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Illumination Control in Visible Light Communication Using Manchester Code with Sync-Mark Signal

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Abstract

In this study, we employed Manchester code for illumination control and flicker prevention of the light-emitting diode (LED) used in a visible light communication (VLC) system. In the VLC transmitter, the duty factor of the Manchester code was utilized for illumination control; in the VLC receiver, the spike signal from an *RC*-high pass filter was utilized to recover the transmitted signal whilst suppressing the 120-Hz noise arising from adjacent lighting lamps. Instead of the clock being transmitted in a separate channel, a sync-mark signal was transmitted in front of each data byte and used as the reference time for transforming the Manchester code to non-return-to-zero (NRZ) data in the receiver. In experiments, the LED illumination was controlled in the range of approximately 12–84% of the constant wave (CW) light via changing of the duty factor from 10% to 90%. This scheme is useful for constructing indoor wireless sensor networks using LED light that is flicker-free and presents capability for illumination control.

Keywords: Visible light communication, LED, Manchester code, duty factor, illumination control, flicker-free, spike signal.

1. INTRODUCTION

With the advances in semiconductor technology in recent years, many types of high-power visible light emitting diodes (LEDs) have been developed and are now widely used as light sources in various fields, such as indoor lighting, street lighting, automobile lighting, and billboard lighting. Compared with conventional light sources such as fluorescent or incandescent lamps, LEDs have high power conversion efficiency, a compact size, and their illumination can easily be controlled by adjusting the injection current. Owing to their high-speed modulation characteristics, LEDs are also being preferentially used as light sources for visible light communication (VLC). VLC is a new type of technology involving illumination and short-distance wireless communication conducted simultaneously using the same light source [1-3]. Visible light and conventional radio frequencies do not interfere with each other; thus, VLC can be considered a good transmission method for enabling construction of safe wireless communication channels in environments where electromagnetic interference should be prevented [4,5].

In VLC systems, LEDs are the typical light sources, and photodiodes or image sensors are used as the detectors. The optical signal radiated from an LED is directly detected by a photodiode through free space. Because the light sources are used simultaneously for lighting and communication, VLC systems should be designed such that the illumination and communication functions do not affect each other [6]. Flicker and illumination control of LED light should be considered in the design of VLC systems. The average optical power should be kept constant during data transmission to prevent flickering of the LED light. Flickering is an unstable illumination condition in which the LED illumination is changed continuously, and this condition can make human sight inconvenient. Thus, VLC systems should be designed to prevent the flickering of LED light. Amplitude shift keying (ASK) or frequency shift keying (FSK) transmission with a subcarrier frequency are convenient transmission methods that can be employed to avoid LED flickering because the average optical power is maintained at a constant level during data transmission [7]. In base-band VLC systems with a relatively low data rate, special codes such as Manchester code can be effective methods to prevent LED flickering. Manchester code keeps the average optical power of LED light constant during data transmission. In this system, the clock synchronized with the transmitter should be

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connected to the receiver circuit to establish the reference time for the conversion of the Manchester code to the original non-return-to-zero (NRZ) code. In VLC systems, it is desirable that the illumination can be easily controlled by the user without affecting data transmission because the LED is also used as a lighting lamp.

In this paper, we used Manchester code with a sync-mark signal for data transmission in a VLC system. The sync-mark signal is transmitted in front of each data byte and is used in the receiver as the reference time for converting the Manchester code to the original NRZ code. Thus, in this system, a separate channel for clock transmission is not required. We used the duty factor of the Manchester code for illumination control. When the duty factor is fixed at a particular value, the average optical power is kept constant; thus, the LED light is rendered flicker-free. When the user wishes to change the illumination, a new duty factor is selected by them. The LED illumination is almost linearly proportional to the duty factor.

In the VLC receiver, the photodiode receives the signal light and recovers the transmitted data. When the photodiode is exposed to light from adjacent lighting lamps that are independent of the VLC system, the received signal can experience interference from the 120-Hz noise, even in the Manchester code transmission. If the noise is not negligible compared to the signal, errors can arise during data transmission, particularly in base-band VLC systems. The 120-Hz noise can easily be eliminated by a simple electrical filter; however, the signal from the transmitter is also distorted, which can cause difficulty in data recovery. To overcome this problem, we used an *RC*-high pass filter (HPF) in the receiver and the spike signals that appear at the leading and trailing edges of each data bit.

A positive spike signal appears at the leading edge of the bit where a "low-to-high" voltage transition occurs, while a negative spike signal appears at the trailing edge where a "high-to-low" voltage transition occurs. Utilizing this phenomenon, the microprocessor in the receiver regenerated the original Manchester code by making "low-to-high" and "high-to-low" voltage transitions at the points of the positive and the negative spikes, respectively. This scheme is simple to realize and is useful for constructing base-band VLC systems that are flicker-free, present capability for illumination control, and are robust against adjacent noise light interference.

2. ILLUMINATION CONTROL AND DATA RECOVERY METHOD

The illumination control method using the duty factor of the Manchester code in the transmitter and the data recovery process in the receiver are described in this section.

2.1 Illumination Control in the VLC Transmitter

Illumination control of the LED light is achieved by changing the duty factor of the Manchester code, as illustrated in Fig. 1.

Fig. 1(a) shows the sync pulse that is used as the reference time for transforming the NRZ input data to the Manchester code in the VLC transmitter. In each period of the sync pulse, *T*, one byte of the NRZ input data is transmitted. Fig. 1(b) shows arbitrary NRZ input data in universal asynchronous receiver and transmitter (UART) format, which includes eight data bits, one start bit, and one stop bit. Fig. 1(c) shows the Manchester code for the NRZ input data. The Manchester code is used to modulate the LED light for flicker prevention and illumination control. The LED light modulated by the Manchester code becomes flicker-free because the average optical power of the LED light is kept constant. The duty factor of the Manchester code is changed by the user for LED illumination control. The duty factor is $D = t_h/t_b$, where t_b is one bit time, and t_h is the duration of the high state in one bit time of the Manchester code.

In this system, we do not transmit the clock through a separate channel for recovery of the Manchester code as NRZ code in the receiver. Instead, the sync-mark signal is transmitted in front of each byte of Manchester code data, as shown in Fig. 1(c). The sync-mark signal is used as the reference time to recover the NRZ data from the Manchester code in the receiver. In order to distinguish the sync-mark signal from the Manchester code, the

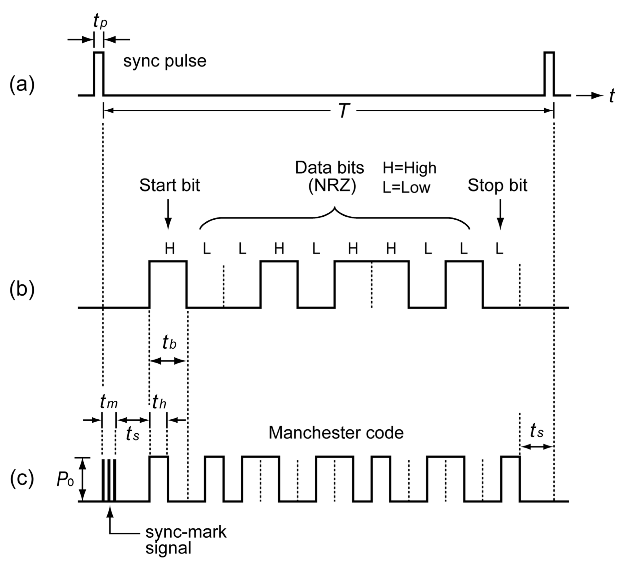

Fig. 1. Generation of the Manchester code and the sync-mark signal: (a) sync pulse, (b) NRZ input data, and (c) sync-mark signal and Manchester code.

bit time of the sync-mark signal is designed to be shorter than that of the Manchester code with the smallest duty factor.

In these experiments, we used six bits "101010" with a bit time of 5 μs for the sync-mark signal. In this case, the length of the sync-mark signal (t_m) was 30 μs, while the bit time of the NRZ data was 104 μs in a 9.6 kbps UART data rate. Two stay times (t_s) exist between the sync-mark signal and the Manchester code in one byte of transmission, as shown in Fig. 1(c). In this modulation scheme, the average optical power of the LED light can be calculated as follows:

$$P_{avg} = \frac{1}{T}\int_0^T P(t)\,dt = \frac{P_0}{T}\left(0.5t_m + \sum_{i=0}^{9} t_h\right) \\ = \frac{P_0}{T}\left(0.5t_m + \sum_{i=0}^{9} t_b\,D\right) = \frac{P_0}{T}(0.5t_m + 10t_bD), \quad (1)$$

where P_{avg} is the average optical power, P_0 is the constant wave (CW) optical power, t_b is one bit time of data, D is the duty factor of the Manchester code, and t_m is the sync-mark signal time. The sync pulse period, T, is the sum of one pulse width (t_p), one sync-mark signal time (t_m), two stay times (t_s), and ten data bit times including one start bit and one stop bit involved in a byte transmission. That is,

$$T = t_p + 2t_s + t_m + 10t_b \quad (2)$$

By substituting Equation (2) into (1), the average optical power normalized to CW power level becomes

$$\frac{P_{avg}}{P_0} = \frac{0.5t_m + 10t_bD}{T} = \frac{0.5t_m + 10t_bD}{t_p + 2t_s + t_m + 10t_b}. \quad (3)$$

In Equation (3), we can see that the illumination of the LED light can be controlled by changing the duty factor, D. Fig. 2 shows the relationship between the average optical power and the duty factor of the Manchester code.

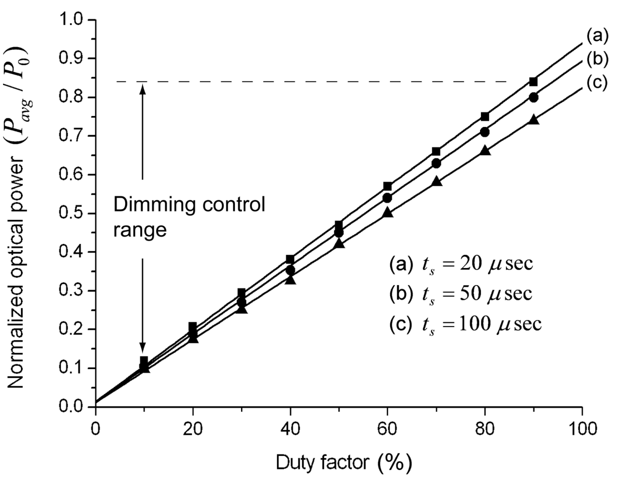

Fig. 2. Relationship between the LED optical power and the duty factor of the Manchester code

In Fig. 2, the three straight lines are the results of Equation (3), and the symbols (■, ●, ▲) are the measured results. In measuring the optical power, we used a 3 × 4 LED array composed of twelve 1 W white LEDs. The LED optical power density was measured using an optical power meter (OMM-6810B). The CW optical power density of the LED array was measured to be P_0 = 1.06 W/m^2 at a distance of 1 m from the LED array. In measurements and calculations, we used a sync pulse width t_p = 10 μs, sync-mark signal time t_m = 30 μs, and one data bit time t_b = 104 μs for a UART data rate of 9.6 kbps. The stay time (t_s) between the sync-mark signal and the Manchester code data was used as a parameter. In Fig. 2, curves (a), (b), and (c) are for stay times of t_s = 20, 50, and 100 μs, respectively. The corresponding illumination control ranges were measured to be (a) 12% to 84%, (b) 11% to 80%, and (c) 10% to 74%.

As seen in Fig. 2, the LED optical power increased almost linearly with the duty factor. As the stay time (t_s) decreased, the proportional slope and the illumination control range increased. As shown in Fig. 2(a), the average optical power normalized to CW LED light (P_{avg}/P_0) was controlled from 12% to 84% as the duty factor (D) was changed from 10% to 90%.

2.2 Data Recovery in the VLC Receiver

In the VLC receiver, the photodiode (PD) detects the VLC signal sent by the transmitter. Because the PD is open to free space, it can be exposed to light from other lighting lamps installed near the transmitter or receiver. The lighting lamps in an office commonly use a 60 Hz power line and may emit 120-Hz noise light, which can cause interference during data transmission. Especially in base-band VLC systems, this interference can be significant when the adjacent lighting is not negligible compared to the VLC transmitter. To overcome this problem, we used an *RC*-HPF at the PD output and the spikes appearing at the output of the filter to recover the transmitted data whilst eliminating the 120-Hz noise. Fig. 3 schematically shows the data recovery process using these spikes in the VLC receiver.

Fig. 3(a) is an example of the PD voltage in which the data waveforms from the transmitter and 120-Hz noise from adjacent lighting lamps are mixed. When the PD voltage passes through the *RC*-HPF, the 120-Hz noise is eliminated, and the rectangular data waveforms are changed to short spikes due to differential operation of the *RC*-HPF, as shown in Fig. 3(b). The positive and negative edge-spikes appear at the leading and trailing edges,

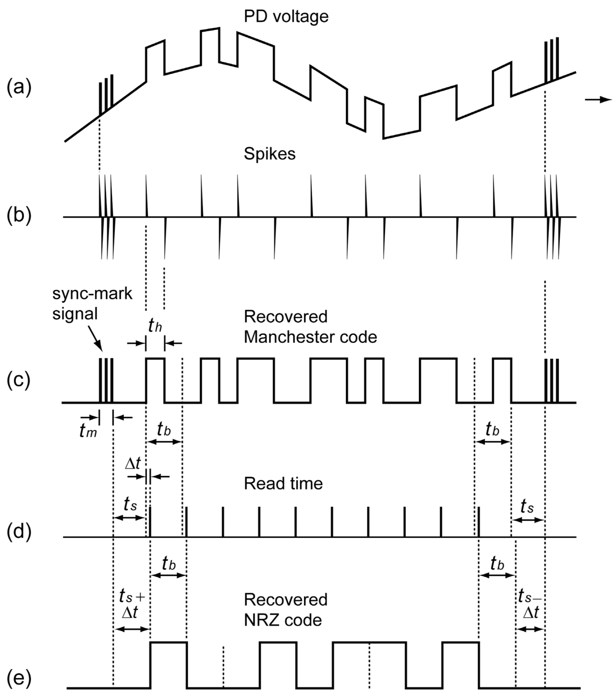

Fig. 3. Data recovery process using spikes in the VLC receiver: (a) PD voltage, (b) spikes at the output of an *RC*-HPF, (c) sync-mark signal and Manchester code regenerated using the spikes, (d) read time of the Manchester code, and (e) recovered NRZ data.

respectively, of the rectangular pulse of the sync-mark signal and Manchester code data. Using these spikes, the microprocessor in the VLC receiver can regenerate the Manchester code, as shown in Fig. 3(c), by performing "low-to-high" and "high-to-low" voltage transitions at the time of each positive and negative spike, respectively.

The sync-mark signal in front of the Manchester code is used as the reference time for recovering the NRZ data in the receiver. In these experiments, we used a sync-mark signal with a bit sequence of "101010" in which one bit time was 5 μs, and the total length of one sync-mark signal was t_m = 30 μs. The microprocessor reads the six bits sequentially with a bit time of 5 μs, and if it matches the predefined bit sequence, it begins to read the voltage level just after the start time of each bit in the Manchester code and determines each bit state of the original NRZ data. At the instant of $t_s + \Delta t$ from the falling edge of the last pulse in the sync-mark signal, the first bit of the Manchester code is read, and the second to tenth bits are read sequentially at each time of t_b from the first bit, as shown in Fig. 3(d). As the result, the NRZ code data bits are recovered from the Manchester code, as shown in Fig. 3(e).

3. EXPERIMENT

3.1 VLC Transmitter

In the VLC transmitter, the NRZ input data is transformed to Manchester code, and the LED light is modulated by the Manchester code. The duty factor of the Manchester code is used to control the illumination of the LED light. Fig. 4 shows a schematic of the configuration of the VLC transmitter.

The VLC transmitter is composed of a microprocessor, current driver, and LED array. In these experiments, we used an Atmega8 microprocessor, DW8501 current driver IC, and 3 × 4 planar LED array composed of twelve 1-W white LEDs. The microprocessor converted the input NRZ data to the Manchester code, including the sync-mark signal.

When the sync pulse was applied to the interrupt-0 (INT0) port, the microprocessor generated the sync-mark signal that was used as the reference time to regenerate the NRZ data in the VLC receiver. In this system, the clock signal for code-conversion was not transmitted in a separate channel; instead, the sync-mark signal was sent in front of each byte of the Manchester code. Immediately following the sync-mark signal, the Manchester code corresponding to the NRZ input data was generated with the duty factor selected by the user. The duty factor of the Manchester code was selected via application of pulses to the interrupt-1 (INT1) port. For each pulse, the duty factor was increased by 10% stepwise in the range from 10% to 90%. The Manchester code was applied to a DW8501, which was used as the current driver for the LED array, and the current proportional to the Manchester code was supplied to the LED array, which then radiated visible light into free space.

We observed the voltage waveforms in the VLC transmitter with an oscilloscope as the duty factor was slowly changed in the range from 10% to 90%. Fig. 5 shows the resulting waveforms observed in the VLC transmitter.

Fig. 5(a) shows the sync pulse with a width of 10 μs and a pulse period of 1.12 ms. Fig. 5(b) shows the input NRZ data that

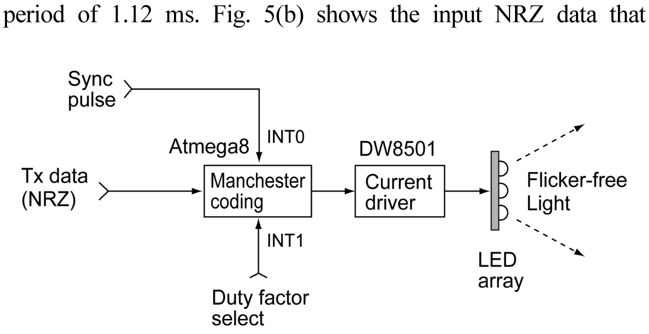

Fig. 4. Configuration of the VLC transmitter.

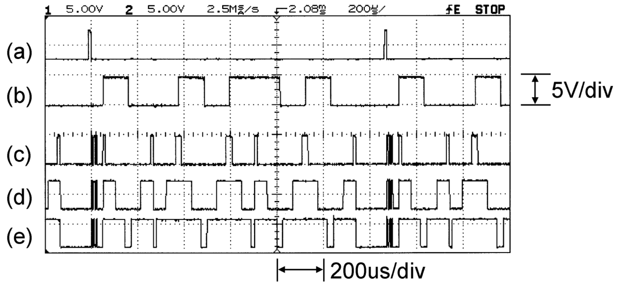

Fig. 5. Voltage waveforms observed in the VLC transmitter: (a) sync pulse, (b) NRZ input data, Manchester codes with duty factors of (c) 10%, (d) 50%, and (e) 90%.

corresponds to the character “K” in 9.6 kbps UART format. The 8-bit code for the character “K” based on the American Standard Code for Information Interchange (ASCII) is “01001011”. When the least significant bit (LSB) is sent first, the bit sequence from left to right becomes “11010010”. One start bit “0” and one stop bit “1” are added in front of and after the 8-bit ASCII code, respectively, and thus the total bit sequence for the character “K” in UART format becomes “0110100101”. A high voltage (H) was used for the “0” bit and a low voltage (L) for the “1” bit. Thus, the voltage waveform for the character “K” became “HLLHLHHLHL”, as shown in Fig. 5(b).

Fig. 5(c), (d), and (e) shows the Manchester codes for the character “K” with duty factors of 10%, 50%, and 90%, respectively. In these waveforms, the length of one sync-mark was $t_m = 30$ µs and the stay time was $t_s = 20$ µs. The black waveforms appearing just after the sync pulse in Fig. 5(c), (d), and (e) are the sync-mark signals, which were composed of six bits “101010” with a 5 µs bit time, hence the total length of one sync-mark signal was $t_m = 6 \times 5$ µs = 30 µs. This sync-mark signal was transmitted in front of each byte of Manchester code, and the falling edge of the last bit of the sync-mark signal was used as the reference time in the receiver for recovery of the NRZ input data sent from the transmitter.

3.2 VLC receiver

Fig. 6 shows a schematic diagram of the VLC receiver used to detect the signal light and recover the NRZ data.

The PD receives the signal light modulated by the Manchester code, and the PD voltage is amplified and passes through the *RC*-HPF, which is composed of a capacitor, C_1, and a resistor, R_1. In these experiments, we used a PIN photodiode model SFH-203, OPA228 op-amps, and two Atmega8 microprocessors. The capacitor and the resistor in the *RC*-HPF were $C_1 = 1$ nF and $R_1 =$ 1 kΩ, respectively. The cut-off frequency of the *RC*-HPF was approximately 160 kHz. The 120-Hz noise was eliminated by the *RC*-HPF, and the spikes appearing at the output of the *RC*-HPF were applied to the inputs of a non-inverting amplifier (Amp1) and an inverting amplifier (Amp2) simultaneously. Diode1, following Amp1 passed the positive spikes while cutting off the negative spikes. The output of diode1 (v_1) was applied to interrupt port INT0 for “low-to-high” transition in microprocessor1 (MIC-1) at each positive spike.

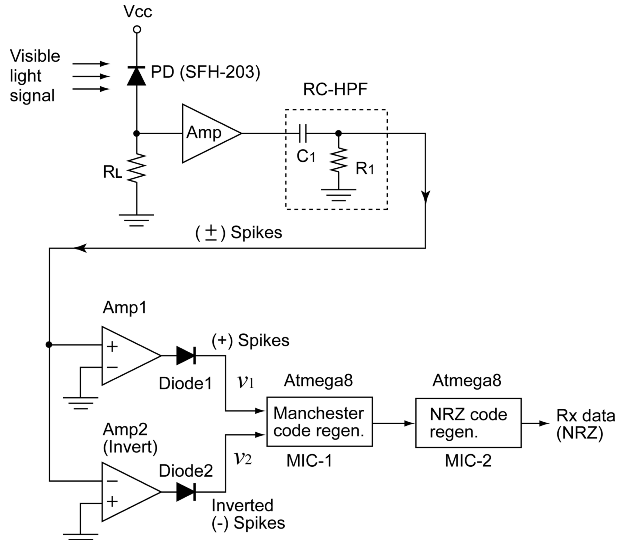

Fig. 6. Configuration of the VLC receiver.

Amp2 was an inverting amplifier, and thus the negative spikes from the *RC*-HPF were changed to positive spikes. Diode2 then passed the positive voltage from Amp2 while cutting off the negative. The output of diode2 (v_2) was applied to interrupt port INT1 for “high-to-low” transition in MIC-1 at each negative spike. Through this process, the sync-mark signal and the Manchester code data were regenerated by MIC-1 using the spikes. MIC-2 read the MIC-1 output and detected the sync-mark signal “101010”. It then began to read the voltage level just after the start of each Manchester code bit and output the NRZ data sent from the transmitter. Fig. 7 shows the signal waveforms observed in the VLC receiver with an oscilloscope.

Fig. 7(a) shows the PD voltage in which the signal from the transmitter was mixed with 120-Hz noise from adjacent lighting lamps. The large slope appearing in the signal was due to the 120-Hz noise. Fig. 7(b) shows the *RC*-HPF output voltage showing positive and negative spikes from the sync-mark signal and the Manchester code. Fig. 7(c) shows the positive spikes at the diode1 output (v_1 in Fig. 6). Fig. 7(d) shows the inverted negative spikes at the diode2 output (v_2 in Fig. 6).

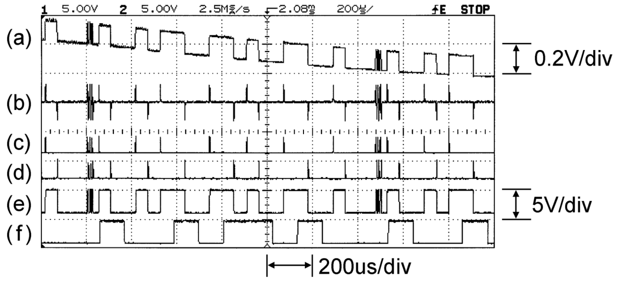

Fig. 7. Voltage waveforms observed in the VLC receiver: (a) PD voltage, (b) *RC*-HPF output, (c) positive spikes, (d) inverted negative spikes, (e) sync-mark signal and Manchester code regenerated using the spikes, and (f) recovered NRZ code

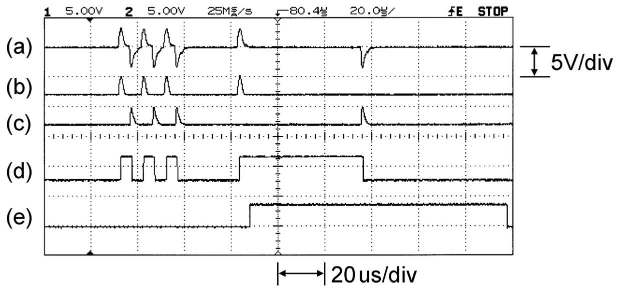

Fig. 8. Voltage waveforms observed in the VLC receiver: (a) *RC*-HPF output, (b) positive spikes, (c) inverted negative spikes, (d) regenerated sync-mark signal and the first bit of the Manchester code, (e) first bit of the recovered NRZ code.

The positive and negative spikes were applied to the INT0 and INT1 ports of MIC-1, respectively, which output the sync-mark signal and the Manchester codes, as shown in Fig. 7(e). MIC-2 read the output voltage from MIC-1, and when the data matched the predefined sync-mark signal of "101010", MIC-2 began converting each Manchester code bit to the corresponding NRZ code bit. Fig. 7(f) shows the regenerated NRZ code. This waveform has the same shape as that sent from the transmitter, as shown in Fig. 5(b). We observed the sync-mark signal in a magnified time scale. Fig. 8 shows the sync-mark signal observed with an oscilloscope with the time scale of 20 µs/div.

Fig. 8(a) shows the positive and negative spikes at the *RC*-HPF output. Fig. 8(b) shows the positive spikes at the diode1 output (v_1 in Fig. 6). Fig. 8(c) shows the inverted negative spikes at the diode 2 output (v_2 in Fig. 6). Fig. 8(d) shows the regenerated sync-mark signal and the first bit of the Manchester code. We used a six-bit sequence "101010" with a bit time of 5 µs for the sync-mark signal, and thus the total sync-mark signal length was $t_m = 30$ µs. The microprocessor read the six bits sequentially immediately following the rising edge of the first pulse of the sync-mark signal; when the bit sequence matched the predefined sync-mark signal, it began to convert the regenerated Manchester code to the NRZ code. Fig. 8(e) shows the first bit of the recovered NRZ code.

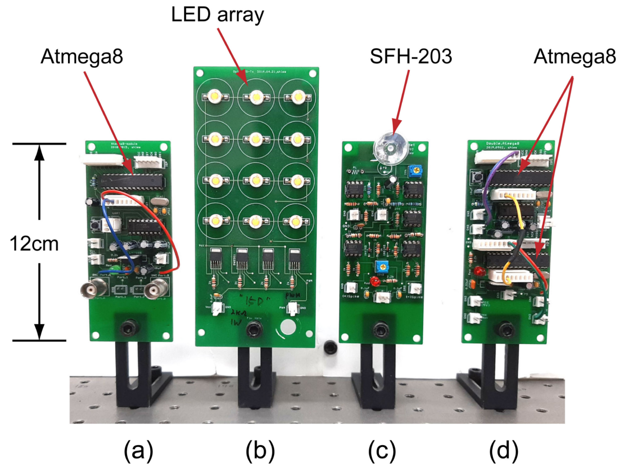

Fig. 9. Circuits used in the experiments: (a) microprocessor circuit in the transmitter, (b) LED array, (c) PD circuit, and (d) microprocessor circuit in the receiver.

Fig. 9 shows the configuration of the circuits used in these experiments.

In Fig. 9, (a) and (b) are the circuits used in the VLC transmitter, while (c) and (d) are those used in the VLC receiver. Fig. 9(a) shows the Atmega8 microprocessor that was used to convert the NRZ input data to the Manchester code in the VLC transmitter. Fig. 9(b) shows the 3 × 4 LED array and its current driving circuit consisting of four DW8501 ICs. Fig. 9(c) shows the PIN photodiode, SFH-203, op-amps, and diodes in the receiver circuit. The PIN photodiode was attached with a receiving lens. Fig. 9(d) shows the two Atmega8 microprocessors that were used for data recovery in the receiver circuit.

4. CONCLUSION

In this study, we developed a new visible light transmission method in which the duty factor of the Manchester code was used for illumination control in the VLC transmitter and a spike detection method was used for data recovery in the VLC receiver. In the VLC transmitter, the Manchester code produces a flicker-free LED light because the average optical power of the LED is kept constant with a fixed duty factor. When the illumination needs to be changed, the duty factor of the Manchester code is changed by the user.

The relationship between the average optical power and the duty factor was calculated and measured experimentally. The average optical power of the LED light was controlled linearly from 12% to 84 % of the CW LED light by changing the duty factor from 10% to 90% stepwise.

In the VLC receiver, an *RC*-HPF was used to generate spikes at the edges of the rectangular data signal while suppressing the 120-Hz noise from adjacent lighting lamps. The spikes were used as an interrupt signal for the microprocessor, which regenerated the sync-mark signal and the Manchester code. The sync-mark signal was transmitted in front of each byte of the Manchester code and was used as the reference time for converting the Manchester code to NRZ code in the receiver. This method simplified the VLC system design as transmitting the clock through a separate channel is not required.

The system configuration introduced in this study is useful for constructing wireless indoor sensor networks using base-band VLC systems that can provide flicker-free lighting, have illumination control capability, and are strong against interference from adjacent noise light.

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