The Optima Methodology of LED Cluster

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Abstract

LED cluster is probably the most relevant among the emerging solid-state lighting techniques. Impressive scenarios of a wide range of color quality and luminous efficiency have been obtained, mostly at the condition of constant ambient temperature. In this paper, we unleash the above constraint; all main factors influencing the spectral power distribution (SPD) are discussed, alongside the implementation of a pentachromatic R/G/B/A/CW platform suitable for clinic use. The proposed algorithm enables the multispectral cluster to modulate the color temperature from 2800K to 8000K in the full range ambient temperature (10^{o}C ~ 100^{o}C) with high color quality scale (CQS > 85 points) and the possibly highest luminous efficiency.

Keywords: solid-state lighting, color quality scale, luminous efficacy, multispectral cluster

1. Objective and Background

Multispectral LEDs cluster, especially for those using the hybrid approach that combines the LED-primary-based and LED-plus-phosphor based approaches, have the potential to be able to simultaneously fulfill the general lighting requirements of high color rendering, energy efficient, and color adjustable by modulating their spectral composition. Nevertheless, the intrinsic property that the spectral power distribution of LED more or less has the nonlinearity effect with respect to the junction temperature and drive current unavoidably affects the overall lighting performance as well as the complexity in spectral modulation. A successful mixing scheme involving the thermal and current issues should be able to possess two primary functions:

1. Precisely estimating the junction temperature and drive current dependences of LED spectra: recently a successful analytical spectrum model has been constructed by introducing the underlying physical principles as much as possible, while the difference between the experimental and physical model has to be compensated by a Gaussian term [1]. On the other hand, empirically utilizing Gaussian model to fit LED spectra can simply incorporate the spectrum power distribution (SPD) with power (P), peak wavelength (λ_0) and spectral width ($\Delta\lambda$) [2]. More general models on the basis of double Gaussian fit were afterward generated to descript the asymmetrical property of LEDs spectra [3-6]. However, most of previous models merely contain the junction temperature or the derive current as a single free parameter. Although most recently the formalism for single-color low power LED spectra in consideration of both temperature and current is derived [7], there is still lack of the formalism for high power LED spectra which can be simply extended to phosphor-converted white light spectrum.
2. Successfully introducing the spectral model into a spectral optimization process: a multispectral mixing is mathematically an underdetermined optimization problem. The main challenges lie in precisely achieving a specific set of tristimulus values and simultaneously obtaining high color quality as well as luminous efficiency, especially under the condition that all of these multiple objectives are implicit functions of temperature and derive current. Furthermore, the published analytical spectral models usually require a large number of fitting parameters making them inappropriate for optimization. To reduce the complexity and enhance the calculation efficiency we make an attempt to directly connect tristimulus values with derive current based on an simple assumption to firstly

reduce the degrees of freedom (more details will be discussed in Section 2.2) and find the optimal solution over a range of color temperature [8]. Afterward we complete the optimization process by unleashing the constraint in ambient temperature to further extent the operable range of the cluster.

In this paper, a practical cluster mixing scheme is proposed in consideration of the spectral model formalism and the optimization for high power LEDs spectra. The dependences of temperature and current as well as the modulation methodology on SPD are constructed. Our approach is based on achieving an acceptable requirement of the color quality scale (CQS) and maximizing the luminous efficiency (LE) over a wild range of color temperature (T_c) and ambient temperature (T_a). Where the CQS is a refinement of general color rendering index (Ra) introduced by the CIE (Commision Internationale de l'Éclairage) and LE is a practical efficiency merit defined as the luminous flux normalized to the electrical input power (watt) expended to operate the LED [9,10].

2. Methods

In colorimetry, metamerism states a phenomenon of matching of an object apparent color with different SPDs. In general lighting the metamerism appears when dealing with the multispectral synthesizing (K-type LED emitters, usually $K > 3$) for a target CIE tristimulus value $\boldsymbol{\varepsilon} = [X\ Y\ Z]^{\mathrm{T}}$. Before adjusting the spectrum of LEDs cluster to approach this target, the current tristimulus value $\tilde{\varepsilon}$ can be described as:

$$\tilde{\boldsymbol{\varepsilon}} = \mathbf{A}\tilde{\mathbf{S}}^{\mathrm{T}}\mathbf{l} \tag{1}$$

where rows of $\mathbf{A}$ are the sampled color matching functions with dimension N, the KxN spectral matrix $\tilde{\mathbf{S}}$ now contains K-type modeled spectra extracted N discrete points, and $\mathbf{l}$ becomes the Kx1 all-ones vector. In this system, two implicit free variables T and I for each type of spectrum make the degrees of freedom turn out to be $2K-3$. Apparently, on this situation it will be time consuming to search an optimal solution to approach $\boldsymbol{\varepsilon}$ and other objectives, i.e. high efficiency and good lighting quality. To solve this issue we assume a localized region including a small number of K-type LEDs has the uniform ambient temperature T_a. This assumption however degenerates the degrees of freedom $2K-3$ into $K-3+1$. On the other hand, we attempt to directly relate the tristimulus value to drive current and have found empirically that a quadratic current basis $\mathbf{i} = [1\ I_1\ I_1^2\ I_2\ I_2^2 \cdots I_k\ I_k^2]^{\mathrm{T}}$ with $(2K+1)$x3 coefficient matrix $\mathbf{C}$ can precisely characterize $\tilde{\varepsilon}$ under a specific T_a. In sum, the Eq. (1) can be rewritten with lower degrees of freedom:

$$\tilde{\boldsymbol{\varepsilon}} = \mathbf{C}^{\mathrm{T}}\mathbf{i} \tag{2}$$

If we now set $\tilde{\boldsymbol{\varepsilon}} = \boldsymbol{\varepsilon}$, an arbitrary current combination will readily be produced by randomly choosing values for $K-3$ currents and then extracting the positive solutions for remained currents. Thus an initial current population, $\mathbf{I_P}$, of "combination changes" with various driving current could be generated. Also the corresponding initial T population, $\mathbf{T_P}$, is obtained. Similarly, the initial SPD population, $\tilde{\mathbf{S}}_{\mathbf{P}}$, comes out via bringing the corresponded T and I in $\mathbf{T_P}$ and $\mathbf{I_P}$. To evaluate the performance of the combinations in $\tilde{\mathbf{S}}_{\mathbf{P}}$, at this step, we introduce a user-defined merit function based on the weighted sum method with the figures of merit LE and CQS:

$$f = w \times \mathrm{CQS} + (1-w) \times \mathrm{LE}, \text{ subject to } w \in [0,1] \tag{3}$$

where w modulates the weight between two figures of merit. Imposing each combination in $\tilde{\mathbf{S}}_{\mathbf{P}}$ to Eq. (3) the merit function would lead to a corresponding value; a table of merit function changes vs. $\tilde{\mathbf{S}}_{\mathbf{P}}$, or equivalently, a table of merit function changes vs. $\mathbf{I_P}$, can be established. Afterward we bring the table into a globe searching engine, continuous genetic algorithm, to achieve an improved spectral synthesizing [11].

3. Results

To implement the proposed scheme a pentachromatic high power cluster composed of four single-colors red/amber/green/blue (R/A/G/B/) and a phosphor-converted cool-white (CW) LED is devised (HELIO Optoelectronics Corp., HMHP-E1LW). Fig. 1 shows five LED spectra at $T_a = 10^{\circ}$C and $I = 350$mA. An adequate layout of LED arrangement with the consideration of the first-order design delivers a uniform illumination at the center of measurement plane [12].

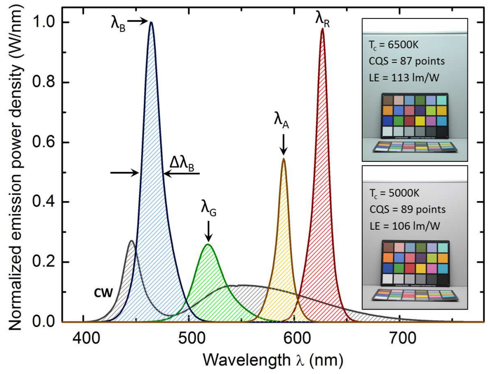

Fig. 1. The high power spectra of red (λ_R: 625nm, $\Delta\lambda_R$: 20nm), green (λ_G: 523nm, $\Delta\lambda_G$: 33nm), blue

(λ_B: 465nm, $\Delta\lambda_B$: 25nm), amber (λ_A: 587nm, $\Delta\lambda_A$: 18nm) and cool-white LEDs at ambient temperature T_a of 10°C with all I of 350mA. The right figures show two real-field tests designed for T_c = 5000K and 6500K respectively.

We firstly exam the temperature dependence of spectra by four cases, T_c = 3200K, 4600K, 6200K, and 7400K distributed over a wild range of color temperature under a specific value of the ambient temperature, T_a = 50°C, as shown in Fig. 2. All cases fulfill the requirements for lighting level = 100 lm, Δxy < 0.01 (T_a = 50°C) and CQS > 85 points with the optimized LE. By changing the ambient temperature without additional compensation and defining the valid bandwidth when chromaticity deviation of Δxy = 0.01, the cluster has relative narrow band (about T_a = 42 °C ~ 56 °C) at lower color temperature range and substantially increases up to around T_a = 25 °C ~ 70 °C at the T_c = 6200K. The chromaticity point shifts toward higher correlated color temperature T_{cc} with the raise of T_a owing to the dramatic deterioration in LEs of the amber and red LEDs as shown in Fig. 3.

In sum, the LE contour map is provided in Fig. 5 under the compensation for whole operational ambient temperatures. Through the above analysis the best performance (LE > 130 lm/W) appears within the lower T_a region (10 °C ~ 20 °C) with the higher power ratio of the white light emitter (4000K < T_c <6500K), and the worst one happens at the higher T_a region (90 °C ~ 100 °C) with the higher power ratio of the red and amber emitters (2800K < T_c < 3200K). If the LE = 100 lm/W is selected as the minimum acceptable efficiency, a full operable range for T_a is workable when T_c > 5200K.

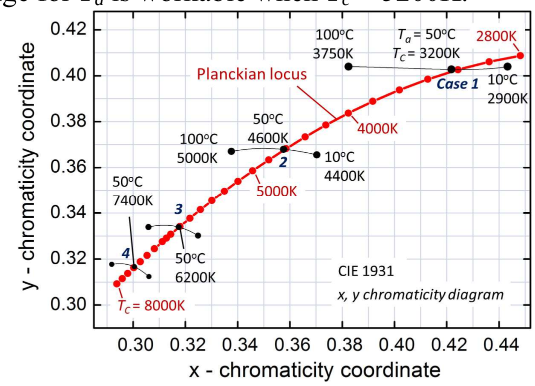

Fig. 3. The temperature dependence of spectra designed for T_c = 3200K, 4600K, 6200K, and 7400K at T_a = 50°C. The chromaticity point shifts toward higher color temperature with the raise of T_a owing to the dramatic deterioration in LEs of the red and amber LEDs.

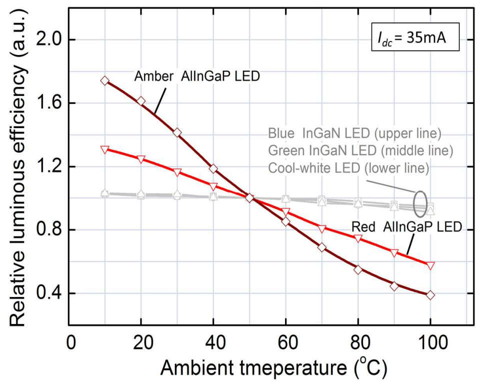

Fig. 4. The temperature dependence of LE for pentachromatic LEDs. When T_a is varied from 10 °C to 100 °C, LEs of amber and red AlInGaP LEDs decrease to 23% and 46% of that at 10 °C while LEs of InGaP LEDs are insensitive to temperature variation.

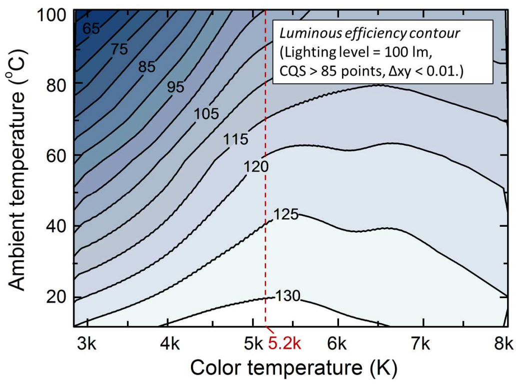

Fig. 5. The LE contour of the pentachromatic LEDs cluster is performed under the predefined requirements (CQS > 85 points, lighting level =100 lm and Δxy < 0.01). When the LE=100 lm/W is selected as the minimum efficiency boundary, a full operation range for ambient temperature can be obtained for T_c > 5200K.

4. Impact

A complete high power LEDs mixing scheme has been proposed in consideration of the spectral formalism and the optimization methodology. The phosphor-converted white light can be approximated by simply decomposing the spectrum into two double-Gaussian models developed from single-color spectrum. In the optimization process, the degrees of freedom can be reduced from $2K-3$ to $K-2$ under the localized uniform T_a assumption and the optimal spectral synthesizing can be obtained via incorporating CGA. In order to implement the proposed scheme, a pentachromatic high power cluster is devised. The limitation in operation window at high T_a and low T_c is mainly due to the dramatically deteriorations in luminous efficiency of amber and red light sources, which could be improved by replacing single emitter to two or more ones to share the total emitting power and reduce the thermal effect induced by drive current. While the optimizations for the number of each type LED, prices and whole volume of the cluster need to be further explored. However, the cluster provides a full operable range in ambient temperature when T_c > 5200K by using the proposed scheme, which makes it feasible to provide a high quality smart lighting system that can be efficiently operated within an extended operation range.

5. Reference

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