth up to at least 350MHz, just as shown in Fig. 4(c). The response of higher frequency than 3-dB frequency point up to at least 350 MHz also works to transmit useful information [20, 21]. In addition, a good design of the optical receiver with good signal processing could help get higher data rates with limited 3-dB bandwidth of VLC link. Therefore, it is possible to realize 550Mbit/s with 233 MHz of 3-dB bandwidth of VLC link.

In order to evaluate the performance of post-equalization circuit. EOE system frequency response and BER versus transmission data rate with different values of post-equalization capacitor C_1 and C_2 were measured, just as shown in Figs. 5(a) and 5(b), we maintain the values of key parameters $R_5 = 10\ \Omega$, $C_2 = 22$ pF, $R_{10} = 10\ \Omega$ and $C_4 = 100$ pF unchanged. When the post-equalization capacitor is 0 pF, the 3-dB bandwidth of VLC system is 220 MHz and data rate is 480 Mbit/s under the BER of 1.4×10^{-9}; when it becomes 3 pF, the 3-dB bandwidth becomes 233 MHz and data rate is 550 Mbit/s under the BER of 2.6×10^{-9}. And when it becomes 5 pF, the gain peak becomes too large of more than 3 dB compared with reference gain at 1 MHz frequency point. If the value of gain peak were too large, the amplifier would be more easily working unstable. In the design of high frequency circuit, we should avoid the response with higher gain peak. The experiment results shows that the data rate is only 535 Mbit/s under the BER of 6.5×10^{-9}. Thus, we choose the value 3 pF of post-equalization capacitor to compensate response of VLC link.

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014

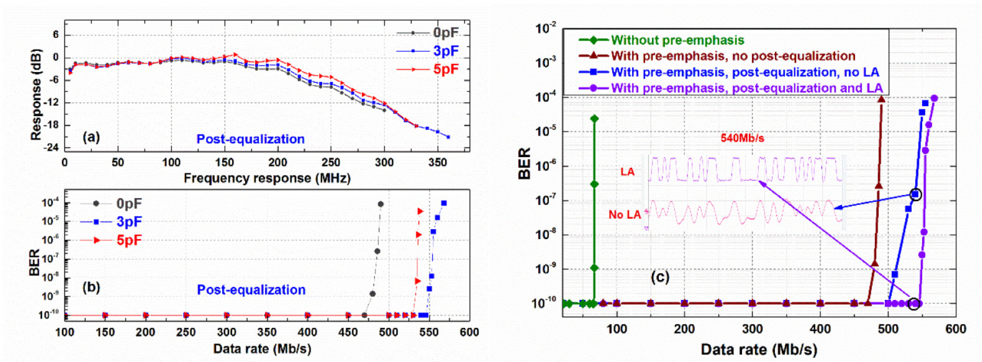

Fig. 5. (a) EOE system frequency response with different values of post-equalization capacitor C_1 and C_2 (the values of C_1 and C_2 are equivalent with 0 pF, 3 pF and 5 pF), under the certain key parameters of pre-emphasis circuit (R_5 = 10 Ω, C_2 = 22 pF, R_{10} = 10 Ω and C_4 = 100 pF). (b) BER versus transmission data rate with different values of post-equalization capacitor C_1 and C_2 (the values of C_1 and C_2 are equivalent with 0 pF, 3 pF and 5 pF), under the certain key parameters of pre-emphasis circuit (R_5 = 10 Ω, C_2 = 22 pF, R_{10} = 10 Ω and C_4 = 100 pF). (c) BER versus transmission data rate (without pre-emphasis; with pre-emphasis and no post-equalization; with pre-emphasis, post-equalization and no LA; with pre-emphasis, post-equalization and LA). BER below 10^{-10} is truncated to this threshold. Inset: measured waveform at 540Mbit/s. All the measurements are at the distance of 60 cm.

Next, we will give a summary of the performance of pre-emphasis and post-equalization circuit, just as Fig. 5(c) shown. Without pre-emphasis circuit and post-equalization, measured data rate is only 66 Mbit/s at the zero BER level. 480 Mbit/s at the BER of 1.4×10^{-9} could be achieved when only the pre-emphasis circuit was used. Then the VLC link data rate could be improved to 550 Mbit/s when the pre-emphasis and post-equalization circuits were both used, the resultant BER is 2.6×10^{-9}. Pre-emphasis circuit places a major role in improving the 3-dB bandwidth and data rate of VLC link, and post-equalization circuit only assist the VLC link get higher 3-dB bandwidth and data rate. We combined the pre-emphasis equalizer and post-equalizer together. Both of them work well. These experimental results reflect good performance of pre-equalizer and post-equalizer we proposed.

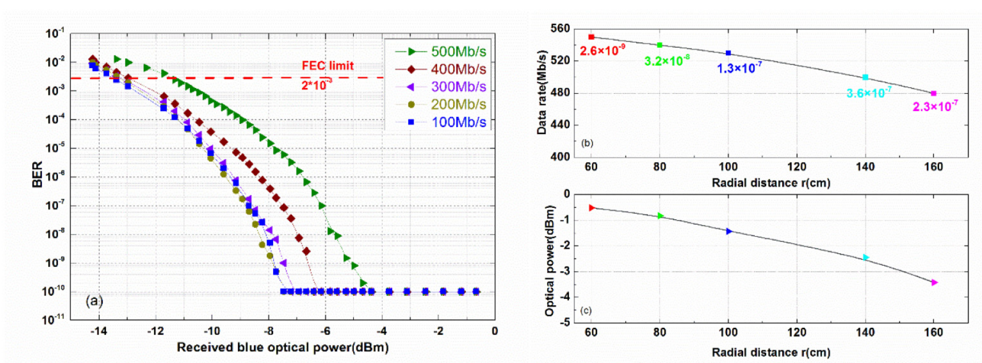

Fig. 6. (a) BER versus received blue optical power at different data rates (100 Mb/s, 200 Mb/s, 300 Mb/s, 400 Mb/s and 500 Mb/s). All the measurements are at the distance of 60 cm. (b) measured transmission data rate versus radial distance r (cm). (c) measured received optical power versus radial distance r (cm).

What's more, BER versus measured received blue-light optical power at different data rates was performed. As illustrated in Fig. 6(a), when the transmission data rate changing from 100 Mbit/s to 300 Mbit/s, the smallest received blue-light optical power under the condition of FEC limit is about −13 dBm, and when transmission data rate is 500 Mbit/s, the optical sensitivity is −11 dBm. The reasons why the curve of 100, 200 and 300 Mbit/s are overlapping are the compensation of pre-emphasis circuit and the amplitude limiting function of TIA and limiting amplifier. These reasons make the response of VLC link flat at modulation 3-dB bandwidth range and the signal well be performed. When the data rate is higher than 300 Mbit/s, the signal to noise ratio (SNR) reduces as frequency increases. Higher data rate means higher received optical power to overcome the SNR penalty due to the limited ability of equalization. Thus the sensitivity of receiver at the date rate of 400 and 500 Mbit/s has about 1 and 1.5 dB penalty. The measured transmission date rate characteristics versus radial distance are shown in Fig. 6(b). When the VLC link is 60 cm, the data rate is 550Mbit/s under the BER of 2.6×10^{-9}; when the radial distance is 160 cm, data rate achieved can also reach 480 Mbit/s with BER 2.3×10^{-7}. Figure 6(c) describes that the received blue light optical power is about −3.5 dBm when the radial distance is 160 cm. when the VLC link distance is longer than 160 cm, the received optical power would be lower than −3.5 dBm. The optical intensity would be too weak to produce lower BER.

In addition, in order to calculate the power consumption of the analog equalizers, we have to make an assumption that the small signal consumption could be ignored due to DC consumption is much larger than small signal consumption. On the basis of this assumption, we could estimate the electrical power loss of analog equalizers in a simple way. For pre-emphasis circuit, the first and second stage is mainly about pre-emphasis technology and the third stage is the current driver. The electrical power loss of analog equalizers P_{loss} could be expressed as

$$P_{loss} \approx \left(\frac{V_{B1}}{R_4} + \frac{V_{B2}}{R_9} + \frac{V_{B3}}{R_{14}}\right) \times 10V \tag{8}$$

We set the $V_{B1} = 3.3V$, $V_{B2} = 5V$, $V_{B3} = 5V$ in the experiment, thus $P_{loss} \approx 1.56$ W. We also did an experiment on testing the electrical power consumption of pre-emphasis circuit by Agilent E3631A, the $P_{loss\text{-}test} = 1.59$ W, which is closely same with the model's result. Such electrical power consumption was mainly used to compensate the LED frequency response. For post-equalization circuit, the amplifier were mainly used for amplify the signal, only two capacitors were used for post-equalization combined with the amplifier, we could ignore the power assumption for post-equalization. As we know, the LED power consumption is large especially for high power LEDs. Compared with the whole VLC system power consumption, the value of 1.56 W is acceptable. On the other side, we used only 1.56W power consumption in exchange for about 77 times 3-dB bandwidth and 550 Mbit/s data transmission. Furthermore, we could change the parameters of pre-emphasis circuit, then power consumption could be lower in the future research work.

In many other lab experiments [11, 13, 15], when DMT or Orthogonal Frequency Division Multiplexing (OFDM) modulation are used, they always utilize a real-time oscilloscope to record and save the received signal first, then perform off-line process on the personal computer. Their method cannot transmit information and process the received information simultaneously, because it is difficult to realize high-speed, high-complexity modulation scheme using hardware such as FPGA and DSP. However, we used the simplest NRZ-OOK modulation scheme, and the VLC link we designed could transmit information and process received information at the same time. We used BER tester to transmit OOK-NRZ data stream and process the received data coming from the optical receiver. Compared with off-line signal processing, our VLC link could process signal in real-time.

In the optical receiver, Limiting amplifier (LA) we used provides approximately 55 dB of gain and offers standard PECL output, which could be perfectly used to recovery the signal just as inset measured waveform in Fig. 5(b) as shown. LA can improve signal quality especially higher data rate region from 500 Mbit/s to 550 Mbit/s, with which VLC link data rate could be improved from 510 Mbit/s to 550 Mbit/s. Our VLC link use simple NRZ-OOK modulation scheme, does not need complex hardware and expensive equipment. Only with a pre-emphasis circuit, optical receiver with post-equalization, a drive amplifier and a Bias-Tee, higher data rate real-time VLC link could be realized. Thus, our VLC link is a good solution for high-speed low-complexity VLC application. The work we did took the pre-emphasis and post-equalization technology further, and was meaningful to promote high-speed VLC industrialization.

Limiting factors to higher data rate in our experiment were the limit bandwidths of PIN-PD, drive amplifier and TIA chip and finite ability of pre-emphasis and post-equalization circuits. The equalizers we designed could be applied to other single LED or LED arrays by only adjusting some key parameters to fit the response of these devices. We will continue to optimal and improve the performance of equalizers we designed and design more practical and effective equalizers to enhance 3-dB bandwidth and data rate of VLC link in the next research work.

4. Conclusion

In this paper, we have demonstrated for the first time an indoor real-time VLC link based on OOK-NRZ Modulation of a commercially available phosphorescent white LED operating up to 550Mbit/s. The resultant BER is 2.6×10^{-9}, which is much less than FEC limit of 3.8×10^{-3}. The 3-dB bandwidth of VLC system was improved from 3 to 233 MHz by using the pre-emphasis and post-equalization circuits that we designed, which was also the highest in VLC systems reported. The distance between LED and receiver could be extended to 160 cm with data rate of 480 Mbit/s and 2.3×10^{-7} of BER. Proposed pre-emphasis and post-equalization circuits do enhance the 3-dB bandwidth and data rate of VLC link significantly. The works we did were the development of VLC pre-emphasis and post-equalization technology. Our VLC link is a good solution for high-speed low-complexity VLC application, which is meaningful to promote high-speed VLC industrialization.

Acknowledgments

This work was supported in part by a grant from the National Key Basic Research Program of China (973 Program) under Grants 2013CB329205 and 2011CBA00608; in part by the National High Technology Research and Development Program of China (863 Program) under Grants 2013AA013602, 2013AA013603, 2013AA03A104 and 2013AA031903; and in part by the National Natural Science Foundation of China under Grants 61036002 and 61178051.

#217439 - $15.00 USD Received 4 Aug 2014; revised 8 Oct 2014; accepted 19 Oct 2014; published 27 Oct 2014