A 3-in-1 indoor wireless optical communication system using white LED

1. DESCRIPTION

This invention is about a 3-in-1 indoor wireless optical communication system, which promises operation of battery-less IC chips, with data communication property employing white LED illumination.

For the first time, this invention fully optimizes the usage of light: 1. to provide room illumination, 2. to power up the battery-less IC chips and 3. to be used as the wireless communication medium. This is a 3-in-1 concept.

a. FIELD OF THE INVENTION

The presented invention relates to an indoor optical wireless communication system in which illumination devices, which are white LEDs usually mounted on the ceiling, are used to transmit data to battery-less mobile and/or wireless terminals which make use of energy extracted from illumination light to supply its receiving circuitry.

b. BACKGROUND

Due to significant energy savings possible with LED technology as well as the increased lifetimes over standard incandescent lighting, white LED is believed to be a promising illumination device for the next generation. There has been dramatic progress in the last few years on white LED technology. To realize the illumination using white LEDs, researches have been carried out in essential related topics including method for providing power to illumination device via an A.C. power line and so on. Today making jump in flux per white LED and reduce cost per lumen in order to significantly penetrate the general illumination market are most important targets, which make it possible to see the outlines of the future of solid state lighting. In the presented 3-in-1 system, white LED is assumed to be the dominated home illumination device.

Wireless optical links are considered as one of solutions for the short-range data exchange. Wireless optical links transmit information by employing an optoelectronic light modulator, typically a light-emitting diode (LED). The task of up/down conversion from baseband frequencies to transmission frequencies is accomplished without the use of high-frequency RF circuit design techniques, but is accomplished with inexpensive LEDs and photodiodes. Since the electro-magnetic spectrum is not licensed in the optical band, spectrum licensing fee is avoided, further reducing system cost. Optical radiation in the infrared and visible range is easily obtained by opaque boundaries. As a result, interference between adjacent devices can be minimized easily

and economically. Hence, indoor wireless optical communication system is envisioned as a complimentary technology to RF links nowadays.

Most present-day optical channels are termed intensity modulated, direct detection channels. There are two popular ways to control the optical intensity of white LED. First is to adjust forward current value since LED is basically a current driving device. Second is to employ Pulse Width Modulation (PWM). For white LED, the optical intensity is directly related to the current but it is not a linear function of the current. In addition, although the optical intensity can be controlled by changing forward current, the change in forward current will also change the color of the output light which is termed as shift of chromaticity coordinate. A benefit of the PWM method is that it enables intensity control with minimum color shift of the output. A simple implementation method is described with reference to FIG.1A showing circuit with a NMOS switch 101 which opens and closes the circuit. That essentially turns LED 102 on and off. The input signal 104 that controls on and off switching of the NMOS 101 is demonstrated in FIG.1B. By modulating the amount of time 'on', which is the shaded region 106, and 'off' 107 within one cycle time 105, the optical intensity of output visible light 103 can be controlled. To increase the intensity, one must increase the time 'on' 106; to decrease the intensity, one must decrease the time 'off' 107. The percentage of 'on' time 106 within one cycle time 105, which essentially determines the optical intensity of output visible light 103, is termed as duty cycle. During the cycle where largest duty cycle appears, the optical intensity of output visible light 103 is the largest. Since human eye has a limit of 60 frames per second, by increasing the frequency of switching, the change then becomes human imperceptible.

Baseband and bandpass modulation schemes have also been investigated for low-power optical communication system. It is concluded that the power efficiency of baseband schemes which includes On-Off Keying (OOK) and Pulse Position Modulation (PPM), is better than the power efficiency of bandpass schemes which includes Phase Reversal Keying (PRK), Quadrature Phase Shift Keying (QPSK), Frequency-Shift Keying (FSK). The further comparison between OOK and PPM shows that PPM has better power efficiency. By adjusting the number of slots per frame, the bandwidth of the modulated signal can be adjusted so as to match the available channel width, thereby optimize the power efficiency independently from the data rate.

Research results have demonstrated that white LEDs are capable of supporting data transmission at medium data rate, which proves the feasibility of this wireless optical communication channel. However, little attention has been paid on the usage of the energy of illuminated radiated by white LEDs. Limited battery capacity and the weight of the battery are the bottleneck of mobile and wireless devices. If light illumination can be used to power up mobile and wireless terminals inside the room, then the battery-less mobile and wireless devices become realizable. Thus it is possible that an indoor mobile and/or wireless terminal, such as a PDA, can be powered up by the

energy radiated by the illumination device (thus a free-energy-cost device), while doing wireless communication to through the illumination.

c. BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the invention are described hereinafter with reference to the drawings, in which:

FIGS. 1A and 1B illustrate circuit implementation of PWM for optical intensity modulation.

FIG. 2 illustrates the 3-in-1 indoor optical wireless communication system concept.

FIG. 3 illustrates building blocks of optical wireless transmission system.

FIGS. 4A and 4B illustrate transmitter block diagram with PPM scheme.

FIGS. 5A, 5B and 5C illustrate mobile and/or wireless terminal block diagram, circuit block diagrams for energy-extracted converter and receiving circuitry.

d. DETAILED DESCRIPTION

Embodiments of the present system are described with reference to FIG. 2. When multiple white LEDs 201 are used as primary illuminating devices, they are installed on the ceiling of a room or could be anywhere in the room. The number and allocation of multiple white LEDs 201 depend on the room size and the luminance desired. According to ISO standard, the luminance which is sufficient for office work should be within range of 300 to 1500Lx. Calculation and examination should be carried out in order to obtain a uniform luminous in all the place of the room. Illumination is the first concept of this 3-in-1 indoor optical wireless communication system.

The second concept of this 3-in-1 indoor optical wireless communication system is to establish an optical transmission channel for high data rate transmission. In order to transmit information in an optical system, one of the quantities defining the optical wave has to be modulated by a signal that contains the information. There are three quantities available: intensity, wavelength and polarization. In presented system, the basic concept is laid on the intensity modulation of white LED light wave. White LED is a current drive device, which makes modulation on the output light possible. The optical intensity of output visible light can be varied according to the signal that contains information, that is to say the information data can be transmitted through the white LEDs 201, and there are designated terminals to receive it within the same room. The designated terminals can be personal computer 203, mobile controller and so on. The terminal 202 in FIG. 2 is assumed to be a simple battery-less receiver. In this description section, a single transmitter-receiver pair and a diffuse (non-LOS) link is assumed for illustration.

The third concept of this 3-in-1 indoor optical wireless communication system is to make use of the energy of visible light from white LEDs to realize the battery-less

mobile and/or wireless terminal. Lighting services are continuously available in most offices, schools days and nights, thus the cumulated energy of illumination light is no longer a small dish. Extracting energy from illumination light to power up other devices is a new and meaningful power saving idea. The essential element to extract energy from illumination light is solar cell 204. The amount of power that solar cell 204 can provide is proportional to the size of solar cell 204. Hence, for electronic devices with high power consumption, the size of solar cell would be very large in order to make these devices battery-less. For example, to supply a mobile phone to operate, the size of solar cell will be larger than 5,000 cm^2. With development of ultra-low-power technologies, and improvement of solar cell efficiency, it would be possible to use extracted energy from illumination light to supply a computer operation in the future. However, the size of solar cell may be still so large that it covers the entire surface of the casing which is shown in FIG. 2.

The presented 3-in-1 indoor optical system is described with reference to system building blocks as shown in FIG. 3. In the transmitter 301, the building block termed as 'optical modulation' 304 or 'entection' is to convert electrical signals into the optical wave. This corresponds to the detection 305 process in the receiver 302 where conversion of an optical wave into a signal in electrical domain is performed. This detection process is termed as direct detection indicating that the receiver 302 measures the optical power of the input signal. After the optical wave has been detected, the resulting signal is ready for demodulation. The modulation block 303 in transmitter converts the information signal into a signal that is optimally adopted to the properties of the optical modulator and demands made on its output signal. The demodulator 306 performs the inverse operation.

In FIG. 4, the block diagram of the transmitter 301 is presented. Conventional implementation circuit for PWM has been described with reference to FIGS. 1A and 1B. Optical intensity of output visible light 103 is modulated according to pulse width of each symbol to be transmitted 104. These pulse widths are expected to be different if symbols to be transmitted are different. It can then be found that the optical intensity of output visible light 103 would be different for different symbols transmitted, which shows that optical intensity of output visible light is transmitting data 104 dependent. For illumination purpose, stable luminance is expected. Hence, conventional implementation method for PWM which causes intensity to be data dependent is not suitable for the presented system.

The modulation scheme used in this system will be Pulse Position Modulation (PPM) in which information is represented by the position of a pulse within a symbol period. By employing PPM scheme, every symbol will have one and only one pulse within its symbol duration which is denoted as one frame time, T_{frame}. That is to say symbols are all with identical duty cycle. Hence the average intensity of output optical visible light over each symbol period is the same rather than data dependent. It is concluded that a constant average optical intensity of output visible light is ensured by using PPM

scheme.

The operation of transmitter is illustrated as below with reference to FIGS. 4A and 4B. Two-level digital signal 404 which contains information is fed into a PPM modulator 401. In the PPM modulator 401, one input symbol consisting of N bits is converted into the position of a pulse within that symbol period T_{fram}. The symbol period with duration T_{frame} is divided into 2^N slots with duration T_{slot} and only one of these slots contains a pulse. The pulse width can equal the slot duration, or be smaller. Therefore, pulse width is expressed as $T_{pulse} = x \cdot T_{slot}$, with $0 < x < 1$. Since the information is represented by the position of a pulse, a timing reference has to be recovered before demodulation is possible. Thus a synchronous demodulator is required for PPM.

The PPM signal 405, which is the output of PPM modulator 401, is then served as control signal of the PMOS switch 402. The working principle is similar as the PWM circuit with NMOS switch 101 shown in FIGS. 1A. White LED 403 is activated by turning 'on' of the PMOS switch 402. Since there is only one pulse within one symbol period T_{frame}, if a NMOS switch 101 is used, then white LED 403 will be only activated for a pulse duration that is $\frac{1}{2^N} T_{frame}$ within one symbol period. The larger the N is, the shorter the white LED 403 will operate and the lower the optical intensity will be, which is not desirable. Therefore, the PMOS 402 is used as the control switch instead of the conventional NMOS 101.

For the PMOS switch 402, when the controlling signal 405 at its gate is at low state, it turns 'on' and connects white LED 403 to the supply voltage 400 which enables operation of the white LED 403; while when the controlling signal 405 at its gate is at high state, it turns 'off' and disconnects the white LED 403 and supply voltage 400 which disables operation of the white LED 403. The PPM signal 405 has only one pulse (high state) within one frame time, therefore within one symbol period T_{frame} the operation time for the white LED will be $\frac{2^N - 1}{2^N} T_{frame}$. As the larger the N is, the closer the operation time approaches to the symbol period T_{frame} and the higher the optical intensity will be. Taking the following case as an example with reference to FIGS. 4A and 4B, the two-level digital data 404 is using 4bits/symbol scheme, with a known symbol period T_{frame} 408. The current symbol to be transmitted is '1001'. It is firstly fed into the PPM modulator 401 where T_{frame} 408 is divided into 16 time slots which is counted as 0, 1, 2... 15. Hence the current symbol '1001' corresponds to 9 which is actually the 10^{th} number counting from 0. Thus there is only one pulse 411 appearing at 10^{th} time slot in the output PPM signal 405. Then the PPM signal 405 serves as input signal of the gate of PMOS 402 which is acting as a switch. White LED 403 is connected to the supply voltage 400 through turning the PMOS switch 402 on. When the pulse 411 at 10^{th} time slot is arriving, the PMOS switch 402 opens the connection

between the white LED 403 and the supply voltage 400, and then the forward current is zero 413 during that time slot. Hence white LED 403 does not emit light when pulses appear. For other time slots, the PMOS switch 402 is on and white LED 403 emits visible light 407. The forward current 406 of white LED 403 is kept identical when the switch 402 is at 'on' state. As a result, optical intensity during the 10^{th} time slot is smaller than that during other 15 time slots. The intensity of output visible light 407 is modulated according to the position of presented pulses.

Embodiments of the battery-less mobile and/or wireless terminal are described with reference to FIGS. 5A, 5B and 5C. There are two major elements of the mobile and/or wireless terminal: an energy-extracted converter 501 to provide power supply, and a receiving circuitry 502.

The block diagram of the energy-extracted converter 501 is presented in FIG. 5B. The energy-extracted converter 501 is expected to convert optical power to electrical power by making use of solar cell 503 and then to provide constant supply voltage 512 to the receiving circuitry 502. Solar cell 503 is the first block of the energy-extracted converter 501 and its size is proportional to the power required for the receiving circuitry 502 to operate. Hence estimation of power to be consumed and calculation of the size of solar cell 503 accordingly are necessary. In order to provide a constant supply voltage 512, a switched-capacitor (SC) type DC-DC converter 504 is employed as the major element of the energy-extracted converter 501. As shown in FIG. 5B, besides the solar cell 503 and the SC DC-DC converter 504, the energy-extracted converter 501 also consists of a storage capacitor 507, a voltage detector 505 and four MOSFET switches 508, 509, 510 and 511. The operation of this energy-extracted converter 501 is as below: When the solar cell 503 starts to generate electrical power, switch P1 508 and P4 511 will be turned on. Thus the generated power is able to be supplied to the receiving circuitry 502 through the SC DC-DC converter 504. The voltage detector 505 is used to sense the voltage level. When the power generated by the solar cell 503 is greater than that dissipated by the receiving circuitry 502, the storage capacitor 507 stores the excess energy by making switch P4 511 off and P3 510 on. On the other hand, when the generated power decreases, the excess energy stored in the storage capacitor 507 is supplied to the receiving circuitry 502 through the DC-DC converter 504 by making switch P1 508 off and P2 509 on. Switches P1-P4 508-511 are controlled by the control unit 506.

The detailed composition of the receiving circuitry 502 is described with reference to FIG. 5C. According to FIG. 3, there are two building blocks: detection 305 and demodulation 306. In the presented system, a reverse biased p-i-n photodiode 513 is employed to detect the intensity modulated incident light 407. The p-i-n photodiode produces an output electrical current which is a measure of the optical power impinging on the optical active surface. The generated electrical current is termed as photocurrent that is proportional to the incident light 407 intensity. The p-i-n photodiode requires relatively low reverse bias voltage which the energy-extracted

converter 501 is able to provide. Followed the p-i-n photodiode 513, there is a trans-impedance amplifier (TIA) 514 which outputs an amplified voltage signal from the photocurrent input. An auto-gain-controlled amplifier (AGC) 515 may be needed to carry out further amplification within specific range. A straightforward demodulator consists of an integrator 516 which integrates during every time slots within a symbol period T_{frame}, accompanied by a comparator 518 that compares the integration results until the smallest value is found. As stated in transmitter section, when there is a pulse appears in the PPM signal, the intensity of output visible light decreases, and within one time frame, there is only one pulse. Hence, within a symbol period T_{frame} the smallest integration result will indicate the time slot at which the pulse appears. The position of the pulse within that symbol period is determined. It is a synchronous demodulator which requires slot and frame clock to be synchronized with that of received signal. As last, a decoder 519 is used to restore the original information data.

2. CLAIMS

What is claimed is:

1. A 3-in-1 indoor wireless optical communication system is capable of providing illumination, powering up mobile and wireless terminals and realizing data communication. The said system comprises fixed stations, modulators, a multiple of white LEDs and mobile terminals within a confined region, and performing wireless optical communication between the said fixed stations and the said mobile and wireless terminals through the said white LEDs' illumination.

2. The 3-in-1 wireless optical communication system of claim 1, wherein said fixed stations generate baseband digital data signals and the said fixed stations can be a Set-Top box, a personal computer, etc.

3. The 3-in-1 wireless optical communication system of claim 1, wherein said modulator following the fixed station modulates the baseband digital data into the transmitted signal. The detailed configuration of the said modulator is determined by the chosen modulation scheme, and the said modulator may also comprise a baseband signal processing unit whenever is needed.

4. The 3-in-1 wireless optical communication system of claim 1, wherein said multiple white LEDs provide illumination for the confined region and radiates visible light consisting transmitted signal to entire confined region. The said multiple white LEDs are considered as a general room illumination device.

5. The 3-in-1 wireless optical communication system of claim 1, wherein said mobile and/or wireless terminal comprises an energy-extracted converter, and a receiver. The said mobile and/or wireless terminal can be a PDA, which is a pocket-product, a notebook, a cell-phone, a laptop, a iPod, a iPhone, or any storage device or even a

fixed computer. The energy-extracted converter is to extract energy from visible light radiated by white LEDs and then to supply the receiving circuitry of the designated terminal with the power extracted. The receiving circuitry is to receive the data transmitted by white LEDs illumination.

6. The 3-in-1 wireless optical communication system of claim 1, wherein said data is transmitted and received between said white LEDs and mobile and wireless terminals and wherein the modulator and white LEDs are served as transmitting device, mobile and/or wireless terminal are served as receiving device.

7. The 3-in-1 wireless optical communication system of claim 3, wherein said baseband signal is modulated to be the transmitted signal. The modulation scheme used can be, but not necessary restricted to, Pulse Position Modulation (PPM), On/Off Keying (OOK), Binary Phase Shift Keying (BPSK). A particular modulation scheme can be chosen depending on the specific application, standard and environmental factors.

8. The 3-in-1 wireless optical communication system of claim 4, wherein the number of white LEDs is determined by the desired luminance. The luminance obtained by multiple white LEDs must achieve the standard level of illumination set by ISO which is in the range of 300 to 1500 Lx.

9. The 3-in-1 wireless optical communication system of claim 4, wherein said illumination light radiated by white LEDs consists of transmitted signal means: light intensity modulation is carried out. The intensity of visible light is varied according to the transmitted signal. And the frequency of change in intensity is fast enough to be humanly imperceptible.

10. The 3-in-1 wireless optical communication system of claim 5, wherein said energy-extracted converter of the mobile and/or wireless terminal comprising: a solar cell to convert optical energy of visible light into electricity, a DC-DC converter, a storage capacitor to store excess power and MOSFET switches. Said energy-extracted converter supplies a constant voltage to receiving circuitry. The MOSFET switches controls connection between the solar cell and the storage capacitor.

11. The 3-in-1 wireless optical communication system of claim 5, wherein said receiving circuitry of the mobile and/or wireless terminal comprising: photodiode to convert the incident visible light to photocurrent, transimpedance amplifier to obtain signal in voltage domain, demodulator and baseband signal processing unit.

12. The 3-in-1 wireless optical communication system of claim 5, wherein said energy extracted from the visible light is used to power up the receiving circuitry of mobile and/or wireless terminal, which requires the mobile and/or wireless