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Spectral design considerations for white LED color rendering

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Abstract. White LED spectra for general lighting should be designed for high luminous efficacy as well as good color rendering. Multichip and phosphor-type white LED models were analyzed by simulation of 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), examining not only R_a but also the special color rendering indices R_i, as well as on the CIELAB color difference ΔE^*_{ab} for the 14 color samples defined in CIE 13.3. Several models of three-chip and four-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 CRI, and the need for improvements is discussed. [DOI: 10.1117/1.2130694]

Subject terms: color rendering; colorimetry; CRI; lighting; luminous efficacy; solid-state lighting; LED; white LED.

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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 tells 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. The U.S. Energy Policy Act of 1992[1] specifies minimum requirements for both the luminous efficacy (lumens per watt) and the Color Rendering Index (CRI)[2] for several 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 from LEDs is realized by mixture of multicolor 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 a four-color mixture is needed, or whether much broader, continuous spectra are required. To evaluate the color-rendering performance of light sources, the CRI,[2] recommended by the Commission Internationale de l'Éclairage (CIE), is available and widely used, but it is known to have deficiencies,[3,4] especially when used for sources having narrowband spectra. A poor correlation between visual evaluation of RGB white LEDs and the CRI is reported.[5] The color-rendering problems of white LEDs are being investigated by the CIE Technical Committee 1-62, with a future plan to develop a new metric.

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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 for the conversion efficiency from the input electrical power (watts) to the output luminous flux (lumens). 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 efficiency*[7]) and the conversion factor from optical power (watts) to luminous flux (lumens). The latter is called the *luminous efficacy of radiation* (LER). Since the 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 the LER are generally in a trade-off. Based on the CRI, color rendering is best achieved by broadband spectra distributed throughout the visible region, while luminous efficacy is highest with monochromatic radiation at 555 nm. This trade-off is evident in many existing lamps. By 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, 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. For this purpose, 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 of the CRI, a simulation program has been developed. Various white LED spectra, of multichip type and phosphor type, were modeled and analyzed in comparison with conventional lamps. The results of the simulation are presented, and the problems and necessary improvements of the CRI are discussed.

2 Color-Rendering Index

The CRI is currently the only internationally agreed-on metric for color rendering evaluation. The procedure for its calculation is, first, to calculate the color differences ΔE_i (in 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 the given illuminant. 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 $\geqslant 5000$ K. The process incorporates the von Kries chromatic adaptation transformation. The *Special Color Rendering Indices* R_i for each color sample are 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 maximum value of R_i (zero color difference) is 100, and the values can be negative if color differences are very large. The *General Color Rendering Index* R_a is given as the average of the first eight color samples:

$$R_a = \sum_{i=1}^{8} \frac{R_i}{8}. \tag{2}$$

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 as its *luminous efficacy* η_v, which is the ratio of the *luminous flux* (lumens) emitted by the source to the input electrical power (watts). It is determined by two factors:

$$\eta_v = \eta_e K, \tag{3}$$

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 with the same meaning), and K is the *luminous efficacy of radiation* (ratio of luminous flux to radiant flux, abbreviated as LER in this paper), and is determined by the spectral distribution $S(\lambda)$ of the source

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

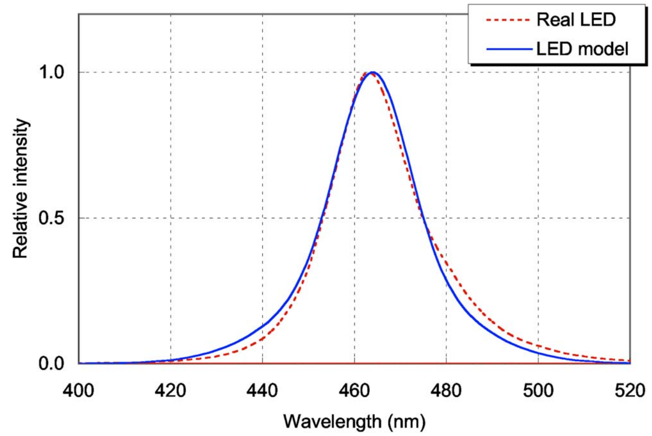

Fig. 1 LED model $S_{LED}(\lambda)$ at 464 nm compared with the SPD of a typical real blue LED.

$$K = \frac{K_m \int_\lambda V(\lambda) S(\lambda)\,d\lambda}{\int_\lambda S(\lambda)\,d\lambda}, \quad \text{where } K_m = 683 \text{ lm/W}. \tag{4}$$

Here K_m is *the maximum LER*, and its value, 683 lm/W (for monochromatic radiation at 555 nm), is defined in the international definition of the candela. While various other terms are used in the LED industry, the terms introduced here are the ones officially recommended internationally.[7]

4 White LED Simulation Program

Mathematical models have been developed for multichip LEDs and phosphor-type LEDs in order to analyze numerous spectral designs of white LEDs. To simulate multichip 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 half spectral width $\Delta\lambda_{0.5}$, is given by

$$S_{LED}(\lambda,\lambda_0,\Delta\lambda_{0.5}) = \frac{g(\lambda,\lambda_0,\Delta\lambda_{0.5}) + 2g^5(\lambda,\lambda_0,\Delta\lambda_{0.5})}{3}, \tag{5}$$

where $g(\lambda,\lambda_0,\Delta\lambda_{0.5}) = \exp\{-[(\lambda-\lambda_0)/\Delta\lambda_{0.5}]^2\}$. The unit of wavelength is the nanometer. 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) less than 5%, depending on the wavelength].

Using the LED model described, spectra of a three-chip (RGB) white LED and four-chip white LEDs with various combinations of peak wavelengths and spectral widths can be created. For these white LED spectra, the simulation program calculates the general CRI, R_a, and special CRIs, R_1 to R_{14}, as well as color differences ΔE^*_{ab} in the CIELAB color space[8] and the LER K. In addition, a broadband phosphor-type white LED model has been developed, based on Planckian radiation in a limited spectral range with some modification. The details of the phosphor LED model are described in Sec. 5.4.

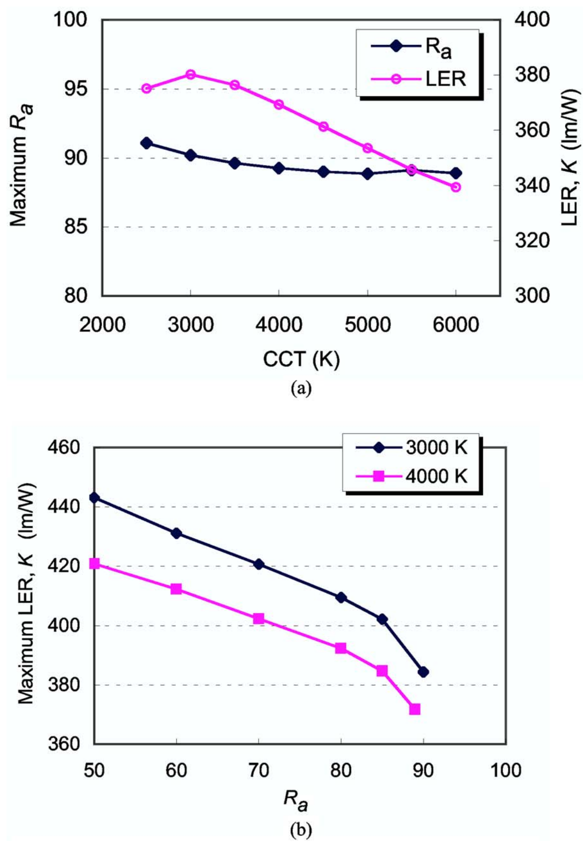

Fig. 2 Examples of optimization of RGB white LED spectra. The peak wavelengths of LEDs range from 452 to 472 nm for blue, from 543 to 553 nm for green, and from 598 to 620 nm for red. $\Delta\lambda_{0.5}$ =20 nm except for green (30 nm). (a) Maximum R_a obtained at varied CCT. (b) Maximum LER, K(lm/W), obtained at varied R_a.

For three-chip and four-chip LED models, the program performs automatic color mixing of each LED to bring its chromaticity coordinate exactly on the Planckian locus for a given 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 K under given conditions. Figure 2 shows examples of such optimization for an RGB white LED model. The index R_a or K was maximized by varying the peak wavelengths of the three LEDs under given conditions. The spectral widths, $\Delta\lambda_{0.5}$=20, 30, and 20 nm for blue, green, and red LEDs were used, which are typical of LEDs currently available. Figure 2(a) shows the maximum R_a obtained at varied CCT (the values of the LER are also plotted), which demonstrates that an RGB white LED can achieve as high as $R_a \approx 90$, and also indicates that R_a is not very dependent on the CCT. It is also observed that the LER decreases for higher CCT. This is because larger power for the blue LED is necessary for higher CCT, while the blue component ($\approx$450 nm) has a very low lumen contribution compared to green or red. Figure 2(b) shows the maximum LER obtained at varied R_a, which demonstrates that RGB white LEDs can produce $K \approx 400$ lm/W with decent R_a values (>80). The data also demonstrate the trade-off between R_a and K, though the slope is not very large. Note that the maximum R_a and K values presented here may not be the highest values under each condition, because the iterative method yields only local maxima. Also, these results are only examples of what the program can do, and are not intended to recommend optimization of source spectra for maximum R_a. There are some serious problems in judging the color rendering of white LEDs with R_a alone, as discussed in later sections. The optimization can be done for various other parameters such as the average of R_i for other sets of samples, or the lowest average ΔE^*_{ab} for a given set of color samples. When optimizing for the LER in real developments, the radiant efficiencies of available LEDs should also be considered. For example, the white LED models shown in Fig. 2 are currently not realistic, because the radiant efficiency (and thus the luminous efficacy) of LEDs with 540- to 555-nm peaks is very low.

The simulation program also 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 a visual impression of the color differences of each sample. The color presentation is achieved by conversion from XYZ to the display RGB space and applying the gamma correction.[9] By calibrating each primary color of the computer display used, accurate colors (within the screen gamut) can be presented on the display, and it might be possible to use this for visual experiments in the future.

To compare the color rendering of white LEDs with that of common existing lamps, the simulation program is also provided with the SPD data on several different types of fluorescent lamps, high-intensity discharge (HID) lamps, and some real white LEDs. The spectral reflectance data on the samples in the program can be shifted in 10-nm steps in either direction in order to examine the sensitivity of the results to small changes of the color of the samples.

5 Results

Table 1 summarizes the results of the calculation for the light sources and LED models analyzed in this study, showing the CCT (unit: K); the general CRI, R_a; a special CRI for strong red, R_9; the LER; etc. The LER and R_a of these sources are also plotted in Fig. 3. The index 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 the red component shrinks the reproducible color gamut and makes the illuminated scene look dull. This is the problem with many of existing discharge lamps. The index $R(9-12)$ 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 in this paper, is the distance from the chromaticity coordinate of the source to 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 the 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 fluorescent lamps is typically controlled to less than ±0.005. For multichip LED models, the spectral width $\Delta\lambda_{0.5}$=20 nm is used for all LEDs except for green ones (30 nm).

[‡]The symbol Δuv is commonly used for this distance, but with no signs (no information on the 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 to 700 nm)	2856	0.000	99	98	100	248
D65 vis	D65 (only in 400 to 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 on 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 2 or more) by the nonuniformity of the $W^*U^*V^*$ color space used in the CRI formula. For example, $R_9=17$ (TRI-P) would correspond to ≈ 60 based on the CIELAB color space. The values of $R(9-12)$ for these lamps, thus, are not good either. Even though R_9 is important, it has not been paid much attention, because R_9 is not included in the calculation of R_a and also probably because increasing the deeper red component reduces the LER and thus the lumen output of the lamp. This has been one of the problems with the CRI. The metric for color rendering is important in that it drives manufacturers to design light spectra to maximize the index R_a.

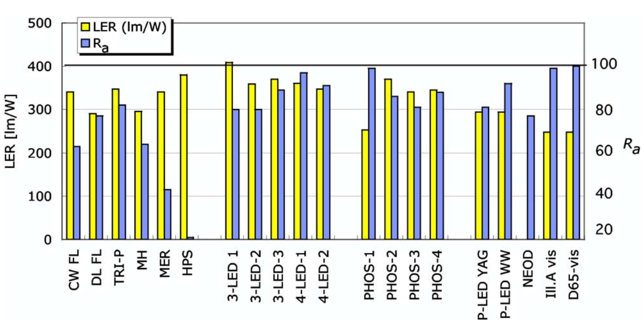

Fig. 3 LER and the general CRI R_a of the conventional sources and LED models analyzed.

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 multichip white LED models. 3-LED-1 is a three-chip LED model optimized for the high-

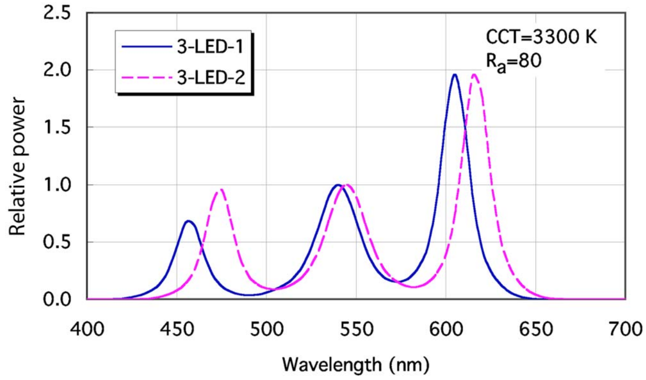

Fig. 4 The SPDs of the two three-chip LED models, both having R_a=80 at 3300 K.

est 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) and the same CCT, with K=359 lm/W. The spectra and the special CRI, R_1 to R_{14}, of these three-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 (R_9=−90, appearing brown) and an $R(9-12)$ of 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 sources having the same R_a can exhibit very different color-rendering performance (possibly having serious problems with saturated colors). This demonstrates that R_a is unreliable for judging the color rendering of three-chip white LEDs and possibly also for conventional light sources having only a few narrow peaks.

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 were shifted by amounts from −20 to +20 nm to examine the sensitivity of the results to small changes of the colors of the 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

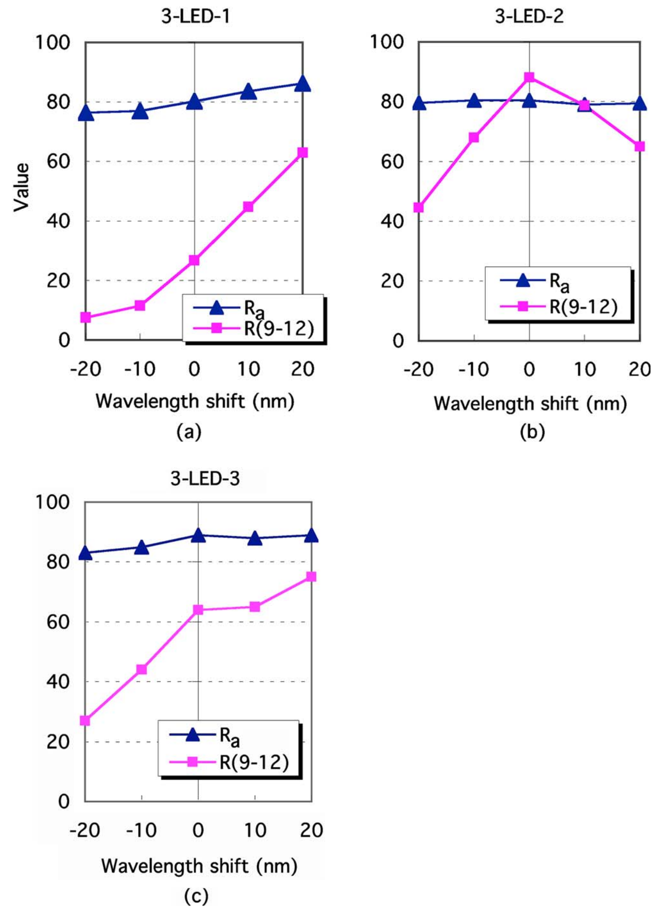

Fig. 6 The changes of R_a and $R(9-12)$ for three-chip white LED models when the wavelengths of the sample spectral reflectance data are shifted.

colors (orange, purple, etc.) may not be accurately rendered (the 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 aware 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.

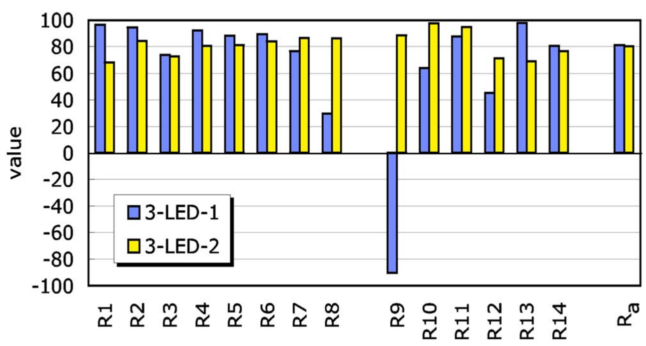

Fig. 5 Special CRI of the two three-chip white LED models shown in Fig. 4.

5.3 *Four-Chip White LEDs*

Figures 7 and 8 show the SPDs and the special CRI values, R_1 to R_{14}, of two four-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. The ΔE^*_{ab} of all the samples is less than 3.1 except for R_{12} (blue), which is 11.9. The model 4-LED-2 is optimized for the highest $R(9-12)$ (=99) at 3300 K, with R_a=91 and K=347 lm/W. The ΔE^*_{ab} of all the samples is 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 in the case of three-chip LED models (Fig. 6) and considered to be not significant.

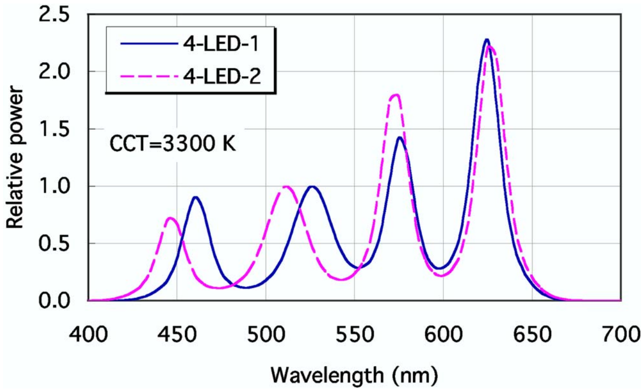

Fig. 7 The SPDs of the two four-chip white LED models 4-LED-1 and 4-LED-2.

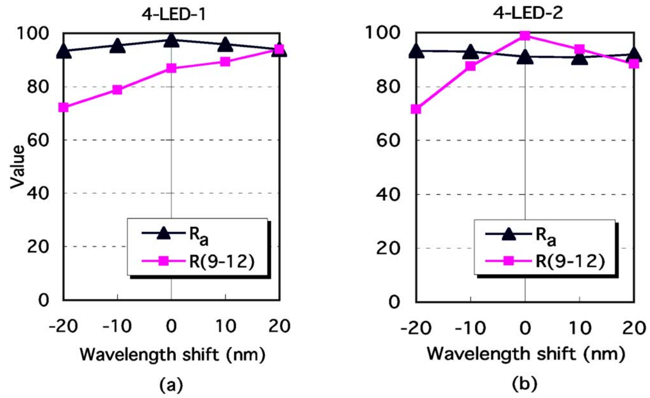

Fig. 9 The changes of R_a and $R(9-12)$ of the four-chip LED models when the wavelengths of the sample spectral reflectance data are shifted.

5.4 *Phosphor-Type White LEDs*

Figure 10(a) shows the SPD of one of the 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 smoothly at both ends of the spectrum, using a half of a Gaussian function. The temperature of the Planckian radiation, both cutoff wavelengths (the half point of the rise or drop), and the width of the half Gaussian function can be varied. Then, another Gaussian function of a given width and height is subtracted from the quasi-Planckian function to produce a valley in the curve. The center wavelength, depth, and width of the valley can be varied.

Figure 10(b) shows the result of simply trying to mimic Planckian radiation as closely as possible for good color rendering, in which case the cutoff wavelengths are set at 400 and 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 that of the good three-chip white LED (370 lm/W, 3-LED-3). If such white LEDs are used, a great amount of energy will be wasted. To improve this, one may think of cutting off both ends of the spectrum, which contribute very little to the luminous output. Figure 10(c) is such an example, where the cutoff wavelengths are set at 450 and 650 nm (PHOS-2 in Table 1). This spectrum produces $R_a=86$ and $K=370$ lm/W, which are comparable to those of the good three-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 acceptable for indoor lighting. To reduce the Duv value, the 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, while 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.

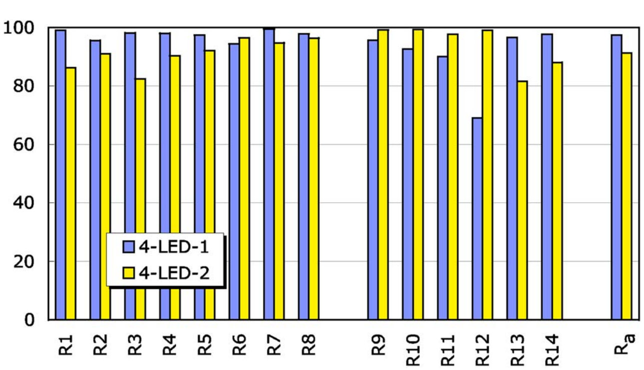

Fig. 8 Special CRI of the four-chip white LED models shown in Fig. 7.

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- to 700-nm region (D65-vis in Table 1) yields an LER of only 248 lm/W, much lower than those of the good three-chip and four-chip LED models (350 to 400 lm/W). There are proposals by a few 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- to 700-nm region. This is not recommended, because it would drive manufacturers to design white LEDs having low luminous efficacy. In addition, as already mentioned, four-chip LEDs, for example, can have as good color rendering as full-spectrum broadband light sources, and need to be studied further.

As indicated, the deviation of chromaticity coordinates of the source from the Planckian locus is not treated well by the CRI. For example, the RGB ratio of the three-chip LED model, 3-LED-2 (3300 K, $R_a=80$, Duv=0.000), is modified so that the chromaticity coordinate deviates in the yellow direction (Duv=+0.015), keeping the same CCT. This light would be very yellowish and will not be acceptable for indoor lighting. However, the R_a value increased to

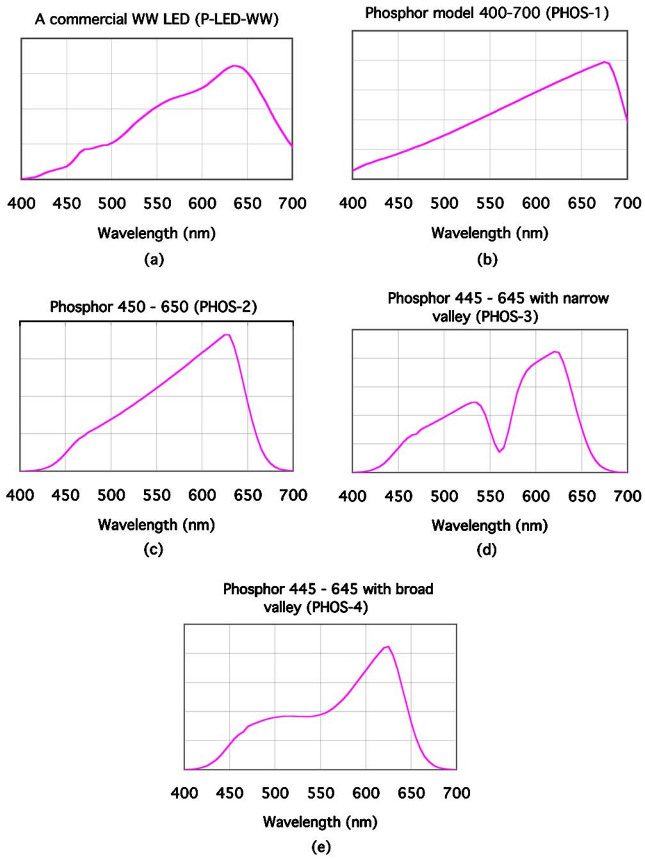

Fig. 10 SPDs of (a) commercially available warm white LED model and (b to e) phosphor-type LED models.

85 rather than decreased. This is a problem related to color constancy and how to handle chromatic adaptation.

6 CCT and Color Preference

Some manufacturers are considering a goal of realizing sunlight 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- to 700-nm region were 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 markets (different countries). For homes in the USA, warm white (2800 K to 3000 K) is dominant; 6500 K white light would not be accepted for homes in the USA. 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 USA. Therefore, "natural daylight" does not describe 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 have been 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 actually 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 by the lamp compared to the reference source. These deviations discount the values of CRI; however, the red-green contrast is enhanced and the color gamut area is increased. This provides more colorfulness to the illuminated scene. It is known 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

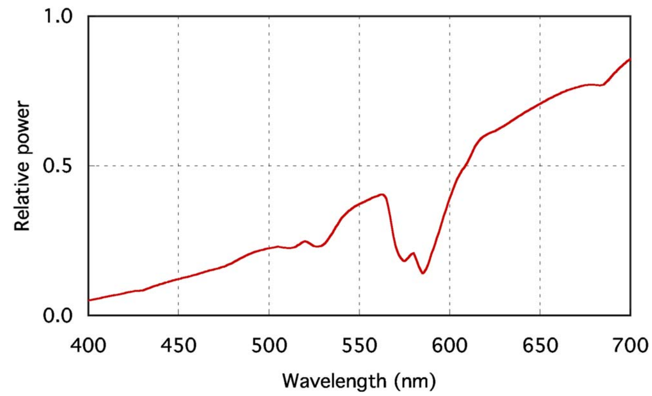

Fig. 11 The SPD of an incandescent lamp with neodymium glass.

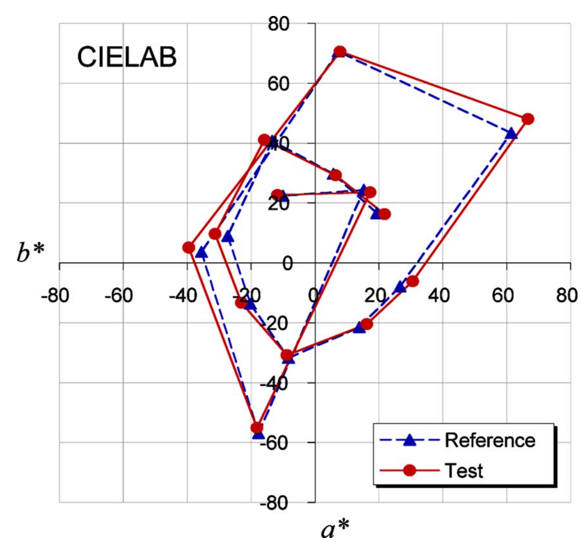

Fig. 12 Colors of the 14 samples in CIELAB space under illumination by the neodymium-glass lamp and the reference source (Planckian).

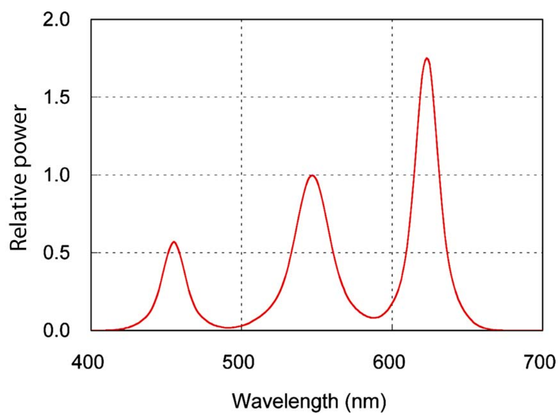

Fig. 13 The SPD of a three-chip white LED model with peak wavelengths 455, 547, and 623 nm.

source. Color shifts in all directions, whether decreasing or increasing chroma, are counted equally; therefore the results are only 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.

Such light source spectra that produce enhanced chroma can be realized by a three-chip white LED. An example is shown in Fig. 13. This is a 3-LED model with the peak wavelengths 455, 547, and 623 nm, and with spectral half-widths 20, 30, and 20 nm, for blue, green, and red, respectively, yielding 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 point of view.

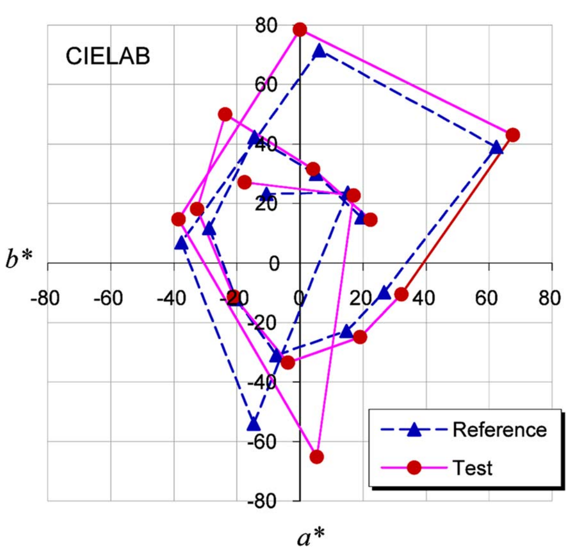

Fig. 14 Colors of the 14 samples in CIELAB space under illumination by the three-chip LED model shown in Fig. 13 and by the reference source (Planckian).

7 Discussion of CRI

In the analyses reported here, 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 shown, R_a alone is not a reliable 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 be considered somehow.
2. The results for three-chip LEDs tend to be sensitive to small variation of color samples, especially for saturated colors. Even though the values of R_9 to R_{12} are good for the given set of samples, rendering of other saturated colors can be poor.
3. The CRI does not take good account for the shift in chromaticity coordinates across the Planckian locus. The index R_a hardly changes with a change of light source chromaticity from Duv=0 to Duv=+0.015, for example. This is a problem related to handling chromatic adaptation and color constancy.
4. The CRI does not consider the direction of color shift. A decrease of chroma has negative effects, and an increase has rather positive effects (increased visual clarity). The directions of color shift should somehow be considered.
5. The plots of color differences in 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 spectrum 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 (the CCT of the reference source moves with that of the 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 of their color-rendering performance together with energy efficiency aspects. The results provided some guidance for design of multichip and phosphor-type white LEDs. It is shown that well-designed three-chip white LEDs may have acceptable color rendering (for indoor lighting) as well as good luminous efficacy, but further study is needed. Four-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 with the CRI have been identified or confirmed in this study. The index R_a is unreliable for the color-rendering performance of white LEDs (as well as for conventional sources). Some of the problems can be addressed by examining R_9 to R_{12} (especially R_9) additionally, but this will not solve the fundamental problems. Also, the need for describing color-rendering performance in one number for general users is strong. A new, improved metric for color rendering, solving these problems, is an urgent need.

References

1. Energy Policy Act of 1992, U.S. Public Law 486, 102nd Congress, 24 October 1992.
2. CIE 13.3:1995, "Method of measuring and specifying colour rendering properties of light sources" (1995).
3. CIE 135/2:1999, "Colour rendering," TC 1-33 closing remarks (1999).
4. J. Schanda and N. Sandor, "Colour rendering, past—present—future," in *Proc. Int. Lighting and Colour Conf.*, pp. 76–85, SANCI (2003).
5. N. Narendran and L. Deng, "Color rendering properties of LED light sources," *Proc. SPIE* **4776**, 61–67 (2002).
6. U.S. Department of Energy, "Illuminating the challenges—solid state lighting program planning workshop report," (2003).
7. CIE 17.4: 1989/ IEC 50(845), "International Lighting Vocabulary" (1989).
8. CIE 15:2004, "Colorimetry," 3rd ed. (2004).
9. CIE 122-1996, "The relationship between digital and colorimetric data for computer-controlled CRT displays" (1996).
10. J. Worthey, "Color rendering: asking the questions," *Color Res. Appl.* **28**(6), 403–412 (2003).
11. K. Hashimoto and Y. Nayatani, "Visual clarity and feeling of contrast," *Color Res. Appl.* **19**(3), 171–185 (1994).
12. D. B. Judd, "A flattery index for artificial illuminants," *Illum. Eng. (N.Y.)* **62**, 593–598 (1967).
13. W. A. Thornton, "A validation of the color-preference index," *J. Illum. Eng. Soc.* **4**, 48–52 (Oct. 1974).

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