100-Mb/s NRZ Visible Light Communications Using a Postequalized White LED

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***Abstract*—This letter describes a high-speed visible light communications link that uses a white-light light-emitting diode (LED). Such devices have bandwidths of few megahertz, severely limiting the data rates of any communication system. Here, we demonstrate that by detecting only the blue component of the LED, and using a simple first-order analogue equalizer, a data rate of 100 Mb/s can be achieved using on–off keying nonreturn-to-zero modulation.**

***Index Terms*—Blue-filter, equalization, light-emitting diode (LED), modulation bandwidth.**

I. Introduction

Modern solid-state lighting that uses light-emitting diodes (LEDs) is increasingly used in a broad range of signaling, display, and illumination applications. As the cost of LEDs falls and their efficiency increases, there is the potential for them to become the dominant standard for general illumination. Additionally, these devices have wide modulation bandwidth (compared with other lighting sources). Using these visible-light sources for both illumination and communications is, therefore, an attractive option. Visible light communications (VLC) is a rapidly growing research area [1], with interest in Asia, Europe, and the U.S. [2]–[4].

There are two types of white-light LEDs used in lighting: 1) devices that use separate red–green–blue emitters, and 2) those that use a blue emitter in combination with a phosphor that emits yellow light. This latter approach is attractive for general illumination due to its lower complexity when compared with the three-emitter device.

One of the main challenges for VLC is providing high data-rate communications using the limited bandwidth of these phosphor-based emitters. This is typically a few megahertz [5], and is caused by the slow time constant of the phosphor. There are a number of approaches to improve the modulation bandwidth, including using a blue-filter at the receiver to filter out the slow yellow component [5], and equalization of the driving circuitry [6]. In both approaches, the VLC modulation bandwidth achieved is approximately 20 MHz, which allows on–off-keying (OOK) nonreturn-to-zero (NRZ) data transmission at approximately 40 Mb/s. A higher data transmission rate at 100 Mb/s over this limited bandwidth can be achieved using modulation techniques such as discrete multitone modulation (DMT), as is reported in [5].

In this letter, we show that using blue filtering in combination with simple receiver equalization, a bandwidth of 50 MHz and data link operating at 100 Mb/s (OOK-NRZ) can be achieved. Such a link is straightforward to implement, and provides an alternative approach to the DMT reported in [5]. The advantage over the technique reported in [6] is that both the blue filtering and equalization are at the receiver, so that complex drive electronics that must be used for every illumination LED is not required. A typical application for such a link is data broadcasting, where a room is illuminated by LEDs that also transmit data. In this case, a large number of LEDs is required, so removing complex drive electronics at the LED simplifies the system significantly.

This letter is organized as follows: the characteristics of the LED are described, and then the equalizer design introduced. The link experiment and results are then detailed, and conclusions drawn.

II. VLC Postequalization

A. LED Response

The measured optical spectrum of a typical white-light (Luxeon STAR) LED is show in Fig. 1(a). It can be seen that the emitted white light consists of a blue component (containing 10% of the overall emitted power) from the LED and a yellow component from the phosphor. The measured frequency responses of different components (white, blue, and yellow) of the emission are shown in Fig. 1(b).

The bandwidth of the white-light response is only 2.5 MHz whereas the blue light response is approximately 14 MHz. The blue response (decibels) can be modeled by the first-order function

$$H_b(\omega) = e^{-\omega/\omega_b} \tag{1}$$

with the fitted coefficient ω_b is equal to $2\pi \times 15.5 \times 10^6$ rads/s. The slope of this approximate curve s_b is determined as -0.24 dB/MHz. The root mean square error between the fitted and actual response slope is 0.08 dB/MHz.

B. Equalization

Fig. 2 shows a diagram of the equalized VLC system under consideration. The VLC transmitter consists of a white Luxeon Star LED (with a 45° beam-shaping lens) whose emitted light is modulated and driven by a data signal and a direct current

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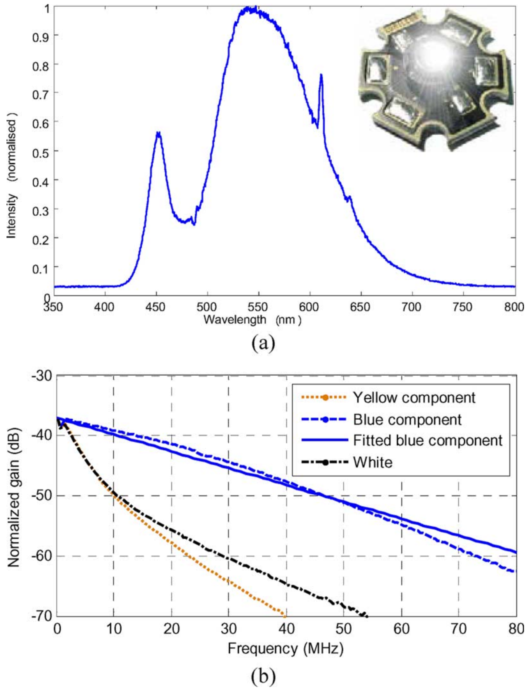

Fig. 1. (a) LED optical spectrum, inset: Luxeon white LED, and (b) modulation bandwidths of individual components and blue-response fitting curve.

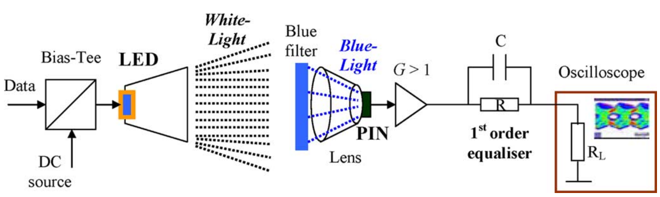

Fig. 2. VLC system with postequalizer.

(dc) via a bias tee. The dc biases the LED in its linear region of operation and also creates sufficient average light power for illumination.

At the receiver, light is collected and the yellow component is blocked by a blue filter and concentration lens and then converted to an electrical signal by a PIN photodetector. The signal is amplified using a transimpedance amplifier and equalized using a first-order equalizer.

The equalizer comprises a capacitor in parallel with a resistor. The equalizer frequency response is expressed by

$$H_e(\omega) = \frac{1}{k} \times \frac{1 + j\omega T}{1 + j\omega \frac{T}{k}} \tag{2}$$

where $1/k = R_L/(R + R_L)$ and $T = RC$. R_L is the load impedance. The magnitude of the equalizer response is

$$|H_e(\omega)| = \frac{1}{k} \times \sqrt{\frac{1 + \omega^2 T^2}{1 + \omega^2 \left(\frac{T}{k}\right)^2}}. \tag{3}$$

Note that $1/k$ is the dc coefficient of the equalizer ($\omega = 0$). The 3-dB point above this equalized dc value is computed as

$$\omega_{3\text{ dB}} = \frac{1}{T}\sqrt{\frac{1}{1 - \frac{2}{k^2}}}. \tag{4}$$

TABLE I
VLC SYSTEM PARAMETERS

Parameters	Values
Luxeon LED part number	LXHL-MW1B
LED drive current	200 mA
Optical modulation depth	40%
LED beam angle (Full width half maximum)	45°
Receiver concentration lens diameter	30 mm
Blue filter central wavelength and width	450 nm, 40nm (60% through)
Photodetector (OSD-15T) detection area	15 mm^2
Preamplifier (Max3664) TIA gain	6KΩ
Preamplifier input-referred noise	55 nA_{RMS}
Receiver input dynamic range	28 dB
Optoelectronic receiver bandwidth	77 MHz
Equalizer capacitor	15 pF
Equalizer resistor	750 Ω
Load (oscilloscope-input impedance)	50 Ω
Electrical low pass filter cut-off frequency	0.7×data-rate

This 3-dB point exists if $k > \sqrt{2}$. $|H_e(\omega)|$ is approximately linear around this 3-dB point. The slope of this response, s_e (dB/MHz), can be, therefore, approximated by

$$s_e = \frac{6\pi T_1}{\sqrt{\frac{1}{1 - \frac{2}{k^2}}}}. \tag{5}$$

Equalization of the blue-light response requires that $s_e = -s_b$ for balancing the contributions of low and high frequency components. From Fig. 1, the predicted bandwidth $\mathrm{BW}_{\max}$ achieved by equalization can be approximately estimated by

$$\mathrm{BW}_{\max} \leq \frac{20\log_{10}(k)}{-s_b}. \tag{6}$$

Selection of T and k according to (5) and (6) will determine the equalized bandwidth and the gain of the equalized signal. Choosing a higher value of k will allow more margin to equalize a wider modulation bandwidth (6). However, this k value is constrained by the input dynamic range ΔP of the receiver, which is determined by the difference between 1) the receiver saturation (maximum allowable power) and 2) the receiver sensitivity (minimum required power) of the PIN and preamplifier due to the effect of signal saturation and low signal-to-noise-ratio, respectively. The constraint, therefore, is

$$|\ 20\log_{10}(k)\ | \leq \Delta P. \tag{7}$$

The equalization process involves the following steps:

1) determine the input dynamic range of the receiver;
2) calculate the possible dc coefficient, maximum bandwidth from (6) and (7), and R;
3) calculate T and determine C.

III. EXPERIMENTAL RESULTS

We first illustrate the equalization process and then demonstrate it in VLC data transmission. The configuration of the VLC system demonstrated is shown in Fig. 2. The link operates over a short distance (10 cm), but this could be extended by using an array of identical LED emitters, as would be typical in LED-based lighting. Parameters used for the link are shown in Table I. Fig. 3(a) and (b) shows the frequency response of

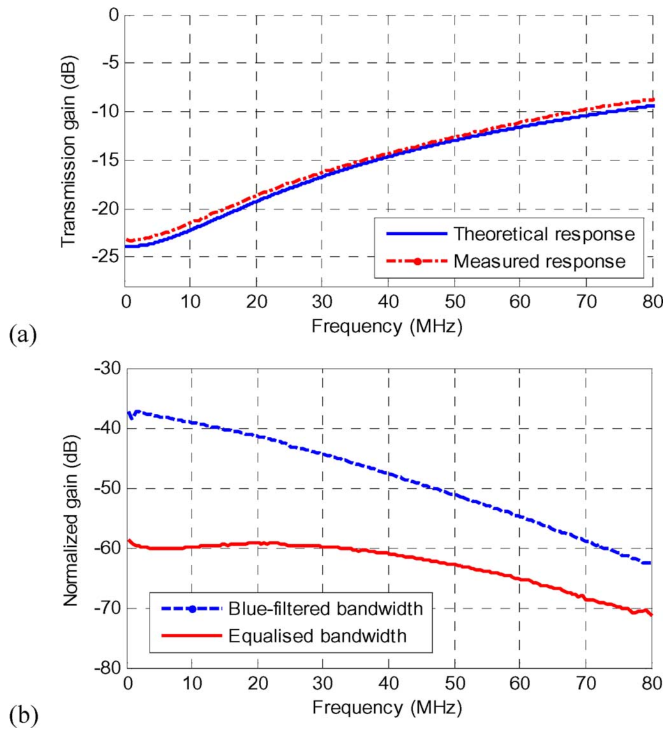

Fig. 3. (a) Theoretical and measured (RC-based) equalizer frequency response, and (b) (measured) equalized modulation bandwidth of 50 MHz using $R = 740\ \Omega$ and $C = 15$ pF.

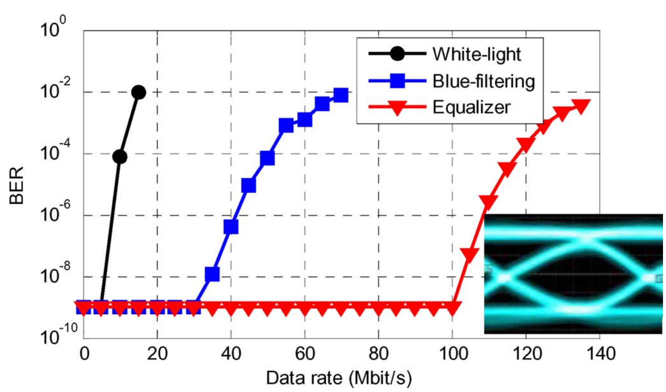

Fig. 4. Evaluated BER versus transmission data rate (for unequalized white and blue-filtering lights and equalized cases). BER below 10^{-9} is truncated to this threshold. Inset: Eye diagram at 100 Mb/s.

an equalizer and the corresponding equalized VLC bandwidth achieved using that. The RC parameters of the equalizer are selected such that the equalization response slope value is close to $-s_b$. It can be seen that a bandwidth of 50 MHz is achieved, when the receiver input dynamic range is 28 dB (Max3664 transimpedance amplifier). The measured bandwidth is less than that predicted [about 80 MHz, from (6)] due to the approximations made in the modeling. The LED response is modeled by a linear function, and the equalization is achieved by using a linear approximation of the equalizer slope to match the modeled LED slope. More sophisticated models may, therefore, allow better agreement, and also potentially higher bandwidth equalization to be achieved.

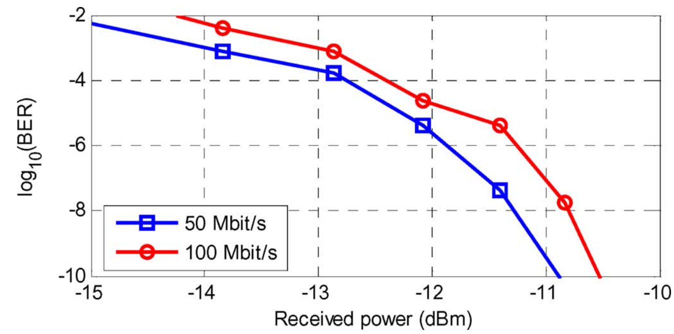

Fig. 5. BER versus received blue optical power at different data rate.

A pseudorandom binary sequence (PRBS)-10 ($2^{10} - 1$) OOK-NRZ data stream with a peak-to-peak voltage swing of 2.5 V is used to modulate the emitted light (corresponding to a 40% optical modulation depth). A short PRBS is used as its length is comparable to packet lengths in Ethernet networks. Fig. 4 shows the measured bit-error-rate (BER) performance versus data rate of the VLC system. It is shown that the raw data rate achieved when detecting white light and only the blue light carrier are approximately 5 and 40 Mb/s for BER threshold of 10^{-9}, respectively. Using the equalizer shown in Fig. 3 increases the data rate to 100 Mb/s at this BER level. Inset is the eye-diagram of the equalized data at 100 Mb/s showing clear eye opening.

Fig. 5 shows the BER against measured received blue-light optical power. This shows that relatively high levels of optical power are required to overcome the signal to noise penalty due to equalization, although optimization of the receiver design is likely to reduce this.

IV. Conclusion

This letter has presented a simple and low-cost approach to equalize the modulation bandwidth of white-LED-based VLC system. The bandwidth achieved is 50 MHz (25 times wider than unequalized LED bandwidth). Data transmission in VLC system is experimentally demonstrated showing that a 100-Mb/s NRZ transmission can be achieved with low BER.

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