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REDUCTION OF ENVIRONMENTAL OPTICAL NOISE IN VISIBLE LIGHT COMMUNICATION USING A CDS CELL

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ABSTRACT

In this paper, we introduce a new method to reduce the 120Hz noise arising from other lighting lamps adjacent to the visible light communication (VLC) system. A Cds cell was installed near the photodiode in the VLC receiver, and the Cds cell voltage was subtracted from the photodiode voltage using a differential amplifier. The Cds cell has a receiving bandwidth much lower than the photodiode, and detects the 120 Hz noise, but it does not respond to the high frequency signal light. Thus the differential output of the photodiode with the Cds cell becomes an amplified signal with the noise reduced. The signal-to-noise voltage ratio was improved by about 17.5 dB using a Cds cell in the VLC receiver.

Keywords: visible light communication, photodiode, Cds cell, 120Hz noise, differential detection.

1. INTRODUCTION

Visible light communication (VLC) is a new technology in which illumination and wireless communications are performed simultaneously using the same light source [1] [2] [3] [4]. The visible light signal radiated from the source is directly received by the photo detector through free space. Using visible light has several advantages. It does not interfere with conventional radio frequencies, and the signal can only be detected within the area illuminated by the signal beam, and thus it provides safer transmission, by preventing electromagnetic interference or outdoor eavesdropping [2]. To date, light emitting diodes (LEDs) have been used as popular light sources for VLC. LEDs have higher conversion efficiency, longer lifetime, are smaller in size and mechanically stronger than conventional lighting lamps such as incandescent or fluorescent lamps. And, their light intensity is easily controlled by simply adjusting the LED injection current.

Because electromagnetic waves in the visible spectrum are used as the transmission carrier in VLC, light from other lamps near the VLC system may also be received and could interfere with the signal in the VLC receiver, degrading transmission quality. The main interfering noise from adjacent lighting is the 120 Hz AC noise produced by lights used for illumination. Fluorescent lamps, incandescent lamps and even some LED lamps driven by the 60 Hz power line emit 120 Hz noise. Therefore, if the VLC system is going to be installed near other existing lamps, appropriate methods to suppress the environmental noise should be considered during the design of the VLC system.

Base-band VLC systems are simple and easy to realize, however, they may be vulnerable to the environmental noise. Optical filters or electrical filters in base-band VLC can be effective at cutting off the induced noise. Subcarrier modulation such as amplitude-shift keying (ASK) or frequency-shift keying (FSK) can also easily suppress the 120 Hz noise arising from other nearby lighting sources [5]. However, this makes the system configuration relatively more complex than the base-band systems.

In this paper, we introduce a new, simple method to reduce the noise effect using a Cds cell in the VLC receiver. A Cds cell is a device whose resistance changes depending on light illumination. In the VLC receiver, a Cds cell installed near the photodiode (PD) detects the noise light and the Cds voltage is subtracted from the PD voltage using a differential amplifier. The Cds cell has a receiving bandwidth that is much lower than that of the photodiode, which detects the 120 Hz noise, however it does not respond to the high signal frequency. Thus, the Cds cell can be used to suppress the noise voltage without affecting the signal voltage. This method is useful for constructing base-band VLC systems for an indoor wireless network that is robust against environmental noise light.

2. SYSTEM MODEL AND METHODS

2.1 VLC transmitter

In the VLC transmitter, the LED light is modulated in a three-level return-to-zero (RZ) waveform in order to prevent flickering of the LED light. If the LED is directly modulated by the non-return-to-zero (NRZ) signal the average optical power is randomly changed when the data is transmitted, and flicker arises in the LED light. Flickering is an unstable lighting condition that makes the user’s eyes uncomfortable, and should be prevented in the VLC system [6]. In our experiments LED flicker was prevented by using three-level RZ modulation, where the average optical power of the LED array was kept constant. A schematic diagram of the transmitter for three-level RZ modulation is shown in Figure-1.

VOL. 13, NO. 24, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

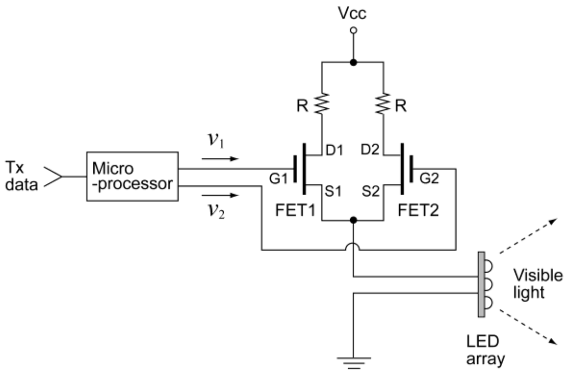

Figure-1. Three-level VLC transmitter.

Two FETs were used to drive an LED array for the three-level RZ modulation of visible light. When NRZ input data was applied to the input port, the microprocessor output two voltages v_1 and v_2 to the gates of the FET 1and FET2, respectively. The source current of an FET is proportional to the gate voltage. Because the sources of the two FETs are tied together, the sum of the two source currents of FET1 and FET2 constitutes a three-level signal and flows to the LED array. We used an Atmega8 microprocessor, two IRF540 FETs, and the LED array was made of six LEDs in the form of a 2×3 planar array. The six LEDs were identical 1 W white LEDs.

To see the three-level RZ modulation waveforms in the VLC transmitter, a character string "\tVLC-test\r\n" was transmitted repeatedly and the voltage waveforms were observed with an oscilloscope. The data rate was 9.6 kbps. Figure-2 shows the voltage waveforms in the transmitter.

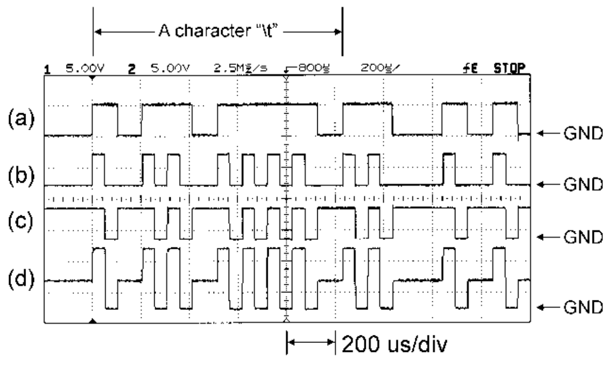

Figure-2. Waveforms in the VLC transmitter. (a) NRZ input signal, (b) gate voltage of FET1, (c) gate voltage of FET2, and (d) three-level RZ signal to LED array.

Figure-2(a) is the non-return-to-zero (NRZ) waveform of the character string in the universal asynchronous receiver-transmitter (UART) format. The American Standard Code for Information Interchange (ASCII) code for the first character "\t" (horizontal tab) is "00001001". In serial transmission using the UART format, the least significant bit (LSB) is sent first, and the bit sequence becomes "10010000". One start bit "0" and one stop bit "1" are added to the bit sequence and the total bit sequence for a character "\t" becomes a ten-bit signal of " 0100100001". High voltage (H) is assigned to bit "0" and low voltage (L) to bit "1" in the UART transmission, thus the character "\t" has a voltage waveform of "HLHHLHHHHL" as shown in Figure-2(a).

Figure-2(b) and (c) are the two voltages v_1 and v_2 which were applied to the gates of FET1 and FET2, respectively. The two signals have a high-to-low transition with a duty factor of 50% when the NRZ bit is in the high state. When the NRZ bit is in the low (L) state, Figure-2(b) and (c) have low and high voltages for the bit time, respectively. The two voltages are applied to the gates of FET1 and FET2. The source currents of FET1 and FET2 are proportional to the gate voltages of Figure-2(b) and (c), respectively.

The two FET source currents are added together and constitute a three-level RZ signal. Figure-2(d) is the three-level RZ signal which corresponds to the sum of the two voltages in Figure-2(b) and (c). It was applied to the LED array. The LED array radiated the three-level RZ visible light in free space. The LED light was flicker-free during data transmission because the average optical power was kept constant at the medium level of the three-level RZ signal.

In order to detect the visible light signal from the LED array, a VLC receiver was installed at a distance of about 2 meters from the VLC transmitter. On the ceiling of the laboratory other LED lamps were installed for indoor illumination and the 120 Hz noise from LED lamps was also detected by the VLC receiver.

2.2 VLC receiver

The VLC receiver was exposed to the light from the VLC transmitter and the adjacent lighting lamps. The light from the VLC transmitter was the three-level RZ signal and those from the adjacent lighting lamps contained 120 Hz noise. We used a photodiode and a Cds cell installed nearby to detect the signal light while eliminating the 120 Hz noise. The VLC receiver was configured as shown in Figure-3.

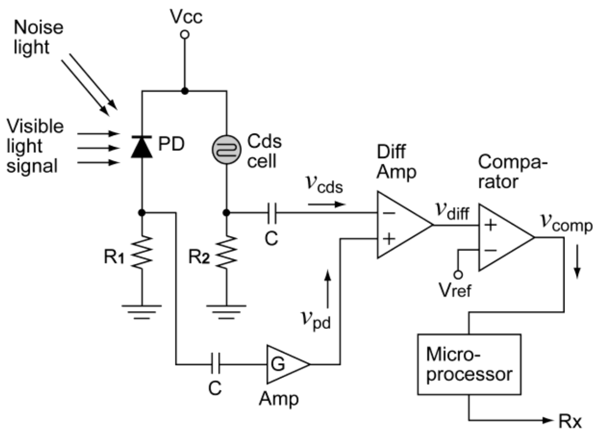

Figure-3. Configuration of the VLC receiver.

VOL. 13, NO. 24, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

The photodiode (PD) generates a signal current proportional to the signal light incident on the absorbing surface. The current flows through the load resistance R_1 and a voltage appears across it. As noted previously, in an environment where other lighting lamps exist near the VLC receiver, the noise light from the lamps is also absorbed by the PD, and a 120Hz noise current is generated which interferes with the signal current. When this noise current is not negligible compared to the signal light, it can affect signal detection. We used a Cds cell to eliminate the noise included in the PD voltage. The Cds cell and a resistance R_2 forms a series circuit and the voltage across the resistance R_2 changes proportionally to the power density of the incident light. The response speed of the Cds cell is different from that of the photodiode.

We measured the AC receiving characteristics of the PD and the Cds cell used in the VLC receiver. Sinusoidal current was applied to the LED array and the detected voltages were recorded. The PD was a silicon PIN photodiode BPW34 whose sensitive area is 7.5mm^2 and we used R_1=1kΩ as its load resistance. The Cds cell was a GL5537 whose diameter was 5mm, and we used R_2=1kΩ for its series resistance. Figure-4 shows the measured AC characteristics of the photodiode and the Cds cell.

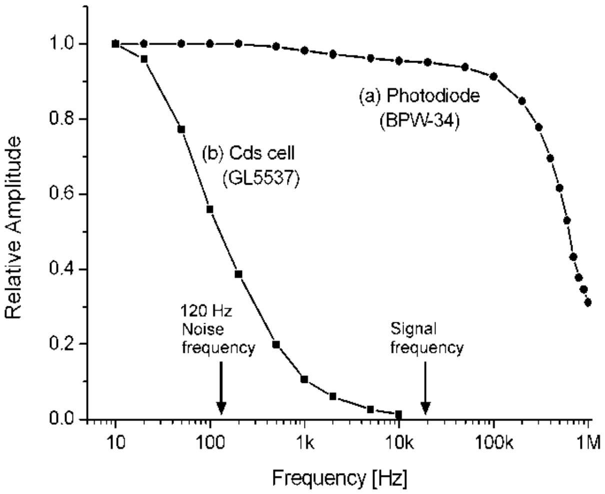

Figure-4. AC characteristics of the PD and the Cds cell.

As shown in Figure-4, the 6dB cutoff frequency of the Cds cell was about 120Hz, and that of the PD was about 600 kHz. The receiving bandwidth of the Cds cell was much lower than the PD. The Cds cell detected the 120Hz noise light from lighting lamp, but did not respond to the RZ signal light from the VLC transmitter. The fundamental frequency of the RZ signal is 19.2 kHz, which corresponds to twice the NRZ 9.6 kbps data rate. When the PD voltage and the Cds voltage were amplified by a differential amplifier, the noise component was reduced while the signal component from the PD was amplified. These phenomena can be illustrated mathematically as follows. The AC voltage of the PD is

$$v_{pd} = G\,\rho_{pd}\,R_1\,S_{pd}\,(P_{sig} + P_{noise}) = k_{pd}(P_{sig} + P_{noise}) \quad (1)$$

where P_{sig} and P_{noise} are the power densities of the signal light and the noise light, respectively. S_{pd} is the receiving area of the photodiode, R_1 is the load resistance, ρ_{pd} is the responsivity of the photodiode and G is the amplifier voltage gain. The constant k_{pd} is

$$k_{pd} = G\,\rho_{pd}\,R_1\,S_{pd} \quad (2)$$

The Cds cell and a resistance R_2 constitutes a series circuit and the voltage across R_2 is

$$V_{cds} = \frac{R_2}{R_{cds} + R_2} V_0 \quad (3)$$

where R_{cds} is the Cds cell resistance and V_0 is the DC supply voltage. In the Cds cell, the signal light is almost cut off and the 120Hz noise is detected due to the low bandwidth of the Cds cell, as shown in Figure-4. The Cds resistance can be expressed as:

$$R_{cds} = R_{cds0} + \frac{dR_{cds}}{dP_{noise}} \times P_{noise} = R_{cds0} + \Delta R_{cds} \quad (4)$$

where R_{cds0} is the DC resistance of the Cds cell, dR_{cds}/dP_{noise} is the ratio of the resistance change to the noise power density. $\Delta R_{cds} = (dR_{cds}/dP_{noise}) \times P_{noise}$ is the Cds resistance change due to the noise light. Substituting (4) to (3), the Cds voltage is expressed as

$$\begin{aligned} V_{cds} &= \frac{R_2}{R_{cds0} + \Delta R_{cds} + R_2} V_0 \\ &= \frac{R_2 V_0}{R_2 + R_{cds0}} \times \frac{1}{1 + \Delta R_{cds}/(R_2 + R_{cds0})} \\ &\cong \frac{R_2 V_0}{R_2 + R_{cds0}} \left\{ 1 - \frac{\Delta R_{cds}}{R_2 + R_{cds0}} \right\} \\ &= V_{cds0} - \frac{R_2 V_0}{R_2 + R_{cds0}} \times \frac{\Delta R_{cds}}{R_2 + R_{cds0}} \end{aligned} \quad (5)$$

where $V_{\text{cds0}} = R_2 V_0/(R_2 + R_{\text{cds0}})$. The AC voltage of the Cds cell due to noise light is

$$\begin{aligned} v_{cds} &= V_{cds} - V_{cds0} = -\frac{R_2 V_0}{(R_2 + R_{cds0})^2} \times \Delta R_{cds} \\ &= -\frac{R_2 V_0}{(R_2 + R_{cds0})^2} \times \left(\frac{dR_{cds}}{dP_{noise}} \right) \times P_{noise} \\ &= k_{cds} P_{noise} \end{aligned} \quad (6)$$

where the constant k_{cds} is

$$k_{cds} = -\frac{R_2 V_0}{(R_2 + R_{cds0})^2} \times \left(\frac{dR_{cds}}{dP_{noise}} \right) \quad (7)$$

ARPN Journal of Engineering and Applied Sciences

The output voltage of the differential amplifier in the VLC receiver is

$$v_{diff} = G_{diff}(v_{pd} - v_{cds}) = G_{diff}(k_{pd}P_{sig} + k_{pd}P_{noise} - k_{cds}P_{noise}) \quad (8)$$

If we make $k_{pd} = k_{cds}$ the noise term in (8) disappears. This condition can be satisfied by adjusting the voltage gain G of the PD amplifier. By equating the two constants in (2) and (7),

$$G\rho_{pd} R_1 S_{pd} = -\frac{R_2 V_0}{(R_2 + R_{cds0})^2} \times \left(\frac{dR_{cds}}{dP_{noise}}\right) \quad (9)$$

The amplifier gain G required for eliminating the noise is expressed as

$$G = -\frac{1}{\rho_{pd} R_1 S_{pd}} \times \frac{R_2 V_0}{(R_2 + R_{cds0})^2} \times \left(\frac{dR_{cds}}{dP_{noise}}\right) \quad (10)$$

Figure-5 is the amplifier voltage gain G versus the resistance R_2 required to eliminate the noise voltage, which is plotted using equation (10).

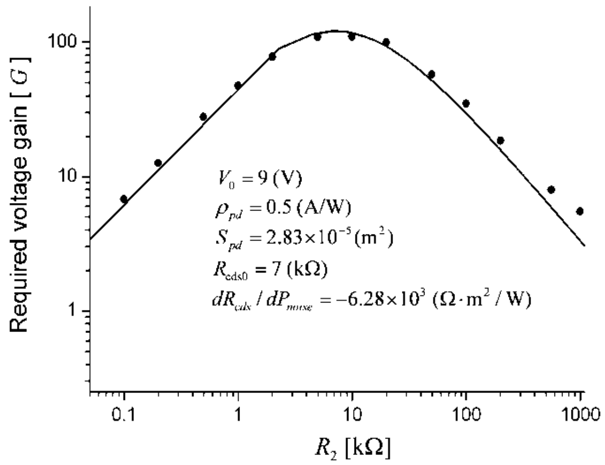

Figure-5. The required gain of the PD amplifier for noise elimination.

In Figure-5, the solid line is the calculation and the symbols (•) are the measured results. In the calculation we used V_0=9V and R_1=1kΩ. The PD responsivity was ρ_{pd}=0.5(A/W) and the PD sensitive area was S_{pd}=2.83 ×10^{-5} m^2. The resistance of the Cds cell was R_{cds0}=7kΩ at a DC illumination of about 0.35W/m^2 and the ratio of the Cds resistance change to noise light was dR_{cds}/dP_{noise} =−6.28×10^3(Ω·m^2/W). This ratio was measured with an optical multi-meter OMM-6810B. As shown in Figure-5, if the series resistance of the Cds cell is fixed, the amplifier gain for noise cancellation is determined, for example when the resistance R_2=1kΩ, the required amplifier gain is G=48. At this condition, the output voltage of the differential amplifier is from (8)

$$v_{diff} = G_{diff} k_{pd} P_{sig} \quad (11)$$

The output voltage is proportional to the signal power and the noise P_{noise} is eliminated. In order to see the operation of the VLC receiver, a character string "\tVLC-test\r\n" was transmitted repeatedly and the voltage waveforms in the VLC receiver were observed with an oscilloscope. Figure-6 is the observed waveforms in the VLC receiver.

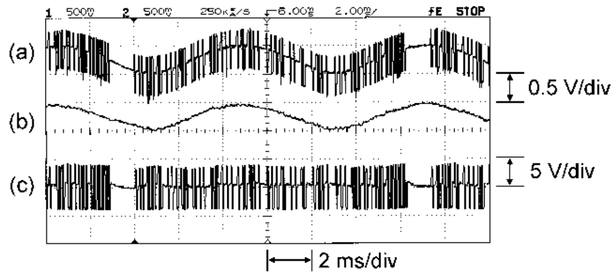

Figure-6. PD and Cds waveforms in the VLC receiver. (a) PD voltage, (b) Cds voltage, and (c) the output voltage of the differential amplifier.

Figure-6(a) is the PD voltage, in which the RZ signal from the VLC transmitter and the 120 Hz noise from the adjacent lighting lamps are mixed. In this waveform, the signal voltage amplitude was about 690mV and the noise voltage amplitude was about 500mV. In this condition the signal-to-noise ratio was

$$V_{sig} / V_{nos} = \frac{690}{500} = 1.38 = 2.8\ (\text{dB}) \quad (12)$$

Figure-6(b) is the Cds cell voltage; the signal was almost cut off and the 120Hz noise amplitude was about 500mV. Figure-6(c) is the differential amplifier output voltage, in which the signal amplitude was about 7.5V and the 120 Hz noise amplitude was about 0.73V. In this waveform, the signal-to-noise ratio was

$$V_{sig} / V_{nos} = \frac{7.5}{0.73} = 10.3 = 20.3\ (\text{dB}) \quad (13)$$

By using the Cds cell in the VLC receiver the signal-to-noise ratio was improved by about 17.5dB. Figure-7 shows the recovered voltage waveforms after the differential amplifier, as observed with an oscilloscope.

VOL. 13, NO. 24, DECEMBER 2018 ISSN 1819-6608
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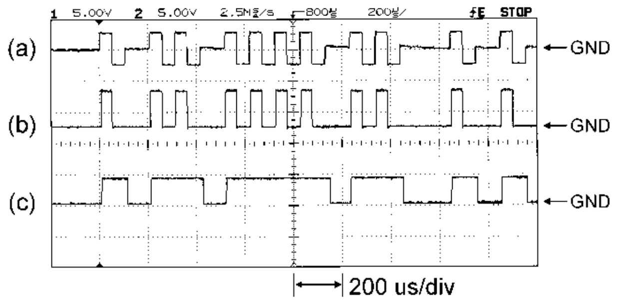

Figure-7. Recovered waveforms in the VLC receiver. (a) three-level RZ output voltage of the differential amplifier, (b) output voltage of the comparator, and (c) NRZ output voltage of the microprocessor.

Figure-7(a) is the output voltage of the differential amplifier, which is the same as Figure-6(c), observed in a different time scale of 200u/div. The center of this waveform is ground level. Figure-7(b) is the comparator output voltage, which corresponds to the positive part of Figure-7(a). The reference voltage of the comparator was set at 1V. At the time of each rising edge of this waveform, the microprocessor started a pulse of 104us which corresponds to one bit time of the NRZ 9.6 kbps. Figure-7(c) is the output voltage of the microprocessor, which has the same waveform as the NRZ input data in the VLC transmitter shown in Figure-2(a). The voltage in Figure-7(c) was connected to a computer serial port and the transmitted characters were observed. Figure-8 shows the characters displayed on the monitor.

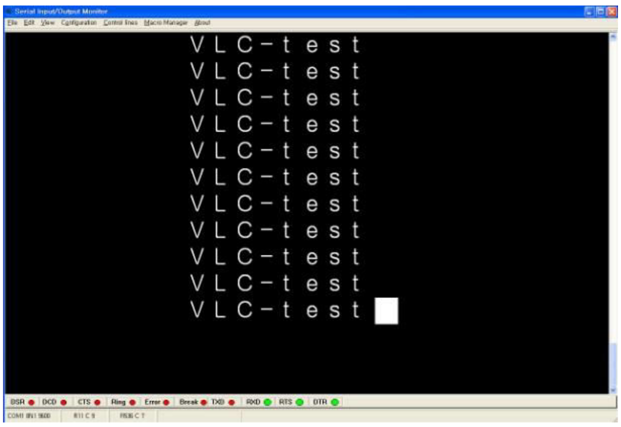

Figure-8. Characters displayed on a monitor.

The input characters applied to the VLC transmitter were "\tVLC-test\r\n". Three of the characters, "\t" (horizontal tab), "\r" (carriage return) and "\n" (line feed) are special characters used for position control, and they are not shown on the monitor. The other eight characters "VLC-test" are shown in Figure-8. We experimentally observed that the 9.6kbps input data were well transmitted while the 120Hz noise from the adjacent lighting lamps was reduced by using a Cds cell in the VLC receiver. Figure-9 shows the circuits used in the experiments.

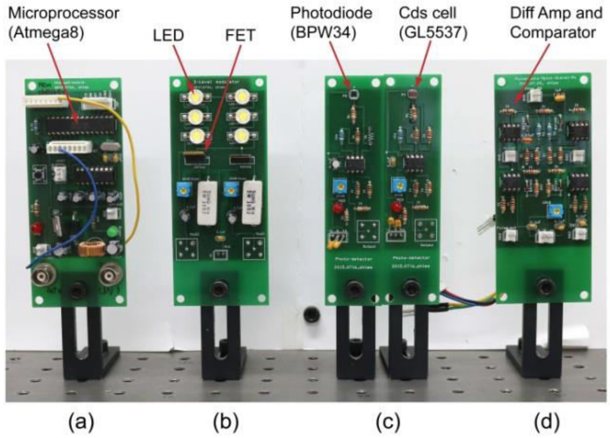

Figure-9. Circuits used in experiments.

Figure-9(a) is the Atmega8 microprocessor circuits used for changing NRZ to RZ waveforms in the VLC transmitter. The same kind of microprocessor circuit was used in the VLC receiver for the reverse operation of changing RZ to NRZ waveforms. Figure-9(b) shows the 2×3 LED array in the VLC transmitter with its current driving circuit for three-level RZ modulation using two FETs. Figure-9(c) shows the PIN photodiode BPW34 and the Cds cell GL5537 used in the VLC receiver. Figure-7(d) is the circuit board, including the differential amplifier and the comparator in the VLC receiver.

3. RESULTS

In environments that contain 120 Hz optical noise from other lighting lamps which is not negligible compared to the VLC signal light, the noise may cause interference in the base-band VLC system. In order to overcome this problem, a Cds cell was used to detect the noise and the Cds voltage was subtracted from the photodiode voltage. Due to its low bandwidth, the Cds cell detected the 120 Hz noise light without responding to the 9.6 kbps signal. The noise component in the PD voltage was effectively suppressed by the Cds voltage through a differential amplifier. In a transmission experiment, the signal-to-noise voltage ratio was improved from 1.38 to 10.3 by reducing the 120 Hz noise voltage with a Cds cell in the VLC receiver.

4. DISCUSSION AND CONCLUSIONS

Base-band modulation in a VLC is simple and easy to implement compared to subcarrier modulations such as ASK or FSK modulation, which use carrier frequencies much higher than the base-band signal. However, the base-band system can be very vulnerable to 120 Hz noise light from other lighting lamps that are installed near the VLC systems. If the noise light is not negligible compared to the VLC signal, some methods need to be employed to overcome this problem.

In this paper we have introduced a new method to reduce the interference of the 120 Hz noise light from other lighting lamps, using a Cds cell near the photodiode in the VLC receiver. We exploited the Cds' characteristics, which is sensitive to 120 Hz noise but does not respond to the high frequency signal light. The Cds cell voltage was proportional to the noise, and was subtracted from the photodiode voltage which contains 120 Hz noise. We experimentally demonstrated that differential detection with a photodiode and a Cds cell is an effective way of reducing the 120 Hz noise induced in the base-band VLC receiver. This configuration is very simple, easy to implement, and it can be widely used for constructing indoor VLC systems that are robust against environmental 120 Hz noise light.

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