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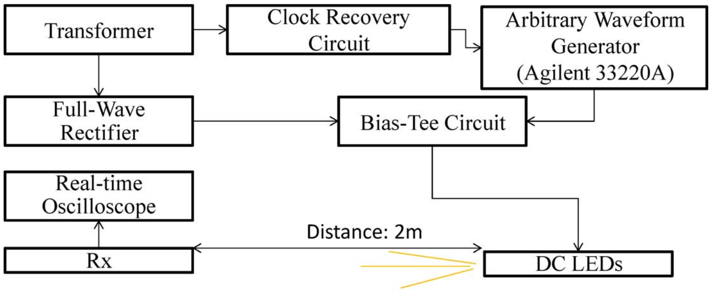

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Alternating-Signal-Biased System Design and Demonstration for Visible Light Communication

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Abstract: In the literature, previous system designs are mainly focused on the use of direct-current light-emitting diodes (DC-LEDs) with fixed voltage bias. As alternating-current (AC)-LEDs are more energy efficient and becoming more and more popular, a driving system supporting AC-LEDs providing lighting and visible light communication (VLC) functions is highly desirable. This paper investigates the alternating-signal-biased system design for VLC, which combines the AC bias voltage signal and electrical data signal to modulate both DC- and AC-LEDs. In the experiment, a 40-LED array is modulated by our proposed system that makes use of current from AC power source while maintaining nondistorted message signal transmission. On–off-keying and quadrature-phase-shift-keying formats are used, and data rates of 60 and 120 kb/s are demonstrated, respectively. The threshold voltage effect and the system extension to support AC-LED are discussed. The alternating-signal-biased system design supporting both DC- and AC-LEDs is also discussed.

Index Terms: Visible light communication (VLC), AC-LED, OOK, QPSK.

1. Introduction

The light emitting diode (LED) lighting provides the advantages of long-life time, low power, inherent safety and compact size; hence it is gradually replacing the conventional incandescent and fluorescent lighting. In addition to the lighting function, it can also provide visible light communications (VLC) for both in-door and out-door applications [1]–[10].

Recently, the LED-based VLC systems have attracted much attention. Different VLC system limitations have been analyzed and potential solutions are proposed to improve these VLC system. For example, solutions of using multiple-resonant equalization [1], post-equalization [2], and spectral-efficient modulation formats [3]–[7] have been proposed to enhance the frequency response of VLC channel. In those previous works, the system designs were focused on the use of DC-LEDs with fixed voltage bias. To provide current to many LEDs in a LED array, it is more energy-efficient to use the AC-LED, which has a circuit structure supporting alternating current [11]. Many AC-LED technologies have been widely researched to provide better lighting. In previous research of

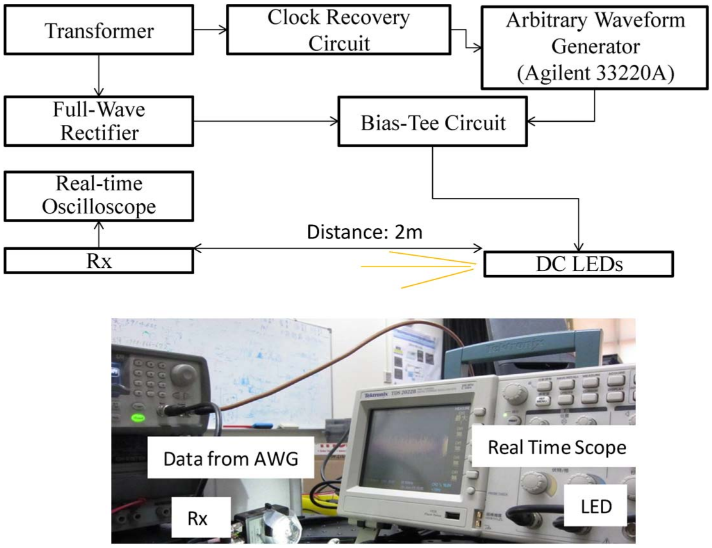

Fig. 1. Experimental setup of the alternating-signal-biased communication system. *Photo: equipment used*.

using AC-LED for VLC, a microcontroller was deployed; however no bit-error-rate (BER) analysis was provided [12], [13].

In this paper, we propose and demonstrate an alternating-signal-biased system design to enhance the system compatibility for both DC-LED and AC-LED. The system is designed using a synchronized signal modulation with clock recovery and bias-tee circuits. Under the test of modulation using both on-off keying (OOK) and quadrature-phase-shift-keying (QPSK), the system is verified to support 5 ms time slot without distortion caused by the threshold voltage limitation of LED. The system extension to support AC-LED has been proposed and analyzed.

2. Experiment and Discussions

The experimental setup for alternating-signal-biased system is shown in Fig. 1. The 110 V_{rms} with a frequency of 60 Hz is provided from power outlet and converted to 9 V_{rms} by transformer. The 9 V_{rms} signal is then connected to two devices: one to the clock recovery circuit and the other one to the full-wave rectifier for driving the LEDs. A 60 Hz square wave synchronized to the AC power bias signal is generated by the clock recovery circuit. This square wave has a duty cycle of $\sim$50%. The sinusoidal wave is rectified to have positive voltage only at the output of the full-wave rectifier.

Arbitrary waveform generator (AWG, Agilent 33220A, as shown in Fig. 1) generates both OOK and QPSK format signal with a symbol rate of 200 Ksymbol/s modulated on 400 kHz carrier. The square wave generated from clock recovery circuit provides the AWG the triggering signal for operating in burst mode. It can be triggered on either rising edge or falling edge of the clock signal. The output of the bias-tee circuit drives the LEDs. In this experiment, a 5 $\times$ 8-LED array (containing 40 LEDs) supporting a voltage up to 12 V is used. Then, after the free-space transmission of 2 m, a PIN Receiver (PIN Rx, Thorlabs PDA36A) is used for signal detection. The electrical signal from the Rx is recorded by the real-time oscilloscope (Tektronix DPO 7354C).

The measurements of this configuration were done with two different modulation formats by programming different *waveforms* on the AWG with proper burst settings controlled by recovered clock. The received waveforms are shown in Fig. 2(a) and (b) using the OOK and QPSK formats in AWG, respectively. We can observe that the rectified AC power bias signal is modulated by the data signal. By using a band-pass filter, the received signals can further be processed to remove the 60 Hz AC power signal. The filtered *waveform* is shown in Fig. 3(a) and (b), respectively.

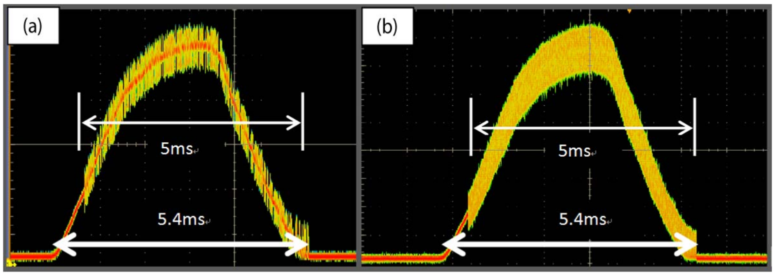

Fig. 2. (a) Measurement with OOK format and (b) with QPSK format.

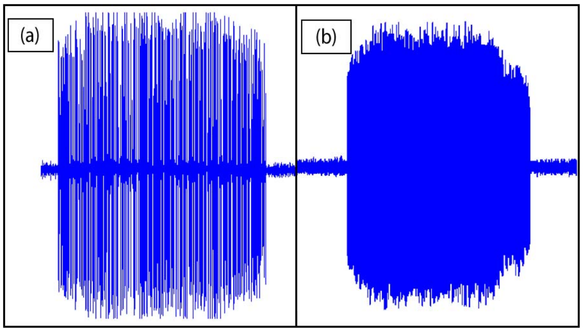

Fig. 3. Measurement of filtered wave in (a) OOK format and (b) QPSK format.

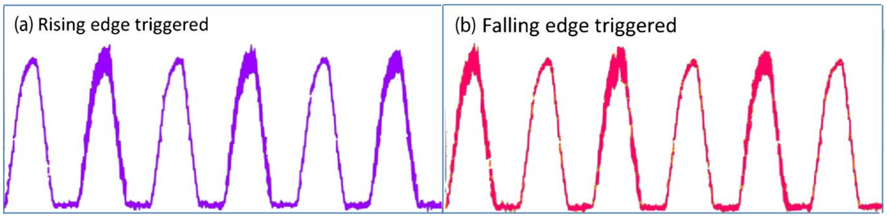

Fig. 4. Time domain waveforms for different trigger settings at transmitter with the same reference trigger for oscilloscope *using (a) rising edge triggered (b) falling edge triggered*.

The verification on the burst mode operation can also be checked with different trigger *settings* on the AWG. The recovered 60 Hz square wave synchronized to electrical AC power line was used as the trigger signal. The trigger setting was set to be triggered by either rising or falling edges. The trigger setting of the real-time oscilloscope was set to be triggered by the AC-line. As shown in Fig. 4, it can be observed in time-domain that the trigger setting can properly control the timing of the message transmission either on the first half cycle or the second half cycle of the 60 Hz wave.

The received signal is analyzed when *the* AWG is triggered on *the* rising edge. The transmitted message signal using OOK and QPSK formats are measured, respectively. *By tuning off the* transmitting message signal, it is observed that the optical signal is not clipped in a limited portion of time. The duration of a half period of the AC power bias signal is $\sim$8.33 ms, and the duration of the optical signal is $\sim$5.4 ms, which is $<$ 8.33 ms owing to the threshold voltage of LED. This duration of optical signal is taken as a time slot for transmitting data. In optical period, the AWG in burst mode transmitted a burst with 1000 symbols (OOK and QPSK). It can be observed that QPSK has a more constant envelope compared with that in OOK in Fig. 3.

Fig. 5 shows signal processing flow diagram used to demodulate the OOK and QPSK symbols, with the corresponding measured eye-diagram shown in Fig. 6. The detail description will be provided in next section. The measured eye-diagrams of OOK, I- and Q-channel of QPSK are

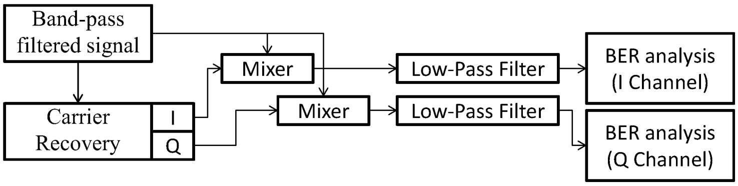

Fig. 5. Demodulation processing flow diagram for removing low-pass signal and down-converting the message signal.

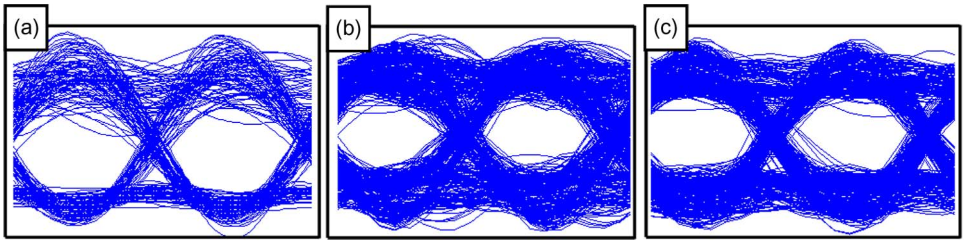

Fig. 6. Received *eye-diagrams of* (a) I-channel signal of OOK format, (b) I-channel signal of QPSK format, and (c) Q-channel signal of QPSK format.

shown in Fig. 6(a)–(c), respectively. The BER performance achieved is 6.26×10^{-10} for OOK format and 9.4×10^{-5} and 2.1×10^{-5} for I-channel and Q-channel signals of QPSK format, respectively.

3. Superposition and Separation of Bias and Modulation Signals in AC-Biased VLC System

In this section, the principle of superposition and separation of AC power and data signals will be discussed. In the signal superposition, a bias-tee circuit is used. It has two input ports and one output port. The driving signal at the output port is a linear combination of AC power bias signal and data signal.

To make the data signal undisturbed by the AC power bias signal, the signals are separated in frequency domain. However, due to the threshold voltage effect of LED, the design of non-overlapped signal spectra of signals is not sufficient to avoid signal distortion. The arrangement of the signal in time-domain is also important. For this reason, the clock recovery circuit aids to achieve non-distorted transmission.

The output of the bias-tee circuit generates a signal that is a linear combination of the two input signals. The rectified 60 Hz power bias signal has lower frequency spectrum, denoted as a(t) in time domain. The data signal using OOK or QPSK format has a higher frequency spectrum from 200 kHz to 400 kHz, denoted as b(t) in time domain. The output of the bias-tee circuit is represented in Eq. (1)

$$x(t) = C_1 a(t) + C_2 b(t). \tag{1}$$

The two constants C_1 and C_2 are the amplitudes, which are determined by the circuit design. This signal is then used to drive the LEDs, and the conversion from electrical signal to optical is related by the V–I characteristic curve of the LEDs. If we assume the input voltage is higher than the threshold voltage of the LEDs and the slope of the curve is C_3, the output optical signal can be represented in Eq. (2)

$$x_{\text{optical}}(t) = C_3(|C_1 a(t) + C_2 b(t)| - V_{\text{threshold}}). \tag{2}$$

The C_3 and $V_{\text{threshold}}$ are positive numbers and the above equation is valid only when the value of x_{optical} is larger than zero; otherwise the output optical signal is zero since the driving voltage is less than threshold voltage, and message signal $b(t)$ will be clipped.

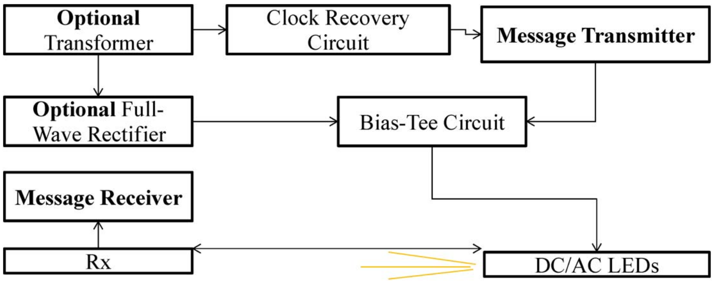

Fig. 7. Extended *system setup supporting* both DC/AC LEDs.

In the time interval where the electrical driving voltage is larger than the threshold voltage of the LEDs, we can calculate the transmitted signal spectrum with two terms and expressed as the following equation:

$$X_{\text{optical}}(f) = C_3(|C_1A(f) + C_2B(f)| - V_{\text{threshold}}(f)). \tag{3}$$

$A(f)$ represents the Fourier Transform of the clipped AC power bias signal. Since the frequency of the power signal is 60 Hz, the spectrum of $A(f)$ is distributed in low-frequency range below 1 kHz. The spectral distribution of data signal $B(f)$ ranges from 200 kHz to 600 kHz and the spectrum is centered at carrier frequency of 400 kHz. Since the spectral distribution is well separated, the band-pass filter can be used to receive the data signal without being disturbed by the AC power bias signal. However, the above equation is only valid when $b(t)$ is not clipped. Hence, the message signal has to be operated in burst mode to avoid loss of signal transmission.

Then, we describe our proposed system *that* can support the scenarios of using both DC-LED and AC-LED. Fig. 1 is modified to Fig. 7. The AWG block in Fig. 1 is generalized as an electrical message transmitter block in Fig. 7 that sends message in burst mode. The optional transformer generates AC-bias signal if a single DC-LED is used. It could be by-passed if the output load is serial-connected with many LEDs so that 110 V_{rms} can be directly used. The optional full-wave rectifier is activated for the DC-LED load; and could be by-passed for AC-LED load. Since the AC-LED has the function of rectifying, the rectifier can be by-passed in the case of using AC-LED as the output load. The oscilloscope is also generalized to be an electrical message receiver in Fig. 7. To describe the optical signal when output is connected with AC-LED, the mathematical functions is redefined with $a(t)$ representing the non-rectified electrical signal of AC power, and $b(t)$ represents electrical message signal from message transmitter. In a short single time-slot where the AC-LED is positively biased, the output optical power is described in Eq. (4)

$$X_{\text{optical}}(f) = C_3(C_1A(f) + C_2B(f) - V_{\text{threshold}}(f)). \tag{4}$$

For the time-slot where the AC-LED is negatively biased, the output optical power is described in Eq. (5)

$$X_{\text{optical}}(f) = C_3(-C_1A(f) - C_2B(f) + V_{\text{threshold}}(f)). \tag{5}$$

The two equations above are valid only when the values are positive. The output optical signal is positively proportional or negatively proportional to the electrical signal from message transmitter depending on the direction of current flow.

After using the band-pass filter, the $B(f)$ term which is the message component can be recovered but with alternating polarity due to the coefficients of C_2 and $-C_2$. The message receiver has to be designed with the capability of identifying the signal burst and the polarity change when the load is AC-LED. This adaptation can be achieved by a short training process. In the above analysis, the alternating-signal-biased system design is shown to support not only DC LED but also AC-LED.

4. Conclusion

Previous system designs were mainly focused on the use of DC-LEDs with fixed voltage bias. As AC-LED is more energy efficient and becoming more and more popular, driving system supporting AC-LED providing lighting and VLC is highly desirable. In this paper, the alternating-signal-biased system design for VLC *was* proposed and demonstrated. 40-LED array *was* modulated using OOK and QPSK signals, and the average data rates were 60 kb/s and 120 kb/s, respectively. The 5.4 ms time window *was* used to transmit 1000 symbols with the symbol rate of 200 Ksymbol/s. The threshold voltage effect and the system extension to support AC-LED was discussed. The alternating-signal-biased system design supporting both DC LED and AC-LED was also discussed.

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