

# Improved modulation speed of LED visible light communication system integrated to main electricity network

C.W. Chow, C.H. Yeh, Y.F. Liu and Y. Liu

In addition to the illumination purpose, using a light-emitting diode (LED) for indoor optical wireless communication has attracted much attention recently. Proposed and demonstrated is the use of a simple on-off keying (OOK) predistortion scheme together with a simple first-order resistance-capacitance equalisation circuit to increase the modulation speed of a white-light high-brightness LED (HB-LED). Optical filtering and complicated modulation formats are not required. Since only OOK modulation is used, the signal modulation and detection are very simple. Also are compared the different combinations of the system designs. By using first-order equalisation together with a predistortion, a bit-error rate of  $<10^{-10}$  at 10 Mbit/s can be easily achieved when using the 1 MHz bandwidth phosphor-based white HB-LED.

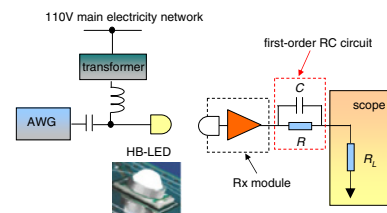
**Introduction:** Owing to the improvement in light-emitting efficiency of the light-emitting diode (LED) and the reduction in cost, it is believed that LED lighting can replace the traditional illumination system in the near future. The power consumption of LEDs is much less than that of traditional lighting, hence it is environmentally friendly. Besides the lighting purpose, the relatively high modulation speed ( $\sim 1$  MHz) of the high-brightness LED (HB-LED) also allows visible light communication (VLC) [1–3]. The LED light can also be connected to the main electricity network, hence, performing optical wireless communication for in-home without adding the burden to the existing and crowded radio frequency (RF) broadband network [4]. The VLC can provide many advantages, such as providing a secure communication link, since the light beam is visible and directional, and providing wireless communication in some radio-frequency (RF) communication restricted areas, such as in hospitals or in an aircraft. The usage of RF communications on such occasions may disturb the other devices and equipment which are related to the lives of people.

Using separate red, green, blue (RGB) LEDs and using a blue LED with phosphor are the two main approaches to implement the HB-LED. The approach of using a blue LED with phosphor is attractive for lighting applications because it does not require three separate LEDs. Hence it is simple and low cost. However, when this type of LED is used for VLC, the direct modulation speed is limited to 1 MHz by the relaxation time of the phosphor. This means that, by using simple on-off keying (OOK) direct modulation, a data rate of up to only 1 Mbit/s can be performed, and this is not enough for future indoor communications. Approaches of using a blue filter at the receiver (Rx) to remove the slow yellow light [5], or using spectrally efficient advanced modulation formats, like discrete multitone (DMT) [6], have been proposed to improve the modulation speed. However, using a blue filter could highly attenuate the signal and reduces the transmission length of the VLC. Using advanced modulation formats will complicate the transmitter (Tx) and Rx designs, and it will increase the cost for the cost-sensitive lighting system and consumer electronics.

In this Letter, we propose and demonstrate the use of a simple OOK predistortion scheme together with a simple first-order resistance-capacitance (RC) equalisation circuit to increase the modulation data rate of a white-light HB-LED. Only OOK modulation is used, which makes the signal generation and detection very simple. Optical filtering and advanced modulation formats are not required. By using first-order equalisation together with a predistortion scheme, a bit-error rate (BER) of  $<10^{-10}$  at 10 Mbit/s operation can be achieved when using the 1 MHz bandwidth phosphor-based white HB-LED.

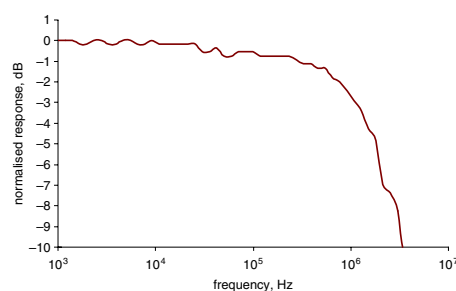
**Experiment:** Fig. 1 shows the experimental setup of the proposed improved modulation speed LED VLC system integrated to the main electricity network. The HB-LED was obtained from Cree (XLamp XR-E LED). It was cool-white in colour, having about 100 lm output when driving at 350 mA. An arbitrary waveform generator (AWG) (Agilent 33220A) with maximum operation speed of 20 MHz was connected to the HB-LED via a bias-tee. The other input port of the bias-tee was connected to a transformer, which stepped down and rectified the 110 V, 50 Hz main electricity to a 3 V DC signal for driving the HB-LED. The modulated white light emitted from the HB-LED first passed through a focusing lens, transmitted a distance of about 1 m

and then received by a silicon-based *pin* Rx (Thorlabs PDA36A). The Rx has a detection wavelength range of 350–1100 nm with responsivity of 0.65 A/W and an active area of 13 mm<sup>2</sup>. It has a bandwidth of 17 MHz and a root mean square (RMS) noise of 530  $\mu$ V. The received electrical signal was then amplified by a wideband coaxial amplifier (Mini-Circuit ZHL-6A), which was connected to a real-time oscilloscope (Tektronix TDS3014C).

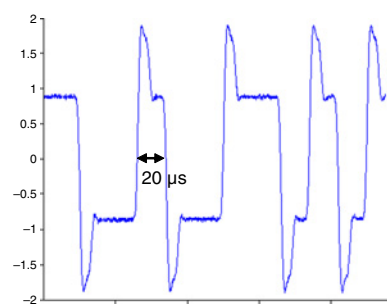


**Fig. 1** Experimental setup of proposed improved modulation speed LED VLC system integrated to main electricity network

**Results:** First, we evaluated the modulation speed of the HB-LED by using the experimental setup as shown in Fig. 1. A sweep driving frequency from 1 kHz to 10 MHz was applied to the HB-LED and the frequency response of the HB-LED was measured. Fig. 2 shows the measured normalised frequency response of the white phosphor-based HB-LED used in the experiment. The 3 dB bandwidth of the LED is slightly larger than 1 MHz, which is the typical modulation speed of the white phosphor-based HB-LED as reported in [6].



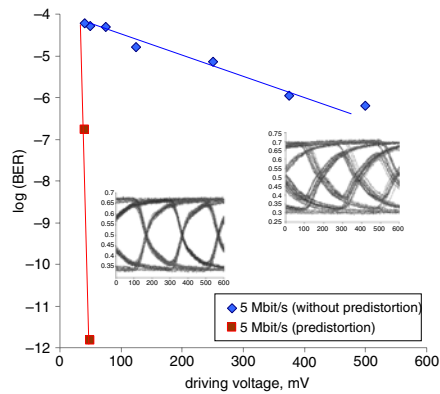
**Fig. 2** Measured normalised frequency response of white phosphor-based HB-LED used in experiment



**Fig. 3** Measured driving voltage from AWG using predistortion scheme with signal over-shoot and under-shoot

Then bit-error rates (BERs) were measured to evaluate the performance of the VLC links. A 5 Mbit/s pseudorandom binary sequence (PRBS) of  $2^{10} - 1$  signal generated by the AWG was applied to the LED. Fig. 3 shows the measured electrical predistorted driving voltage from the AWG with signal over-shoot and under-shoot. In the predistortion scheme, the peak-to-peak voltage outside the signal over-shoot and under-shoot regions was purposely reduced in order to keep the same root-mean square (RMS) voltage driving condition. The duty cycle of the over-shoot and under-shoot is  $0.5/T$ , where  $T$  is the bit-period. Fig. 4 shows the 5 Mbit/s BER curves without and with the predistortion schemes. For the HB-LED without using the precompensation scheme, an error floor appears at BER of  $10^{-6}$ . This is due to the limited modulation speed of the HB-LED, which only has a 3 dB modulation bandwidth of about 1 MHz. Hence we can observe at the inset eye diagram that the eye opening is small due to the high inter-symbol

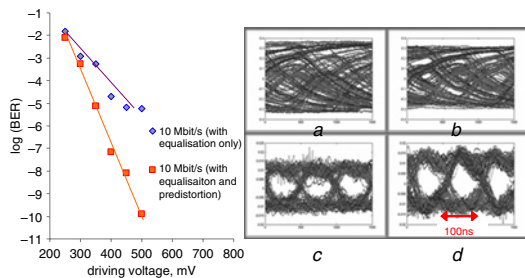
interference (ISI). When using the predistortion scheme, error free ( $<10^{-12}$ ) operation can be achieved without observing any error floor.



**Fig. 4** Measured 5 Mbit/s BER curves without and with predistortion scheme

Insets: Corresponding eye diagrams

Next, we increased the modulation speed to 10 Mbit/s. BER cannot be measured even in the case of using signal predistortion. Hence, we included a RC equalisation circuit at the Rx as shown in Fig. 1. The first-order RC equalisation circuit is a parallel-connected resistor and capacitor [6]. The values of the resistor (2.5 k $\Omega$ ) and capacitor (30 pF) were properly selected to optimise the experiment. Fig. 5 shows the 10 Mbit/s BER measurements. We can observe that the eye diagrams are completely closed for the following cases: without using predistortion and RC-equalisation, and using predistortion only, as shown in Figs. 5a and b, respectively. When only the RC-equalisation was used, improved performance can be observed, and a BER of  $10^{-5}$  can be measured with an error floor. When using both the predistortion and RC-equalisation, error-free operation of BER  $<10^{-10}$  can be measured, with a widely open eye diagram as shown in Fig. 5d. The experimental results show that the equalisation plays an important role for synchronisation, and the predistortion scheme can further improve the signal-to-noise ratio.



**Fig. 5** Measured 10 Mbit/s BER curves with equalisation only and with both equalisation and predistortion

Insets: Eye diagrams of a without using predistortion and RC-equalisation, b using predistortion only, c using RC-equalisation only, and d using both predistortion and RC-equalisation

**Conclusions:** We have developed a 10 Mbit/s white LED VLC system. By using simple signal predistortion and simple first-order RC-equalisation, a BER of  $<10^{-10}$  at 10 Mbit/s operation can be easily achieved when using the 1 MHz bandwidth white-light HB-LED. Optical filtering and advanced modulation formats are not required.

**Acknowledgment:** This work was supported in part by the National Science Council, Taiwan under contracts NSC-97-2221-E-009-038-MY3, NSC-98-2221-E-009-017-MY3.

© The Institution of Engineering and Technology 2011

15 February 2011

doi: 10.1049/el.2011.0422

One or more of the Figures in this Letter are available in colour online.

C.W. Chow and Y.F. Liu (Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Rm 216A, Tin Ka Ping Building, Hsinchu 30010, Taiwan)

E-mail: cwchow@faculty.nctu.edu.tw

C.H. Yeh (Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Hsinchu 31040, Taiwan)

Y. Liu (Hong Kong Productivity Council (HKPC), Hong Kong)

## References

- 1 Komine, T., and Nakagawa, M.: 'Fundamental analysis for visible-light communication system using LED lights', *IEEE Trans. Consum. Electron.*, 2004, **50**, pp. 100–107
- 2 Le Minh, H., Ghassemlooy, Z., O'Brien, D., and Faulkner, G.: 'Indoor gigabit optical wireless communications: challenges and possibilities'. Proc. Int. Cong. Transparent Optical Networks, Munich, Germany, 2010, (Th.A3.1)
- 3 O'Brien, D., Faulkner, G., Le Minh, H., Bouchet, O., El Tabach, M., Wolf, M., Walewski, J.W., Randel, S., Nerreter, S., Franke, M., Langer, K.-D., Grubor, J., and Kamalakis, T.: 'Home access networks using optical wireless transmission'. Proc. Personal, Indoor and Mobile Radio Communications, Cannes, France, 2008, pp. 1–5
- 4 Komine, T., and Nakagawa, M.: 'Integrated system of white LED visible-light communication and power-line communication', *IEEE Trans. Consum. Electron.*, 2003, **49**, pp. 71–79
- 5 Vučić, J., Kottke, C., Nerreter, S., Buttner, A., Langer, K.-D., and Walewski, J.W.: 'White light wireless transmission at 200+ Mb/s net data rate by use of discrete-multitone modulation', *IEEE Photonics Technol. Lett.*, 2009, **21**, pp. 1511–1513
- 6 Le Minh, H., O'Brien, D., Faulkner, G., Zeng, L., Lee, L., Jung, D., Oh, Y., and Won, E.T.: '100-Mb/s NRZ visible light communications using a postequalized white LED', *IEEE Photonics Technol. Lett.*, 2009, **21**, pp. 1063–1065