Color Rendering and Luminous Efficacy of White LED Spectra

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ABSTRACT

White LED spectra for general lighting should be designed for high luminous efficacy as well as good color rendering. Multi-chip and phosphor-type white LED models were analyzed by simulation on their color characteristics and luminous efficacy of radiation, compared with those of conventional light sources for general lighting. Color rendering characteristics were evaluated based on the CIE Color Rendering Index (CRI), using not only R_a but also the special color rendering indices R_i as well as the CIELAB color difference ΔE^*_{ab} for the 14 color samples defined in CIE 13.3. Several models of 3-chip and 4-chip white LEDs as well as phosphor-type LEDs are optimized for various parameters, and some guidance is given for designing these white LEDs. The simulation analysis also demonstrated several problems with the current CIE Color Rendering Index (CRI), and the need for improvements is discussed.

Keywords: Color rendering, Colorimetry, CRI, lighting, luminous efficacy, solid state lighting, LED, white LED

1. INTRODUCTION

One of the most important characteristics of light sources for general lighting is color rendering. Color rendering is a property of a light source that shows how natural the colors of objects look under the given illumination. If color rendering is poor, the light source will not be useful for general lighting. U.S. Energy Policy Act of 1992[1] specifies minimum requirements for both the luminous efficacy (lumens per watt) and Color Rendering Index (CRI)[2] for common types of lamp products sold in the USA. This is an important aspect to be considered for white LEDs being developed for general lighting.

White light by LEDs is realized by mixture of multi-color LEDs or by combinations of phosphors excited by blue or UV LED emission, and thus, they have greater freedom in spectral design than conventional sources. Questions arise on how the spectra of white LEDs should be designed for good color rendering performance, e.g., whether RGB white LEDs can satisfy the need, or four-color mixture is needed, or whether much broader, continuous spectra are required. To evaluate color rendering performance of light sources, Color Rendering Index (CRI)[2] recommended by the Commission Internationale de l'Eclairage (CIE) is available and widely used, but it is known to have deficiencies[3,4], especially when used for sources having narrow-band spectra. A poor correlation between visual evaluation of RGB white LEDs and the CRI is reported[5]. The color rendering issues of white LEDs are investigated by the CIE Technical Committee 1-62 with a plan to develop a new metric.

The main driving force for solid-state lighting is the potential of huge energy savings on the national or global scale[6]. Thus, when considering spectra of light sources for general illumination, another important aspect to consider is luminous efficacy (lumens per watt). The term *luminous efficacy* is normally used as the conversion efficiency from the input electrical power (watt) to the output luminous flux (lumen). The luminous efficacy of a source is determined by two factors: the conversion efficiency from electrical power to optical power (called *radiant efficiency* or *external quantum efficiciency*[7]) and the conversion factor from optical power (watt) to luminous flux (lumen). The latter is called *luminous efficacy of radiation* (lumen/watt) and is hereinafter denoted as LER. Since LER and color rendering are determined solely by the spectrum of the source, white LED spectra should be optimized for both of these aspects.

The difficulty is that color rendering and LER are generally in a trade-off relationship. Based on the CRI, color rendering is best achieved by broadband spectra distributed throughout the visible region, while luminous efficacy is best achieved by monochromatic radiation at 555 nm. This trade-off relationship is evident in many existing lamps. By

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studying the CRI, some people are led to believe that white LED spectra should mimic the spectrum of the sun or a blackbody. While such spectra would give high CRI values no doubt, they would suffer significantly from low LER. The challenge in creating LEDs for use as illumination sources is to provide the highest possible energy efficiency while achieving best color rendering possible. As such, an accurate metric of color rendering is of importance. If the metric is incorrect, energy will be wasted.

To analyze the possible performance of white LEDs and also the problems in the CRI, a simulation program has been developed. Various white LED spectra, multi-chip type and phosphor type, were modeled and analyzed in comparison to conventional lamps. 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 is currently the only internationally agreed metric for color rendering evaluation. The procedure for the calculation is, first, to calculate the color differences ΔE_i (on the 1964 $W^*U^*V^*$ uniform color space – now obsolete) of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination. The first eight samples are medium saturated colors, and the last six are highly saturated colors (red, yellow, green, and blue), complexion, and leaf green. The reference illuminant is the Planckian radiation for test sources having a correlated color temperature (CCT) < 5000 K, or a phase of daylight[‡] for test sources having CCT ≥ 5000 K. The process incorporates the von Kries chromatic adaptation transformation. The *Special Color Rendering Indices* R_i for each color sample is obtained by

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

This gives the 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:

$$R_\mathrm{a} = \sum_{i=1}^{8} R_i / 8 \tag{2}$$

The score for perfect color rendering (zero color differences) is 100. Note that “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 RADIATION

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:

$$\eta_\mathrm{v} = \eta_\mathrm{e} \cdot K \tag{3}$$

where η_e 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* (ratio of luminous flux to radiant flux, denoted as LER in this paper), and is determined by the spectral distribution $S(\lambda)$ of the source as given by,

$$K = \frac{K_\mathrm{m} \int_\lambda V(\lambda)\, S(\lambda)\, \mathrm{d}\lambda}{\int_\lambda S(\lambda)\, \mathrm{d}\lambda} \quad \text{, where } K_\mathrm{m} = 683 \text{ [lm/W]} \tag{4}$$

While various other terms are used in the LED industry, the terms introduced above are the ones officially recommended internationally[7].

[‡] One of daylight spectra at varied correlated color temperatures. The formula is available in Ref. 8.

4. WHITE LED SIMULATION PROGRAM

Mathematical models have been developed for multi-chip LEDs and phosphor-type LEDs in order to analyze numerous designs 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, $S_{\mathrm{LED}}(\lambda)$, for a peak wavelength λ_0 and the half spectral width $\Delta\lambda_{0.5}$ is given by,

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

The unit of wavelength is nm. Figure 1 shows an example of this LED model compared with the SPD of a typical real blue LED spectrum (measured at NIST with a relative expanded uncertainty (k=2) of less than 5 % depending on the wavelength).

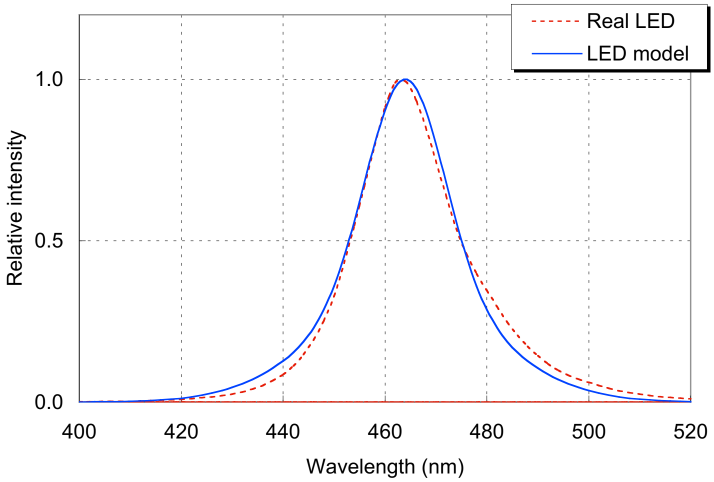


Figure 1. LED model $S_{\mathrm{LED}}(\lambda)$ with λ_0= 464 nm compared with the SPD of a typical real blue LED.

For multi-chip LEDs, the program can 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 the average of R_i for specific colors or maximizing LER under given conditions. The phosphor-type white LED model is made based on Planckian radiation given in a limited spectral range with some modification. More details of the phosphor LED model are desccribed in section 5.4.

The program calculates the general CRI, $R_{a,}$ and special CRI, R_1 to R_{14}, as well as color differences ΔE^*_{ab} and LER, K [lm/W] of the given source. The program then presents the actual colors of the 14 color samples of CIE 13.3 under the reference illuminant and test light source 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 the CIELAB coordinates to account for color constancy) to the display RGB space and applying the gamma correction[9]. To compare the color rendering of white LEDs with common existing lamps, the program is also provided with the SPD data of a few different types of fluorescent lamps, high intensity discharge (HID) lamps, and some real white LEDs. The spectral reflectance data of the samples in the program can be shifted in 10 nm steps in either direction in order to examine the sensitivity of the results on small changes of color samples.

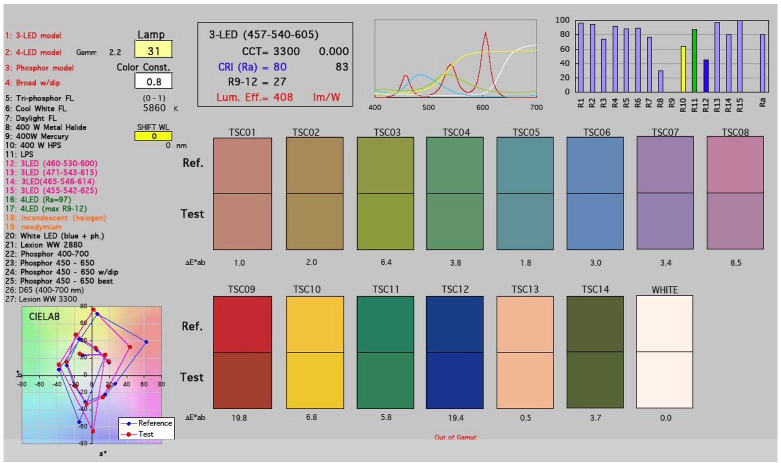


Figure 2. Front panel of the simulation program presenting the color appearance of the 14 samples under the reference illuminant and a test source. (The colors may not be reproduced accurately on print.)

5. RESULTS

Table 1 summarizes the results of the calculation for the light sources and LED models analyzed in this study, showing CCT (K), general CRI－R_a, special CRI for strong red – R_9, LER (lm/W), etc. The LER and R_a of these sources are also plotted in Fig. 3. R_9 is included in the table because the red-green contrast is very important for color rendering[10, 11], and red tends to be problematic. Lack of red component shrinks the reproducible color gamut and makes the illuminated scene look dull. This is the problem of many of existing discharge lamps. R(9-12) is the average of the special color rendering indices R_9 to R_{12} of the four saturated colors (red, yellow, green, and blue). Duv, introduced only in this paper, is the distance from the Planckian locus on the CIE 1960 uv chromaticity diagram, with polarity, plus (above the Planckian locus) or minus (below the Planckian locus)[‡]. It is important that chromaticity coordinate of illumination is very close to the Planckian locus since greenish or pinkish white light is not accepted for general illumination, and Duv of fluorecent lamps is typically controlled to less than ±0.005.

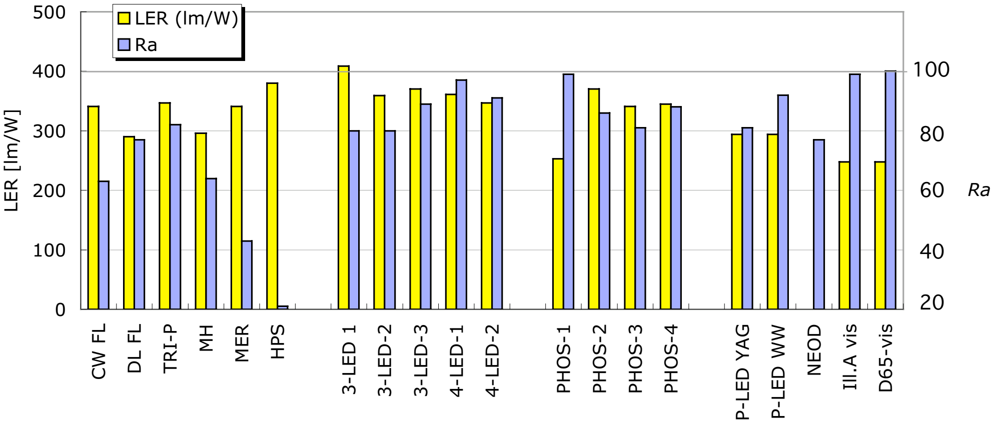


Figure 3. LER (lm/W) and the general CRI, R_a, of the sources and LED models analyzed.

[‡] Δuv is commonly used for this distance but with no signs (no information on direction of the deviation).

Table 1. Summarized results for the light sources and LED models analyzed.

Symbol	Description	CCT (K)	Duv	R_a	R_9	R(9-12)	LER (lm/W)
CW FL	Cool White fluorescent lamp	4290	0.001	63	-89	13	341
DL FL	Daylight fluorescent lamp	6480	0.005	77	-39	13	290
TRI-P	Triphosphor fluorescent lamp	3380	0.001	82	17	47	347
MH	Metal halide lamp	4280	0.007	64	-120	19	296
MER	High pressure mercury lamp	3750	0.000	43	-101	-29	341
HPS	High pressure sodium lamp	2070	0.001	20	-214	-43	380
3-LED 1	3 chip LED model (457/540/605)	3300	0.000	80	-90	27	409
3-LED-2	3 chip LED model (474/545/616)	3300	0.000	80	89	88	359
3-LED-3	3 chip LED model (465/546/614)	4000	0.000	89	65	64	370
4-LED-1	4 chip LED model (461/527/586/637)	3300	0.000	97	96	87	361
4-LED-2	4 chip LED model (447/512/573/627)	3300	0.000	91	99	99	347
PHOS-1	Phosphor model warm white (400-700)	3013	0.000	99	97	99	253
PHOS-2	Phosphor model warm white (450-650)	3007	0.011	86	26	67	370
PHOS-3	PHOS-2 with narrow dip at 560 nm	3000	0.000	81	47	61	341
PHOS-4	PHOS-2 with broad dip in green	3000	0.000	88	46	75	345
P-LED YAG	Phosphor LED (YAG phosphor)	6810	0.004	81	24	61	294
P-LED WW	Phosphor LED (warm white)	2880	0.008	92	72	80	294
NEOD	Incand. lamp with neodymium glass	2757	-0.005	77	15	60	-
Illum. A vis	Illum.A (only in 400-700 nm)	2856	0.000	99	98	100	248
D65 vis	D65 (only in 400-700 nm)	6500	0.003	100	98	100	248

5.1 Conventional light sources

The first six sources in Table 1 are conventional discharge lamps commonly used, including fluorescent lamps and HID lamps. The data of these lamps are only samples and not representative of the type of lamp. Among these lamps, the triphosphor lamp has the highest CRI, $R_a = 82$. It should be noted that the values of R_9 of most of these lamps are very poor, though R_9 values are exaggerated (by factor of two or more) due to nonuniformity of the $W^*U^*V^*$ color space used in the CRI formula. For example, R_9=17 (TRI-P) should be around 60 based on the CIELAB color space. R(9-12) values of these lamps, thus, are not good, either. Even though R_9 is important, it was not paid high attention due to the fact that R_9 is not included in the calculation of R_a and also probably because increasing deeper red component reduces LER and thus the lumen output of the lamp. This has been one of the problems in CRI. The metric for color rendering is important in that it drives manufacturers to design light spectra to maximize the index such as R_a.

5.2 Three-chip white LEDs

The second group in Table 1 and Fig. 3 (3-LED-1 to 4-LED-2) is a group of multi-chip white LED models. 3-LED-1 is a 3-chip LED model optimized for the highest LER at R_a=80 and 3300 K, and has a very high LER (K=409 lm/W). 3-LED-2 is optimized for the highest R(9-12) (=88) at the same R_a(=80), with K=359 lm/W. The spectra and the special CRI, R_1 to R_{14}, of these 3-chip LED models are shown in Figs. 4 and 5. Both models have the same R_a value of 80, but 3-LED-1 exhibits very poor rendering of red (appearing brown) and R(9-12) only 27, whereas, 3-LED-2 exhibits good rendering of all the four saturated colors as well as the medium saturated colors. This is a case where the sources having the same R_a can exhibit very different color rendering performance (possible serious problems with saturated colors). This demonstrates that R_a is not trustable to judge the color rendering of 3-chip white LEDs and possibly also for conventional light sources having only a few narrowband peaks.

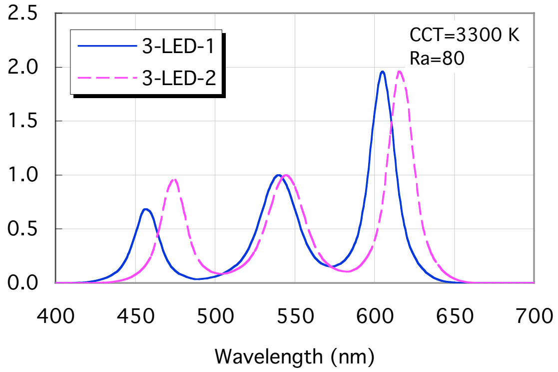


Figure 4. The SPDs of the two 3-chip LED models both having R_a=80 at 3300 K.

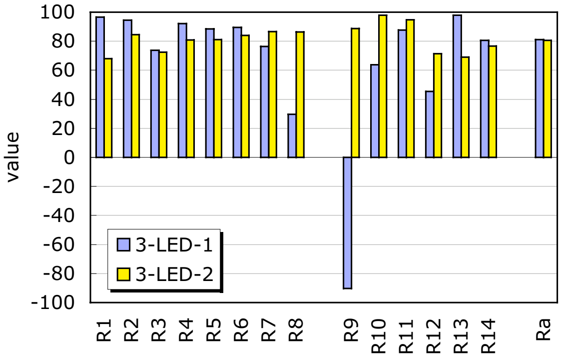


Figure 5. Special CRI of the two 3-chip white LED models shown in Fig. 4.

Then, is R(9-12) a good indicator? Since saturated colors have sharp changes in spectral reflectance curves, R(9-12) may cause some irregular results with SPDs having large valleys between peaks in the spectral distribution curve. As a simple test, all the sample spectral reflectance data are shifted from –20 nm to +20 nm to examine the sensitivity of the results to small changes of color samples. Figure 6 shows the changes in R_a and R(9-12) caused by the shifts. As expected, R(9-12) is found to be very sensitive to the wavelength shift of the samples while R_a is fairly stable. This means that, even if R(9-12) is good, color rendering of some other saturated colors (orange, purple, etc.) may not be accurately rendered (hue will shift). 3-LED-3 is optimized for highest CRI (R_a=89), K=370 lm/W, at 4000 K. This model also exhibits strong sensitivity of R(9-12) to sample color shifts. While R(9-12) is an important number to look at, one should be alerted that the results do not apply to all the saturated colors. 3-LED-2 and 3-LED-3 seem to have fairly good color rendering performance except for this problem, which should be studied further.

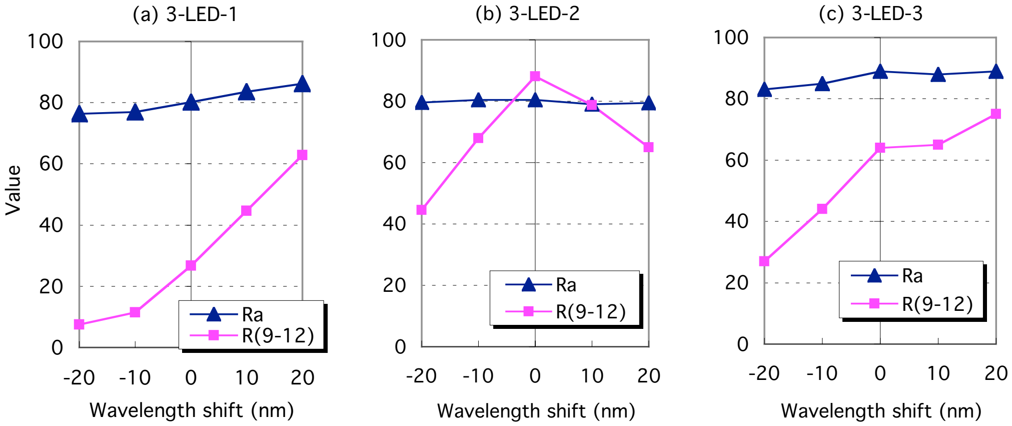


Figure 6. The changes of R_a and R(9-12) of 3-chip white LED models when the wavelength of the sample spectral reflectance data are shifted.

5.3 Four-chip white LEDs

Figures 7 and 8 show the SPDs and the special CRI values, R_1–R_{14}, of two 4-chip LED models. 4-LED-1 is optimized for the highest R_a(=97) at 3300 K, with R(9-12)=87 and K=361 lm/W. ΔE^*_{ab} of all the samples are less than 3.1 except for R_{12} (blue) being 11.9. 4-LED-2 is optimized for the highest R(9-12) (=99) at 3300 K, with R_a=91 and K=347 lm/W. ΔE^*_{ab} of all the samples are less than 2.4. With both models, all the sample colors are presented excellently. Figure 9 shows the results of the wavelength shifting test. The sensitivity of R(9-12) is much less than the case of 3-chip LED models (Fig. 6) and found to be not significant.

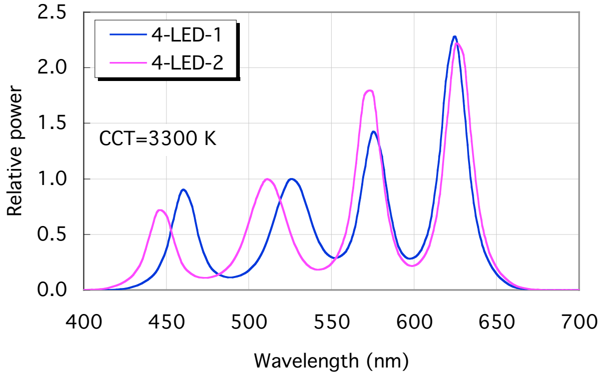


Figure 7. The SPDs of the two 4-chip LED models 4-LED-1 and 4-LED-2.

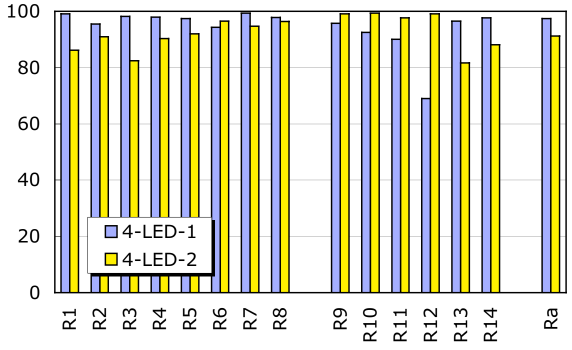


Figure 8. Special CRI of the 4-chip white LED models shown in Fig. 7.

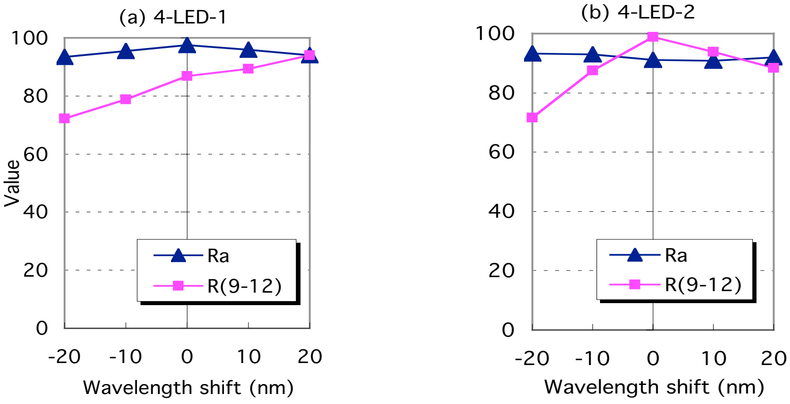


Figure 9. The changes of R_a and R(9-12) of the 4-chip LED models when the wavelength of the sample spectral reflectance data are shifted.

5.4 Phosphor type white LEDs

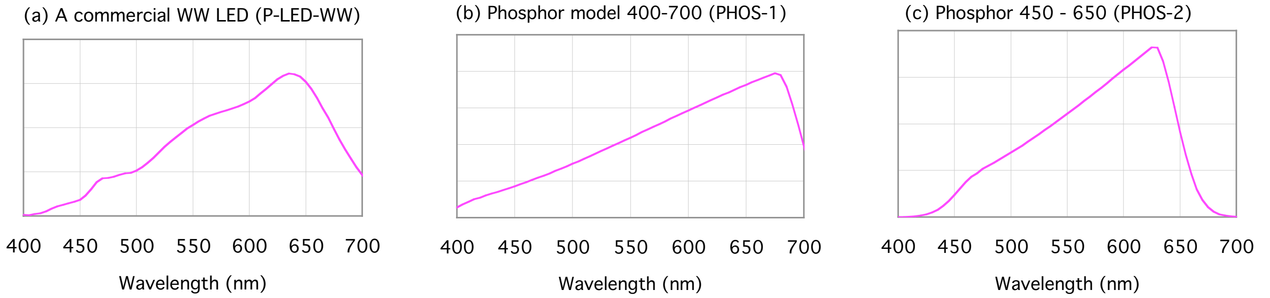
Figure 10 (a) shows the SPD of one of commercially available, warm-white LEDs using phosphors, denoted P-LED-WW in Table 1 and Fig. 3. The spectrum is designed to mimic Planckian radiation. Following this example, a simple model for phosphor-type white LEDs is made using Planckian radiation that is cut off at both ends of the spectrum smoothly using a half of a Gaussian function. The model can add a negative curve using a Gaussian function of a varied spectral width to produce a valley in the Planckian spectrum. The wavelengths of both ends (the half point of the rise or drop), the center wavelength, depth, and the width of the valley are the variables for the model.

If one tries to mimic Planck's radiation as close as possible for good color rendering, an answer is given in Fig. 10 (b), where the cut-off wavelengths are set to 400 nm to 700 nm (denoted PHOS-1 in Table 1). As found in Table 1, the color rendering of this source is excellent with R_a=99. However, the LER is 253 lm/W, only 68 % of the good 3-chip white LED (370 lm/W, 3-LED-3). If such white LEDs are used, a great amount of energy would be wasted. To improve this, one may think of cutting off both ends of the spectrum that contribute very little to the lumen. Figure 10

(c) is such an example where the cut-off wavelengths are set to 450 nm to 650 nm (PHOS-2 in Table 1). This specrum produces R_a=86 and K=370 lm/W, which are comparable to the good 3-chip LEDs. However, one should pay attention to Duv. It is +0.011, which indicates that the light is fairly yellowish and may not be accepted for indoor lighting. To reduce the Duv value, green (or yellow-green) part of the spectrum should be reduced. The SPD shown in Fig. 10 (d) is one solution to this, where a narrow valley is made at 560 nm (PHOS-3 in Table 1). The Duv value is reduced to zero, with R_a=81 and K=341 lm/W. From this condition, the spectrum is optimized for the highest R_a value by varying the valley parameters. The result is shown in Fig. 10 (e). This yields R_a =88, R(9-12)=75, and K=345 lm/W, yet keeping Duv=0.000. The color rendering of this source is probably good enough for office and home lighting. The example of a commercially available warm white LED shown in Fig. 10 (a) has a high value of R_a (=92) but Duv=+0.008, rather yellowish, and also, K=294 lm/W, which can be further improved.

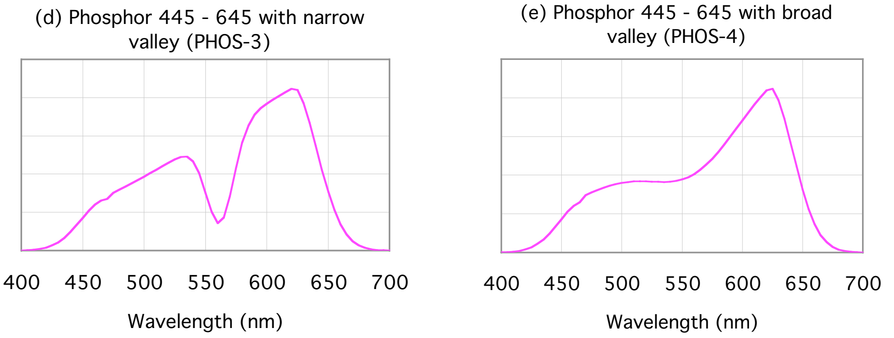
The same considerations should apply when white LED spectra are designed to mimic daylight spectra. For example, the D65 spectrum cut out in the 400 nm to 700 nm region (D65-vis in Table 1) yields the LER of only 248 lm/W, much lower than the good 3-chip or 4-chip LED models (350 lm/W – 400 lm/W). There are proposals by a few different groups to judge color rendering performance by the closeness of the SPD curve to the Planckian radiation or daylight spectrum (of the same CCT) in the 400 nm to 700 nm region. This is not recommended because this would drive manufacturers to design white LEDs having low luminous efficacy. In addition, as presented above, 4-chip LEDs, for example, can have as good color rendering as full-spectrum broadband light sources, which needs to be studied further.

As indicated above, the deviation of chromaticity coordinates of the source from the Planckian locus is not treated well by CRI. For example, the RGB ratio of the 3 chip LED model, 3-LED-2 (3300 K, R_a = 80, Duv = 0.000), is modified so that the chromaticity coordinate deviates to a yellow direction (Duv = + 0.015) keeping the same CCT. This light would be very yellowish and will not be acceptable for indoor lighting. However, R_a value increased to 85 rather than decreased. This is a problem related to chromatic adaptation and how to handle color constancy.


(a) A commercial WW LED (P-LED-WW)

(b) Phosphor model 400-700 (PHOS-1)

(c) Phosphor 450 - 650 (PHOS-2)


(d) Phosphor 445 - 645 with narrow valley (PHOS-3)

(e) Phosphor 445 - 645 with broad valley (PHOS-4)

Figure 10. A commercially available warm white LED (a), and phosphor-type LED models (b) – (e).

6. CCT AND COLOR PREFERENCE

Some manufacturers are considering a goal of realizing sun light spectra or daylight spectra with white LEDs because these are the most natural light that the human eyes have been adapted to and because LED technology makes it possible. However, two points should be considered. First, the energy aspect. If such full-spectrum white LEDs mimicking Illuminant D65 or D50 in the 400 nm to 700 nm region are made, their LER would be only about 250 lm/W as discussed in the previous section. Second, "natural daylight" implies that the CCT of the source would be 6500 K (D65) or 5000 K (D50) at least. The CCT of fluorescent lamps, for example, has been designed for people's preference in the targeted market (different countries). For homes in the U.S., warm white (2800 K to 3000 K) is dominant. 6500 K white light would not be accepted for homes in the U.S. But in Japan, for example, 5000 K is dominant. Some other countries prefer even higher CCT up to 7500 K. Preferences for offices are different. For example, 4200 K is common in the U.S. Therefore, "natural daylight" would not apply to all markets and applications.

Another aspect to be considered for acceptance in the market is color preference. As an example, incandescent lamps with neodymium glass have been in the market for many years and they are gaining popularity recently. The spectrum of this type of lamp is shown in Fig. 11. There is strong absorption in the yellow region. The color rendering characteristics are shown in Table 1 (see NEOD). It shows R_a=77 and R_9=15, fairly poor, but the lamps are advertised for more brilliant colors than normal incandescent lamps, and are preferred by many people. The reason for the popularity of this type of lamp is explained in Fig. 12, which shows the plots of colors of the 14 samples in the CIELAB color space under illumination by the neodymium-glass lamp and the reference source (Planckian). It is observed that the chroma of red and green samples is increased from the reference source. These deviations discount the values of CRI; however, red-green contrast is enhanced and the color gamut area is increased. This provides more colorfulness to the illuminated scene. It is known for long time that people prefer slightly enhanced chroma of illuminated objects[12, 13]. Another study[11] shows that visual clarity is well correlated with the gamut area produced by the four saturated colors (red, green, yellow, blue). If visual clarity is increased, this is not just a matter of preference. The present CRI simply evaluates the color shifts from the reference source to test source. The color sifts in any directions, whether decreasing or increasing chroma, are counted equally, therefore the results are rather for color fidelity. For overall color rendering, decreased chroma is worse than increased chroma or hue shift, so the directions of color differences should somehow be considered.

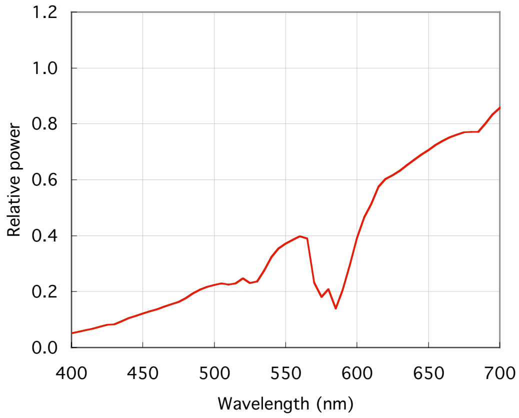


Figure 11. The SPD of an incandescent lamp with neodymium glass.

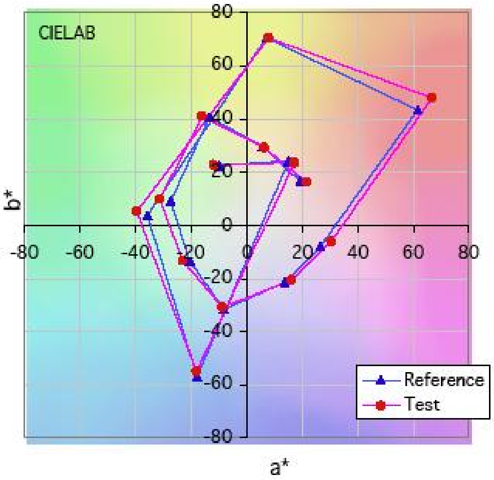


Figure 12. Plots of colors of the 14 samples on the CIELAB space under illumination by the neodymium-glass lamp and the reference source (Planckian). (The background color is only for rough indication)

Such light source spectra that produce enhanced chroma can be realized by a 3-chip white LED. An example is shown in Fig. 13. This is a 3-LED model with the peak wavelengths 455 nm, 547 nm, and 623 nm, with spectral half-width, 20 nm, 30 nm, and 20 nm, for blue, green, and red, respectively. CCT=3300 K, R_a=73, R(9-12)=50, K=363 lm/W. The CIELAB a^*, b^* coordinates of the 14 samples are plotted in Fig. 14. The color fidelity of this source will not be good, but the color gamut is notably enlarged. This may be an interesting white light spectrum to be studied from a preference aspect.

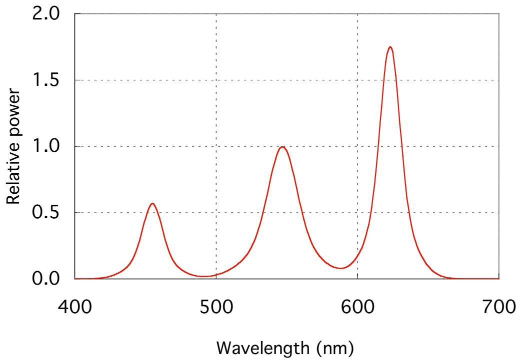


Figure 13. The SPD of a 3-chip white LED model with peak wavelengths 455 nm, 547 nm, and 623 nm.

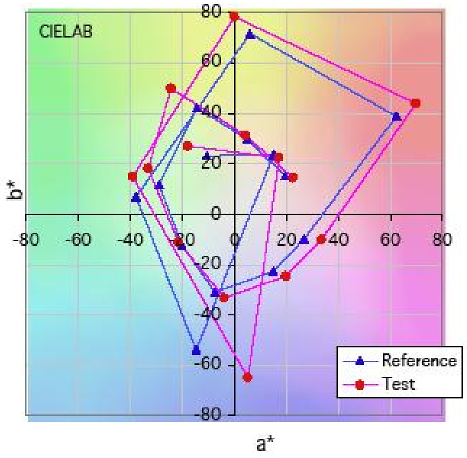


Figure 14. Plots of colors of the 14 samples on the CIELAB space under illumination by the 3-chip LED model shown in Fig. 13 and by the reference source (Planckian). (The background color is only for rough indication.)

7. DISCUSSIONS ON CRI

In the analyses reported above, it is demonstrated that such an index as R_a, if it is accurate, would be a useful tool to design spectra of white LEDs. However, as already demonstrated, R_a alone is not a trustable metric for color rendering, especially for white LEDs. The additional indices for saturated colors such as R_9 and R(9-12) also need to be examined. Several problems with the CRI (particularly, R_a) that have been identified or demonstrated in this study are summarized below.

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 even though R_a is fairly good. Saturated colors should somehow be considered.

2) The results for 3-chip LEDs tend to be sensitive to small 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 CRI does not account for the shift in chromaticity coordinates across the Planckian locus well. R_a hardly changes with a change of light source chromaticity from Duv = 0 to Duv = +0.015. This is a problem related to chromatic adaptation and color constancy.

4) The CRI does not consider the direction of color shift. The decrease of chroma has negative effects and increase has rather positive effects (increased visual clarity). The directions of color shift should be somehow considered.

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

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

8. CONCLUSIONS

Various white LED models have been analyzed by simulation on their color rendering performance together with energy efficiency aspects. The results provided some guidance for design of multi-chip and phosphor-type white LEDs. It is shown that well-designed 3-chip white LEDs may have acceptable color rendering (for indoor lighting) as well as good luminous efficacy, but further study is needed. 4-chip white LEDs with appropriate design are shown to have excellent color rendering as well as good luminous efficacy. Phosphor type LEDs can have excellent color rendering but tend to have lower luminous efficacy. Attention should be paid to the value of Duv when designing spectra of phosphor-type white LEDs. Finally, several problems of the CRI have been identified or confirmed in this study. R_a is not a trustable index for color rendering performance of white LEDs (as well as for conventional sources). Some of the problems can be addressed by examining $R_9 – R_{12}$ additionally, but this will not solve the fundamental problems. Also, the need to describe color rendering performance in one number is strong. A new, improved metric for color rendering solving these problems is in urgent need.

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