200 Mb/s visible optical wireless transmission based on NRZ–OOK modulation of phosphorescent white LED and a pre-emphasis circuit

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We present a high-speed visible light communication (VLC) link that uses a commercially available phosphorescent white light-emitting diode (LED). Such devices have few megahertz bandwidth due to the slow response of phosphorescent component, which severely limit the transmission data rate of VLC system. We propose a simple pre-emphasis circuit. With blue-filtering and the pre-emphasis circuit, the bandwidth of VLC system can be enhanced from 3 to 77.6 MHz, which allows non-return-to-zero on-off-keying (NRZ–OOK) data transmission up to 200 Mb/s with the bit error ratio of 5.3×10^{-7} which is below 10^{-6}. The VLC link operates at the room illumination level of ~1000 lx at 1.1 m range using a single 1 W white LED.

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White light-emitting diodes (LEDs) are considered to be a promising candidate for future indoor lighting. These lighting sources have the ability of simultaneous illumination and data transmission. The advantages of visible light communication (VLC) include low cost, high security, non-interference with ratio frequency bands[1], and so on. VLC is becoming an emerging technology for high speed and short-range optical wireless communication that stimulates worldwide research and global standardization efforts[2].

One way to improve the VLC system transmission data rate is to enhance the bandwidth of VLC system. Commercially available phosphorescent LEDs are attractive for general illumination as well as communication because of its higher efficiency and lower complexity. The modulation bandwidths of such devices are in lower megahertz range (typically 3–5 MHz) due to the long response time of the yellow phosphor. There are a number of approaches to improve bandwidth of VLC link, including the use of a blue filter at the receiver to filter out the slow yellow component[3], multiple-resonant pre-equalization[4–6], and post-equalization of the receiver[7–9]. With pre-equalization, the bandwidth of VLC system is 45 MHz and transmission data rate is up to 80 Mb/s[5]. Fujimoto *et al.*[10] showed a pre-emphasis circuit and a VLC link using a single RGB-type white LED in which its data rate could reach 477 Mb/s with only red LED modulated and green and blue LEDs OFF state at the distance of 40 cm. And as the distance was increased to 1.6 m, only 100 Mb/s could be achieved. The operating speed of RGB-type white LEDs is higher than that of the phosphorescent white LEDs, because the RGB-type LED has no low-speed phosphor layer[10]. However, the phosphor-based white LEDs are more attractive for general illumination due to their lower complexity when compared with RGB-type LEDs. Another way to improve the transmission data rate of VLC system is using advanced modulation format. By using spectrally efficient modulation techniques such as orthogonal frequency-division multiplexing (OFDM)[11–13], discrete multi-tone modulation, multiple input–multiple output-OFDM, and wavelength division multiplexing, 513 Mb/s, 1.1 Gb/s, 3.4 Gb/s, and 3.75 Gb/s VLC systems have been demonstrated[14-18].

We propose a simple pre-emphasis circuit and demonstrate a high-speed VLC link using a commercially available phosphorescent white LED. With blue-filtering and the pre-emphasis circuit, a bandwidth of 77.6 MHz has been achieved in our VLC system, which allows non-return-to-zero on-off-keying (NRZ–OOK) data transmission up to 200 Mb/s with the bit error ratio (BER) below 10^{-6}. We confirm that 200 Mb/s is the highest data rate based on pre-emphasis technology and NRZ–OOK modulation of phosphorescent white LED. The VLC link operates at the room illumination level of ~1000 lx at 1.1 m range using a single 1 W white LED.

Figure 1 shows a simple VLC pre-emphasis circuit. We use a wideband and current feedback amplifier (OPA695). The amplifier is used to amplify the signal and enhance the modulation index of LED. The circuit contains a passive equalizer (PEQ) that comprises a capacitor C_1 in parallel with a resistor R_1 and a load resistor R_2.

The transfer function of pre-emphasis circuit is expressed by

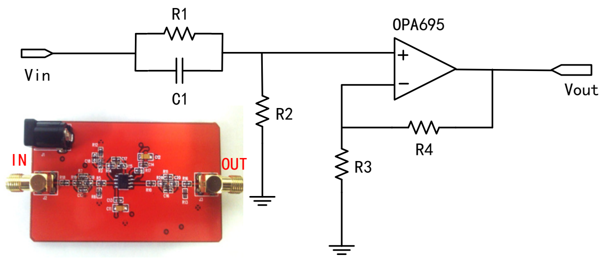

Fig. 1. VLC pre-emphasis circuit.

$$H(j\omega) = \left(1 + \frac{R_4}{R_3}\right) \times \frac{R_2}{R_1 + R_2} \times \frac{1 + j\omega/\omega_1}{1 + j\omega/\omega_2}, \tag{1}$$

where $\omega_1 = \frac{1}{R_1 C_1}$ and $\omega_2 = \frac{R_1 + R_2}{R_1 R_2 C_1}$. The magnitude of the pre-emphasis circuit response is

$$H(j\omega) = \left(1 + \frac{R_4}{R_3}\right) \times \frac{R_2}{R_1 + R_2} \times \sqrt{\frac{1 + \omega^2/\omega_1^{\,2}}{1 + \omega^2/\omega_2^{\,2}}}. \tag{2}$$

We can calculate the magnitude response of the pre-emphasis circuit through Eq. (2) in theory. The 3 dB point above $H(0) = \left(1 + \frac{R_4}{R_3}\right) \times \frac{R_2}{R_1 + R_2}$ is computed as

$$\omega_{3\text{dB}} = \omega_1 \omega_2 \sqrt{\frac{1}{\left(\omega_2^{\,2} - 2\omega_1^{\,2}\right)}}. \tag{3}$$

The frequency $f_1 = \frac{1}{2\pi R_1 C_1}$ is matched with the corner frequency of signal from LED blue light. The experiment results may be a little different from the ideal theory model, but the ideal model can explain the feasibility of the pre-emphasis circuit in theory. In the experiment, we designed the amplifier (OPA695) circuit firstly, then got the LED blue light response, set R_2 (1–10 kΩ) and calculated the R_1 value according to the dynamic range of the blue light response, and then determined capacitor C_1.

To sum up, the PEQ decay, the low-frequency signal amplitude, and the amplifier can amplify the equalized signal to increase the modulation index of LED. However, in the experiment, the PEQ and amplifier are integral and interdependent. The value of R_1, C_1, and R_2 should be designed properly in consideration of the non-idealities of amplifier. The amplifier ought to have enough bandwidth to make sure signal undistorted.

Figure 2 shows the VLC system experimental setup. We first measured the electro-optical-electro (EOE) channel frequency response using network analyzer (Agilent E5071B), followed by the measurement of NRZ–OOK-based transmission performance. The output signal from network analyzer or BER tester (Agilent 81250) was processed by the pre-emphasis circuit that we designed, and then superimposed the signal that had been pre-emphasized onto the LED direct current power supply via a Bias-Tee (Aeroflex 8810). Its output was directly supplied to the white LED. The light source was a commercial phosphorescent white LED (OSRAM LUW W5AM), devised for general lighting. A 15° full opening angle lens was fixed to make sure that light transmits along the regular direction.

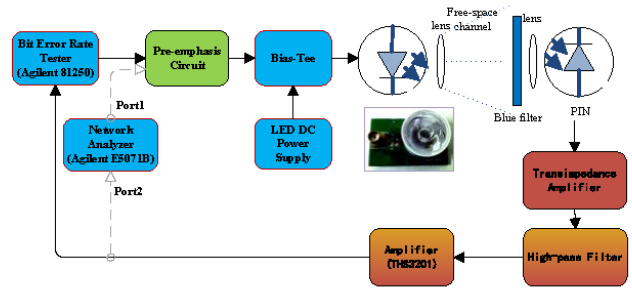

Fig. 2. VLC system experimental setup.

The analog receiver consisted of following components. An optical blue filter (400–500 nm, transmissivity is 90%) which can suppress the phosphorescent component of the white LED and an optical lens were fixed in front of a PIN photodiode (HAMAMATSU, S10784). The optical signal from the LED was converted to electrical current signal through the PIN photodiode and then the current signal was amplified to voltage signal by a low-noise transimpedance amplifier (TIA) circuit. High-pass filter can filter out 50–60 Hz power signal and reduce low-frequency noise. Then a wideband current feedback amplifier (TH3201) boosted the signal level up to the operation range of the BER tester.

Figure 3 shows the VLC experiment link. Two convex lenses were used to focus the light and make the light transmit to a certain direction. The blue filter can be placed anywhere between LED and receiver, it was fixed in line with LED, receiver, and two lenses. The PIN diode was placed focusing the convex lens near to the receiver. The parameters for the VLC experimental link are shown in Table 1.

According to Ref. [9], illuminance is an important design parameter, and a level of ~1000 lx is typical for indoor lighting. Thus, illuminance value of around 1000 lx was chosen in agreement with the lighting standard for well-lit working environments. The VLC link operates over 1.1 m where the illuminance value is about 1000 lx.

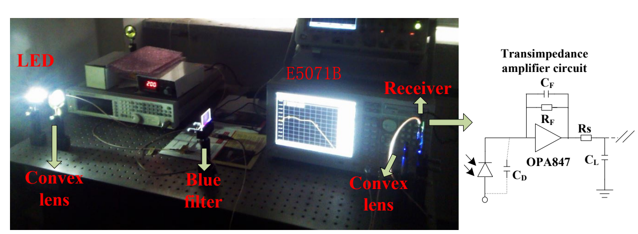

Fig. 3. VLC experiment link.

Table 1. VLC Experimental Link Parameters

Parameters	**Values**
Pre-emphasis Circuit	$R_1 = 2.5$ kΩ, $C_1 = 10$ pF, $R_2 = 1$ kΩ $R_3 = 150$ Ω, $R_4 = 500$ Ω
LED Drive Current	200 mA
TIA Gain	$R_F = 7.5$ kΩ
TIA Compensation Capacitor	$C_F = 0.2$ pF
3 dB Cutoff Frequency of High-pass Filter	159 Hz
Photo Detector Detection Area	9 mm^2
Capacitor of Photodiode	$C_D = 4.5$ pF when $V_B = 2.5$ V
Photo Sensitivity of Photodiode	0.3 A/W at 440 nm

All the experiments including system bandwidth measurement, BER versus data rate, and so on have been performed under the condition of the desired brightness level of ~1000 lx in front of the receiver. Brightness levels were measured by a light meter placed at the position of the receiver in the otherwise dark laboratory. Longer distance could be achieved if more identical LEDs were used. Furthermore, an operational amplifier OPA847 was applied to design the TIA circuit as shown in Fig. 3.

Figure 4 shows the LED optical spectrum measured by a spectrograph. It can be seen that the emitted white light consists of a blue component and a yellow component from the phosphor. The peak wavelength of LED blue light is 440 nm. And the blue optical power is only 20% of the overall emitted power.

For phosphor-based white LED, the bandwidth of white light response is only 3 MHz limited by slow response of phosphorescent component as shown in Fig. 5. Blue filter can suppress the phosphorescent portion of the optical spectrum, leaving the faster directed modulated blue light. With blue filter, the bandwidth of VLC system is improved to 12 MHz which is measured 3 dB cutoff frequency of receiver as shown in Fig. 5. Pre-emphasis circuit can decrease the response in the low-frequency region; relatively increasing the amplitude of signal in the high-frequency component. Figure 5 shows the normalized response of pre-emphasis circuit. The range of pre-emphasis signal magnitude changes from 0 to 6 dB range. With the pre-emphasis circuit, the bandwidth of VLC system becomes 77.6 MHz (measured 3 dB cutoff frequency of receiver).

In Fig. 5, it also can be seen that as frequency changes from 30 to 70 MHz, the response of blue light remains flat. This is a normal phenomenon caused by compensation capacitor C_F. In general, the most important key elements to the TIA design are R_F and C_F, and the TIA gain R_F we designed is 7.5 kΩ. Smaller capacitor value and higher bandwidth of VLC link can be achieved. Compensation capacitor C_F can be set to control the frequency response of TIA and makes the response flat in frequency region from 30 to 70 MHz. It is necessary to use TIA load capacitor C_L to improve phase margin and avoid self-oscillating. In short, for an optimized designing of TIA the proper compensation capacitor value should be chosen.

Furthermore, to verify the VLC system transform performance, eye diagrams and BER measurements as a function of data rate and received blue optical power were performed. A pseudorandom binary sequence-9 ($2^9 - 1$) NRZ–OOK data stream with a peak–to–peak voltage swing of 0.6 V is used to modulate the emitted light. Figure 6 shows the eye diagram of VLC system with pre-emphasis circuit. The eye diagram has clear and open eyes when the data rates are 50, 100, 160, and even 200 Mb/s, and the magnitude of eye diagram is about 500 mV. Eye diagrams were measured by wide-band oscilloscope (Agilent 86100C).

Figure 6 shows the measured data rate achieved when detecting blue component with the pre-emphasis circuit or without the pre-emphasis circuit. Without the pre-emphasis circuit, the data rate achieved is 86 Mb/s with

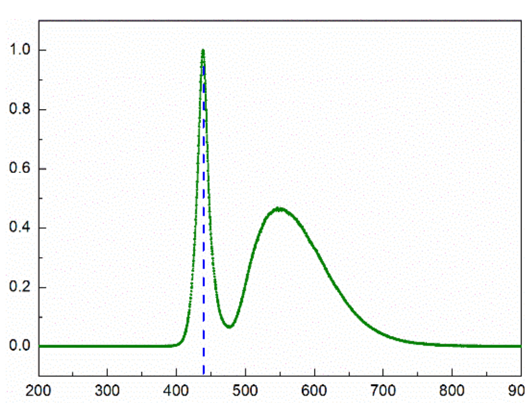

Fig. 4. Measured LED optical spectrum.

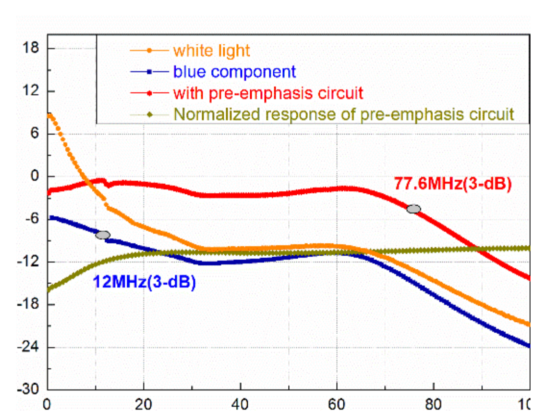

Fig. 5. EOE system frequency response of different cases (without pre-emphasis circuit, with pre-emphasis circuit, and normalized response of pre-emphasis circuit).

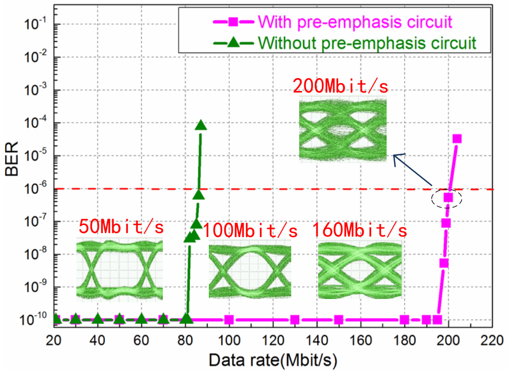

Fig. 6. BER versus transmission data rate (with pre-emphasis circuit or without pre-emphasis circuit). BER below 10^{-10} is truncated to this threshold. Inset: Eye diagram of VLC system with pre-emphasis circuit at different data rates (50, 100, 160, and 200 Mb/s).

BER of 6.0 × 10^{-7} which is below 10^{-6}. From the above analysis, we can see that the compensation capacitor C_F could make the response flat in frequency region from 30 to 70 MHz. Such flat region helps the data rate improve to 86 Mb/s. With pre-emphasis circuit, the data rate achieved is 200 Mb/s with BER of 5.3 × 10^{-7} which is below 10^{-6}. All the above experimental results of BER are measured by BER tester (Agilent 81250).

Figure 7 shows the BER versus measured received blue-light optical power. We can read smallest received blue optical power at different data rates with a certain low BER; in other words, the curve in Fig. 7 reflects the sensitivity of receiver. Higher data rate means higher received optical power to overcome the signal-to-noise penalty. Compared with post-equalization technology[7], pre-emphasis technology could improve the sensitivity of optical receiver significantly.

In conclusion, we describe a simple VLC pre-emphasis circuit and present a high-speed VLC link using a commercially available phosphorescent white LED. With blue-filtering and pre-emphasis circuit, the VLC system bandwidth increases from 3 to 77.6 MHz in our VLC system, which allows NRZ–OOK data transmission up to 200 Mb/s with the BER below 10^{-6}. The VLC link operates at the room illumination level of ~1000 lx at 1.1 m range using a single 1 W white LED. Longer distance can be achieved if more identical LEDs are used. The parameters of pre-emphasis circuit should be carefully chosen and the amplifier needs a wide bandwidth. To the best of our knowledge, VLC pre-emphasis circuit can be applied to pulse amplitude modulation, OFDM, and other advanced modulation formats. We suggest spectrally efficient modulation techniques combing pre-emphasis circuit to improve the VLC link transmission data rate.

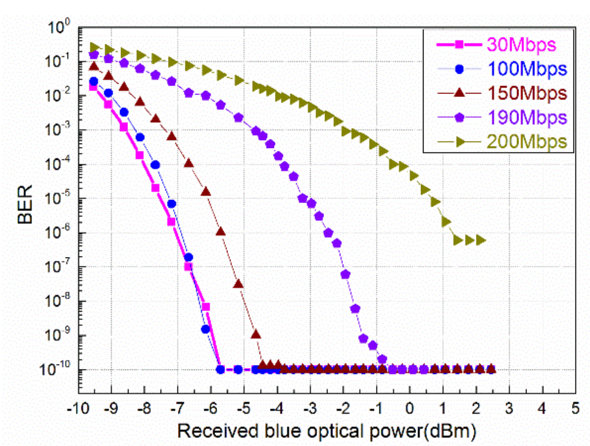

Fig. 7. BER versus received blue-light optical power at different data rates (30, 100, 150, 190, and 200 Mb/s).

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