LED Light Equipment with Optical Wireless Communication Functions

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Abstract: LED (Light Emitting Diode) lighting equipments can be redeveloped and employed to not only just illumination, but also can wirelessly send audio data for users. In order to make an LED bulb has two channels for stable lighting and high-quality communicates, we used LEDs with different wavelengths, which are visible light for illuminations (including dimming and toning) and infrared for data transmissions in one LED bulb. The light from LED of the communication channel is modulated by PWM (Pulse Width Modulation) method to carry original sound signal. The receiving terminal is a compact battery-less photoacoustic device and it can convert directly the light into the sound by using a solar cell and an audio cell such as an earphone or a speaker. Using our lighting communication equipment, optical audio information can be real-timely obtained in any illuminated area via the compact battery-less wireless terminal.

Keywords: optical wireless communications, LED lighting communication equipment, pulse width modulation, photoacoustic data transmission, compact battery-less information terminal.

1. Introduction
Wireless communication has become a ubiquitous part of human life. As wireless communication carrier, radio and ray are complementary transmission media, and different applications favor the use of one medium or the other. Radio is favored for applications in which user mobility must be maximized or where transmission though walls or over long range is required. For indoor of near distance or high security area, however, spatial optical communication is good because it has no frequency restrictions on all bands for data transmission, human safety because optical carriers are electromagnetic wave free, and adequate privacy protection by directionality of light [1-3]. On the other hand, an attractive possibility in optical wireless communications is that the existing lighting infrastructure can be reused for ubiquitous information transmission [4-5].

We are developing a new LED lighting equipment with data transmission functions based on the optical wireless communication technique. In our lighting communication system, a commercial LED bulb is refitted and became two work channels, one is for general lighting (including dimming and toning) by using the visible-light LEDs, and other is to send audio data by using the infrared LEDs. The spatial infrared radiation is modulated by PWM method to carry the audio signals, and the contents of original sound data are saved in a micro memory card that can be exchanged and read/written easy. In order to make the receiving terminal an energy-conservation device, we have developed a compact battery-less photoacoustic terminal by using the solar cells to not only just supply power, but also to convert

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the optical signals from the LED source into the audio signals to drive an earphone or a speaker [6]. So using our lighting communication equipment, sound data information can be real-timely obtained in any illuminated area via our photoacoustic information terminal. Our purpose is to construct a ubiquitous communication environment with flexible multimedia information support for users.

In this paper, an optical wireless communication system by using the LED lighting is first constructed, and then the LED bulb with data transmission function and the compact portable terminal with optical/audio converting function are proposed by using the spatial optical modulation and communication technique. And we implemented the LED communication bulb and its receiving terminal, and tested their data transmission quality. Finally, the eye safety is evaluated when using our LED bulb to do data communications because the radiation in visible light and near infrared (wavelength $\lambda=400nm-1400nm$) can pass through the human cornea and be focused by the lens onto the retina. The results indicate that the developed LED lighting communication system is effective for photoacoustic data transmission of about 3 meters range.

2. Data-Communication Principles of the Light Equipment

The LED bulb communication system for audio data transmission is shown in Fig 1. It consists of two component subsystems. On the lighting environment side, a white light LED bulb with infrared sending LEDs to use not only just illumination, but also can wirelessly send audio information for users. To make the LED bulb stable lighting characteristics and good communicates quality, we divide the emission spectrum from one LED bulb into two optical channels by LEDs of different wavelength. At the visible wavelength band channel, one white light LED is used to illuminate, dimming and toning, and at the infrared wavelength channel, there are ten LEDs of the peak wavelength $\lambda=860nm$ are employed to radiate sufficient light power to carry the audio signals for data transmission. The emission spectrum of the LED bulb with two optical channels is shown in Fig 2. The abscissa is the radiation wavelengths. We can see that there are three peaks in this graph. Left two peaks (wavelengths are about 450nm and 530nm) are spectrum intensities of the visible-light LED for lighting channel and the other (wavelength is about 860nm) is the infrared LED for communication channel.

The PWM encoding method is used to modulate the spatial infrared radiation to carry original sound signals. The sampling frequency for PWM codes is 44 kHz. The PWM method is a square wave modulated. This modulation infects on the sampling frequency and the duty cycle of the signal. The amplitude of the signal remains stable during time. Figure 3 is an example of PWM modulation for sine signal by our communication system.

![Fig. 1 The LED lighting communication system.](image1)

![Fig. 2 The emission spectrum of the LED bulb with two optical channels.](image2)
At the receiving terminal side, a compact battery-less information terminal is used to receive and convert light signals from the infrared LEDs into audio signals. The principle of this receiving terminal is shown in Fig. 4. Proposed information terminal is a photoacoustic transmission device, and it is composed of a solar cell, an optical filter has appropriate wavelength band corresponding to the infrared LED, and an earphone (or a speaker). The solar cell and the earphone are directly connected without any electronic circuit. We also can use a micro spherical solar array to receive the light from different direction. When the solar cell is irradiated by the modulated infrared light from the infrared LED, the solar cell will generate electricity by the strength of the optical modulation signal and drive the earphone directly without the signal processing. So users can hear the sound, which it same as the original voice source from the earphone.

2.1 The LED Bulb for Data Sending

Figure 5 is the developed LED bulb with data transmission function. It consists of three submodules, which are the visible-lighting module, the infrared-communication module, and the controlling and contents module.

On the visible-lighting module, the emission mechanism of the lighting LED is that exciting a yellow fluorescent material at the 530-nm wavelength by using a blue LED at the 450-nm wavelength to generate pseudo-white light, as shown in Fig. 6(a). So its spectrum distribution consists of an excitation spectrum of blue light and a yellow fluorescence spectrum, as shown in Fig. 6(b). The color temperature of this white LED is about 4500K, which is corresponding to the daylight chromaticity, and average color rendering index $R_a$ is about 80-85 (maximum value of $R_a$ is 100, which is corresponding to the sunlight at daytime). On the other hand, we also will consider that if can use a full-color LED as the illumination source for toning at the lighting channel to various applications in further study and development.
In order to obviate the interference between two optical channels, we have chosen the infrared LED (see Fig. 7(a)), which has 860-nm wavelength at peak emission \( I = f(\lambda) \) as shown in Fig. 7(b) at the communication channel. Figure 7(c) is the dependence of the normalized radiation intensity on the half angle \( I = f(\phi) \) for this infrared LED. We can see it has the breadth of ± 20 deg. Using a larger-power LED as the radiation source for spatial optical communications is also important and required because the communication distance is direct proportion with the square root of transmitted optical power [7]. Selected transmittal LED has 1-watt radiation power at its peak wavelength (860nm), and there are ten LEDs in one bulb for the communication channel (see Fig. 5).

In the controlling and contents module, a current memory card (micro SD card) is used to store the original-sound contents, so users can rewrite their contents easily. And a micro PIC (peripheral interface controller) is employed to amplify biasly the sound signals and modulate the infrared radiation by the PWM method to carry them for data transmission. If the full-color LED is used at the lighting LED module, the PIC chip also can use for toning.

In order to decrease the radiation loss for good SNR (signal to noise ratio) at the data transmission channel, wide-band and high-transmissivity optical material is chosen as the cover of the LED bulb. This cover has the light transmissivity is over 98% at the band from 360nm to 1000nm.

### 2.2 The Photoacoustic Terminal for Data Receiving

Tow-types photoacoustic terminals are developed as shown in Fig. 8 (a) and (b). Each of them consists of the solar cell, the optical bandpass filter, and the earphone. Figure 8(a) and (b) are for indoor and outdoor, respectively.
The solar cell in Fig. 8(a) is a compact plate of $30\, \text{mm} \times 20\, \text{mm}$, and it can generate $0.5\,-\,\text{V}$ voltage to optic-acoustic converting. The optical bandpass filter not only can decrease light noise, but also can realize the multi-language service by using the WDM (wavelength division multiplexing) technique. We also developed a photoacoustic card (dimensions are $86\, \times\, 56\, \times\, 7\,\text{mm}^3$) for outdoor applications as shown in Fig. 8(b). The receiving side of the card has pocket-like structure to shade the stray light such as sunshine at outdoor. An array with twelve spherical solar cell (diameter of sphere is $1.8\, \text{mm}$) can receive light ray from different direction. Each solar cell is injected in a visible-cut plastic-polymer lens also to shutoff the stray-light. The sound hold is placed in the center of dome-like bulge on the card. The bamboo body is chosen for harmony with nature. The solar cells in both Fig. 8(a) and (b) are employed to not only just for signal receiving and optics-acoustic converting, but also can provide power, so these terminals are battery less.

3. Communication-Characteristics Evaluations of the Light Equipment

Figure 9 is the developed optics-acoustic wireless communication system including the LED bulb and the photoacoustic terminal. We evaluated the performance of this communication system as following.

3.1 The Evaluation for Communication Quality

In wireless communication, when data are transmitted along a spatial path, especially in a higher frequency, receiving signals may suffer waveform distortion such as corruption, dispersion by crosstalk noise or jitter, which eventually causes intersymbol interference and results the attenuation of communication quality.
To investigate the data-transmission quality of this communication system, we constructed an experimental system as shown in Fig. 10 (a) to detect and compare its eye diagrams on sending and receiving side. The eye diagram is a useful and insightful illustration of the degradation of signals. The wider the eye opening, the greater the noise immunity. A plate solar cell as the photoacoustic sensor is illuminated by light from the LED bulb. The distance from the sender (LED bulb) to the receiver (solar cell) is 200 cm. A mini earphone as the sound output cell is connected directly with the solar cell. The output audio signals are detected by a sound level meter and displayed on an oscilloscope (via the channel 2 of the oscilloscope) to analyze the signal waveforms. To compare the change from the sending waveform to the receiving waveform, the sending signals are also detected via the channel 1 of the oscilloscope. The results of the detected eye patterns are shown in Fig. 10 (b) for sending waveform, and Fig. 10 (c) for receiving waveform. We can see that the eyes of the receiving waveform are clearly open for the transmission distance of 2 meters.

Fig. 10 The method and results for eye-pattern detection: (a) experimental setup, (b) eye pattern on sending side, and (c) eye pattern on receiving side.

To investigate the possible area of data transmission of this communication system, the dependences of the sound signal level on communication distances and rotation angles are measured by using the experimental setup of the Fig 10 (a).

Fig. 11 Dependences of the receiving sound levels on: (a) data transmission distances and (b) rotation angles.

First, to obtain the dependence of the receiving sound levels on distances, the distance between the LED bulb and the solar cell is changed from 100 cm to 600 cm by the step of 50 cm. Each sound level corresponding to a different data transmission distance is detected by the sound level meter. Measurement results are plotted in Fig. 11 (a). We can
see that when the distance is about 260 cm, the normalized sound level is reduced by -3dB to half of the maximum value. This result indicates that the active work distance of this communication system is in the range of about 3 meters.

Next, to investigate the angle area of this system, the solar cell is set on a rotation stage and rotated within the possible range for the light receiving. The distance from the LED bulb to the solar cell is 200 cm. Measurement results are shown in Fig. 11 (b). We can see that the normalized sound levels decrease with increase in the absolute value of rotation angles, and the half-angle breadth is about ±20 deg.

Finally, we also evaluated the BER (bit error rate) of this communication system for the transmission distance of 200 cm by using a bit error rate meter, and results indicate that the BER of our communication system is less than 10⁻⁸.

3.2 The Evaluation for Eye Safety

By the above-mentioned analysis, the communication quality and transmission area of an optical communication system are always proportional to the received optical average power. This implies that the high optical power is needful. But available optical transmission power may be limited by considerations of eye safety because the radiation from 400 nm to 1400 nm can pass through the human cornea (equivalent to a bandpass filter) and be focused by the lens onto the retina (as shown in Fig. 12), where it can potentially induce the damage of the eye [8, 9]. So how to guarantee safety of human eyes is also a major problem in an indoor spatial optical communications environment when using an apparent source, which the wavelength bandwidth between 400 nm and 1400 nm to carry data information [10].

![Fig. 12 Imaging system of the human eye: f=17 mm is the focal length of the combination of the lens and the cornea.](image)

In order to evaluate the eye safety of developed LED bulb, we constructed an experimental system as shown in Fig. 13 to measure the radiation power at an optical detection sensor, which is equivalent to the retina.

![Fig. 13 Evaluation system for human eye safety.](image)

In this optical system, the developed LED bulb as the measured radiation source (it can be consider as a point source) is placed on front focal plane of a collimating lens $L_c$. The focal length of the lens $L_c$ is $f_c = r = 200$ mm, where $r$
is the minimum near point of convergence, that is the worst-case exposure distance in the retina lesion when using an incoherent radiation such as the LED as a carrier source. The L_Φ is an imaging lens like the lens of the eye, and its focal length f_Φ = 17 mm which is equal to the focal length f of the eye in Fig. 12. An iris blade is placed between two lenses L_c and L_Φ like the iris of the eye, and it has a limiting aperture of D_a = 7 mm (largest diameter, i.e., the most dangerous diameter of human pupil in a dark place). The radiation power on the optical sensor is detected by a power meter. An aperture diaphragm is used to control the quantity of light on the optical sensor, and its diameter D_b = f_Φ f_Φ, where the Φ = 100 mrad (by International Electrotechnical Commission (IEC) standards [11]) is a maximum vision angle.

The allowable exposure limit (AEL) for eye safety of light transmitters is governed by the IEC standards. If average emitted optical power from the measured source, which is detected by the optical power meter (see Fig. 13) is less than this AEL, then that the measured source is safe for human eye. The AEL depends on the wavelength, diameter, and emission semiangle of the measured source. The longer the wavelength, the larger diameter and semiangle, the value of the AEL greater, the measured source is safer for the human eye. For our LED bulb, because of internal visible (for lighting) and infrared (for communications) LEDs have larger emission semiangles, so its image is dispersed on the optical sensor, that is the retina. So measured average emitted optical power by the optical system of the Fig. 13 is much less than the AEL, which means that the LED bulb is safe for human eye.

4. Conclusions
We have developed an LED lighting equipment with optical wireless communication functions as described here, and employed it to transmit audio information in both indoor and outdoor. We also have evaluated its communication quality and eye safety. We plan to construct a ubiquitous communication environment with flexible multimedia information support by using the existing lighting infrastructure. Further study and development of the LED bulb for both lighting and communication such as for image data transmission will be conducted.

References