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Low cost, high color rendition, CCT variable lighting system based on W-G-B LED

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ABSTRACT

This article proposes a novel approach of tunable correlated color temperature (CCT) lighting system with high color rendition using three component color mixing concept. Using Grassmann's color mixing theory, phosphor coated warm white LED source (CCT 2800 K) is mixed with the blue (467 nm) and green (527 nm) LED light sources and a detailed mathematical formulation is derived for easy controlling of variable CCT and experimentally validated in this article. As a result, the locus of the blended light source is very close to the Planckian locus on Commission Internationale de l'Eclairage (CIE) 1931 chromaticity diagram. The generated color of the light sources is evaluated by both CIE color rendering index (CRI) method and Illuminating Engineering Society (IES) TM-30-18 method. This proposed system provides a wide range of CCTs starting from 2800 K to 7500 K with a very high CRI (CIE R_a) value of 94, color fidelity index (IES R_f) score of around 85 and color gamut index (IES R_g) of 95. As this system uses only three color component, the cost of this system is comparatively low with respect to other high CRI, tunable CCT lighting system available in market.

1. Introduction

High brightness light emitting diodes (LED) become very popular because of its luminous efficacy, high brightness, good color rendering index (CRI), low power consumption, low ultra violet emission and environment friendly nature, compared to traditional fluorescent lamps and incandescent lamps. Besides that white light with different correlated color temperature (CCT) can be generated using LEDs and it can be dimmed to desirable level utilizing its switching property and pulse width modulation (PWM) or amplitude modulation (AM) control technique. The concept of fixed CCT lighting system is getting changed day by day. Several researches on biological and psychological effect of light on human health [1–5] are going on. Surprisingly the factor came out that the dynamic CCT lighting system (which is close to the daylight CCT pattern) instead of constant CCT lighting system in offices, will increase the productivity of the work as well as it controls the hormonal balance on human health. Besides that the requirement of high CRI lighting system with different CCTs makes the LEDs most popular. High CRI lighting is mainly required where identifying the object color and critical task performance will take place. Textile industry, food processing industry, shopping mall etc. need a high CRI light source [6, 7]. Museum, art gallery etc. require precision lighting system where the identification of object color plays an important role and objects must be safe from the emission of infrared heat and the ultra violet radiation from the light source, else the object may get damaged [8]. Another requirement of high CRI lighting system is in the medical sector where surgical tasks are performed [9].

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People are doing research worldwide to increase the photometric and colorimetric parameters of LED like the CRI, efficacy, variable CCT, dimming control etc. Generally LED white light is generated for general application by applying a coating of *YAG*:Ce^{3+} yellow phosphor on the *InGaN* blue LED chips [10]. The CRI of those lamps is around 80–85 with a high efficacy of 100−200 lm/W [11]. If one looks into that LED spectrum, a spectral gap in the red and cyan region is noticeable [12]. Researchers have been working to mitigate this problem and increase the CRI of LED light source by replacing the yellow phosphor with red phosphor ($Na_{0.7}Li_{0.15}K_{0.15}La_{0.6}Eu_{0.4}MgWO_6$) [13], far red emitting phosphor ($SrMgAl_{10}O_{17}$:Cr^{3+}) [14], cyan phosphor ($Na_{0.5}K_{0.5}Li_3SiO_4$: Eu^{2+}) [12], combination of red and yellow-green phosphor [15], combination of red and green phosphor [10] and combination of blue-red-green emitting phosphor [16] etc. In this technology the CRI value is increased up to 95, but it compromises the luminous efficacy of the lamp, which drops to 60−80 lm/W with a constant CCT.

Another approach was discussed in several articles to increase the CRI with CCT changing lighting system is the color mixing of lights based on the Grassmann's law of additive color [17], which states that, two or more color source can be mixed to generate another blended color source. In some previous studies the variable white light source is generated by the mixing of red-green-blue (R-G-B) sources [18–20] and red-green-blue-amber (R-G-B-A) sources [21,22] are demonstrated. This type of system has CRI between 80 and 90 but the chromaticity shifts due to dimming and temperature variation is noticeable. It is reported that the chromaticity shift in phosphor coated white light is less compared to color mixing of monochromatic light sources when similar dimming method is applied to it [23]. Another wide range tunable CCT (2500 K–12500 K) and illuminance control lighting system by mixing of cool white – blue and cool white – red is reported [24] to generate CCTs above 6500 K and below 6500 K respectively with CRI value near 90. In this system the co-ordinate of blended CCT lies on the cool white and blue joining locus and cool white and red joining locus. So the deviation of blended CCT point from the Planckian locus is noticeable, hence D_{uv} value increases. Color mixing using warm white-cyan-red sources for museum lighting is reported [25] where both CRI and R9 values are greater than 90. But it is applicable for very small CCT varying range (around 200 K). A simulated work is reported using red-green-blue-cyan-amber-white (RGB-CAW), RGB-amber and RGB-white LEDs [26], where tunable CCT range is 3200 K–7500 K and maximum CRI 97 is achieved for RGB-CAW luminaire, but this system is hard to realize in practical application and the system cost will be very high as it uses six colors of LEDs. Researchers have been working with five component color mixing methodology [27] and achieved the CRI above 90, but the electronic control of such lighting system is very difficult and hard to practical realization.

In the present article, the concept of color mixing of phosphor coated warm white light source having CCT 2800 K, blue (wavelength 467 nm) and green (wavelength 527 nm) light source is demonstrated, mathematically formulated and experimentally validated in detailed. Here, warm white light source is mixed with the blue and green light source to meet the required CCT and illuminance. PWM technique is used to control the average current flowing through the LEDs. Hence, average illuminance of individual light sources can be controlled. Using this concept a wide change of CCT from 2800 K to 7500 K is achieved and the color of the light is evaluated by both Commission Internationale de l'Eclairage (CIE) CRI method and Illuminating Engineering Society of North America (IES) TM-30-18 method, which shows that the system has very high CRI R_a value of maximum 94 and minimum 90, R9 value of maximum 92 and IES R_f (color fidelity index) score is maximum 88 and minimum 81 and IES R_g (color gamut index) lies between 91 and 95 and others parameter like local chroma shift per hue angle bin, local hue shift per hue angle bin etc are provided in this article which enhance the reliability of the system. There are many high CRI lighting products are already available in market. These products are developed either by phosphor coating methodology or by color mixing of more than three LED chips and the cost of such system is very high. A high CRI light source which is generated by phosphor coating methodology have fixed CCT; whereas color mixing of multi chip LEDs can generate tunable CCTs. As this proposed system uses only three LEDs, the cost of the system is low compared to other similar systems and it can generate wide range of CCTs with high color rendition; which makes this system very unique.

2. Selection criteria of LED light sources

The current state of the art to produce high CRI and tunable CCT lighting system is described in the earlier section. This paper proposes the color mixing of phosphor coated warm white light source (pc-WW LED having CCT 2800 K) with the blue and green light source. The objective of proposed system is to generate a wide range of CCTs with high color rendition. CCT of the warm white light source is chosen as a reference point, from where CCT will start increasing by mixing of blue and green color. If one looks into the spectral distribution of yellow phosphor coated warm white light source, a spectral gap will be visible in green-cyan region (490 nm–540 nm) and the red region (650 nm–700 nm). If this spectral gap is filled by incorporating respective light sources, the CRI value will increase, but there will be an impact on CCT. If the spectral energy in the long wavelength region increases (650 nm–700 nm), CCT will decrease. Similarly if spectral energy in the short wavelength increases (450 nm–540 nm), CCT will increase. Considering the goal of this proposed work, increment of spectral energy in shorter wavelength region have been done by adding green (Peak wavelength is 527 nm and full-width-half-maximum (FWHM) is 40 nm) and blue light source (Peak wavelength is 467 nm and FWHM is 30 nm) with warm white light source. FWHM of the green light source should be high for better color rendition result. Incorporation of green light source will increase the color rendition of the blended light source and combination of blue-green light source will help to increase the CCT values with color rendition. To generate tunable wide CCT range, blue-green blending ratio needs to be changed only. The blending ratio of blue-green source needs to be changed in a way that the chromaticity co-ordinate of the blended white light source will follow the Planckian locus, hence D_{uv} value will be small. Another factor of choosing the LEDs is luminous efficacy. Luminous efficacy of the blended light source will depend on the luminous efficacy of individual light sources used in color mixing. Higher the efficacy of warm white, green and blue light source, high efficacy of blended light source is obtained.

3. Mathematical formulation of lighting control scheme

The chromaticity co-ordinates of warm white $W(x_w, y_w)$, green $G(x_g, y_g)$ and blue $B(x_b, y_b)$ light sources are shown on Commission Internationale de l'Eclairage (CIE) 1931 chromaticity diagram in Fig. 1. Required chromaticity co-ordinate for the target CCT is $T(x_t, y_t)$ which will be any arbitrary point on the Planckian locus shown in the CIE 1931 chromaticity diagram within the CCT range 2800 K to 7500 K. The straight line connecting the points $W(x_w, y_w)$ and $T(x_t, y_t)$ will intercept the blue $B(x_b, y_b)$ – green $G(x_g, y_g)$ connecting line at point $M(x_m, y_m)$. As the required CCT changes, chromaticity co-ordinate of point $T(x_t, y_t)$ will change, hence the blue-green blending point $M(x_m, y_m)$ will also change. So, the point $M(x_m, y_m)$ depends on the value of point $T(x_t, y_t)$.

3.1. Mathematical formulation to find the co-ordinate of points $T(x_t, y_t)$ and $M(x_m, y_m)$

The chromaticity co-ordinate of $T(x_t, y_t)$ can be derived by the Eqs. (1)–(4) [28,29] for a required CCT (Tc).
For $2222K \leq Tc \leq 4000K$

$$x_t = -0.2661239\frac{10^9}{Tc^3} - 0.2343580\frac{10^6}{Tc^2} + 0.8776956\frac{10^3}{Tc} + 0.179910 \quad (1)$$

$$y_t = -0.9549476{x_t}^3 - 1.37418593{x_t}^2 + 2.09137015x_t - 0.16748867 \quad (2)$$

For $4000K < Tc \leq 25000K$

$$x_t = -3.0258469\frac{10^9}{Tc^3} + 2.1070379\frac{10^6}{Tc^2} + 0.2226347\frac{10^3}{Tc} + 0.240390 \quad (3)$$

$$y_t = 3.0817580{x_t}^3 - 5.87338670{x_t}^2 + 3.75112997x_t - 0.37001483 \quad (4)$$

The slope of *W-T* line is equal to the slope of *W-M* line as the points *W, T* and *M* lies on a same straight line. Hence,

$$y_m = \left(\frac{y_t - y_w}{x_t - x_w}\right)(x_m - x_w) + y_w \quad (5)$$

The slope of *M-B* line is equal to the slope of *G-B* line as the points *G, M* and *B* lies on a same straight line. Hence,

$$y_m = \left(\frac{y_g - y_b}{x_g - x_b}\right)(x_m - x_b) + y_b \quad (6)$$

The point M will be any point on the *G-B* line. The value of x_m and y_m depend on the required CCT value and point $T(x_t, y_t)$. Depending upon the required CCT, blue-green blending ratio will change, hence the blue-green blending point $M(x_m, y_m)$ will also change. From (5) and (6) it can be written that,

$$x_m = \frac{(y_t - y_w)(x_g - x_b)x_w - (y_g - y_b)(x_t - x_w)x_b + (y_b - y_w)(x_t - x_w)(x_g - x_b)}{(y_t - y_w)(x_g - x_b) - (y_g - y_b)(x_t - x_w)} \quad (7)$$

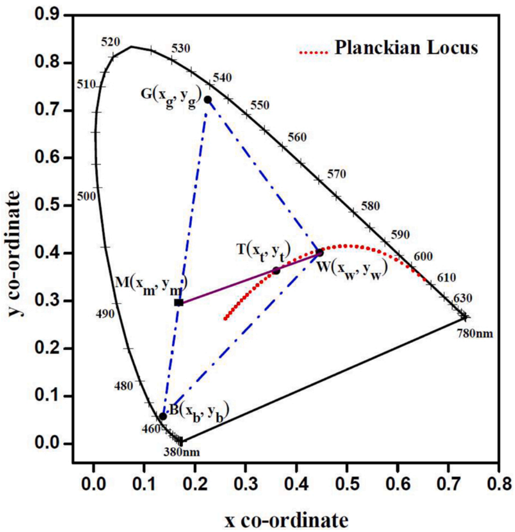

Fig. 1. Chromaticity co-ordinate, blending lines and Planckian locus is shown in CIE 1931 chromaticity diagram.

Substituting (7) in (6), y_m can be derived.

3.2. Formulation of green-blue illuminance to achieve the point M (x_m, y_m)

The point $M\,(x_m, y_m)$ lies on the line connecting blue-green source points. 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,

$$x_m = x_b W_{c1} + x_g W_{c2} \; and \; y_m = y_b W_{c1} + y_g W_{c2} \tag{8}$$

Where, weighted coefficients W_{c1} and W_{c2} are given by

$$W_{c1} = \frac{\frac{Y_b}{y_b}}{\frac{Y_b}{y_b} + \frac{Y_g}{y_g}} \; and \; W_{c2} = \frac{\frac{Y_g}{y_g}}{\frac{Y_b}{y_b} + \frac{Y_g}{y_g}} \tag{9}$$

Y_b and Y_g are the luminance value of blue and green light source respectively. Grassmann's law of color mixing stated that,

$$W_{c1} + W_{c2} = 1 \tag{10}$$

When the distance between source and object is fixed, reflectance of surrounding is fixed, transmittance of the medium is constant then luminous parameter Y is equivalent to illuminance E. Maximum illuminance of blue source is E_{bM} and green source is E_{gM}. To achieve the point M, duty cycle of blue source is DC_b and green source is DC_g. Hence, the individual illuminance of blue and green source to achieve the point M is given by

$$E_b = E_{bM} DC_b \text{ and } E_g = E_{gM} DC_g \tag{11}$$

Substituting (11) in (9),

$$W_{c1} = \frac{\frac{E_{bM}DC_b}{y_b}}{\frac{E_{bM}DC_b}{y_b} + \frac{E_{gM}DC_g}{y_g}} \text{ and } W_{c2} = \frac{\frac{E_{gM}DC_g}{y_g}}{\frac{E_{bM}DC_b}{y_b} + \frac{E_{gM}DC_g}{y_g}} \tag{12}$$

Let, ratio of two weighted co-efficient,

$$r(W_{c2}, W_{c1}) = \frac{W_{c2}}{W_{c1}} \tag{13}$$

From (12) and (13) it is found that,

$$r(W_{c2}, W_{c1}) = \frac{E_{gM}}{E_{bM}} \frac{DC_g}{DC_b} \frac{y_b}{y_g} \tag{14}$$

Peak illuminance ratio of green and blue source is

$$\mathrm{r}(E_{gM}, E_{bM}) = \frac{E_{gM}}{E_{bM}} \tag{15}$$

Duty cycle ratio of green and blue source is

$$r(DC_g, DC_b) = \frac{DC_g}{DC_b} \tag{16}$$

y co-ordinate ratio of green and blue source is

$$r(y_g,\ y_b) = \frac{y_g}{y_b} \tag{17}$$

Substituting (15)-(17) in (14), we get,

$$r(W_{c2}, W_{c1}) = \frac{\mathrm{r}(E_{gM}, E_{bM})\; r(DC_g, DC_b)}{r(y_g,\ y_b)} \tag{18}$$

Duty cycle ratio of green and blue source is,

$$r(DC_g, DC_b) = \frac{r(W_{c2}, W_{c1}) r(y_g,\ y_b)}{\mathrm{r}(E_{gM}, E_{bM})} \tag{19}$$

Solving first of (8), (10) and (13), value of $r(W_{c2}, W_{c1})$ can be found.

$$r(W_{c2}, W_{c1}) = \frac{x_b - x_m}{x_m - x_g} \tag{20}$$

The maximum illuminance of the point $M(x_m,y_m)$ is E_{mM}, can be derived by the linear addition of blue and green sources when the maximum illuminance of blue and green source is fixed.

$$E_{mM} = E_b + E_g \text{ or, } E_{mM} = E_{bM}DC_b + E_{gM}DC_g \tag{21}$$

$$\text{and, } E_{mM} = E_{bM} + \frac{L_{bm}\left(E_{gM} - E_{bM}\right)}{L_{bg}} \tag{22}$$

Where, Linear distance between $B(x_b, y_b)$ and $M(x_m,y_m)$ points is

$$L_{bm} = \sqrt{\left\{(x_b - x_m)^2 + (y_b - y_m)^2\right\}} \tag{23}$$

Linear distance between $B(x_b, y_b)$ and $G(x_g,y_g)$ points is

$$L_{bg} = \sqrt{\left\{\left(x_b - x_g\right)^2 + \left(y_b - y_g\right)^2\right\}} \tag{24}$$

Substituting (11), (15) and (16) in (21) value of DC_b can be found and it is given by

$$DC_b = \frac{E_{mM}}{E_{bM}(1 + \mathrm{r}\left(E_{gM}, E_{bM}\right)r\left(DC_g, DC_b\right))} \text{ and } DC_g = DC_b\ r\left(DC_g, DC_b\right) \tag{25}$$

3.3. Formulation of warm white-green-blue illuminance to achieve the point $T\ (x_t,y_t)$ with constant illuminance

Now to achieve the required CCT point $T\ (x_t,y_t)$ illuminance of warm white light source and the illuminance of point $M\ (x_m,y_m)$ is mixed with proper ratio. Maximum illuminance of warm white light source is E_{wM}. Maximum illuminance of $M\ (x_m,y_m)$ point is

$$E_{mM} = E_{bM}DC_b + E_{gM}DC_g \tag{21}$$

Duty cycle to achieve the required CCT point T of warm white source is DC_w and point M is DC_m. Hence, the illuminance of warm white source and the point M at the required CCT point T is given by

$$E_w = E_{wM}DC_w \text{ and } E_m = E_{mM}DC_m \tag{26}$$

So, the blue and green source illuminance for the required CCT point T will be

$$E_{bT} = E_{bM}DC_bDC_m \text{ and } E_{gT} = E_{gM}D_gD_m \tag{27}$$

Similarly, the duty cycle ratio of warm white source and point M is given by

$$r(DC_w, DC_m) = \frac{r(W_{c4}, W_{c3})\ r(y_w,\ y_m)}{r(E_{wM},\ E_{mM})} \tag{28}$$

Where, duty cycle ratio of warm white light source and point M is $r(DC_w, DC_m)$

$$r(DC_w, DC_m) = \frac{DC_w}{DC_m} \tag{29}$$

Peak illuminance ratio of warm white source and point M is

$$r(E_{wM},\ E_{mM}) = \frac{E_{wM}}{E_{mM}} \tag{30}$$

y co-ordinate ratio of warm white source and point M is

$$r(y_w,\ y_m) = \frac{y_w}{y_m} \tag{31}$$

Weighted co-efficient ratio of warm white source and point M mixing is

$$r(W_{c4}, W_{c3}) = \frac{x_w - x_t}{x_t - x_m} \tag{32}$$

Where, W_{c3} *and* W_{c4} are weighted co-efficient of warm white light source and point M blending.

At the target CCT point $T\ (x_t,y_t)$ the required illuminance E_r is the summation of illuminance of warm white source and the point M.

(Note: the required or target illuminance of the system should not be greater than the illuminance of warm white light source at full glow condition.)

$$E_r = E_w + E_m \tag{33}$$

Substituting (26), (29) and (30) in (33), DC_m and DC_w can be calculated.

$$DC_m = \frac{E_r}{E_{mM}(1 + r(E_{wM},\ E_{mM})r(DC_w, DC_m))} \quad and \quad DC_w = DC_m\ r(DC_w, DC_m) \tag{34}$$

To get the target CCT $T\ (x_t, y_t)$ and the target illuminance E_r, illuminance contribution of individual light source is given by

$$\text{Warm White Light source illuminance } E_w = E_{wM}DC_w \tag{35}$$

$$\text{Blue Light source illuminance } E_{bT} = E_{bM}DC_bDC_m \tag{36}$$

$$\text{Green Light source illuminance } E_{gT} = E_{gM}DC_gDC_m \tag{37}$$

Duty cycle requirement of individual LEDs to achieve target CCT with target illuminance is given below.
Duty cycle of warm white light source is

$$DC_w \tag{38}$$

Duty cycle of blue light source is

$$DC_bDC_m = \frac{E_{mM}DC_m}{E_{bM}(1 + \mathrm{r}(E_{gM}, E_{bM})r(DC_g, DC_b))} \tag{39}$$

Duty cycle of green light source is

$$DC_gDC_m = DC_bDC_m\ r(DC_g, DC_b) \tag{40}$$

4. Implementation of the proposed system

In the previous section a detailed mathematical derivation has been derived to find the PWM duty cycle of individual LEDs to achieve the required CCT and illuminance. These derivations are implemented in a microcontroller and the microcontroller generates the PWM signals for individual LEDs. Generated PWM signals are then fed to MOSFET drivers and MOSFET drivers drive the switching MOSFET accordingly. When the PWM signal is in high state, the MOSFET will conduct and the LED will be turned on and when the PWM signal is in low state, MOSFET will remain in off state and the LED will remain off. So, the on time and off time of the LEDs depend on the duty cycle of the PWM signal and the average illuminance of the LEDs is controlled by the duty cycle of the PWM signal. Three different LED drivers have been used to provide the power to the LEDs and a 12 V DC power supply is used to drive the microcontroller and the MOSFET drivers. The developed hardware of the system is shown in Fig. 2.

The LEDs used in this system is a 1 W P4 type LEDs. Total 18pcs warm white LED, 18pcs blue LEDs and 18pcs green LEDs are being used in this system and individual color LEDs are connected in series. For that three 60 V/ 300 mA constant voltage constant current drivers have been developed. The measured photometric parameter of the warm white LED string is shown in Table 1 and blue and green LED strings are shown in Table 2. The LED arrangement in the luminaire is shown in Fig. 3.

5. Experimental results and discussion

The experiments were performed in a dark room, where stray light cannot enter. The luminaire was mounted in a matte black painted wooden box and the setup was placed in a window less black painted dark room. The measuring instruments were placed in the black wooden box, 7.5 ft below the luminaire. CL200A croma-meter (make Konica Minolta) has been used to measure the CCT, illuminance and chromaticity co-ordinates. The CRI and spectral power density (SPD) have been measured by CL70 F CRI meter (make Konica Minolta). IES R_f and IES R_g have been calculated by the IES TM-30-18 calculation tool, developed by IES. The calculations are based on the SPD values of the color which are generated from the CRI meter. The illuminance of the system is considered 200 lx for all CCTs from 2800 K to 7500 K.

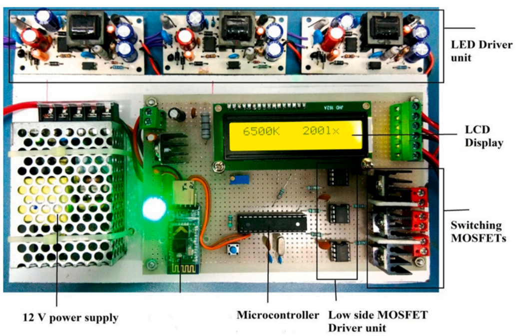

Fig. 2. Developed hardware of the proposed system.

Table 1
Measured photometric parameter of the warm white LED string.

CCT	Maximum illuminance	CIE R_a	CIE R9	IES R_f	IES R_g	Chromaticity Co-ordinate	
						x	y
2828 K	301 lx	86	27	87	95	0.4464	0.4010

Table 2
Measured photometric parameter of the blue and green LED string.

LED string	Peak Wavelength	FWHM	Maximum illuminance	Chromaticity Co-ordinate	
				x	y
Blue LED	467 nm	30 nm	43.1 lx	0.1371	0.0576
Green LED	527 nm	40 nm	186.4 lx	0.2256	0.7222

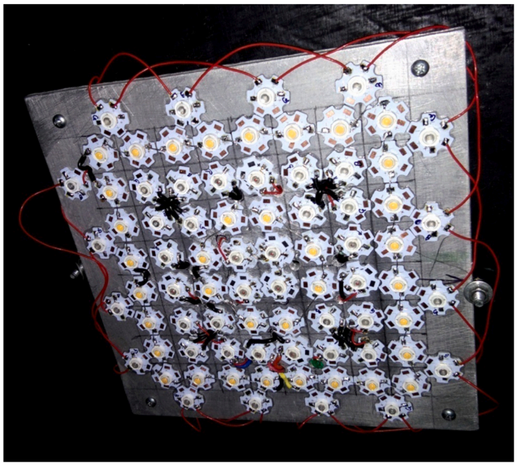

Fig. 3. LED arrangement in the luminaire.

5.1. Simulated and experimental results of CCT and illuminance

The mathematical formulas are first simulated in MATLAB, and then it is experimentally validated. The simulated results are closely fitted with the experimental results. The illuminance contribution of blue LED in both simulation and experimental are matching, whereas illuminance contribution of warm white source and green source are deviated maximum 5% from the simulated values. But the total illuminance in experimentally validated results is same for all CCTs. The detailed simulated and experimental data for target illuminance 200 lx for CCTs 2800 K to 7500 K are given in Table 3, which show the experimentally achieved illuminance of warm white source is less compared to simulated results, whereas experimentally achieved illuminance of green source is higher

Table 3
Simulated and experimental data for 200 lx.

Set Point CCT (K)	MATLAB simulation result			Experimental result			Measured CCT (K)
	Illuminance (lx)			Illuminance (lx)			
	Warm white	Blue	Green	Warm white	Blue	Green	
2800	199.1573	−0.5299	1.3726	200	0	0	2828
3000	190.7172	0.3992	8.8836	190.6	0	9.6	2998
3500	174.2810	2.5960	23.1230	174.7	2.7	22.6	3503
4000	162.2891	4.6288	33.0822	163.6	4.7	32	3968
4500	153.0862	6.4780	40.4359	149.6	5.6	44.8	4457
5000	146.0394	8.1335	45.8270	140	7	52.6	4967
5500	140.5177	9.6180	49.8643	135.3	8.6	55.4	5426
6000	136.1074	10.9490	52.9435	131.3	10.1	58.3	5933
6500	132.5234	12.1437	55.3329	128.1	11.6	60	6422
7000	129.5658	13.2177	57.2165	124.5	12.5	63.7	6925
7500	124.9979	14.0589	60.9432	119.3	13.4	66.9	7477

compared to the simulated results. It is seen, maximum error in CCT occurred 78 K at 200 lx, which is acceptable as specified in ANSI C78.377-2008 [30].

5.2. Locus of the blended light source

The locus of developed blended light source is shown in Fig. 4 along with the Planckian locus, and the upper limit and lower limit of CCT tolerance range, specified by the ANSI C.78.377-2008. Warm white light source used for mixing has the chromaticity point below the Planckian locus and other blended CCT points are above the Planckian locus. From Fig. 4 it is clearly visible that the developed light source's CCTs are very close to the Planckian locus. In ANSI C.78.377-2008 upper and lower tolerance limit of CCTs are given from 2700 K to 6500 K. This developed system follows the standard and the values are within the tolerance range.

5.3. Measurement of CIE CRI (R_a and R9)

Another objective of the proposed system is to improve the color rendition of the light source. Here, CRI is measured using CL70 F CRI meter (make Konica Minolta). The warm white source used here, has CRI value of 86 and adding blue and green component with this a maximum CRI of 94 is achieved successfully at CCTs 4500 K–5000 K and it goes above 90 for all CCTs from 3000 K to 7500 K. The measured CRI value for all CCTs is shown in Fig. 5. In general purpose LED lighting system it has been found that the red object identification parameter R9 value is very low. The warm white light source used here has R9 value 27 at CCT 2800 K. This proposed system has another advantage that the R9 value has been increased to 92 at CCTs 6500 K–7500 K. The measured R9 value at different CCTs is shown in Fig. 6. At CCTs 4000 K, 4500 K, 5500 K and 6500 K, the R9 values are 70, 71, 81 and 92 respectively, which makes this system more effective in various applications where R9 value plays very important role like art galleries, museum, textile shop etc.

CIE general CRI (R_a) is characterized by the average color fidelity of light source. Color rendition is a subjective perception which includes color naturalness, vividness, visual clarity and preference. One signal parameter, metric or measure cannot accurately describe all subjective perception of color of any light sources. However, CIE R_a is incomplete color measurement especially for LEDs as specified by CIE [31]. IES describes a method to quantify the color rendition of a light source in their technical memorandum i.e. ANSI/IES TM-30-18 [32], which defines both overall average properties (color fidelity, gamut area) and hue specific properties (local color fidelity, local chroma shift, local hue shift etc) of a light source using both numerical and graphical methods [32]. Color property of the developed system is also evaluated using IES TM-30-18 evaluation method and described in next section.

5.4. Measurement of IES color fidelity index (R_f) and color gamut index (R_g)

IES R_f is the most updated color evaluation parameter, which provides average color fidelity of a light source. Conceptually it is equivalent to CIE R_a and functionally different due to improvements in calculation framework. In this work the developed light source is evaluated by this method also. IES R_f scores for different CCTs from 2800 K to 7500 K are shown in Fig. 7. The warm white light source used in this experiment, have IES R_f score of 87. The maximum R_f achieved for this system at CCT 3000 K is 88. Up to CCT 5500 K, R_f score is above 85 and it drops to 82 at CCT 7500 K. The downfall in R_f value occurs due to increment of energy at shorter wavelength region as CCT increases.

One more parameter involving in color average property is the color gamut index (R_g). R_g is a measure of the area spanned by the average coordinates of the color equivalent samples (CES) in each hue angle bin. The maximum and minimum value of R_g can be 140 and 60 respectively. At R_f score of 100, R_g value will be 100; which implies that the area of the reference illuminant is exactly equal to the area of the test source at *a'-b'* plane in CAM02-UCS. Reduction or increment in R_g from 100 will cause a reduction in R_f score of the color. R_g value at different CCTs is given in Table 4, which shows that the warm white light source has the R_g value of 95 and deceases to 91 at CCT 7500 K. The R_g values of the system with different R_f value at different CCTs are shown in Fig. 8.

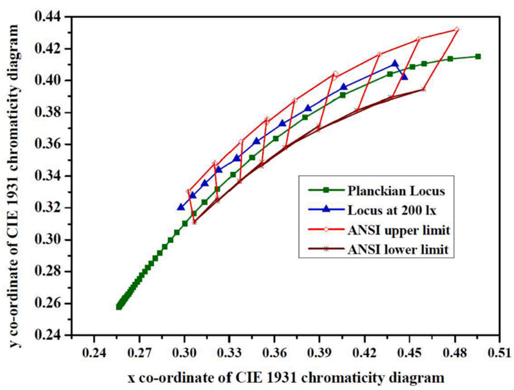

Fig. 4. Locus of developed light source in CIE 1931 chromaticity diagram.

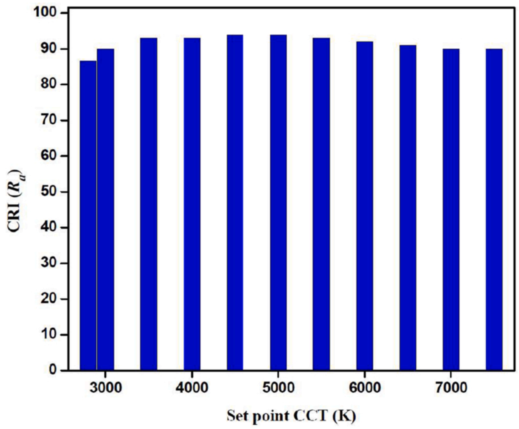

Fig. 5. Measured CRI at different CCTs.

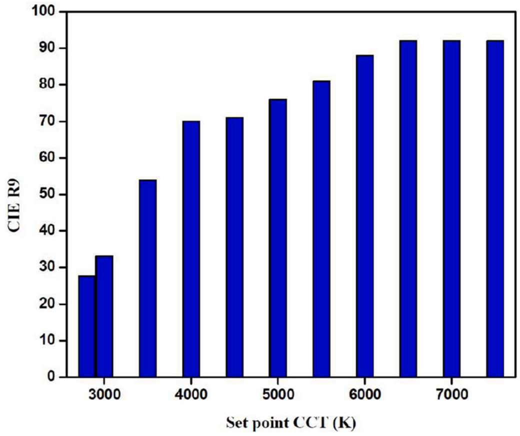

Fig. 6. Measured R9 values at different CCTs.

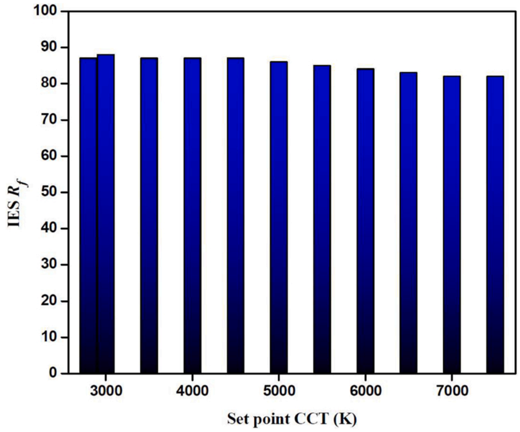

Fig. 7. IES R_f values at different CCTs.

5.5. Local chroma shift per hue angle bin

Chroma shift is a hue specific property of light source which is denoted in graphical form as specified in IES TM-30-18. The purely shift in the vectors of the color vector graph (CVG) is quantified in a series of 16 measures referred to as local chroma shift, where each

Table 4
IES R_g values at different CCTs.

CCT (K)	2800	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500
IES R_g	95	95	94	94	94	94	93	93	93	91	91

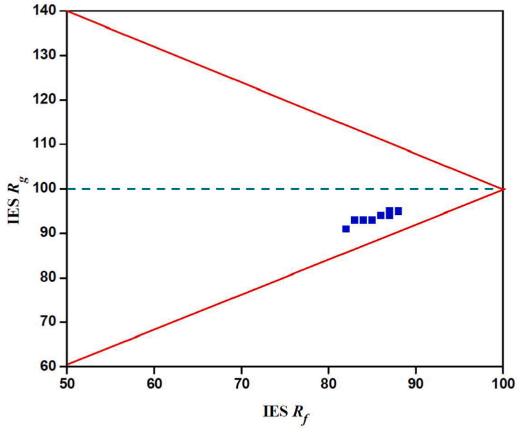

Fig. 8. IES R_g values at different IES R_f values for this system.

value corresponds to each hue angle bin. This method represents the shift of chroma of test source color from the reference illuminant at each hue angle bin. Fig. 9 shows the local chroma shift per hue angle bin at CCTs 3000 K, 4000 K, 5500 K and 7500 K. At CCT 3000 K the maximum shift in chroma is -8% at 1st and 7th hue angle bin. At CCT 4000 K -11 % shift is noticeable at 5th hue angle bin. At CCT 5500 K and 7500 K maximum shift is -14 % and -20 % respectively. So, in this system as CCT increases the chroma shift is also increased and it is limited to 20 % from the reference illuminant.

5.6. Local hue shift per hue angle bin

Hue shift is a hue specific property of light source which is denoted in graphical form as specified in IES TM-30-18. The purely tangential shift in the vectors of the CVG is quantified in a series of 16 measures referred to as local hue shift where each value is related to each hue angle bin. Fig. 10 shows the local hue shift per hue angle bin at CCTs 3000 K, 4000 K, 5500 K and 7500 K. The maximum

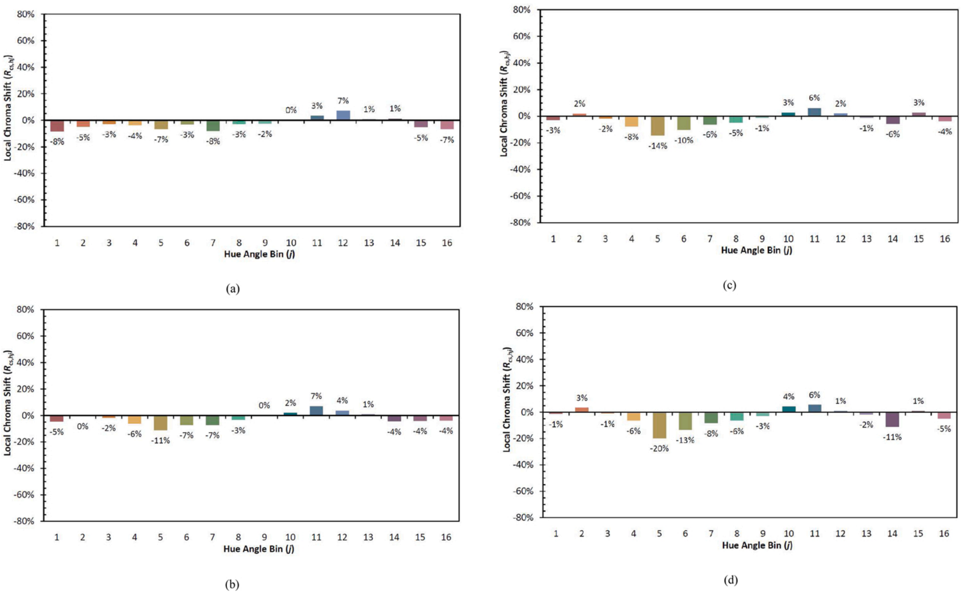

Fig. 9. Local chroma shift at different hue angle bin for CCT (a) 3000 K (b) 4000 K (c) 5500 K (d) 7500 K.

hue shift (0.28) occurs at CCT 7500 K and from Fig. 10. (a) to (d) it is noticeable that the value of maximum hue shift increases as the CCT increases. The one possible reason behind these phenomena may be the lower relative spectral power at high wavelength region at higher CCT range. Adding small amount red component with this system may resolve this effect as well as the color rendition will improve further.

5.7. SPD of the developed light source

Relative spectral power of the blended light sources at CCTs 2800 K, 4000 K, 5500 K and 7500 K are shown in Fig. 11. The warm white light source used in this system having CCT 2800 K, has a peak spectral power at 623 nm wavelength. The other two sources have peak spectral power at 467 nm, 527 nm wavelength. As the CCT increases, the spectral power of 467 nm and 527 nm wavelength also increase. Increment of small amount of spectral power at 527 nm wavelength increases the color rendition of the overall system.

6. Conclusion

A low cost high color rendition W-G-B LED based lighting system with wide range of CCTs is presented in this article. A simple mathematical formulation is described here in details. The hardware implementation of the system is done and experimentally validated. A MATLAB simulation based results are produced and a comparison between simulated result and experimentally validated results are shown. A wide range of CCTs from 2800 K to 7500 K is successfully achieved. Generated colors of the blended light source are evaluated by both CIE CRI method and IES TM-30-18 method, which proves the reliability of the system. Generated light source has maximum CRI value 94 at CCT 4500 K–5000 K, with high color fidelity index around 85. The local chroma shift and local hue shift is very small, which proves that the generated color of the light sources are closely fitted with the reference illuminant. The high CRI, tunable CCT light sources available in market, use at least four chips for mixing, which increases the system cost as well as the hardware complexity. Using three chips color mixing this system produces the best possible color rendition throughout the CCT range. Thus the system cost decreases. Addition of red component with this system will further increase the color rendition, CRI as well as color fidelity and reduce the local chroma shift and local hue shift from the reference illuminant, but the system cost will increase with this addition.

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Declaration of Competing Interest

The authors report no declarations of interest.

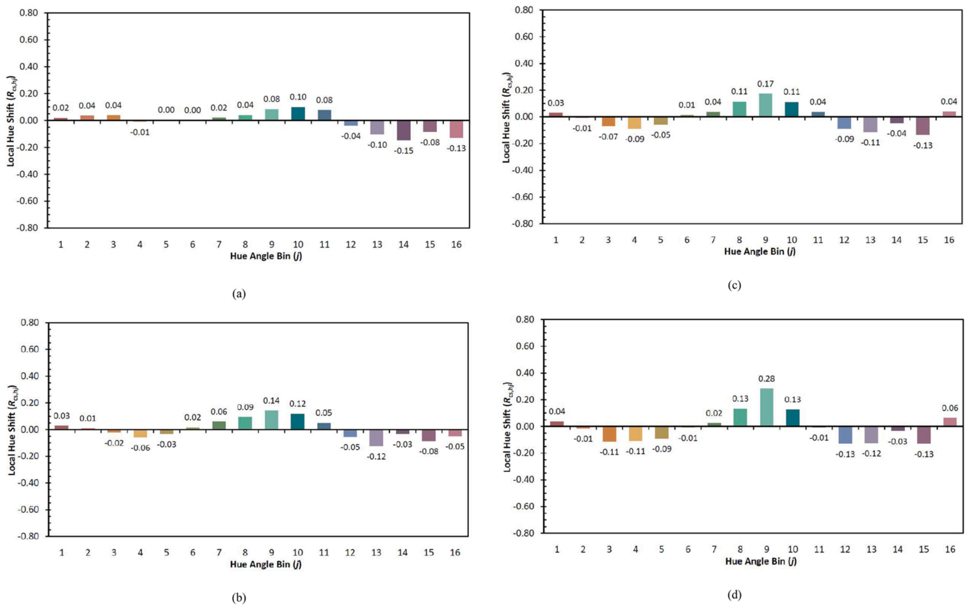

Fig. 10. Local hue shift at different hue angle bin for CCT (a) 3000 K (b) 4000 K (c) 5500 K (d) 7500 K.

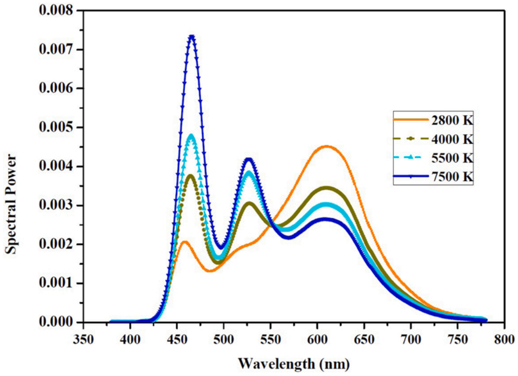

Fig. 11. SPD of developed light source at different CCTs.

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