

A High Color Rendering Index on Multichip LED Light Source

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ABSTRACT

Light source carrying a high color rendering index (CRI) finds potential applications in people's everyday life as well as lighting industry. Combination of multi-wavelength LED light sources with designated direct emission sources can achieve warm-white and cool-white light. A generic design of high CRI multi-wavelength light-emitting-diode (LED) light source, using flyback converter, pulse width modulation (PWM) voltage control, variable resistor, and timer, is proposed. The PWM pulse is for the voltage control of cascade LEDs, while variable resistor manipulates the current flowing through LEDs. A design of dimming drive with cascade-connected electronic switch is also proposed. By adjusting the width of the dimming signal, the average value of forward current pulse can be changed, and therefore the objective, the tuning of the amount of light output, can be fulfilled. The advantage of the proposed design is its short response time.

Keywords: CRI; PWM Dimming; LED; Flyback Converter

1. Introduction

The use of LED in lighting applications is overwhelming. The traditional light sources using either incandescent or fluorescent have been shifted to the solid-state's due to their intrinsic limitations/factors, almost impossible to overcome or to be substituted.

Smart lighting nowadays may be fulfilled by the employment of digitally controlled multi-chip LED systems, belonging to the category of solid state lighting (SSL). SSL offers many advantages such as control of color rendering, chromaticity control, better light quality, and energy-saving; controllability of spectral power distribution, color temperature, temporal modulation, spatial distribution, and polarization properties are feasible [1]. Meanwhile, a trade-off must be made between color rendering and luminous efficacy of the radiation of LEDs. The most significant property of SSL is associated with the development of artificial light sources. Two approaches for white LEDs are phosphor-conversion LED lamp and multi-chip polychromatic LED lamp. The output light emission and forward voltage of LED vary with the temperature and current passing through it. The performance of LED diodes is always fluctuating with the thermal condition of the LED device/system [2]. The control of color rendering is through the introduction of multi-chip LED light source in this analysis.

A prototype of LED light source with 9 different LED chips is constructed. The effects of light mixture with different color temperatures are visualized. We can take the advantage of LED's small full-width-half-max (FWHM) attribute, having a CRI of 98% and higher. The mixture of color spectral distribution functions can be obtained by the linear combination of each LED spectrum. The mimics of natural light sources with the proposed multi-wavelength LED light source are demonstrated via the comparisons of the measured color temperatures and the computed ones as well as corrected color temperature (CCT).

2. Led Light Source Fundamentals

2.1. CIE Color Definition

First, the color rendering index is defined by CIE color definition.

2.2. Color Temperature

The color temperature of a light source is the temperature of an ideal black-body radiator that radiates light of comparable hue to that light source. The temperature is conventionally expressed in terms of absolute temperature, kelvin (K) [3]. Higher color temperatures (5000 K or more) are called cool colors (blueish white); lower color

temperatures (2700 - 3000 K) are called warm colors (yellowish white through red) [4]. The polynomial formula for corrected color temperature (CCT) T is [5]

$$T = -437n^3 + 3601n^2 - 6861n + 5514.31 \quad (1)$$

with inverse line slope n ,

$$n = \frac{(x - 0.3320)}{(y - 0.1858)} \quad (2)$$

where (x, y) is the chromaticity coordinates. The chromaticity coordinates is based on standard tristimulus (X, Y, Z) , defined by the International Commission on Illumination (CIE). The transformation from RGB to CIE color space (X, Y, Z) is

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.7689 & 1.7517 & 1.1302 \\ 1 & 4.5907 & 0.0601 \\ 0 & 0.0565 & 5.5943 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3)$$

The transformation from (X, Y, Z) to chromaticity coordinates is $x = X/(X + Y + Z)$ and $y = Y/(X + Y + Z)$.

2.3. Color Rendering Index (CRI)

The color rendering index (CRI) is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or natural light source [4].

2.4. Multiwavelength LED Spectrum

A composite light spectrum is a linear combination of each LED spectrum, $S_i(\lambda)$,

$$S(\lambda) = \sum_i \alpha_i S_i(\lambda) \quad (4)$$

where α_i is the proportion under equivalent power assumption. The goal is to make $S(\lambda)$ close to those CIE-defined standard light spectrum of D50, D65, and D75, choosing color temperatures of 5000 K, 6500 K, and 7500 K, respectively. An objective function E can be defined in order to compute those optimums of α_i ,

$$E = \sum_j [S_j(\lambda) - D_j(\lambda)]^2 \quad (5)$$

where color temperature 5000 K, 6500 K, and 7500 K are for $j = 1, 2,$ and $3,$ respectively and $D_j(\lambda)$ is the spectrum of the CIE-defined standard light source.

2.5. LED Power Source with Power Factor Correction Functionality

The most attractive and beneficial attribute of LED lighting technology is its energy efficiency. LED power supply may come from a DC power source or, alternatively, transforming from AC power source after passing

through a rectifier; basically, a DC power source may not provide any power factor correction (PFC) functionality as well as dimming capability for LED. Therefore, a fly-back converter is included in the proposed LED power source module. The proposed LED drive with PFC is shown in **Figure 1**.

2.6. LED Dimming Design

Varying the forward drive current can dim an LED array; using a voltage regular or a variable resistor will accomplish the dimming requirement. An alternative way is to employ PWM. Two key factors, pulse width and duty cycle, can make LED light to vary its intensity. By turning the LED off for a short period of time will illude the human eyes, perceiving the LED as a continuous light stream. Therefore a LED drive circuitry is required to produce appropriate pulse width and frequency. The propose LED dimming design uses LM555 timer and variable resistor for the control of output pulse width. **Figure 2** shows the design of dimming circuitry.

3. Simulation and Experiment

A flyback converter with power factor correction functionality in combination with LM555 timer generating PWM signal is made to implement on a LED array, consisting of three cascade LEDs. The output of the flyback converter is connected to the input of the LM555. These three cascade LEDs play the role of load. By varying the duty cycle and the ratio of the variable resistor, the PWM pulse width can be changed accordingly.

The input DC voltage range is 5 ~ 15 V; the load to the LED module is consisted of 4 cascade LEDs. LED dim-

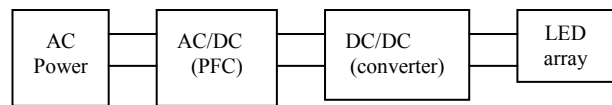


Figure 1. LED power source with PFC functionality.

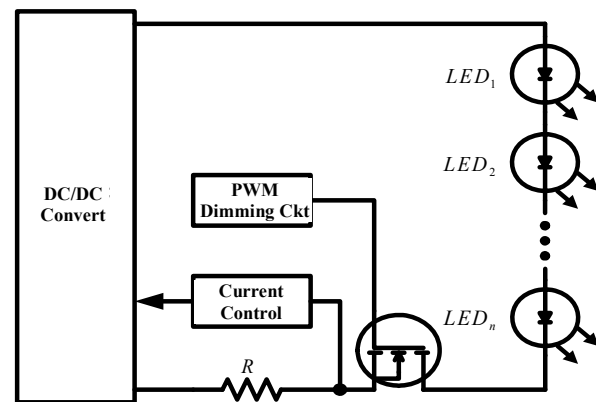


Figure 2. The schematics of cascade-connected switch dimming design.

ming drive is fulfilled via the tuning of variable resistor, width of PWM pulses, on/off timing of control/triggering of electronic switch. An example using resistor ratio (0.2, 0.5, 0.8) associated with duty cycle (0.2, 0.5, 0.8) and 5K Hz for the switching frequency of PFC is conducted to simulate the corresponding voltage output across LEDs and the forward current through LEDs. Simulation results show that the larger the duty cycle, the larger the output voltage; the forward current and output voltage are proportional to the variable resistor ratio, as expected. Simulation also shows that a duty cycle of 0.8 or higher will always make the output quantities diverge.

Nine different kinds of LED chips, AlGaInP and In-GaNA, are introduced in all constructed LED modules, being packaging with 4 parallel-arranged LED chips in order to increase their brightness level and emission area. A prototype of multi-wavelength LED light source with dimming capability is constructed, and is shown in **Figure 3**.

The wavelengths and nomenclatures are listed in **Table 1**. Three designated mix of color and their associated

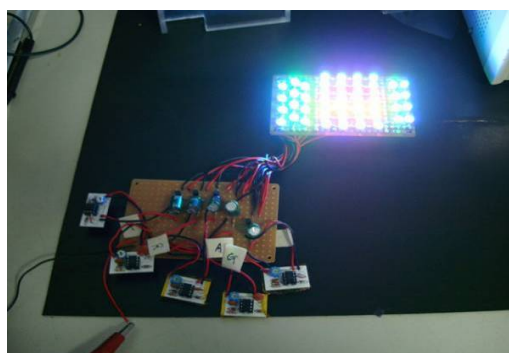


Figure 3. The emission of the multiwavelength of the LED light source module.

percentage of emission are listed in **Table 2**.

Table 3 records the mimic of the color temperature/ chromaticity coordinates of natural light sources. Therefore the proposed multi-wavelength LED light source can mimic a variety of natural light sources ranging from outdoor to indoor. The performance of the proposed LED light source is also evaluated using the NIST’s scenario. The values of R_a , the general color rendering index, as well as the corresponding computed color temperature for all 14 samples are listed in **Table 4**, illustrating the performance of the proposed LED light source via R_a . u'

Table 1. Wavelength of led chips.

No.	Color assignment	Wavelength(nm)
1	B1	455.0 ~ 457.5 nm
2	B2	470.0 ~ 472.5 nm
3	G	520.5 ~ 522.5 nm
4	Y1	561.0 ~ 563.3 nm
5	Y2	568.8 ~ 571.0 nm
6	O1	586.0 ~ 590.0 nm
7	O2	590.1 ~ 592.0 nm
8	R1	617.9 ~ 619.8 nm
9	R2	620.0 ~ 622.6 nm

Table 2. Mix of led light.

No.	Color Assignment	Emission (%)
1	B1 + B2	41.6%
2	G	33.4%
3	Y1 + Y2 + O1 + O2 + R1 + R2	25%

Table 3. Mix of led light.

No.	x	y	Color Temperature (T) (measured)	N	T (computed)	Mimic of different light sources
1	0.2998	0.303	7674	-0.27474403	7680	White-light
2	0.3005	0.3101	7486	-0.25341915	7491	White-light
3	0.303	0.3001	7489	-0.25371829	7494	White-light
4	0.2981	0.298	7921	-0.30213904	7928	White-light
5	0.2961	0.2961	8136	-0.32547597	8144	White-light
6	0.2865	0.2973	8933	-0.40807175	8943	Morning
7	0.2857	0.3423	7864	-0.29584665	7871	Outdoor shade region
8	0.3332	0.3461	5466	0.007485964	5463	Noon daylight, Direct sun
9	0.3649	0.3813	4467	0.168286445	4460	Afternoon
10	0.3605	0.3937	4647	0.137085137	4640	Afternoon
11	0.3877	0.399	3970	0.261257036	3960	Late afternoon
12	0.4338	0.426	3235	0.423813489	3220	Sunrise or sunset
13	0.4703	0.4512	2973	0.521100226	2855	Sunrise or sunset; household light bulbs
14	0.247	0.2651	17514	-1.07187894	17544	North light, blue sky

Table 4. Measurements (based on D65).

No.	x	y	Color Temperature (measured)	Color Temperature (computed)	u' (CIE)	v' (CIE)	$\Delta u'v'$	R_a
1	0.2998	0.303	7674	7680	0.1987	0.3031	0.0191	99.91
2	0.3005	0.3101	7486	7491	0.1964	0.3098	0.0124	99.94
3	0.303	0.3001	7489	7494	0.2022	0.2986	0.0240	99.89
4	0.2981	0.298	7921	7928	0.1994	0.2989	0.0233	99.89
5	0.2961	0.2961	8136	8144	0.1987	0.2980	0.0242	99.89
6	0.2865	0.2973	8933	8943	0.1912	0.3041	0.0192	99.91
7	0.2857	0.3423	7864	7871	0.1748	0.3507	0.0366	99.83
8	0.3332	0.3461	5466	5463	0.2055	0.3280	0.0096	99.96
9	0.3649	0.3813	4467	4460	0.2132	0.3441	0.0268	99.88
10	0.3605	0.3937	4647	4640	0.2059	0.3576	0.0364	99.83
11	0.3877	0.399	3970	3960	0.2211	0.3481	0.0349	99.84
12	0.4338	0.426	3235	3220	0.2395	0.3483	0.0492	99.77
13	0.4703	0.4512	2973	2855	0.2517	0.3514	0.0613	99.72
14	0.247	0.2651	17514	17544	0.1737	0.2908	0.0396	99.82

and u' are defined by Equations (6) and (7).

$$u' = \frac{4x}{(-2x+12y+3)} \quad (6)$$

$$v' = \frac{6y}{(-2x+12y+3)} \quad (7)$$

transforming CIE's chromaticity (x, y) into u' and v' . $\Delta u'v'$ is the Euclidean distance between the CIE 1960 target chromaticity and the Planckian chromaticity coordinates [6,7].

4. Conclusion

An artificial multiwavelength/multichip LED light source with dimming control, consisting of 9 different LED chips, is implemented to achieve the goal of this paper, *i.e.*, obtaining high CRI value. The key feature is to introduce PWM, power factor correction, and an electronic switch in the design of circuitry; dimming function is also included in the design. The verification of the proposed LED light source to mimic the natural light source is conducted through the comparisons of the measurements of color temperature with the computed ones. The manipulation of color rendering, a figure of merit for any white light source, is fulfilled as well, and the performance of the proposed LED light source is visualized via those high CRI values, which in average are greater or

equal to 98%.

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