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Variable CCT constant illuminance white LED light communication system with dimming feature

Basudeb Das *, Shubham Bardhan, Tapas Maity, Saswati Mazumdar

Electrical Engineering Department, Jadavpur University, Kolkata 700032, India

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ABSTRACT

This paper proposes a novel approach of visible light communication (VLC) system through variable correlated color temperature (CCT) and constant illuminance white LED lighting system with dimming feature in indoor. To validate the concept, a 2 MHz optical communication channel bandwidth is implemented and the effect on lighting quality is experimentally verified in this article. The CCT changing and constant illuminance lighting system is developed using the warm white (CCT 2800 K), red and blue LEDs. Color mixing of lights is based on the Grassmann's color mixing Law by controlling the duty cycle of the light sources. This prototype produces the CCT ranging from 2300 K to 11000 K with dimming control. The measured CCT is very accurate with respect to the set point CCT and it is within the tolerance range as specified in the ANSI standard C78.377 (ANSI 2008) where the CCT may follow daylight CCT pattern or any set range throughout the day and in evening it may glow at any constant CCT as the user wishes. A very high CRI value (*Ra* 89) is successfully achieved with the constant illuminance of 240 lx in the working plane at 7.5ft distance from the luminaire and during the data transmission that light level is dimmed to 151 lx, so that user realizes that the data transmission has been started. This type of system is especially designed for closed room office lighting, conference room lighting, classroom lighting where the CCT changing lighting system is required along with a communication channel.

1. Introduction

Innovation of LEDs has changed the concept of traditional lighting and people are thinking the use of light beyond illumination. From this point of view a concept has come, visible light communication (VLC), namely the Li-Fi (Light-Fidelity); transfer of data through visible light at very high speed. Li-Fi may be used as a supplement of Wi-Fi in indoors where point to point communication is necessary. The previous research on Li-Fi (Grantham et al., 1999; Chen et al., 2016; Son et al., 2013; Ziyan et al., 2013; Shiliang et al., 2016; Motoi and Shinichiro, 2019; IEEE 802.15.7, 2012) uses a fixed correlated color temperature (CCT) white light sources as transmitter as well as illuminating the working plane. In close rooms like the modern offices, institutes, people are completely isolated from the outer environmental condition, especially from daylight. The quality (CCT) and quantity (illuminance level) of daylight varies throughout the day depending upon the time of the day and sky condition (Pinho et al., 2013). CCT of the daylight of Kolkata, the city of India, where this work has been done varies from 2300 K at sunrise to 5000 K at noon and exceeds 10000 K at overcast conditions (Das et al., 2018). Daylight has a strong psychological and photo-biological effect on human body and mind. People staying under artificial light may suffer from seasonal affective disorder (SAD) caused by lack of daylight (Yang et al., 2019). Previous studies showed that the secretion of cortisol and melatonin hormones is influenced by the light (Yang et al., 2019; Commission Internationale de l'Eclairage, 2004). These two hormones play an important role in sleep and alertness. These two rhythms should be maintained for good health condition. Instead of using fixed CCT lighting system in offices, institutes, multi-storied buildings, CCT changing daylight emulating artificial lighting system is the best possible solution to overcome these problems.

In past few years many research and development is taking place for CCT changing lighting system with mixing of different light colors, having different control strategies. In some previous studies, monochromatic lights red-blue-green (Tang et al., 2014; Muthu et al., 2002) or red-blue-green-amber (Gilman et al., 2013) were mixed

* Corresponding author.
E-mail address: basudebdas.1991@gmail.com (B. Das).

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to get different shades of white light. These systems required complex control system and have poor color rendering index (CRI). CCT variable light sources can be implemented by mixing two different white light sources (cool white and warm white) (Kim et al., 2015; Chen et al., 2015). In such system CRI can be improved but CCT is limited to higher and lower CCT light sources used for blending. Wide range of CCT cannot be produced using these systems.

This article proposes a variable CCT lighting scheme which can be used in visible light communication. This system works in two modes, (i) CCT of the system will follow the preset daylight CCT pattern throughout the day, (ii) data transmission mode where the light level will change, CCT remain same. A phosphor coated warm white LED (PC-WW LED) having CCT of 2800 K is mixed with the blue LED to achieve the CCT higher than 2800 K. Whereas red LED is blended with the same PC WW LED to get the CCT below 2800 K. A wide range of CCT from 2300 K to 11000 K is achieved using this concept. A PC WW LED is mixed with the monochromatic LEDs for four reasons: firstly, to achieve wide range of CCT compared to CW and WW color blending, secondly, better CRI value (here, CRI value is 89) compared to RGB and RGBA LED blending, thirdly, chromaticity shifts for PC LED are lower than monochromatic RGB LEDs and fourthly, to establish a communication channel along with the same lighting system. The pulse width modulation (PWM) technique is used to control the brightness of red and blue LEDs by controlling the duty cycle of the control pulses, whereas the warm white light source is fixed at 50% duty cycle which will be used as an optical communication channel for data transmission. The frequency of the PWM signal used for warm white light source determines the data-rate and bandwidth of the communication channel. To prove the concept, a 2 MHz channel bandwidth is used in this experiment. Two different illuminance levels are maintained in this system. When the data is being transmitted maximum illuminance of this system becomes 151 lx at CCT of 11000 K and in normal CCT varying mode, the maximum illuminance becomes 240 lx throughout the CCT range and maximum CRI value obtained as 89. The detailed description of the system with necessary block diagram and experimental results are described in the following sections.

2. Overview of the proposed system

The purpose of the proposed system is to generate a wide range CCT of light source having high CRI values as well as communication features. Control of the illuminance of the light source are being done at two stages; (i) when data is not being transmitted through the light source and (ii) when data is transmitted through the light source establishing a reliable and noiseless communication channel. By default this system will follow a preset daylight CCT pattern throughout the day at a constant illuminance of 240 lx at the working plane. If someone wants to transmit data, it will be selected manually by a switch. For good communication channel establishment, illuminance level on the working plane will be dimmed only; there will be no effect on CCT. Block diagram of the proposed system is shown in Fig. 1.

Here a manual selection switch is used to enable the communication channel. The signal coming from this switch comes to the CCT and illuminance control unit and to the multiplexer simultaneously. When the multiplexer gets the 'High' signal, it passes the signal coming from the data processing unit; else it passes the signal coming from the CCT and illuminance control unit. Output of the multiplexer drives a MOSFET driver, which is a TTL to 12 V converter to make the MOSFET Q1 on and off according to the signal coming to its gate. The CCT and illuminance of the light source is controlled by a microcontroller. When the signal coming from the switch is in 'Low' state (communication channel is not activated) microcontroller sends a set of PWM signal to the warm white, blue and red LEDs maintaining the illuminance maximum at 240 lx and the CCT may be controlled at any value between 2300 K and 11000 K. When the signal coming from the switch is in 'High' state (communication channel is activated) microcontroller sends another set of PWM signal to blue and red LEDs and the warm white LED gets the signal from the data processing unit. During this operation the illuminance level will be shifted to maximum 151 lx. MOSFETs Q1, Q2 and Q3 are used to switch on and off the warm white, blue and red LEDs respectively according to the signal coming from the microcontroller through MOSFET drivers. Here the data is being transmitted through the warm white LEDs only. A data

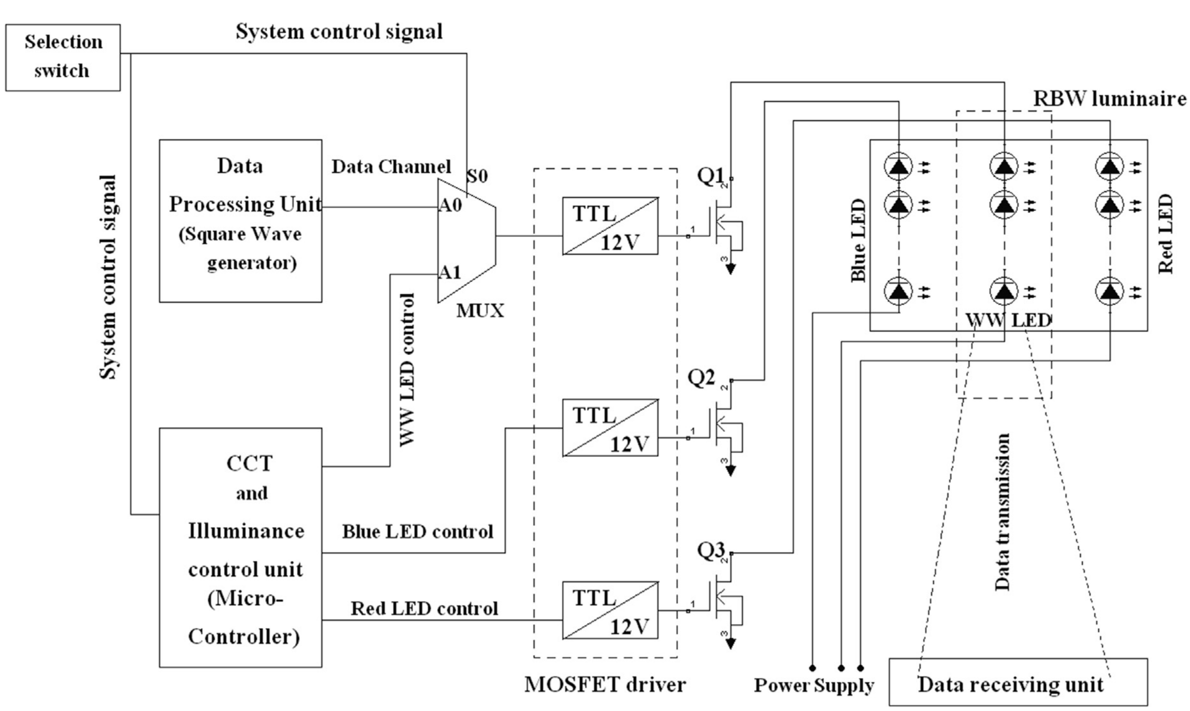


Fig. 1. Block diagram of the proposed system.

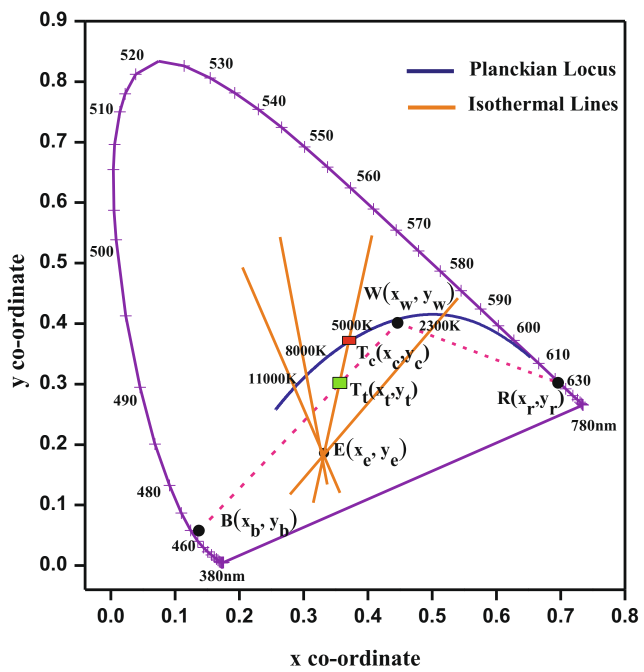


Fig. 2. Source points, Blended CCT point, Planckian locus and Isothermal lines are shown in CIE 1931 chromaticity diagram.

Table 1
Specification of the LEDs used in the luminaire.

LED color	No. of LED used	Total forward drop	Maximum current
Warm White (2824 K)	24	36 V	600 mA
Blue (474 nm)	6	18 V	300 mA
Red (633 nm)	3	6.6 V	300 mA

receiving unit is placed at the working plane to receive the data coming through it. The detailed description of the CCT control scheme and the optical communication is given below.

2.1. Wide range CCT control scheme

In this system the color mixing follows the Grassmann's law of color mixing (Murdoch, 1985). According to Grassmann's law, color mixing obeys the law of addition. If the tri-stimulus values (X, Y, Z) of two colors are known, they can be added to obtain the tri-stimulus values of the resultant. Usually a color can be specified in terms of its chromaticity coordinates (x, y) and its luminance (L), which is proportional to the tri-stimulus value Y. The chromaticity coordinates (x, y) of this blended color will be somewhere on the straight line connecting the chromaticity coordinates of two colors on CIE 1931 chromaticity diagram. The tri-stimulus distribution function $\bar{y}(\lambda)$ is exactly similar to the relative spectral luminous efficiency curve V (λ). Hence any photometric parameter like luminous flux (φ), luminance (L) or illuminance (E) is proportional to tri-stimulus value Y. So, a blended color can be generated by mixing of the illuminance of two primary colors, and the detailed formulation of mixing two colors is already discussed in several articles (Malik et al., 2018, 2020). The color mixing is based on the illuminance contribution of individual light sources. The illuminance can be controlled by controlling the current flowing through the LED. LED current can be controlled by either continuous current reduction technique or by pulse width modulation (PWM) technique. I-V characteristic of LED is non-linear in nature. So, a small change in voltage can cause significance change in current as well as light output. Continuous current reduction method is an analog dimming method to control the current. PWM dimming method is a digital approach, which can be implemented by controlling the duty cycle of the control pulses. LED will be ON when pulses are in high state and LED will be OFF when pulses will be in low state. So, the average light output can be controlled by controlling the ON and OFF time of the LED. PWM dimming increases the dimming range and also precise dimming can be achieved using it (Dyble et al., 2005). In color mixing approach a precise dimming control is required for stable light output. In this

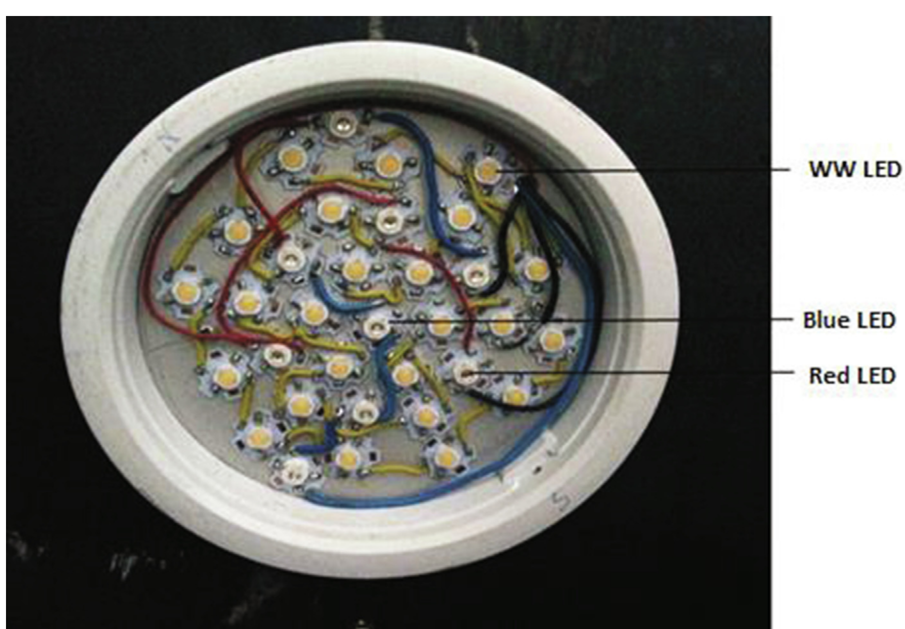
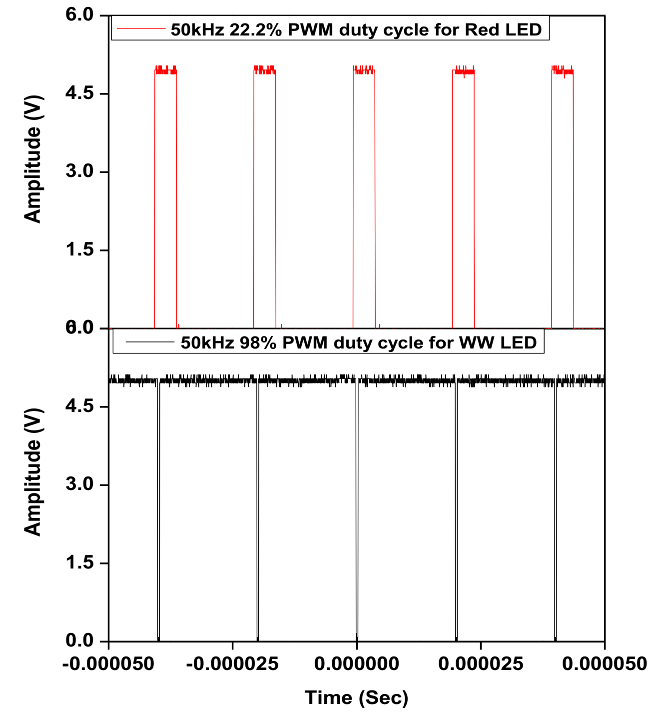
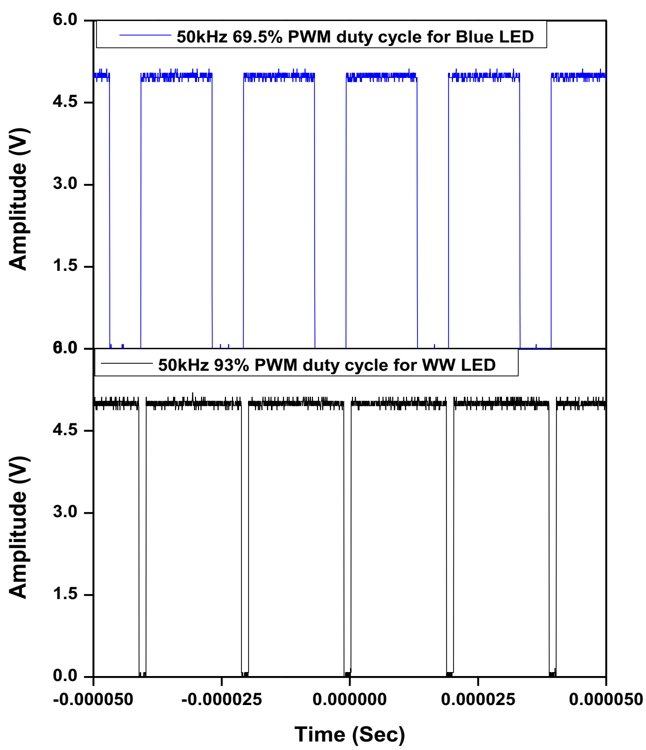


Fig. 3. Arrangement of LEDs in a luminaire.

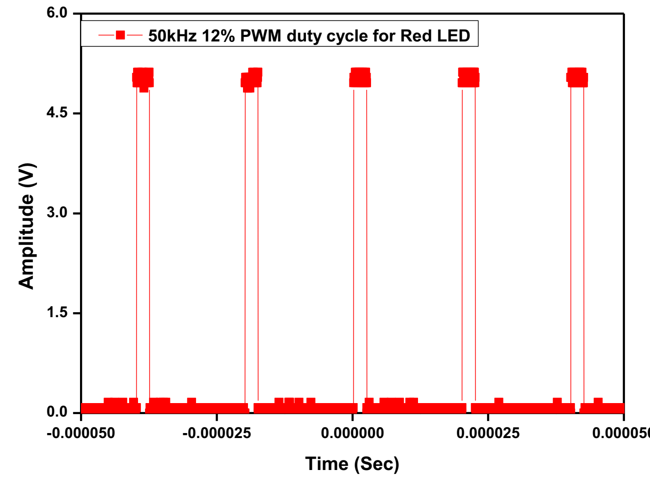


(a)

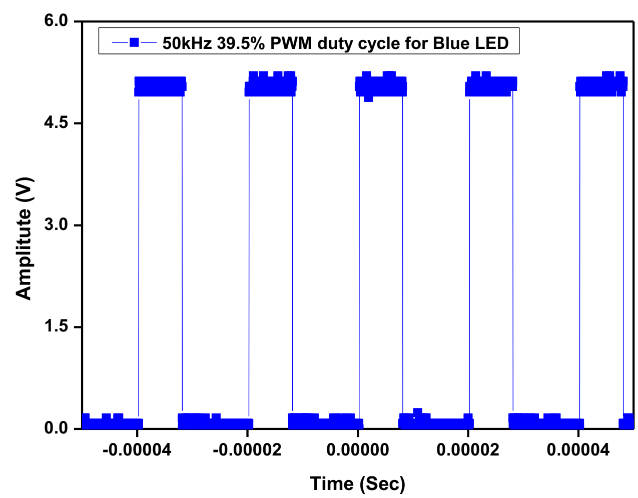


(b)

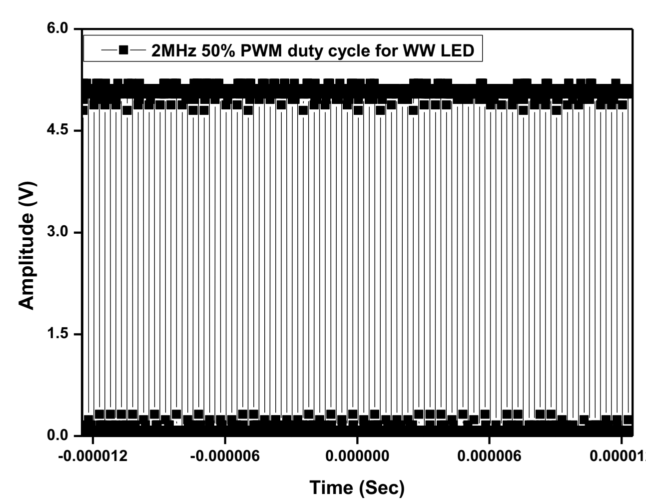
Fig. 4. Control signal for CCT (a) 2700 K, (b) 6500 K with illuminance of 240 lx, when data channel is disabled.



(a)



(b)



(C)

Fig. 5. Control signal when data channel is enabled for (a) Red LED at CCT 2700 K, (b) Blue LED at CCT 6500 K (C) WW LED for all CCTs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Operational frequency of individual light sources in both conditions.

Data channel disabled condition			Data channel enabled condition		
Red	WW	Blue	Red	WW	Blue
50 kHz	50 kHz	50 kHz	50 kHz	2 MHz	50 kHz

proposed work the PWM dimming method is used for dimming of individual light sources.

In this proposed work a wide range CCT has been generated by using three light sources, i.e. warm white, red and blue source. To reduce the complexity of lighting control only two sources have been mixed at a time and third one remains unused. The warm white light source is used here, having CCT of 2800 K. To achieve the CCTs from 2300 K to 2800 K, only warm white and red sources are being mixed and to achieve the CCTs from 2800 K to 11000 K, blue source is being mixed with the warm white source. Below 2800 K, the blended CCTs will lie on the warm white and red source connecting line and blended CCTs above 2800 K will lie on the warm white and blue source connecting line. The proposed concept is shown in CIE 1931 chromaticity diagram in Fig. 2.

Here, $W\ (x_w, y_w)$ is the chromaticity point of the used warm white light source, $R\ (x_r, y_r\ )$ and B $(x_b, y_b\ )$ are the chromaticity point of used red and blue light source respectively. $T_c(x_c, y_c)$ is the chromaticity point of CCT 5000 K, generated by blackbody radiation, lies on the Planckian locus. $T_t(x_t, y_t\ )$ is the chromaticity point of 5000 K, which lies on the isothermal line of 5000 K. Both $T_t\ (x_t, y_t\ )$ and $T_c(x_c, y_c)$ have same CCTs as they are lying on same isothermal line, but D_{uv} value will differ. $E(x_e, y_e)$ is a point on xy plane of CIE 1931 chromaticity diagram from where all isothermal line passes and the value of x_e and y_e are 0.3320 and 0.1858 respectively, described by C. S. McCamy (McCamy, 1992). In other hand, $T_t\ (x_t, y_t)$ is the blended CCT point which is generated by mixing of warm white light source and blue light source and that point is on the line, connecting $W\ (x_w, y_w\ )$ and B $(x_b, y_b\ )$ as proposed earlier.

In generalize way it can be stated that the blended CCT point $T_t(x_t, y_t\ )$ will lie on the isothermal lines of respective CCT and it will also lie on the $W\ (x_w, y_w\ )$ - $R\ (x_r, y_r\ )$ connecting line (for CCTs below 2800 K) and $W\ (x_w, y_w\ )$ - B $(x_b, y_b\ )$ connecting line (for CCTs above 2800 K). The target CCTs can be achieved by illuminance mixing of two light sources in proper ratio. To achieve the target CCT, individual light sources should be dimmed to required illuminance value by controlling the PWM duty cycle of control signal. A detailed mathematical formulation is given below in generalize way to determine the required duty cycle to achieve a target CCT point.

2.2. Generalized mathematical formulation to achieve a target CCT point

The chromaticity co-ordinate of any CCT point $T_c(x_c, y_c)$, which is on the Planckian locus and generated by blackbody radiation can be

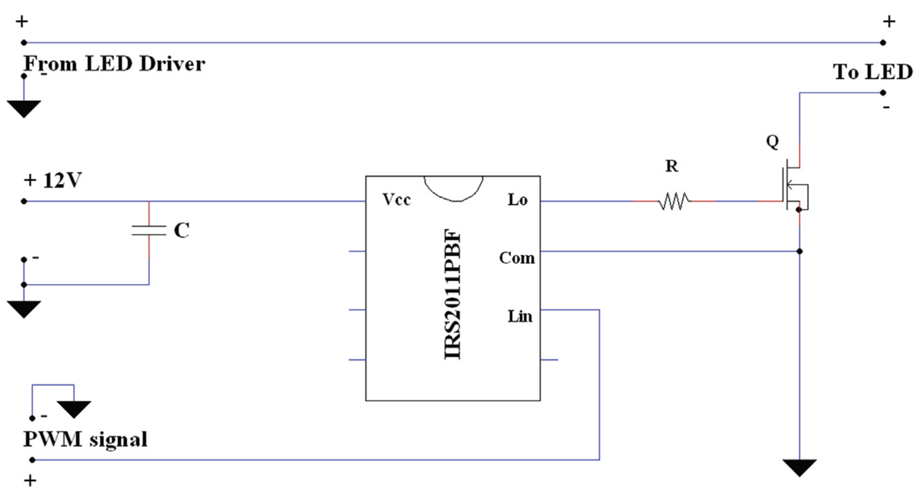


Fig. 6. Schematic of switching Circuit to control the LED.

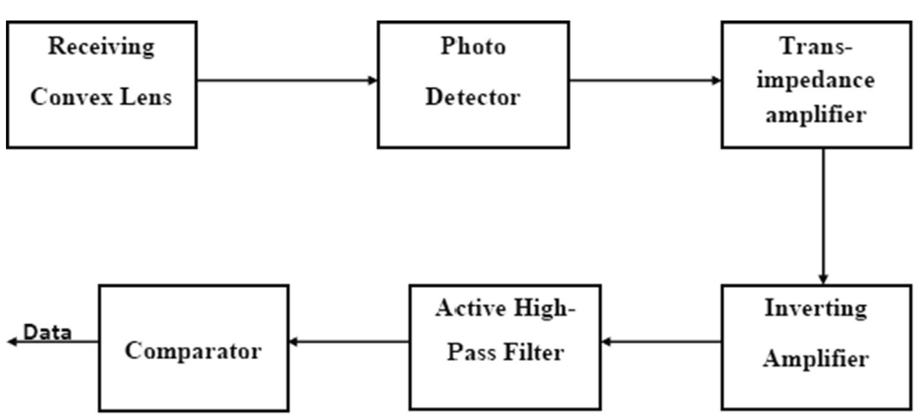


Fig. 7. Block diagram of the data receiver unit.

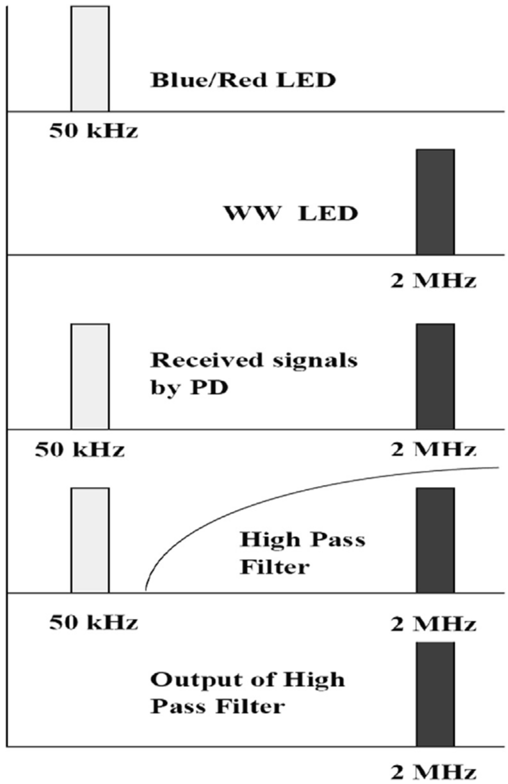


Fig. 8. Frequency classification of the system for data transmission.

derived by the equations (1)–(4) (Kim and Chang Yeong, 2002) for a CCT*(Tc)*.

For, 2222 $K \leq Tc \leq 4000\ K$

$$x_c = -0.2661239\frac{10^9}{Tc^3} - 0.2343580\frac{10^6}{Tc^2} + 0.8776956\frac{10^3}{Tc} + 0.179910 \tag{1}$$

$$y_c = -0.9549476{x_c}^3 - 1.37418593{x_c}^2 + 2.09137015x_c - 0.1674886 \tag{2}$$

For, 4000 $K < Tc \leq 25000\ K$

$$x_c = -3.0258469\frac{10^9}{Tc^3} + 2.1070379\frac{10^6}{Tc^2} + 0.2226347\frac{10^3}{Tc} + 0.240390 \tag{3}$$

$$y_c = 3.0817580{x_c}^3 - 5.87338670{x_c}^2 + 3.75112997x_c - 0.37001483 \tag{4}$$

The blended CCT point $T_t(x_t, y_t)$ lies on the connecting line of white-blue sources considering that the target CCT is 2800 K or above. For target CCT below 2800 K, these equations will be same, only blue source point will be replaced by red source point. From Grassmann's law of color mixing it is found that the vertices of blended color can be derived by the linear weighted sums of the chromaticity co-ordinates of two mixing light sources. Hence,

$$x_t = x_w WC_1 + x_b WC_2 \text{ and } y_t = y_w WC_1 + y_b WC_2 \tag{5}$$

where, weighted coefficients WC_1 and WC_2 are given by

$$WC_1 = \frac{\frac{Y_w}{y_w}}{\frac{Y_w}{y_w} + \frac{Y_b}{y_b}} \text{ and } WC_2 = \frac{\frac{Y_b}{y_b}}{\frac{Y_w}{y_w} + \frac{Y_b}{y_b}} \tag{6}$$

where, Y_w and Y_b are the luminance value of white and blue light source respectively. Grassman's law of color mixing using two light sources stated that,

$$WC_1 + WC_2 = 1 \tag{7}$$

When the distance between source and object is fixed, reflectance of surrounding is fixed, transmittance of the medium is constant and then luminous parameter Y is equivalent to illuminance E. Let, Maximum illuminance of white source is E_{wM} and blue source isE_{bM}. To achieve the blended CCT point $T_t(x_t, y_t)$, illuminance of these two light sources should be mixed in proper ratio and it can be done by controlling the duty cycle of PWM control signal of warm white light source and blue light source.

Let, the required duty cycle of warm white source is DC_w and blue source is DC_b. Hence, the average illuminance $E_w$and E_b of white and blue light source respectively is related to their maximum values as follows.

$$E_w = E_{wM}DC_w \text{ and } E_b = E_{bM}DC_b \tag{8}$$

Equation (6) can be re-written as,

$$WC_1 = \frac{\frac{E_{wM}DC_w}{y_w}}{\frac{E_{wM}DC_b}{y_w} + \frac{E_{bM}DC_b}{y_b}} \text{ and } WC_2 = \frac{\frac{E_{bM}DC_b}{y_b}}{\frac{E_{wM}DC_w}{y_w} + \frac{E_{bM}DC_b}{y_b}} \tag{9}$$

Let, ratio of two weighted co-efficient is $R(WC_2, WC_1)$. Then,

$$R(WC_2, WC_1) = \frac{WC_2}{WC_1} \tag{10}$$

So, from equation (9) and (10), it can be stated that,

$$R(WC_2, WC_1) = \frac{E_{bM}}{E_{wM}}\frac{DC_b}{DC_w}\frac{y_w}{y_b} \tag{11}$$

Peak illuminance ratio of light sources is

$$R(E_{bM}, E_{wM}) = \frac{E_{bM}}{E_{wM}} \tag{12}$$

Duty cycle ratio of light sources is

$$R(DC_b, DC_w) = \frac{DC_b}{DC_w} \tag{13}$$

y co-ordinate ratio of light sources is

$$R(y_b, y_w) = \frac{y_b}{y_w} \tag{14}$$

Substituting equation (12)-(14) in equation (11), we get

$$R(WC_2, WC_1) = \frac{R(E_{bM}, E_{wM})R(DC_b, DC_w)}{R(y_b, y_w)} \tag{15}$$

Duty cycle ratio of light sources can be re-written as

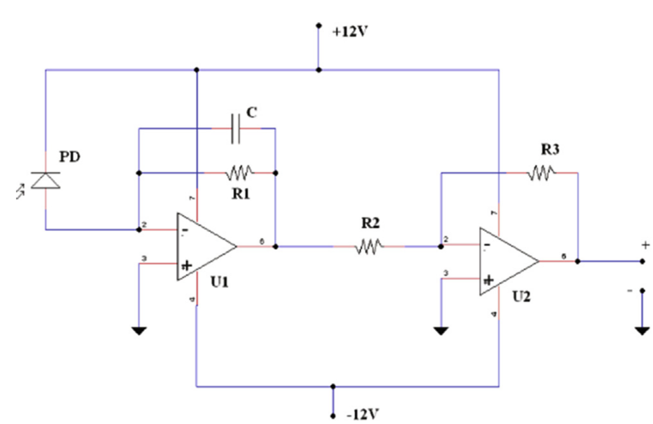


Fig. 9. Circuit diagram of *trans*-impedance amplifier with inverting amplifier.

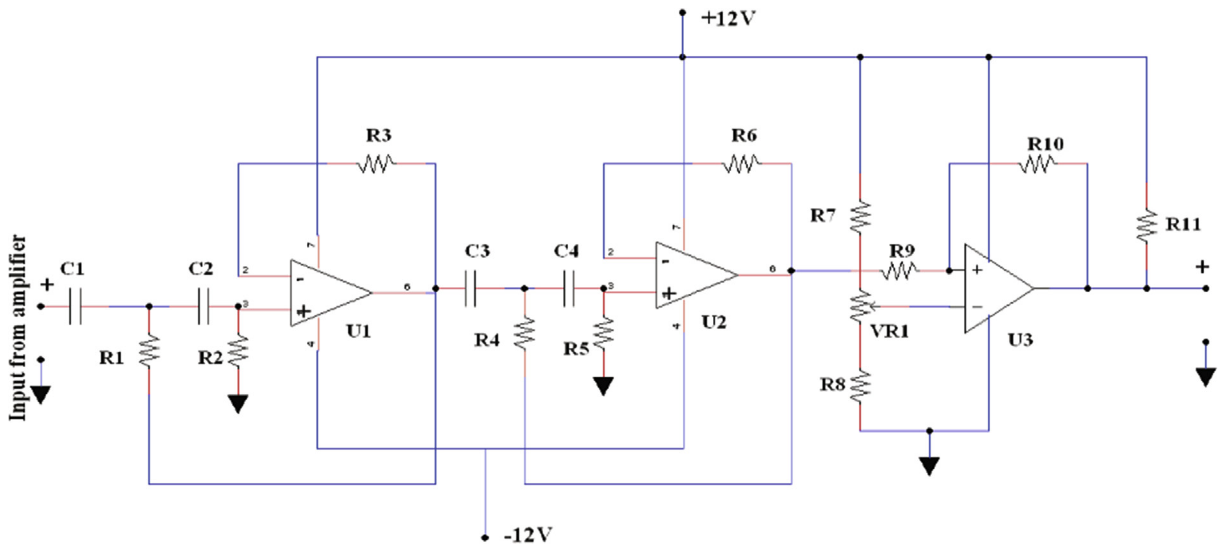


Fig. 10. Circuit diagram of 4th order high pass filter and the comparator.

$$R(DC_b, DC_w) = \frac{R(WC_2, WC_1)R(y_b, y_w)}{R(E_{bM}, E_{wM})} \tag{16}$$

Solving equation first equation of (5), (7), and (10), value of $R(WC_2, WC_1)$ can be found.

$$R(WC_2, WC_1) = \frac{x_w - x_t}{x_t - x_b} \tag{17}$$

If the chromaticity co-ordinate of the blended CCT point is known, then using equation (16) duty cycle ratio of two sources can be calculated. The blended CCT point is a intersection point of $T_c(x_c, y_c)$- $E(x_e, y_e)$ line and $W(x_w, y_w)$ - $B(x_b, y_b)$ line.

Slope *(k)* of the line connecting two points $T_c(x_c, y_c)$ and $E(x_e, y_e)$ on xy plane is given by

$$k = \frac{y_e - y_c}{x_e - x_c} \tag{18}$$

The blended CCT point $T_t(x_t, y_t)$ is on the connecting line of $T_c(x_c, y_c)$ and $E(x_e, y_e)$. Hence slope of $T_t(x_t, y_t)$ - $E(x_e, y_e)$ line will be also k. So, y_t can be given by:

$$y_t = y_e + k(x_t - x_e) \tag{19}$$

Again, the slope *(l)* of the line connecting two points $W(x_w, y_w)$ and $B(x_b, y_b)$ on xy plane is

$$l = \frac{y_w - y_b}{x_w - x_b} \tag{20}$$

Which is the slope of the line connecting $T_t(x_t, y_t)$and $B(x_b, y_b)$ as $T_t(x_t, y_t)$ is situated on the $W(x_w, y_w)$ and $B(x_b, y_b)$ connecting line. Then y_t can be written as:

$$y_t = y_b + l(x_t - x_b) \tag{21}$$

By solving equation (20) and (21), x_t can be determined.

$$x_t = \frac{kx_e - lx_b + y_b - y_e}{k - l} \tag{22}$$

y_t can be calculated by replacing the value of x_t in equation (21).

Substituting the value of x_t in equation (17), $R(WC_2, WC_1)$ can be found and required duty cycle ratio $R(DC_b, DC_w)$ can be calculated using equation (16).

Now the required illuminance (E_t) of the blended light source is the contribution of average illuminance of warm white (E_w) and blue (E_b) light source.

$$E_t = E_w + E_b \tag{23}$$

Substituting equation (8), (12), (13) in equation (23) we get,

$$DC_w = \frac{E_t}{E_{wM}(1 + R(E_{bM}, E_{wM})R(DC_b, DC_w))} \tag{24}$$

DC_bcan be calculated from equation (13)

$$DC_b = R(DC_b, DC_w)DC_w \tag{25}$$

The duty cycle of the primary light sources, which have been used to generate a blended light source is a function of target CCT point and well as required illuminance at that target CCT point. At the target CCT point if required illuminance level changes, then the PWM duty cycle of primary sources will also change, but the duty cycle ratio or average illuminance ratio will always same for that particular CCT point. The specification of warm white, red and blue LEDs are given in Table 1 and the LED arrangement in the luminaire is shown in Fig. 3.

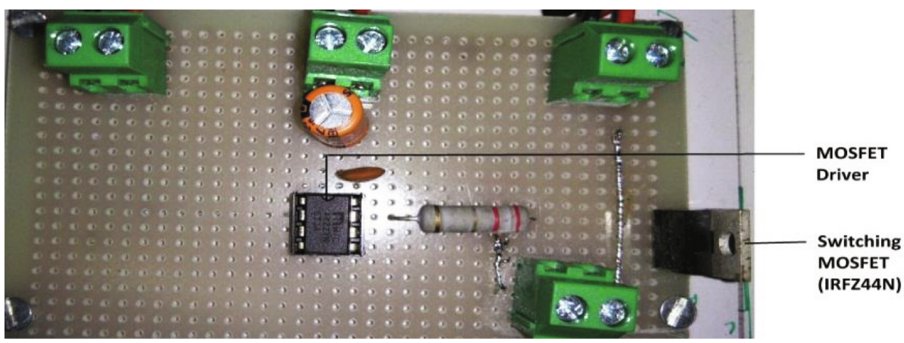
The mathematical derivations have been implemented in the microcontroller used in this system, i.e. ATmega 32 to generate wide range CCT. The PWM control signals are generated from microcontroller for CCT 2700 K and 6500 K with constant illuminance of 240 lx, are shown in Fig. 4(a) & (b) respectively when the data is not transferred i.e. when the data channel is disabled by the switch. The PWM signal frequency of WW, Red and Blue LEDs for that condition is taken as 50 kHz.

2.3. Data transmission scheme

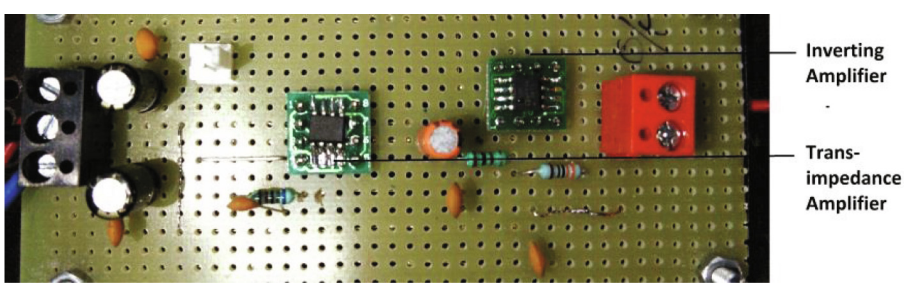
This system also can be used as a VLC transmitter unit by selecting the channel by the switch. When the signal coming from the switch is in high state, the data is transferred through the warm white LED. To transmit data from one computer to another computer a USB to TTL converter (FTDI 232 RQ module gives a data rate up to 3 Mbps) may be used and for higher data rate (greater than 3 Mbps), FPGA and Ethernet based communication system is the best possible solution. During the transmission of data the warm white LED glows at 50% duty cycle, so a high state and a low state will come repeatedly as digital data is transmitted in form of binary number. In TTL logic, binary ‘1’ is represented by 5 V and binary ‘0’ is represented by 0 V. A simple ON-OFF keying modulation technique is being used for data transmission. But a problem may arise when a continuous binary ‘1’ is transmitted or continuous binary ‘0’ is transmitted. The warm white light source will be in ON state and OFF state respectively and the average illuminance may vary and a shift of CCT may occur. To mitigate this problem a simple line coding technique, called Manchester coding may be used. According to IEEE 802.3 Manchester coding format, the binary ‘1’ will be represented by binary ‘0’ then ‘1’ and binary ‘0’ is represented by binary ‘1’ then ‘0’. So for every single bit a high state and a low state will occur and the problem of continuous ON or continuous OFF of warm white light source will be mitigated and the CCT shift will not occur. The data-rate of the VLC system depends upon the switching frequency of the warm white LEDs. To prove this concept, this proposed work has chosen 2 MHz switching frequency for the warm white LED for data transmission. That means the PWM signal with 50% duty cycle and a frequency of 2 MHz is selected for the warm white LEDs. The frequency of the PWM signal of red and blue LEDs are chosen in a way that it can be filtered out at the receiver end using an active high-pass filter. Here a 50 kHz switching frequency is selected for red and blue LEDs and it can be filtered out using a 4th order active high pass filter at the receiver end. The detailed experiment of the CCT changing system is performed taking this parameter in account and the waveforms of the control signals for CCT 2700 K and CCT 6500 K at data channel enabled condition with a dimmed illuminance level are shown in Fig. 5 and the operational frequency of individual light sources in both condition is shown in Table 2.

3. Hardware description of the system

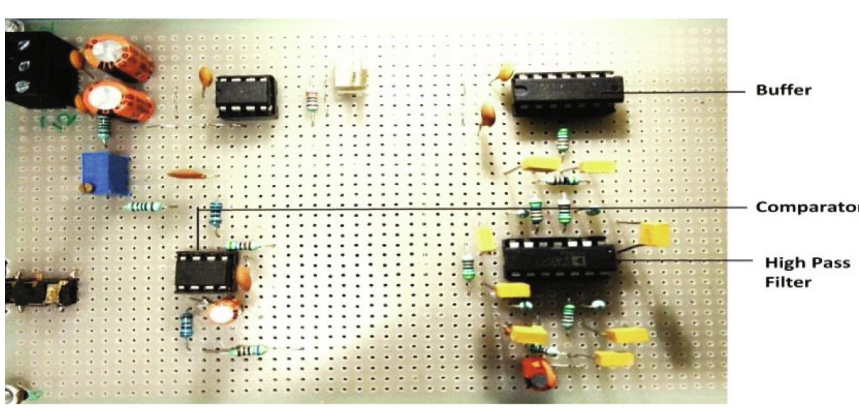
As per the block diagram referred in Fig. 1, for CCT and illuminance control an ATmega 32 microcontroller and for data processing unit a square wave generator is used. The 2 input multiplexer 74LVC1G157 is used to transmit either data or the WW light control



(a)



(b)



(c)

Fig. 11. Developed (a) switching Circuit to control the LED (b) *trans*-impedance amplifier with inverting amplifier (c) 4th order high pass filter and the comparator.

Fig. 12. Experimental set-up.

signal to the WW LED. The low side MOSFET drivers IRS2011PBF are used to convert the TTL level control signal to 12 V signal to drive the n- channel MOSFETs (IRFZ44N) for switching the LEDs on and off according to the control signal coming from the controller. The constant current and constant voltage (CC/CV) drivers with different power ratings are used to power up the LEDs. The schematic of switching circuit to control the illuminance of LED according to the PWM control signal is shown in Fig. 6.

When the data is being transmitted the warm white LED is operated at 2 MHz frequency and the blue and red LEDs are operated at 50 kHz frequency and the transmitted signal is received at the working plane at a distance of 7.5ft from the light source. The block diagram of the data receiver unit is shown in Fig. 7.

The data receiver unit consists of a convex lens to increase the light receiving area, a photo-detector to receive the transmitted signal, a *trans*-impedance amplifier followed by a inverting amplifier to amplify the signal received by the photo-detector, an active high-pass filter to extract the required transmitted signal and a comparator to convert the signal in TTL level. The photo-detector used to detect the transmitted signal, has responsivity in all visible light range. So the photo-detector detects the 2 MHz frequency as well as 50 kHz frequency, which will create noise in the receiving signal. To avoid the noise an active high pass filter is used. The frequency classification of the system during data transmission is shown Fig. 8.

Photo-detector detects the incident light falling on it and converts it in a very small amount of current (in μA). The current generated from the photo detector depends on the amount of light falling on it. In standard practice a *trans*-impedance amplifier is used to convert the photo current into voltage and to achieve a sufficient voltage level another inverting amplifier is used. The diagram of the *trans*-impedance amplifier and the inverting amplifier is shown in Fig. 9.

The photo-detector used in this work is BPW24R with a reverse voltage of +12 V. Op-Amp U1 is ADA4625-1 used to design the *trans*-impedance amplifier. The bandwidth of the *trans*-impedance amplifier depends on the photo-detector's capacitance (C_D), input capacitance of the Op-Amp U1 (C_{in}), feedback capacitor C, feedback resistor R1 and the unity gain bandwidth product (GBP) of the Op-Amp U1. After 1st stage amplification to achieve the suitable voltage level another inverting amplifier is used using the Op-Amp U2, which is OP37. After the amplification of received signal it is passed through a 4th order active high-pass filter to suppress the signal other than 2 MHz, which is made using Op-Am OP462. To covert the filtered 2 MHz signal in TTL level a comparator LM393 is used. At the output of the comparator the transmitted 2 MHz square wave signal is retrieved. The circuit diagram of the high-pass filter and the comparator is shown in Fig. 10 and the developed circuits are shown in Fig. 11.

4. Evaluation of system performance

This prototype is developed and the experiments are performed in the Illumination Engineering Section, Electrical Engineering Department, Jadavpur University, Kolkata, India. The measurement of communication link is done using Keysight S-series infinium oscilloscope, the CCT, chromaticity co-ordinates, illuminance and Duv values are measured using the CL200A Chroma-meter (Make Konica Minolta) and the values are verified using the CRI-Illuminance

Fig. 13. Transmitted and processed received signal at 2 MHz frequency.

Fig. 14. Received signal and corresponding eye diagram of the signal.

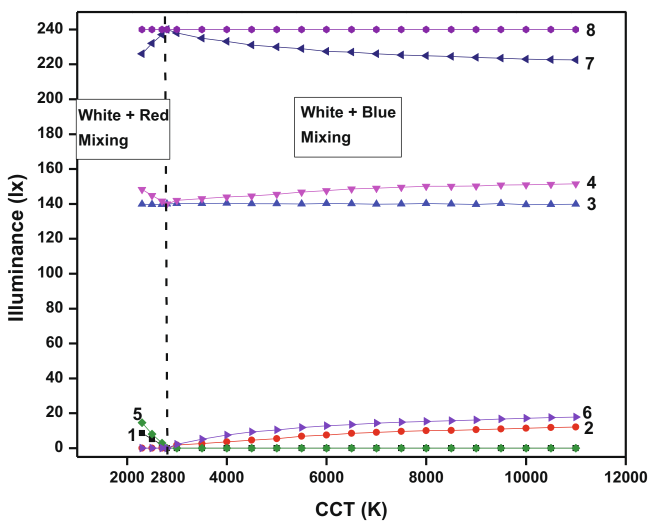


Fig. 15. Illuminance contribution of individual light sources and blended source. A: 1-Red LED, 2- Blue LED, 3- Warm White LED and 4- Mixed illuminance of source when data channel is enabled. B: 5-Red LED, 6- Blue LED, 7- Warm White LED and 8- Mixed illuminance of source when data channel is disabled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

meter CL70F (Make Konica Minolta). The experimental set-up is shown in Fig. 12.

4.1. Evaluation of communication link

In this proposed work a 2 MHz square wave signal is sent as data through the warm white LED and at a distance of 7.5ft it is received by the data receiver unit. Here 2 MHz square wave signal is generated by Keysight arbitrary waveform generator and the received data is analyzed by Keysight S-series infinium oscilloscope. The transmitted 2 MHz signal and the processed received signal is shown in Fig. 13. The processed received signal is the output TTL signal of the comparator.

Here the yellow trace is the multiplexer's output signal when the data channel is activated which is fed to the MOSFET driver and the blue trace is the processed received signal, which is the output signal of the comparator. In Fig. 13, the horizontal division is 500 ns and the vertical division is 2 V, which shows both transmitted and received signal have same frequency, i.e. 2 MHz and both are TTL level signal, i.e. 0 V and 5 V. There is a phase delay occurs due the processing of the data from transmitter side to receiver side. The eye diagram of the received signal is shown in Fig. 14, which shows the transmitted channel is very less noisy.

4.2. Measurement of duty cycle and illuminance for different set point CCT

The first experiment was performed to determine the required illuminance of individual light sources to produce the required CCT for both cases, first considering the data channel of the system being dis-

Table 3
Duty cycles of individual light sources with CCT.

Set point CCT (K)	Duty Cycle of Individual Light Sources (%)					
	Data channel disabled condition			Data channel enabled condition		
	Red	WW	Blue	Red	WW	Blue
2300	75.4	92	0	45.5	50	0
2500	46.2	96	0	26.2	50	0
2800	0	100	0	0	50	0
3000	0	98	12	0	50	6
4500	0	95	49	0	50	24
6000	0	93.5	65.7	0	50	35.5
7500	0	92.5	74	0	50	44
9000	0	90.5	81.5	0	50	51.4
11,000	0	89	90	0	50	60

abled and second, considering the data channel of the system being enabled. The results are shown in Fig. 15, which shows that the illuminance of the blended light source is fixed at 240 lx throughout the CCT range by controlling the illuminance of the WW LED when the data channel is disabled. When the illuminance of red LED is maximum, the illuminance of WW LED becomes lower to maintain the blended illuminance constant. The same thing is happening when blue light is mixed with the WW LED. Whereas, the illuminance of blended light source become variable with CCT when data channel is enabled. The maximum illuminance at this case is 151 lx, which is happening for the CCT 11000 K.

Fig. 15 shows the illuminance contribution of individual LEDs respectively when the data channel is disabled and enabled. In data channel disable condition the PWM signals for warm white, blue and red LEDs are generated from the microcontroller ATmega32A and frequency of the PWM signals are 50 kHz. For CCTs lower than 2800 K warm white light is mixed with the red color. As the CCT of the blended light source decreases, the illuminance contribution of red color increases, relative spectral power of red increases as well as the duty cycle increases. To make the illuminance constant the warm white illuminance decreases accordingly. At CCT 2800 K, when no color is mixed with the warm white light, the duty cycle of warm white source is maximum, i.e. 100% and the illuminance is also 240 lx. For CCTs greater than 2800 K, the blue color is mixed with the warm white source. As the CCT increases from 2800 K, the blue content in the blended light source is also increased by increasing the duty cycle of the blue LED. So the illuminance of warm white light decreases accordingly and throughout the CCT range from 2300 K to 11000 K a constant illuminance level is maintained.

In data channel enable condition, PWM signals for blue and red LEDs are generated from the microcontroller ATmega32A and frequency of the PWM signals are 50 kHz. Signal for WW LED is coming from the data processing unit with frequency of 2 MHz and having fixed duty cycle of 50%. To get the CCTs from 2300 K to 11000 K only the illuminance of red and blue light source will change. For CCTs lower than 2800 K only the illuminance of red light source changes and as CCT decreases, the spectral power of red color increases by increasing the duty cycle of that light source. Similarly, CCT increases from 2800 K to 11000 K, only the spectral power of blue color increases. In that case the illuminance is not fixed throughout the CCT range; it depends on the illuminance contribution of red and blue light source. For sudden change in data channel; from enabled to disabled or disabled to enabled, only the illuminance level will change, the CCT remains same. Duty cycles of individual light sources in both cases are shown in Table 3.

4.3. Measurement of CCT and error CCT

CCT of the developed system is measured using the CL200A Chroma-meter (make Konica Minolta) in both conditions of data channel. It is found that the measured CCT is very close to the set point CCT in both cases and it is in the tolerance range specified by ANSI standard (specification of chromaticity of solid state lighting product) ANSI C78.377-2008 (American National Standards Institute, 2008). The deviation of measured CCT from set point CCT is shown in Table 4. The error occurs in measured CCT when the data channel is in enabled condition.

4.4. Measurement of Duv, CRI and spectral power distribution

The deviation of measured CCT co-ordinates from the Planckian locus is given by the parameter D_{uv}. By definition, as the red, warm-white and blue connecting line is always below the Planckian locus; D_{uv} becomes negative for all CCT points. Specified D_{uv} value in the ANSI C78.377-2008 is ± 0.006 when CCT lies between 2700 K and 6500 K. The D_{uv} plot with respect to CCT is shown in Fig. 16 where it is clearly visible that the spectral power of red content is maximum at CCT 2300 K. When the blue color is mixed with the warm white source, relative spectral power of blue color increases with the increment of the CCT values.

Table 4
Deviation of measured CCT from set point CCT in both conditions.

Set point CCT (K)	Tolerance limit as per ANSI C78.377–2008 (K)	Deviation from set point CCT when data channel disabled	Deviation from set point CCT when data channel enabled
2300	–	+1	+39
2700	2725 ± 145	+1	+18
3000	3045 ± 175	+12	+14
4500	4503 ± 243	+1	+38
6500	6530 ± 510	+12	+78
7500	–	−4	−37
9000	–	−10	+10
11,000	–	+50	+100

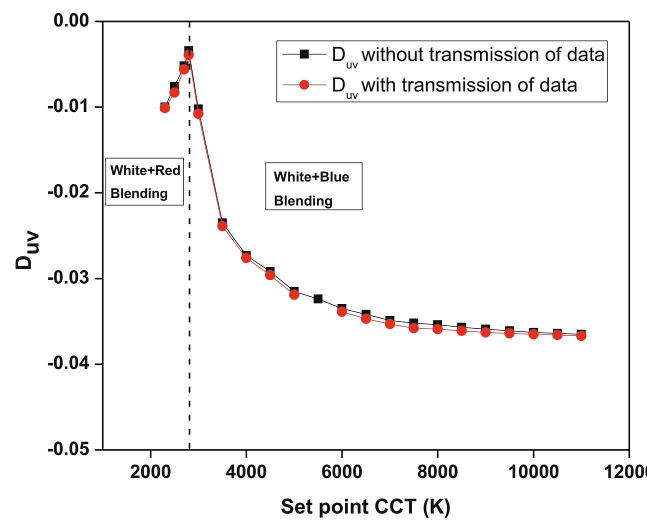


Fig. 16. D_{uv} at different CCT point.

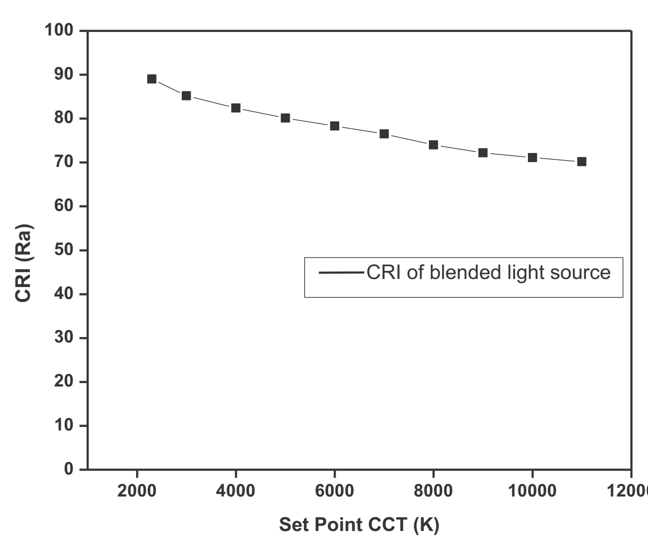


Fig. 17. CRI value at different set point CCT.

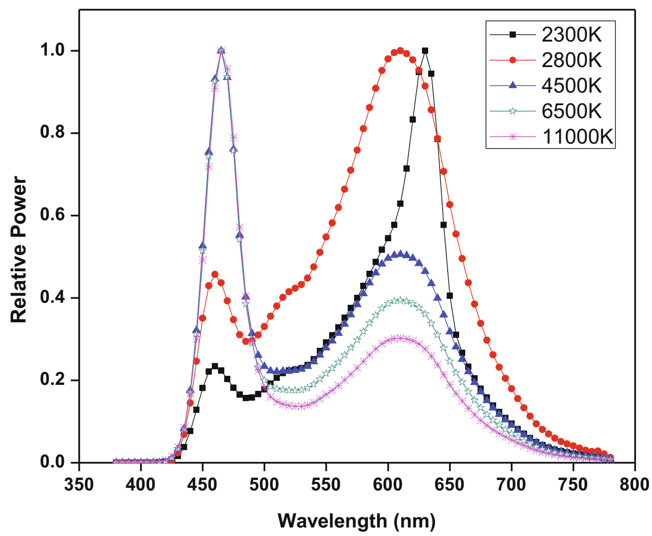


Fig. 18. Relative spectral power of developed light source at different CCT.

It is observed that the magnitude of the D_{uv} values is higher compared to the ANSI standard; a probable solution to mitigate this problem is discussed in the conclusion section. To ensure the quality of color of the light produced by the system, the most common color rendition metric CRI is used. It has been measured by Konica-Minolta CL70F CRI-Illuminance meter. The values of CRI for the CCT range 2300 K to 11000 K is shown in Fig. 17, where the CRI value is above 80 for CCT up to 5000 K and maximum CRI value is 89 at CCT 2300 K. CRI at 11000 K CCT is 70.2. Total 21% deviation in CRI is noticeable for the CCT range of 2300 K to 11000 K. The relative spectral power of developed light source at different CCT is shown in Fig. 18, where the spectral power of the red color is maximum at CCT 2300 K. When the blue color is mixed with the warm white source, the relative spectral power of the blue color is being increased gradually as CCT increases.

5. Conclusion

A detailed study of variable CCT constant illuminance white LED light communication system with dimming feature is presented in this article. To prove the concept, VLC system is designed for 2 MHz bandwidth, it may be increased further as per the requirement. The CCT range from 2300 K to 11,000 K is successfully achieved in this system. The experimental results of transmitted and received data prove that the optical channel is very reliable channel for communication with the bandwidth of 2 MHz. The disturbance in CCT is noticeable when data channel is enabled; reason behind this disturbance is the poor frequency response of the warm white LED. Though it is within the tolerance range specified by the ANSI standard, the result may be better if a LED with better frequency response is used instead of these LEDs. The drawback of the system is Duv value becomes higher for higher CCT range. It is happening because the spectral power of blue color is much higher compared to other colors and the spectral power of the green region is much less compared to other colors. This problem may be mitigated by using green and blue light source instead of blue light source only, so that the locus connecting to warm white and green–blue point will be much closer to the Planckian locus and the Duv value will decrease and presence of green spectrum in the blended light source will increase the CRI value of the system. The experiment, on this concept is in progress.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Basudeb Das received the B.Tech degree in Electronic & Communication Engineering from West Bengal University of Technology, Kolkata, India in 2013 and M.E. degree in Illumination Engineering under Electrical Engineering Department, Jadavpur University, Kolkata, India in 2017, where he is currently working towards the Ph.D degree in Electrical Engineering. His research interests include Optical Wireless Communication, CCT changing Lighting System, Solar powered dynamic lighting system and electronic control of light.

Shubham Bardhan received the B.Tech degree in Electrical Engineering from West Bengal University of Technology, Kolkata, India in 2017. He is currently pursuing his M. E. degree in Illumination Engineering under Electrical Engineering Department, Jadavpur University, Kolkata, India. His research interests include CCT changing system and Visible light Communication.

Tapas Maity received the B.Tech degree in Electrical Engineering from West Bengal University of Technology, Kolkata, India in 2013. He is currently pursuing his M.E. degree in Illumination Engineering under Electrical Engineering Department, Jadavpur University, Kolkata, India. His research interests include Optical Wireless Communication and dynamic lighting control.

Saswati Mazumdar received the B.E.E., M.E., and Ph.D. degrees in electrical engineering (EE) from Jadavpur University (JU), Kolkata, India, in 1982, 1984, and 1996, respectively. She worked first as CSIR Senior Research Fellow, then System Development Engineer in a DOE-funded Project in the Department of EE, JU. From 1987, she joined in teaching in the department of EE, JU. She acted as Director of School of Illumination Science, Engineering and Design, JU from 2006 to 2014. She is currently working as a Professor in the Department of EE, JU, Kolkata, India. She has now 33 years of experience in lighting research and teaching. She developed a modernized Illumination Engineering Laboratory in the Department of EE, JU. She has founded one full-time Master's Course on Illumination Engineering and another part-time Master's course on Illumination technology and design in JU. She has executed a large number of R&D and Consultancy Projects on illumination and allied fields. Her primary research areas are controllers of lighting systems, renewable energy-based lighting systems, smart lighting systems, LEDs and LASER communication, interior and exterior lighting design, and color control of modern lighting-system.