SIMULATION ANALYSIS OF WHITE LED SPECTRA AND COLOR RENDERING

OHNO, Y.

National Institute of Standards and Technology, USA

ABSTRACT

Three-color and four-color white LED models were analyzed by simulation on their color rendering properties compared with those of conventional lamps for general lighting. The analysis focused on the trade-off between color rendering performance and luminous efficacy. The results of the simulation demonstrated several problems with the current CIE Color Rendering Index, and the need for improvements are discussed.

Keywords: color rendering, CRI, luminous efficacy, LED, white LED, solid-state lighting

1. INTRODUCTION

There have been significant advancements in light-emitting diodes (LEDs). High brightness LEDs are now available in all colors and their efficiency is being improved at a great pace. White LEDs are highly expected for use in general lighting due to the potential of great energy savings. White LEDs are produced either by multi-tip LEDs (e.g., red, green, blue) or by combining phosphors excited by blue or ultraviolet (UV) LED emission; thus, white LEDs have greater freedom in spectral design than conventional sources. The spectra of white LEDs can be very different from those of conventional sources, and questions arise on what the spectra of white LEDs should be for best color rendering. The CIE Color Rendering Index (CRI) [1] is currently the only internationally agreed metric and is widely used, but it is known to have deficiencies [2], especially when used for LEDs. An effort has started in CIE (TC1-62) to investigate color rendering of LED light sources. Various ways for improvement of CRI are proposed [3].

When considering spectra of light sources for general illumination, another important aspect to consider is luminous efficacy of radiation (hereinafter denoted as LER, lumens per watt), which is the conversion factor from optical power (watt) to luminous flux (lumen) and is determined solely by the spectrum of the source. The LER and color rendering are both critical parameters for light sources used for general lighting, and these two are generally in trade-off relationship. Based on the CRI, color rendering is best achieved by broadband spectra distributed throughout the visible region, while LER is best achieved by monochromatic radiation at 555 nm. This trade-off relationship is evident in many existing lamps. By studying the CRI, some people are lead to believe that white LED spectra should mimic the spectrum of the sun (daylight) or blackbody. While such spectra would give high CRI no doubt, they would suffer from much lower LER resulting in lower luminous efficacy of source (lumens per electrical watt). The challenge in creating LEDs for use as illumination sources is to provide the highest possible LER while achieving sufficiently good color rendering. As such, an accurate metric for color rendering is of importance. If the metric is incorrect, energy will be wasted.

To analyze the possible color rendering performance of white LEDs and also the problems in CRI, a simulation program has been developed and various white LED spectra, mainly by multi-chip LEDs, were analyzed in comparison to various conventional sources. The results of the simulation are presented, and the problems and expected improvements of the CRI are discussed.

2. COLOR RENDERING INDEX (CRI)

The CRI [1] is currently the only internationally agreed method for color rendering evaluation. The procedure for calculation is, first, to calculate the color differences ΔE_i (on the 1964 W*U*V* uniform color space – now obsolete) of selected 14 Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination. The reference illuminant is the Planckian radiation for a test source having CCT < 5000 K, or a phase of daylight [4] for a test source having CCT ≥ 5000 K. The process incorporates the von Kries chromatic adaptation transformation. The *Special Color Rendering Index* R_i for each color sample is obtained by

$$R_i = 100 - 4.6\,\Delta E_i \quad ; (i=1, \ldots, 14). \qquad (1)$$

This gives an evaluation of color rendering for each particular color. The *General Color Rendering Index* R_a is given as the average of the first eight color samples (medium saturation). The score for perfect color rendering (zero color differences) is 100. "CRI" is often used to refer to R_a, but the CRI actually consists of 15 numbers; R_a and R_i (i=1 to 14).

3. LUMINOUS EFFICACY OF A LIGHT SOURCE

The energy efficiency of a light source is evaluated by *luminous efficacy of a source* (often called simply "luminous efficacy"), which is the ratio of *luminous flux* (lumen) emitted by the source to the input electrical power (watt). The luminous efficacy of a source, η_v [lm/W], is determined by two factors:

$$\eta_v = \eta_e \cdot K \tag{2}$$

where η_v is the *radiant efficiency* of the source (ratio of output radiant flux to input electrical power; *external quantum efficiency* is often used in the same meaning). K is the *luminous efficacy of radiation* (LER: ratio of luminous flux to radiant flux), and is determined by the spectral distribution $S(\lambda)$ of the source as given by,

$$K = \frac{K_m \int_\lambda S(\lambda)V(\lambda)\mathrm{d}\lambda}{\int_\lambda S(\lambda)\mathrm{d}\lambda} \quad ;\text{where } K_m = 683 \text{ [lm/W]} \tag{3}$$

4. SIMULATION OF WHITE LEDs

To simulate multi-chip LEDs, the following mathematical model for LED spectra has been developed. The spectral power distribution (SPD) of a model LED, $S_{LED}(\lambda)$, for a peak wavelength λ_0 and the half spectral width $\Delta\lambda_{0.5}$ is given by,

$$\begin{aligned} S_{LED}(\lambda, \lambda_0, \Delta\lambda_{0.5}) &= \left\{ g(\lambda, \lambda_0, \Delta\lambda_{0.5}) + 2 \cdot g^5(\lambda, \lambda_0, \Delta\lambda_{0.5}) \right\} / 3 \\ \text{where } g(\lambda, \lambda_0, \Delta\lambda_{0.5}) &= \exp\left[-\left\{ (\lambda - \lambda_0) / \Delta\lambda_{0.5} \right\}^2 \right] \end{aligned} \tag{4}$$

The unit of wavelength is nm. Fig. 1 shows an example of this LED model compared with the SPD of a real blue LED spectrum.

A simulation program has been developed to simulate three-chip or four-chip white LEDs, with automatic color mixing for each LED to bring its chromaticity coordinate exactly on the Planckian locus for a given correlated color temperature (CCT). This allows the use of an iterative method to optimize LED spectra for maximizing the R_a (or average R_i of specific colors) or maximizing LER under given conditions. The program calculates the general and special color rendering indices (R_a, R_1 to R_{14}) as well as LER, K [lm/W]. The color differences in ΔE^*_{ab} are also calculated. The program then presents the actual colors of the 14 color samples of CIE 13.3 under the reference illuminant and test illuminant on the computer display, which provides visual impression of the color appearance of the samples (Fig. 2). The color presentation is achieved by conversion from XYZ (calculated back from CIELAB coordinates) to the display RGB space and applying gamma correction [5]. To compare the color rendering of white LEDs with common existing lamps, the program is also provided with SPDs of different types of fluorescent lamps, high intensity discharge lamps, special

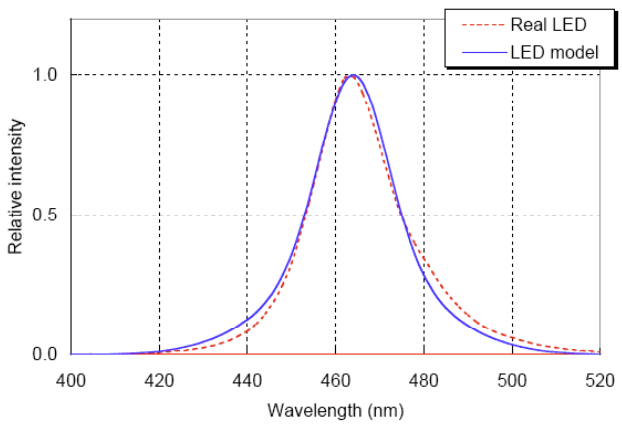

Figure 1. LED model $S_{LED}(\lambda)$ at 460 nm compared with the SPD of a real LED.

incandescent lamps, and some hypothetical SPDs such as equal energy white. The spectral reflectance data of the samples in the program can be shifted (by 20 nm, 40 nm, etc.) in order to examine the sensitivity of results on variation of color samples.

5. RESULTS

Figure 3 shows the results of calculations of LER and R_a on some conventional lamp samples (on the left side) and some of LED sources (on the right side). The descriptions of the sources are given in Table 1. The data of the lamps are only samples and not representative of the type of lamp. Traditional sources #1 through #6 are discharge lamps. Sources #9 through #11 (3-LED-1, 3-LED-2, and 4-LED) are the multi-chip LED models using 20 nm spectral width, except for green (30 nm).

3-LED-1 is optimized for the highest LER at $R_a = 80$ and 3300 K, and has a very high LER ($K = 408$ lm/W). However, the red sample appears to be brown ($R_9 = -90$). The average of four saturated colors (R_9 to R_{12}) is 26. In another combination (474 nm, 545 m, 616 nm), the average of (R_9 to R_{12}) is made to 88 while R_a(=80) is the same, and all the saturated colors appear much better. This demonstrates that R_a is not reliable to judge the color rendering of 3-chip white LEDs.

3-LED-2 is optimized for highest CRI ($R_a = 89$, $K = 370$ lm/W). It shows much better color rendering ($R_9 = 65$, etc.). However, tests by shifting the sample colors indicated that the results are rather sensitive to variations of color samples.

4-LED model presents excellent color rendering ($R_a = 97$, or $\Delta E^*_{ab} < 4.4$). The changes of results by shifting the sample colors are found to be not significant.

Sources #7 and #8 are the spectra of Illuminant A and D65 cut out in the 400 nm to 700 nm region only, simulating white LEDs mimicking blackbody or daylight spectra. Both of these has LER of only about 250 lm/W, much lower than the three-chip or four-chip LED models (350 – 400 lm/W) mentioned above. This demonstrates that sources mimicking blackbody or daylight spectrum would have poor energy efficiency.

6. DISCUSSIONS ON CRI

Such a metric as CRI, if it is accurate, would be a useful tool to design spectra of white

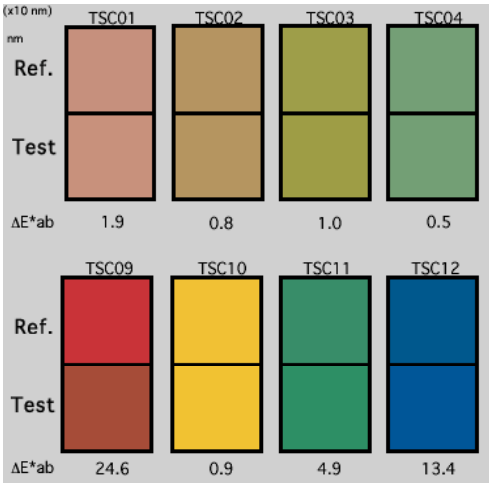

Figure 2. An example of color appearance presentation of the samples of CIE 13.3. (only 8 of the 14 colors are shown.)

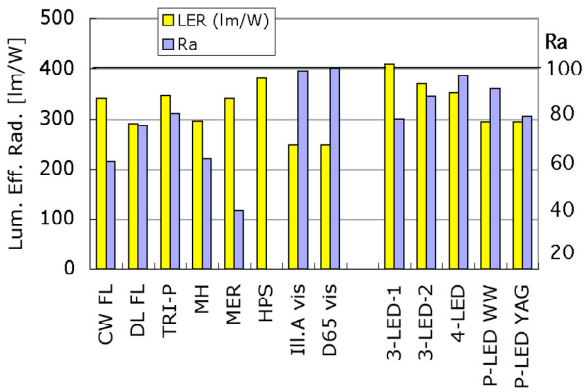

Figure 3. LER and CRI (R_a) of conventional lamp samples and LED model sources.

Table 1. Descriptions of lamps on Fig.3

#	Symbol	CCT (K)	Description
1	CW FL	4290	Cool White FL
2	DL FL	6480	Daylight FL
3	TRI-P	3380	Triphosphor FL
4	MH	4280	Metal halide
5	MER	3750	Mercury
6	HPS	2070	High Press. Sodium
7	Illum. A vis	2856	Illum.A (only in 400-700 nm)
8	D65 vis	6500	D65 (only in 400-700 nm)
9	3-LED 1	3300	3-LED (457/540/605)
10	3-LED 2	4000	3-LED (465/546/614)
11	4-LED	4000	4-LED (461/527/586/637)
12	P-LED WW	2880	White LED WW
13	P-LED YAG	6810	White LED (blue + YAG)

LEDs as demonstrated above. However, in this simulation, several problems of CRI have been identified.

1) Since R_a is determined only with medium-saturated colors, the color rendering of saturated colors (R_9 to R_{12}), particularly R_9, can be very poor while R_a is fairly good. Saturated colors should somehow be considered.

2) The results for three-chip LEDs (less problem for four-chip) tend to be sensitive to variation of color samples, especially for saturated colors. Even though the values of R_i are good for the given set of samples, rendering of other colors can be poor.

3) The 2000 K (very reddish) blackbody or daylight spectra at 20,000 K (twilight) gives $R_a = 100$ though colors do not render well. This indicates a problem in the definition of the reference source (CCT of the reference source moves with that of test source). Chromatic adaptation is assumed to be too perfect. Very low or very high CCT should be penalized.

4) The CRI does not account for the shift in chromaticity coordinates across the Planckian locus well. For example, the chromaticity coordinate of a compact fluorescent lamp (2900 K, $R_a = 84$) is moved from $\Delta uv = 0$ to $\Delta uv = +0.015$ in the yellow direction. The R_a is still 84 while this color is very yellowish and unacceptable for room lighting. This implies a problem in handling chromatic adaptation or color constancy.

5) The CRI does not consider the direction of color shift. The incandescent lamp with neodymium coating showed $R_a = 77$ while this type of lamp is often preferred to normal incandescent lamps ($R_a = 99$). R_a is lower because the chroma of red and green samples are increased. Other references [6, 7] indicate that increased chroma (thus, larger gamut area) provides better visual clarity and sensation of good color. The directions of color shift should be considered somehow.

6) The plots of color differences on W*U*V* scale (outdated) indicates significant nonuniformity compared to CIELAB. The distortion is notable particularly in the red region.

The CRI needs to be improved on these aspects or a new model to be developed. Visual evaluation will be necessary to validate a new model and to develop recommendations on spectral design for white LEDs for solid-state lighting.

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Author:
Yoshi Ohno
National Institute of Standards and Technology
100 Bureau Drive, Mailstop 8442, Gaithersburg, MD 20899
Phone: 301-975-2321
E-mail: ohno@nist.gov