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AC-based phosphor LED visible light communication by utilizing novel signal modulation

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Abstract We propose and demonstrate a new AC-light emitting diode based visible light communication system, in which the message signal is up-converted to 400 kHz frequency band and combine with the 60 Hz AC-power from the outlet. A special design bias-tee circuit is first implemented to combine the message signal and the AC-power for minimizing the signal distortion. Thus, the spectra of both signals are well separated. A special design clock recovery is used to synchronize the AC-power with the message signal; hence the message signal can be correctly applied to the rectified AC-power cycle.

Keywords AC LED · Visible light communication (VLC) · Networking

1 Introduction

Light emitting diodes (LEDs) have the benefits of high-efficiency, low-cost and long lifetime etc. Hence, LED would be important for general lighting in the near future. Furthermore, LED could also be used in visible light communication (VLC) due to its characteristic of faster modulation speed when compared with the conventional lighting sources, such as fluorescent lamp. Besides, the LED VLC transmission can provide the advantages of license-free, electromagnetic interference free (EMI-free), and cable free wireless communications. However, due to the direct modulation bandwidth limitation of the LED, digital equalizations

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and blue filter were used to enhance the VLC modulation speed (Wang et al. 2012; Khalid et al. 2011; Chow et al. 2011). Besides, the modulation formats of orthogonal frequency division multiplexing (OFDM), discrete multi-tone (DMT), and electrical pre-distortion have been investigated to increase the data rate of LED VLC. However, nearly all the VLC is implemented by using DC-powered LED (Chow et al. 2011; Wang et al. 2011; Vucic et al. 2010).

Recently, in order to drive the LED lamp directly from the AC-power outlet, AC-powered LED has been proposed for general lighting (Jung et al. 2011). However, the demonstration of using AC-powered LED for VLC is very little. One example is employing a micro-controller for encoding the on-off keying (OOK) signal onto the AC-powered LED (Jenq et al. 2011). In this example, as the modulation depth of the OOK varies during the AC cycle from the outlet, the demodulation using the high-pass filter would distort the OOK signal. Besides, the micro-controller only provided very low data rate for the AC-LED VLC system and the bit-error-rate (BER) evaluation is missing.

In this work, we propose and demonstrate a new AC-LED based VLC system, in which the message signal is up-converted to 400 kHz frequency band and combine with the 60 Hz AC-power from the outlet. A special design bias-tee circuit is implemented to combine the message signal and the AC-power for minimizing the signal distortion. The bias-tee circuit has three ports; two of them are the input ports and one of them is the output ports. The input ports are designed so that one port coupled the low-frequency signals to the output and the other port coupled the high-frequency signals to the output. The signal leakage has to be blocked for the signal to transmit from one input port to the other input port. The spectra of both signals from input ports are well separated. A special design clock recovery is used to synchronize the AC-power with the message signal; hence the message signal can be correctly applied to the rectified AC-power cycle. The message signal was operated at a symbol rate of 200 kbit/s within the rectified AC-power cycle (the average data rate is 60 kbit/s). The BER of $\sim 10^{-9}$ was achieved under a transmission distance of 2 m.

2 Experiment and results

The experimental setup of our proposed VLC system is shown in Fig. 1. Here, the AC power was also converted to 9 V_{rms} from 110 V_{rms} from the 60 Hz AC-power outlet. It was then sent to the clock recovery circuit. The clock recovery circuit generated a 60 Hz square wave for an arbitrary waveform generator (AWG, Agilent 33220A). Moreover, a half-wave rectifier is used to clip the negative voltage part of the AC signal. In the experiment, the AWG was operated in burst-mode and triggered by the clock signal from clock recovery circuit. The 200 kbit/s OOK signal was modulated in a 400 kHz carrier in the digital domain, when the arbitrary waveform was in 1,000-symbol duration (5 ms).

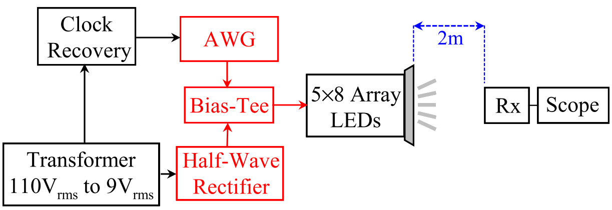

Fig. 1 Experimental setup of the proposed AC-LED VLC system

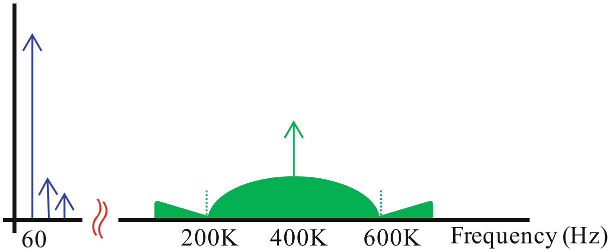

Fig. 2 Schematics output spectra of the AC-power and message signal after the bias-tee

The AC signal and message signal was combined by a bias-tee. The output of the bias-tee was a linear combination of AC signal and message signal. It was used to drive the 40(5 $\times$ 8) LED-array for lighting and VLC. The LED-array deployed in the measurement was commercially available, with maximum driving voltage of 12 V. Using the message signal source alone cannot provide enough driving current for the 40 LEDs. Hence, with the aid of AC-power via the bias-tee and the synchronization via the clock recovery circuit, the LED can be properly biased at the linear region with error-free VLC transmission. After a free-space transmission of 2 m, the visible light was received by the PIN receiver (Thorlabs PDA36A) and the electrical signal was captured by the real-time oscilloscope (Tektronix DPO 7354C). Here the received pattern was synchronized to the pattern of AWG and the half-rectified AC signal. Finally, the received digital waveform was processed by MATLAB program for BER evaluation.

Figure 2 shows the schematics power spectral density (PSD) of the electrical signal at the output of the bias-tee. The spectrum was the superposition of the half-wave rectified 60 Hz AC signal (Blue) and the up-converted OOK signal (Green). The PSD presented a mixed signal of a non-periodic message signal (hence using Fourier Transform, FT) and a periodic AC-power signal (hence using Generalized Fourier Transform). The arrow represented the scaling factor of a Dirac delta function. The graph presented the relative quantity and the exact scale may differ from different rectifier circuit and different modulation depth of the message signal. The mathematical expression of the baseband OOK message signal $s_1(t)$ in both time and frequency domain can be expressed in Eqs. (1) and (2) respectively:

$$s_1(t) = p(t) * rect\left(\frac{t}{T}\right) + 1 \tag{1}$$

$$S_1(f) = P(f) \times sinc\left(\frac{f}{F}\right) + \delta(f) \tag{2}$$

$p(t)$ is a one-period discrete-time bipolar pseudo random binary sequence (the value is randomly chosen from 1 or -1), F is the baud-rate and T is the period. $p(t)$ and $P(f)$ is a FT pair.

If we assume that $p(t)$ is long enough (in our experiment, the length of PRBS is 1,000), then its transform $P(f)$ is nearly constant over a wide frequency range. Thus $S_1(f)$ has an envelope profile of sinc function. The 400 kHz frequency up-conversion of $S_1(f)$ can be expressed mathematically by $S_2(f)$:

$$S_2(f) = S_1(f - 400K) + S_1(f + 400K) \tag{3}$$

As shown in Fig. 2, the message signal spectrum is well separated from the low frequency spectrum of the AC-power signal. The spectral separation minimizes the spectral overlapping

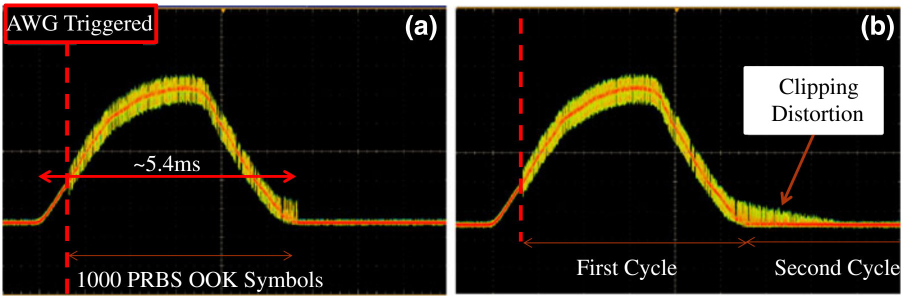

Fig. 3 Received waveform signals when **a** the message signal was correctly applied to the rectified AC-power cycle and **b** the message signal window was too long hence the AC-power clipping in the negative cycle creates message signal distortion

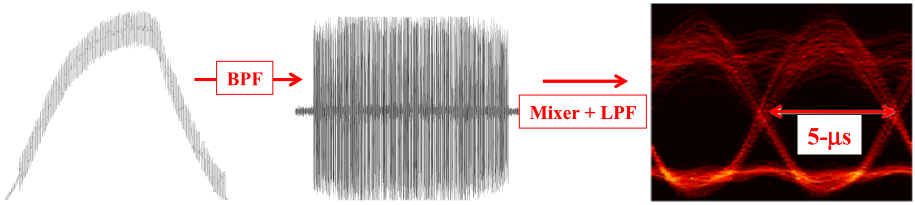

Fig. 4 The received waveform signals at different stages for post-processing

of AC power signal on the message signal, and we can demodulate the received signal without being affected by AC power signal using digital post-processing.

Figure 3a shows the received waveform signals when the message signal was correctly applied to the rectified AC-power cycle and Fig. 3b shows the message signal window was too long hence the AC-power clipping in the negative cycle creates message signal distortion. The properly superposition of the frequency up-converted message signal onto the rectified AC-power cycle shows that the proposed clock recovery circuit and bias-tee circuit are working correctly.

Figure 4 shows the received signals at different stages of post-processing. The received waveform by the real-time oscilloscope at the first stage was the superposition of the rectified 60 Hz AC-power signal and the message signal. Using the digital post-processing, the band-pass filter (BPF) with a pass-band from 200 to 400 kHz was applied to remove the low frequency AC-power signal. And the band-pass filtered waveform was an up-converted OOK signal. The second stage was a coherent mixer with a low-pass filter (LPF), which down-converted the signal to the baseband. Then, the processed waveform at baseband was analyzed by plotting the eye-diagram. The statistics at the best sampling point of the eye-diagram provide the quality (Q) factor of 6, which corresponds to the BER of $\sim 10^{-9}$. The bit rate was 60 kbit/s when using the half-wave rectified AC-power signal shown in this demonstration. The data rate could be doubled to 120 kbit/s if the full-wave rectified AC-power is used.

3 Conclusion

We have first proposed and demonstrated an AC-power signal-biased modulation in LED VLC system. A special design bias-tee circuit was used to combine the message signal and the AC-power signal, which provided the large bias-voltage for the LED array to be operated in the linear region. The baseband OOK message signal was frequency up-converted to avoid the spectral overlap with the AC-power signal, and the experiment was conducted to verify the design. A special design clock recovery was used to synchronize the AC-power with the message signal; hence the message signal can be correctly applied to the rectified AC-power cycle. A free-space VLC transmission system was demonstrated at a symbol rate of 200 kbit/s within the rectified AC-power cycle (the average data rate is 60 kbit/s). The achieved distance is 2 m with error-free performance.

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