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Indoor Wireless Voice Broadcasting System Using Three-Level LED Modulation

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Abstract: In this study, we implemented a visible light communication system for indoor voice broadcasting using three-level Light Emitting Diode (LED) modulation. In the transmitter, two parallel FETs were used as a three-level LED driver whose current was proportional to the sum of the sync pulse and the data bits. In the receiver to recover the transmitted data, a two-diode circuit separated the three-level photodiode voltage into sync pulse and data bits. The data bits were coded in Manchester code, so that, the LED light would not flicker. The system configuration is very simple and easy to use because sync pulse and data bits are transmitted simultaneously by one LED array. This structure can be easily utilized to construct a wireless guidance system for product description using LED light at various exhibitions, department stores and shopping malls.

Key words: Visible light communication, three-level modulation, LED, indoor voice broadcasting

INTRODUCTION

Recently, due to innovative developments in the field of semiconductor technology, various types of high-power Light Emitting Diodes (LEDs) have been developed and widely used in a variety of fields such as indoor lighting, street lighting and automobile lighting. Compared to conventional lighting devices such as fluorescent or incandescent lamps, LEDs have advantages of higher power conversion efficiency, smaller size and simpler lighting control and their use is steadily increasing. In addition, since, LED is capable of high-speed modulation by injection current control, Visible Light Communication (VLC) technology performing illumination and communication simultaneously is under continuous development (Komine and Nakagawa, 2004; Cheong *et al*., 2013; Lee, 2015). VLC generally uses a single light source for lighting and communication; the illumination condition of the light emitting diode should not be affected by communication. In order to maintain steady illumination without flickering during communication, LED modulation with subcarriers such as Amplitude Shift Keying (ASK) or Frequency Shift Keying (FSK) may be easily used. Recently, Pulse Position Modulation (PPM) and On-Off Keying (OOK) with Run Length Limited (RLL) line code has been proposed as a method of mitigating flickering and dimming control (Ma *et al*., 2012; Rajagopal *et al*., 2012; Kim and Lee, 2016).

In this study, we newly introduce a simple VLC method that uses three-level LED modulation to transmit sync pulse and data simultaneously. In the VLC transmitter, an LED array is driven by a three-level LED modulator that is composed of two parallel Field Effect Transistors (FETs). One FET current is proportional to the sync pulse and the other FET is proportional to the data bits; thus the LED light driven by the sum current of the two FETs outputs three-level light. The highest level and the middle level of the LED light correspond to the sync pulse and data bits, respectively. Because the sync pulse is periodic and the data bits use the Manchester code, the average optical power of the LED array is kept constant and thus flicker-free for a longer observation time than the Maximum Flickering Time Period (MFTP). In this system, MFTP is the same as the sync pulse repetition frequency of 16 kHz which is much higher than the value of 200 Hz that is generally considered to be safe (Rajagopal *et al*., 2012). In the VLC receiver, the PhotoDiode (PD) voltage after a capacitor is also of three levels however, the middle level is automatically changed to the ground and the positive and the negative voltages correspond to the sync pulse and the data bits, respectively. Two diodes are used to separate the sync pulse and the data bits the original signal is recovered using the sync pulse and the data bits.

In experiments, we used this three-level VLC system for indoor voice broadcasting. This three-level VLC system is very simple and convenient to use because it

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does not require a separate channel for sync pulse transmission; it is also without flicker. This structure can be used to construct an indoor wireless voice broadcasting system or a wireless guidance system for product description at various exhibitions, department stores and shopping malls using LED illumination.

MATERIALS AND METHODS

The three-level VLC system is composed of a transmitter and a receiver. The system configuration of the transmitter and a receiver are described as follows.

Three-level VLC transmitter: The three-level VLC transmitter is schematically illustrated in Fig. 1. It is composed of an Analog-to-Digital Converter (ADC), a microprocessor, two Field Effect Transistors (FETs) and an LED array. Analog input signal is applied to the input port of ADC. The microprocessor generates sync pulses and simultaneously sends them to the enable port of the ADC and to the gate of FET1. The sync pulse enables the ADC to sample the analog input signal and the ADC outputs eight-bit parallel data and sends them to the input port of the microprocessor. The microprocessor reads the parallel data, changes them to serial data bits in Manchester code format and sends them to the gate of the FET2.

The two FET drain terminals are connected thus, two drain currents are added and make a three-level signal current. The drain current of FET1 is proportional to the sync pulse; that of FET2 is proportional to the data bit. The total current flows to the LED array and the output light intensity is proportional to the sum of sync pulse and data bit. Three-level visible light from the LED array radiates into free space. The optical power of the LED array may be illustrated as shown in Fig. 2.

Figure 2a denotes the waveform of the sync pulse light of the LED array. T is the period of the sync pulse, equal to the sampling rate of the input analog signal. The amplitude of the sync pulse is P_0 and the width is τ_p. Figure 2b is the waveform of the data bit light of the LED array. This waveform is an example of eight-bit data " 00000010" in the Manchester code. One bit time is τ_d and the interval time between eight-bit frames is τ_0. Data bit "0" has a "low-to-high" transition and data bit "1" has a "high-to-low" transition. The LED light during the interval time τ_0 is kept at high power. We used the Manchester code for data transmission in order to produce flicker-free LED illumination. Figure 2c shows the total LED light which includes the sync pulse and data bits. The total LED light becomes a three-level signal, in which level 0 corresponds to no light, level1 to data bit and level 2 to sync pulse. The average optical powers due to the sync pulse and the data bit can be expressed by Eq. 1 and 2, respectively:

$$P_1, avg = \frac{1}{T}\int_0^T P_1(t)dt = P_0\tau_p/T \quad (1)$$

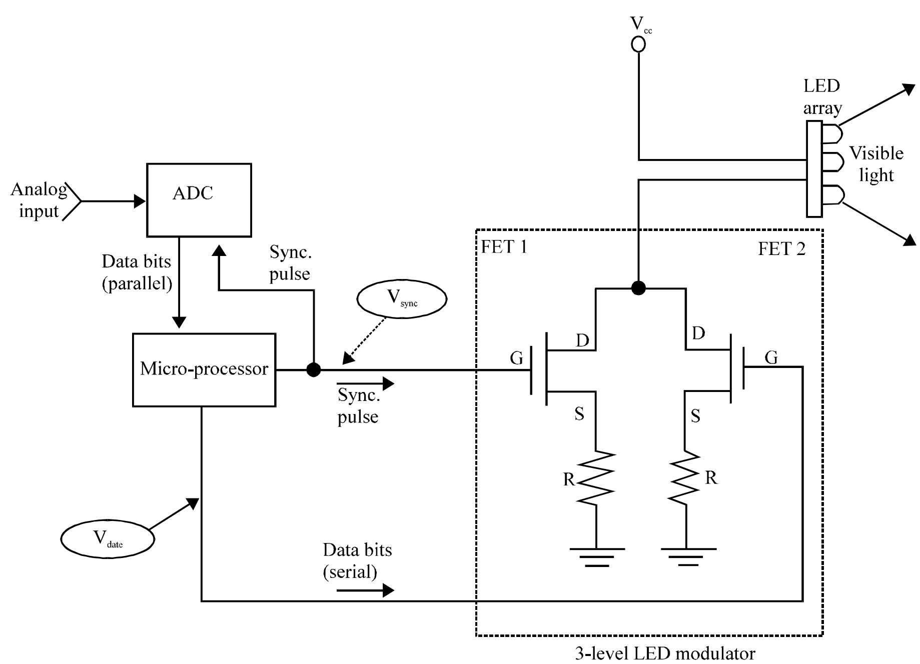

Fig. 1: Three-level VLC transmitter

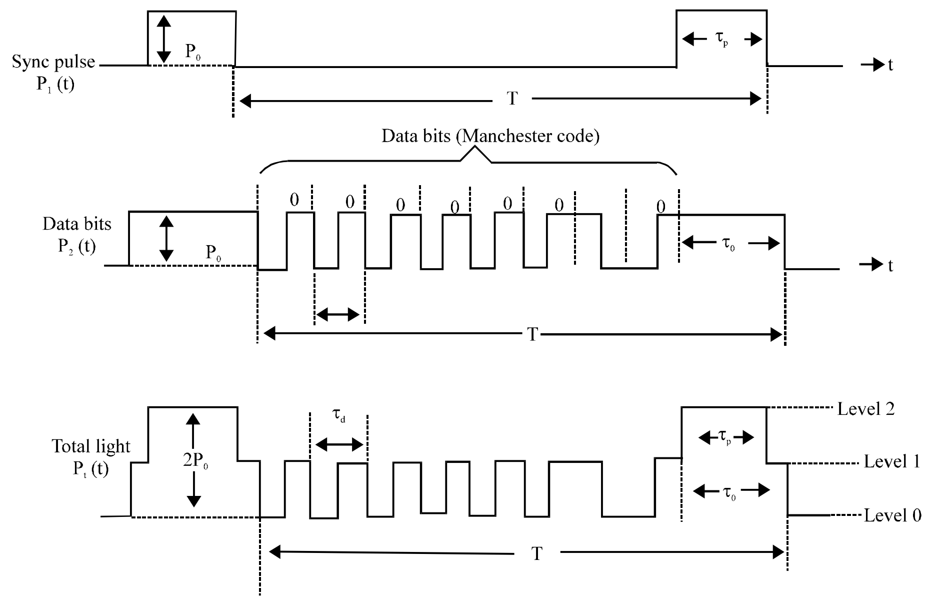

Fig. 2: Optical signal waveforms from the LED array

$$P_2, avg = \frac{1}{T}\int_0^T P_2(t)dt = \frac{P_0}{T}(8\times 0.5\tau_d+\tau_0) \quad (2)$$

The total average power of the LED array is the sum of Eq. 1 and 2:

$$Pt, avg = \frac{1}{T}\int_0^T P_1(t)+P_2(t)dt = \frac{P_0}{T}(\tau_p+4\tau_d+\tau_0) \quad (3)$$

If the sync pulse width is set equal to four times the bit time, that is $\tau_p = 4\tau_d$:

$$Pt, avg = \frac{P_0}{T}(8\tau_d+\tau_0) = \frac{P_0}{T}\times T = P_0 \quad (4)$$

As shown in Eq. 4, if we set the sync pulse width equal to four times the bit time, the average optical power is constant at P_0 and thus, the LED illumination is maintained uniform without flickering for an observation time longer than the sync pulse period. The LED output light is radiated to the free space and a part of the light reaches the VLC receiver.

Three-level VLC receiver: A three-level VLC receiver is schematically shown in Fig. 3. The VLC receiver is composed of three parts: a photodetector, a sync pulse-data splitter and a signal recovery circuit. A Photodiode (PD) detects the three-level signal light radiated by the VLC transmitter. The PD voltage can be described as follows:

$$V_{pd}(t) = k\rho R_L[P_1(t)+P_2(t)] \quad (5)$$

Where:

k = An optical coupling constant from the LED array to the photodiode

ρ = The responsivity of the photodiode

R_L = The load resistance

$P_1(t)$ and $P_2(t)$ = The optical powers of the LED array for sync pulse and data bits, respectively

The PD voltage is sent to a sync pulse-data splitter. There the PD voltage is amplified, goes through a capacitor and is applied to diode 1 and 2. The PD voltage is positive however, after it goes through capacitor C, the average voltage automatically goes to 0 V. That is, level1 of the three-level signal becomes the ground and level 2 and level 0 become the positive and negative voltages, respectively. The voltage after capacitor C can be written as:

$$V_c(t) = k\rho R_L G[P_1(t)+P_2(t)-P_0] = k\rho R_L G[P_1(t)+P_2(t)]-V_0 \quad (6)$$

Where:

G = The voltage gain of the amplifier

V_0 = $k\rho R_L G P_0$

P_0 = The average optical power of the LED array

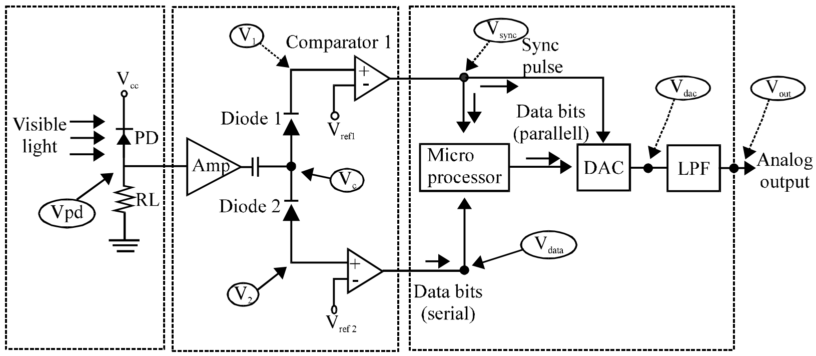

Fig. 3: Three-level VLC receiver

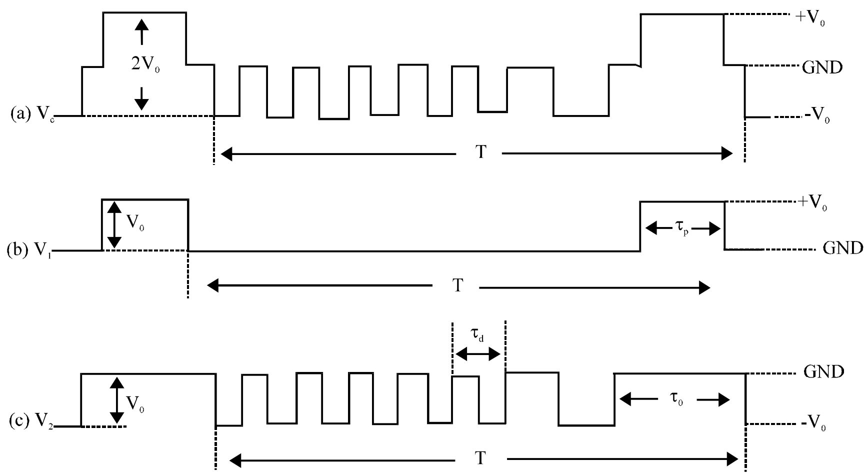

Fig. 4: Electrical signal waveforms in a VLC receiver

$$V_c(t) = k\rho R_L G\times 2P_0 - V_0 = V_0 \quad (7)$$

At the time at which data bits are received, $P_1(t) = 0$ and V_c becomes ground or negative depending on the data bit light $P_2(t)$:

$$V_c = (t) = \begin{cases} 0 & \text{when } P_2(t) = P_0 \\ k\rho R_L G\times(-P_0) = -V_0 & \text{when } P_2(t) = 0 \end{cases} \quad (8)$$

Figure 4 schematically shows the voltages in the sync pulse-data splitter. Figure 4a is the voltage after capacitor C (V_c in Fig. 3). The peak-to-peak amplitude is $2V_0$ and the average voltage is 0 V. The positive voltage corresponds to the sync pulse and the negative voltage to the data bits. The positive and negative voltage signals are separated by diode 1 and diode 2 in the sync pulse-data splitter. Figure 4b denotes the positive voltage after diode 1 (V_1 in Fig. 3), it constitutes the sync pulse in the receiver. The amplitude of the sync pulse is V_0, the pulse width is τ_p and the pulse period is T. Figure 4c denotes the negative voltage after diode 2 (V_2 in Fig. 3) which is constituted of data bits. The amplitude of the data bit is V_0, the one bit time is τ_d and the frame period is T.

The sync pulse and the data bits are finally recovered by comparator 1 and comparator 2, respectively. The reference voltage of comparator 1 is set to $V_0/2$ and that of comparator 2 to $-V_0/2$. The outputs of comparator 1 and comparator 2 become the positive sync pulse and the positive data bits, respectively. The sync pulse is sent to a microprocessor and DAC. The positive data bits from comparator 2 are sent to the input port of the microprocessor. At the time of the falling edge of the sync pulse, the microprocessor starts to read the serial data bits, changes them to parallel bits and outputs them to the DAC input port. The DAC converts the digital data to analog output voltage. Through this process, the signal transmitted by three-level LED modulation is recovered in the VLC receiver.

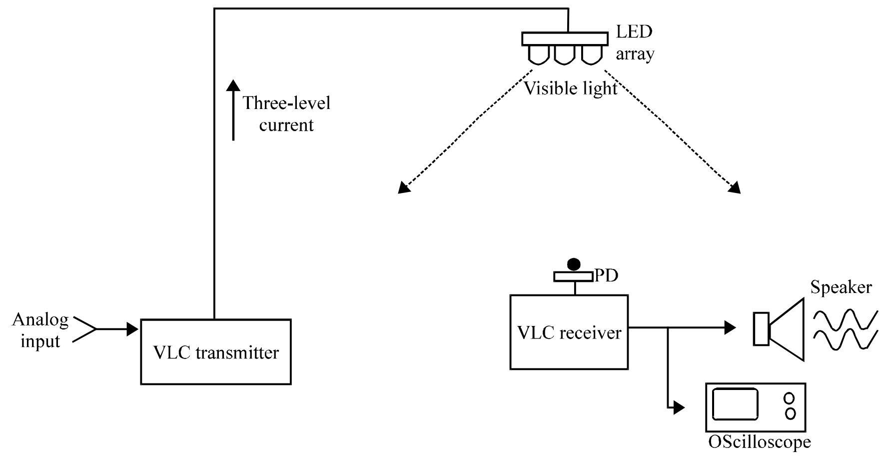

Fig. 5: Experimental setup

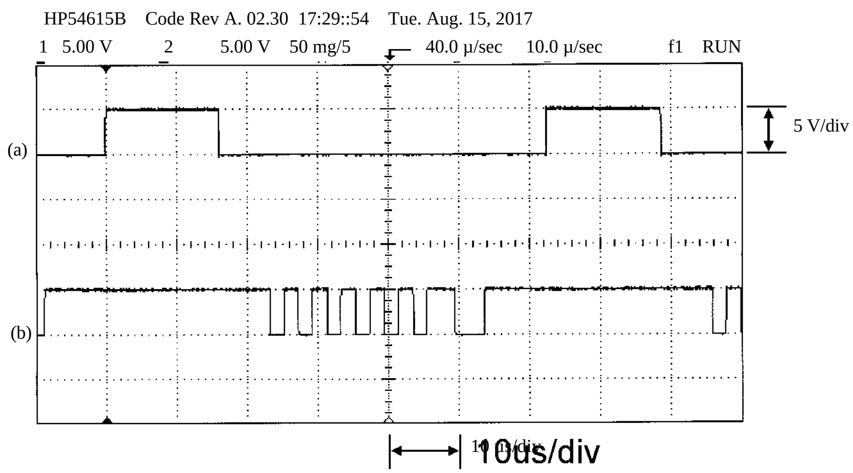

Fig. 6: Waveforms observed in VLC transmitter: a) Sync pulse and b) Data bits

VLC system setup: Figure 5 is a schematic diagram of the experimental setup. An LED array was installed near the ceiling of the laboratory and connected to a three-level VLC transmitter via a transmission line. The LED array was made of six identical LEDs in the form of a 2×3 array; each LED was a 1 W white LED. The visible light from the LED array was radiated into free space. A VLC receiver was placed on the table and received the LED light. The distance from the LED array to the receiver was about 2 m.

The devices used in the VLC transmitter and in the receiver were as follows. In the VLC transmitter, an Atmega 32 microprocessor, AD7822 analog-to-digital converter and two IRF540 FETs were used. In the photodetector part of the VLC receiver, an S6968 PIN photodiode, 1 kΩ load resistor and LM7171 op-amp were used. In the sync pulse-data splitter of the receiver, two 1N4148 diodes were used to split sync pulse data bits and two LM7171 op-amps were used for comparator 1 and comparator 2. In the signal recovery part of the receiver, an Atmega32 microprocessor and AD557 digital-to-analog converter were used. We used a HP 52615B oscilloscope to observe the waveforms in the transmitter and the VLC receiver.

Observed waveforms: We applied DC 1 V to the analog input port of the transmitter as shown in Fig. 1 and observed the waveforms of the sync pulse and data bits outgoing from the microprocessor to the FETs. Figure 6 shows the waveforms observed with an oscilloscope in the VLC transmitter. Figure 6a shows the voltage waveform of the sync pulse (V_{sync} in Fig. 1) going from the microprocessor to FET1 gate in the VLC transmitter. The pulse repetition frequency was 16 kHz and the pulse width was 16 μs. The pulse repetition frequency was the same as the sampling frequency of the input analog signal at

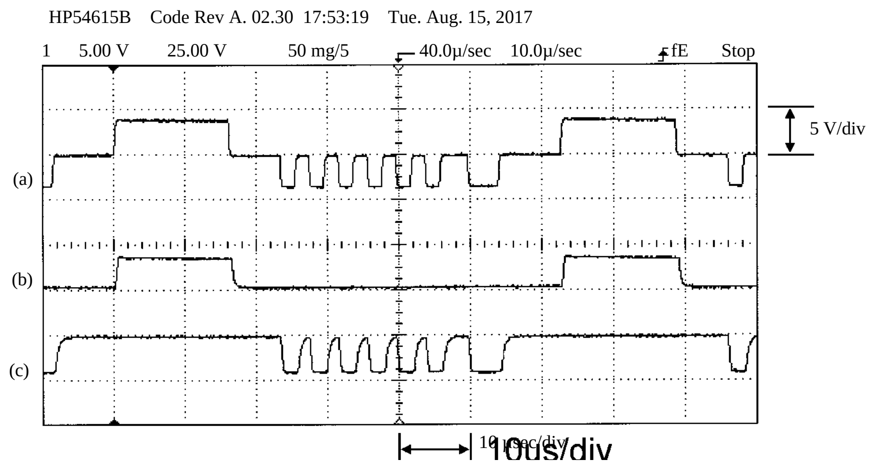

Fig. 7: Waveforms observed in VLC receiver; a) PD voltage; b) Sync pulses and c) Data bits

the ADC. The ADC generated eight parallel bits and sent them to the input port of the microprocessor. The microprocessor changed the parallel data bits to serial Manchester code with a duty factor of 50%. Figure 6b shows the voltage waveforms of the data bits going from the microprocessor to the gate of FET2 (V_{data} in Fig. 1). The eight serial data bits were sent in the order of the Least Significant Bit (LSB) first; the data were "00000010" in Manchester code format. The data value was 64 in decimal numbers which denotes that the input voltage is 1 V when the reference voltage of the ADC is 4 V. That is $V_{in} = (64/256)\times4$ V = 1 V. One bit time was 4 us. Bit "0" had a "low-to-high" transition and bit "1" had a "high-to-low" transition. We used the Manchester code for LED modulation and the sync pulse width was set to be four times one bit time in order to produce flicker-free illumination by keeping the average LED light power constant as described in Eq. 4. The visible light generated by the LED array was radiated into the free space in the laboratory and was received by a PIN photodiode in the VLC receiver.

Figure 7 shows the waveforms observed in the VLC receiver. Figure 7a is the PD voltage after passing through an amplifier and capacitor C (V_c in Fig. 3). The voltage gain of the amplifier was 100 and C was 1 uF. This is a three-level digital signal that corresponds to the sum of the sync pulse and the data bits. In this system, maximum flickering time period (MFTP) is the same as the sync pulse repetition frequency of 16 kHz which is much higher than the value of 200 Hz that is generally considered to safe.

This three-level signal was applied to diode 1 and diode 2. Figure 7b is the voltage waveform after diode 1 (V_1 in Fig. 3) was used for the sync pulse in the VLC receiver circuit after passing through comparator 1. This pulse is a binary signal in which the high level is positive and the low level is the ground voltage. Figure 7c is the voltage waveform after diode 2 (V_2 in Fig. 3) which corresponds to the data bits. This is a binary signal in which the high level is the ground and the low level is negative voltage. The voltages in Fig. 7b and c were applied to the input ports of comparator 1 and comparator 2, respectively. The reference voltage of comparator 1 was 2 V; that of comparator 2 was -2 V.

Figure 8 shows the sync pulse and data bit signals recovered by the comparators. Figure 8a is the output voltage of comparator 1 (V_{sync} in Fig. 3). This signal was used for the sync pulse in the VLC receiver circuit. The recovered sync pulse in Fig. 8a had the same shape as that of the pulse that was sent by the VLC transmitter, as shown in Fig. 6a. The sync pulse was applied to the interrupt port of the microprocessor and to the enable port of the DAC. Figure 8b shows the data bits recovered by comparator 2 (V_{data} in Fig. 3). These were the same as the serial data bits "00000010" in Manchester code format that was sent by the VLC transmitter as shown in Fig. 6b). Figure 8c shows the short pulses that were generated by the microprocessor for the purpose of checking the read time. The read time started 8 us after the falling edge of the sync pulse; the read interval was 4 us which was the same as the one bit time. The microprocessor read the eight-bit serial data, changed them to eight-bit parallel data and sent them to the input port of the DAC. The DAC generated analog output voltage corresponding to the data.

In order to see that analog input signal in the VLC transmitter was well recovered by the VLC receiver, we applied a sinusoidal voltage to the input port of the VLC transmitter and observed the output signal in the VLC receiver. Figure 9 shows the sinusoidal voltage wave

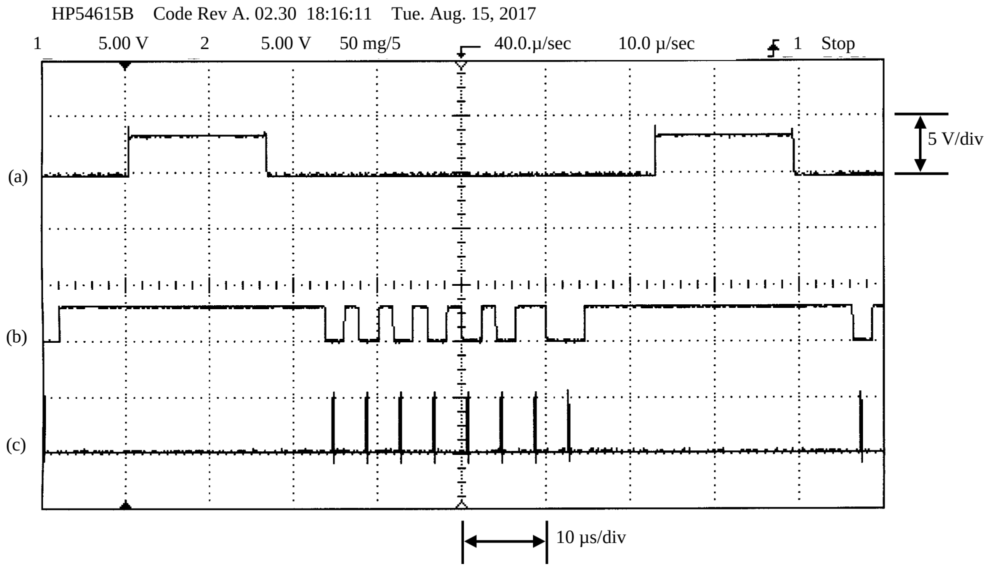

Fig. 8: Recovered signals in VLC receiver: a) Recovered sync pulse; b) Recovered data bits and c) Read time of data in Manchester code

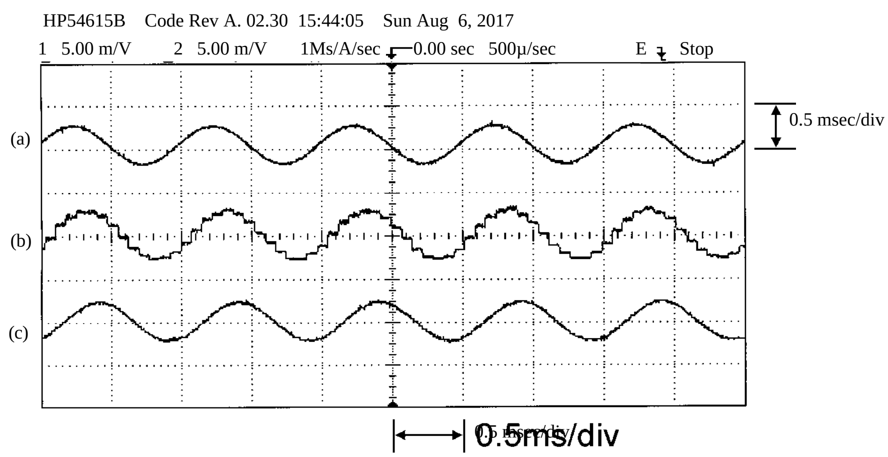

Fig. 9: Sinusoidal waveforms observed in VLC system: a) Sinusoidal voltage applied to transmitter; b) DAC output voltage in receiver and c) Recovered sinusoidal voltage in receiver

forms, observed with an oscilloscope. Figure 9a is the sinusoidal voltage applied to the input of the VLC transmitter. The frequency was 1 kHz and the peak-to-peak amplitude was 0.5 V. Figure 9b is the output voltage of the DAC in the VLC receiver. The DAC output signal showed a quantized waveform which then passed through a low pass filter. The Low Pass Filter (LPF) was composed of a 1 kΩ resistor and a 0.1 uF capacitor. Figure 9c shows the LPF output voltage waveform. The sinusoidal voltage at the LPF output had the same shape as that of the input signal, however, it had a time delay of 0.17 msec. The time delay appeared due to the processing time in the VLC transmitter and receiver; it did not cause problems in indoor voice broadcasting. In this way, we confirmed experimentally that we can transmit an analog signal synchronously using three-level LED modulation without a separate channel for sync pulse transmission.

As an example of application of the three-level VLC system, we used this system for indoor wireless voice broadcasting. We sent arbitrary music to the input port of the VLC transmitter and connected a speaker to the output port of the VLC receiver.

Figure 10 shows the voltage waveforms, observed in the transmitter and receiver using an oscilloscope. Figure 10a shows the analog input signal in the VLC transmitter at an arbitrary time in the music. Figure 10b

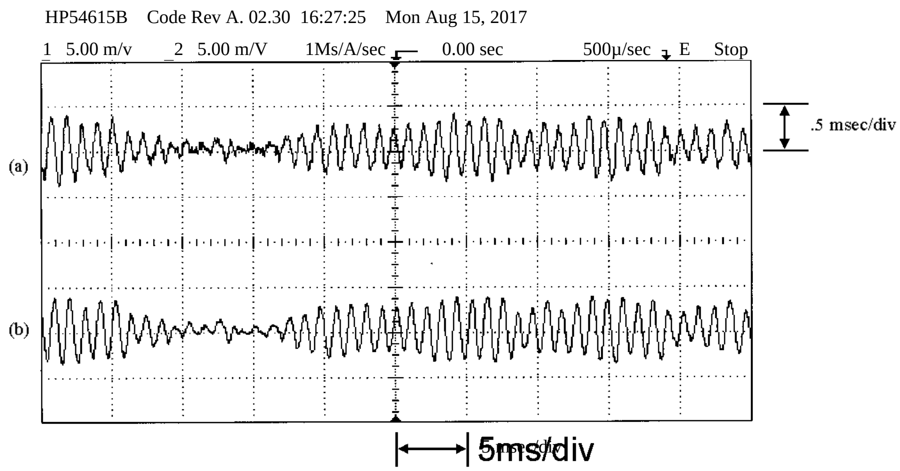

Fig. 10: Analog voice waveforms observed in VLC system: a) Analog input signal applied to transmitter and b) Recovered output signal in receiver

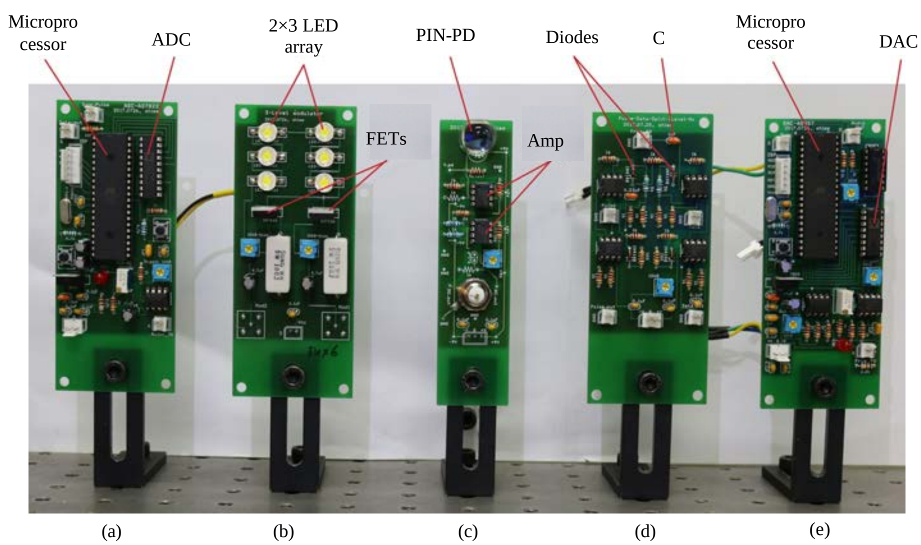

Fig. 11: Printed Circuit Boards (PCBs) used in experiments: a) Transmitter circuit; b) LED array; c) Photodetector circuit; d) Sync pulse-data splitter and e) Signal recovery circuit

is the output signal of the VLC receiver. As shown in Fig. 10, the two waveforms were almost identical and the voice transmission was good. This VLC system can be utilized to construct a short-range wireless guidance system using LED illumination for product description at booths in exhibition halls or at corners in department stores.

Figure 11 shows the circuit boards used in the experiments. Figure 11a is the VLC transmitter circuit including microprocessor and ADC. Figure 11b shows the 2×3 LED array and the two FETs that were used for the three-level light source. Figure 11c denotes the photodetector circuit which is composed of a PIN photodiode and an amplifier. Figure 11d is the sync-pulse-data splitter circuit which includes two diodes and a capacitor. Figure 11e is the signal recovery circuit including a microprocessor and DAC.

RESULTS AND DISCUSSION

We have experimentally demonstrated that we can implement an indoor wireless voice broadcasting system using three-level LED modulation. In this system sync pulse and data bits were transmitted simultaneously through an LED array without flickering. In the VLC transmitter, three-level LED light was produced by a two-FET circuit in which FET1 and FET2 were driven by sync pulse and data bits, respectively. In the sync pulse-data splitter circuit in the VLC receiver, sync pulse and data bits were separated by two diodes.

In the three-level VLC system, the LED array showed constant illumination with a maximum flickering time period (MFTP) of 16 kHz which was the same as the sync pulse repetition frequency and was much higher than the value of 200 Hz that is generally considered to safe. In addition, this structure is very simple and easy to use because the sync pulse and the data bits are simultaneously transmitted through one LED array and the system does not require a separate transmission channel for the sync pulse.

CONCLUSION

As an example of application, we used this system in experiments for indoor wireless voice broadcasting. Using LED illumination, this VLC system can be widely utilized to construct short-range wireless voice broadcasting systems, for example guidance systems for product description at booths in exhibition halls or at corners in department stores.

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