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Color Issues of White LEDs

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Introduction

For white LEDs to be used for general lighting, they should have appropriate white color and good color rendering performance for illuminated objects. Color rendering, as well as energy efficiency (efficacy), have been the two most important criteria for traditional light sources for general lighting. U.S. Energy Policy Act (EPACT 1992)[1] specifies the minimum color rendering indices (explained later) as well as the minimum efficacy of common lamps. Color rendering is determined solely from the spectrum of the source. Thus, the spectra of white LEDs need to be designed to meet requirements in both aspects. Color rendering is best achieved by broadband spectra distributed throughout the visible region, while the efficacy is best achieved by a monochromatic radiation at 555 nm (green) where the human eye response reaches its maximum. Thus color rendering and efficacy are the two properties in trade-off. For example, a low pressure sodium lamp (having a light orange color, used in some highways and parking lots) has an efficacy of about 200 lm/W, the highest among available discharge lamps, but the colors of objects are not distinguishable. A red car (or any other colors) in a parking lot looks gray. On the other hand, a xenon arc lamp, having a very similar spectrum as day light with excellent color rendering, has an efficacy of only about 30 lm/W.

An advantage of LEDs is that they are available in almost any wavelength in the visible region, and the spectrum design of white LEDs may be more flexible than for traditional discharge lamps where the available spectra depends on available phosphors and emissions from gas. In the case of multiple-chip white LEDs, white light can be achieved by mixture of two or more LEDs of different peak wavelengths. When color rendering is calculated, however, we find that two-chip LEDs can never achieve acceptable color rendering properties. Three-chip (or more) white LEDs are expected to provide good color rendering that can be used for general lighting. Phosphor-type white LEDs can also have good color rendering since the phosphors generally produce broadband radiation. The drawback would be a limitation of available spectra, which would pose a difficulty to control the color and color rendering characteristics.

The evaluation method for color rendering of light sources is well-established by CIE (Commission Internationale de l clairage = International Commission on Illumination), and the color rendering index [2] is widely used in the lighting industry since 1965. Below, some fundamentals of the CIE colorimetry system [3] including the color rendering index are described, and the design of white LEDs using the colorimetry system is discussed. The definitions of the terms in photometry and colorimetry used in this section follow Ref. 4.

Chromaticity Coordinates and Color Temperature

White LEDs, or any other light sources for general lighting, should have a white color in order to show all the colors of illuminated objects appropriately. Color of light is expressed by the CIE colorimetry system [3]. The spectrum of a given light is weighted by the *XYZ color matching functions* [5] as shown in Figure 1. From the resultant three weighted integral values (called *tristimulus values X, Y, Z)*, the *chromaticity coordinate x, y* is calculated by $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$. Any color of light can be expressed by the chromaticity coordinate *x, y* on the *CIE 1931 (x, y) chromaticity diagram*, as shown in Figure 2. The boundaries of this horseshoe-shaped diagram are the plots of monochromatic light (called the *spectrum locus)*. Also plotted near the center of the diagram is the so-called *Planckian locus*, which is the trace of the chromaticity coordinate of a blackbody at its temperature from 1000 K to 20000 K. The colors on the Planckian locus can be specified by the blackbody temperature in kelvin and is called *color temperature*. The colors around the Planckian locus from about 2500 K to 20000 K can be regarded as *white*, 2500 K being

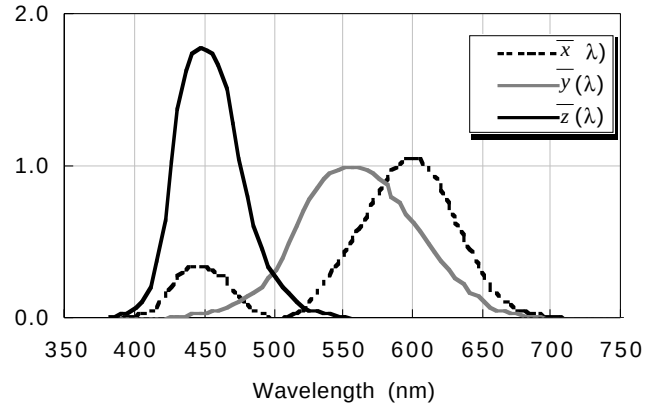


Figure 1 – CIE 1931 XYZ color matching functions.

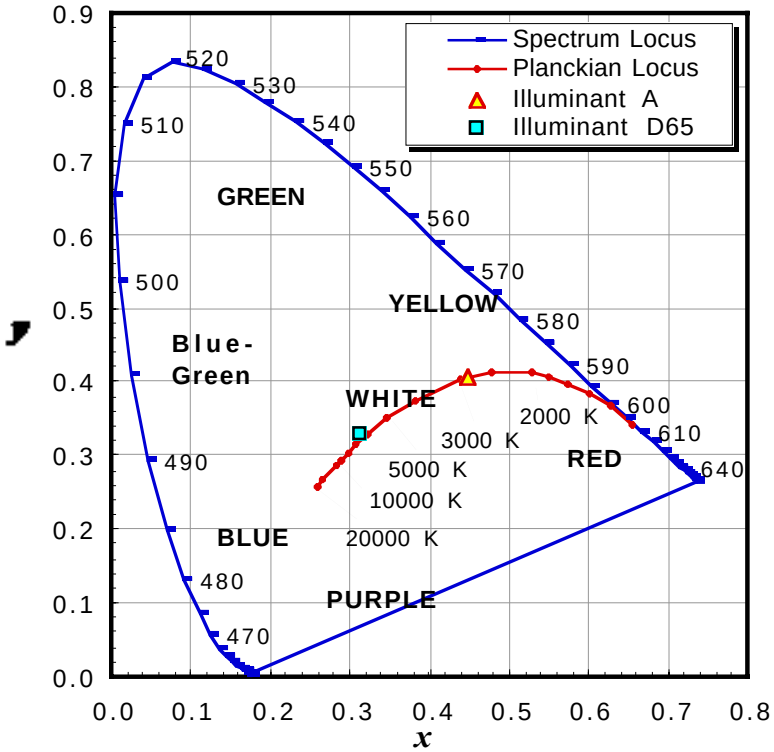


Figure 2. CIE 1931 (*x*,*y*) chromaticity diagram.

reddish white and 20000 K being bluish white. The point labeled "Illuminant A" is the typical color of an incandescent lamp, and "Illuminant D65" the typical color of day light, as standardized by the CIE [6]. The colors of most traditional lamps for general lighting fall in the region between these two points (2850 K - 6500 K). The color shift along the Planckian locus (warm to cool) is generously accepted or purposely varied for general lighting for desired mood, while color shift away from the Planckian locus (greenish or purplish) is hardly acceptable. Figure 3 shows the chromaticity coordinates of 23 common fluorescent lamps [7] as an example.
Strictly speaking, color temperature cannot be used for colors away from the Planckian locus, in which case what is called *correlated color temperature* (CCT) is used. CCT is the temperature of the blackbody whose perceived color most resembles that of the light source in question. Due to the nonuniformity of the *x,y* diagram, the iso-CCT lines are not perpendicular to the Planckian locus on the *x,y* diagram (see Figure 3). To calculate CCT, therefore, another improved chromaticity diagram (CIE 1960 (*u,v*) diagram - now superceded by 1976 (*u',v'*) diagram [3]) is used, where the iso-CCT lines are perpendicular to the Planckian locus by definition.

An important characteristic of the chromaticity diagram is that light stimuli on the diagram are additive. A mixture of two colors will produce a chromaticity coordinate falling on the line between the chromaticity coordinates of the two colors. Figure 4 shows an example of mixing two colors of LEDs, one at 485 nm (blue) and another at 583 nm (orange) with a half-bandwidth of 20 nm. The mixture of these two colors having

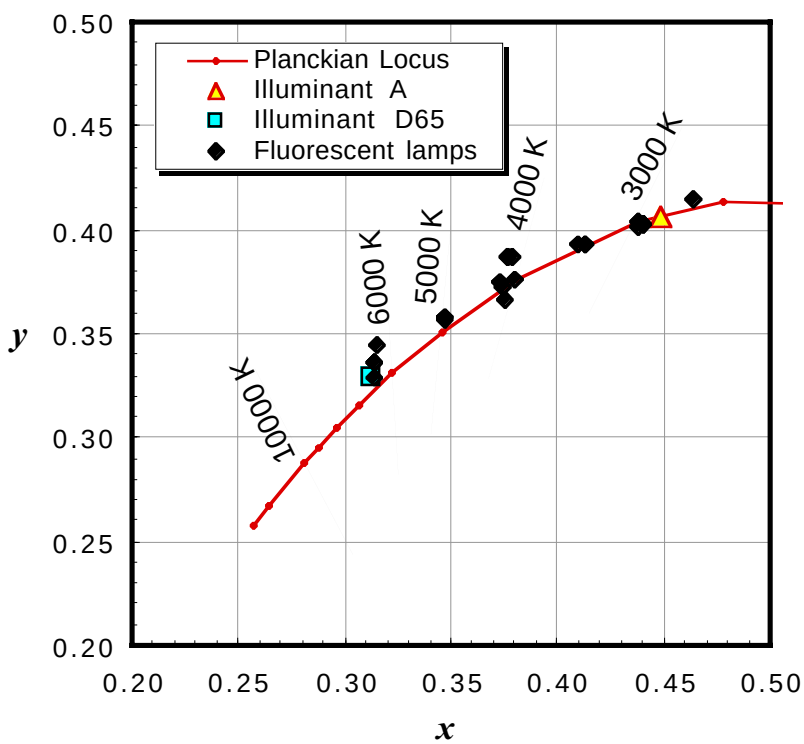


Figure 3. Chromaticity coordinates of 23 common fluorescent lamps.

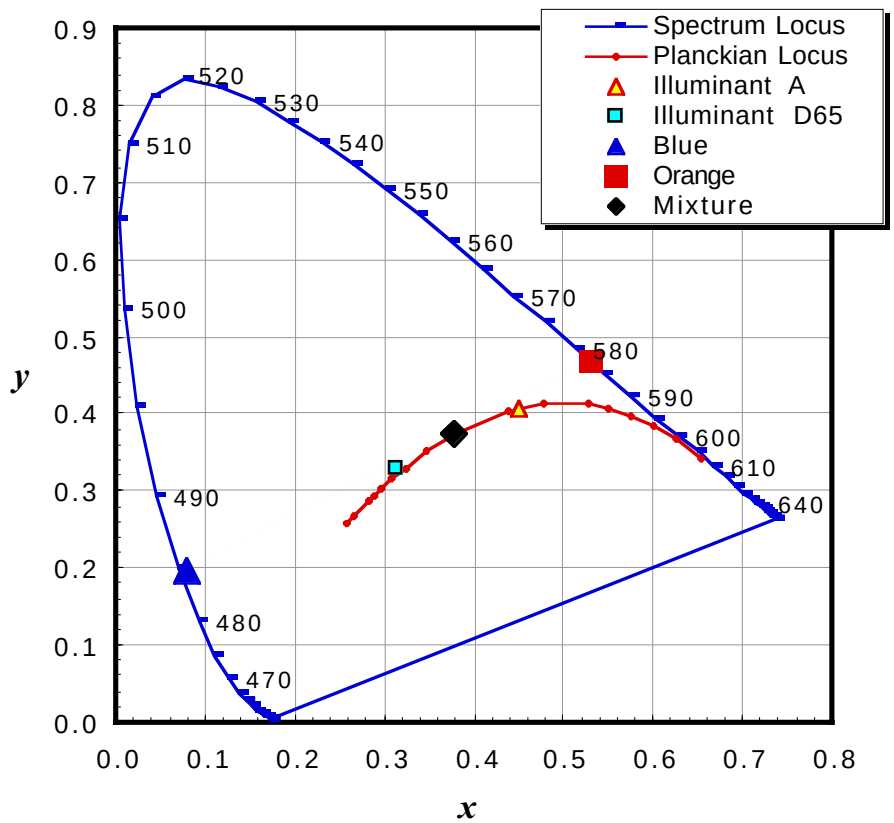


Figure 4. Mixture of two colors on the (*x*,*y*) chromaticity diagram.

the same optical power will produce white color at about 4000 K (shown as a diamond). But, note that, even though the color of this mixed light looks white on white paper, the color rendering is unacceptable (see next subsection) and is not usable as a light source for general lighting (green and purple would look gray).

Color Rendering Index

Color rendering of a light source is evaluated by comparing the appearance of various object colors under illumination by the given light source with that under reference illumination (day light for CCT>5000 K, Planckian radiation for CCT<5000 K). The smaller the color differences of the object colors are, the better the color rendering is. The standardized method, the *color rendering index* (CRI), is defined by the CIE [2] and has been in wide use in the lighting industry for many years. In this method, 14 Munsell samples of various different colors, including several very saturated colors, were carefully selected. The color differences, denoted as ΔE_i, of these color samples under the test illumination and under the reference illumination are calculated on the 1964 $W^*U^*V^*$ uniform color space [2]. The process incorporates corrections for chromatic adaptation. Then the *Special Color Rendering Index* R_i for each color sample is calculated by $R_I = 100 - 4.6\,\Delta E_i$. This value gives an indication of color rendering for each particular color. The *General Color Rendering Index*, R_a, is given as the average of R_i for the first

eight color samples that have medium color saturation. With the maximum value being 100, R_a gives a scale that matches well with the visual impression of color rendering of illuminated scenes. For example, lamps having R_a values greater than 80 may be considered high quality and suitable for interior lighting, and R_a greater than 95 may be suitable for visual inspection purposes. Thus, the spectral distribution of white LEDs should be designed to achieve the R_a value required for the aimed applications. For comparison with conventional light sources, the CRI (R_a values) of several common types of fluorescent lamps and HID (High Intensity Discharge) lamps are shown in Table 1 [7].

Table 1. General CRI of common lamps

	CCT	R_a
Daylight	6430	76
Cool white	4230	64
White	3450	57
Warm white	2940	51
Broad-band1	6500	90
Broad-band2	5000	95
Broad-band3	4150	90
3 narrow bands1	5000	81
3 narrow bands2	4000	83
3 narrow bands3	3000	83
Cool white deluxe	4080	89
Warm white deluxe	2940	73
Metal halide	4220	67
Metal halide, coated	3800	70
Mercury, clear	6410	18
Mercury, coated	3600	49
High pressure sodium	2100	24
Xenon	5920	94

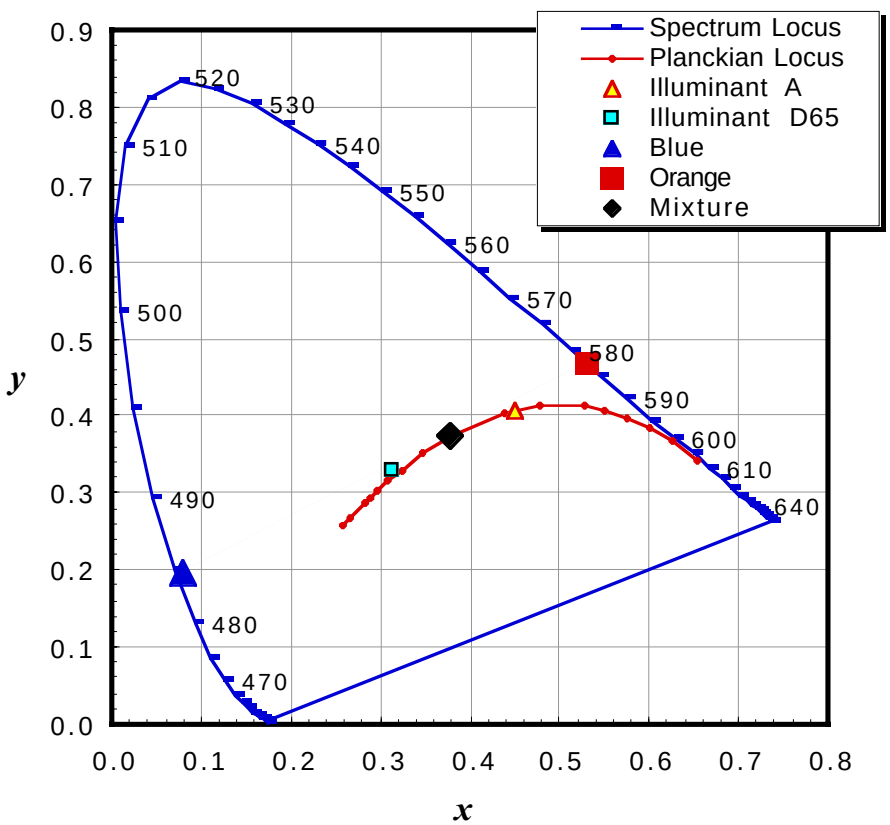


Figure 4. Mixture of two colors on the (*x*,*y*) chromaticity diagram.

Luminous Efficacy

Energy efficiency of light sources involves 1) efficiency of conversion from electrical power (W) to optical power (*radiant flux*) (W), and 2) conversion from radiant flux (W) to luminous flux (lumen = lm), which is a theoretical value determined by the spectral distribution of light, and is called *luminous efficacy of radiation, K,* (unit in lm/W). The luminous efficacy of monochromatic radiation $K(\lambda)$ at wavelength λ , is shown in Figure 5, and is given by

$$K(\lambda)=K_m \times V(\lambda) \text{ [lm/W]}, \text{ where } K_m=683 \text{ [lm/W]}.$$

where $V(\lambda)$ is the spectral luminous efficiency (of photopic vision) defined by CIE [8] and is the basis of photometric units. K_m is a constant given in the definition of the candela, and is called *maximum luminous efficacy of radiation*. As shown in Figure 5, $K(\lambda)$ peaks at 555 nm, and falls off at both ends of the visible region. The values of $K(\lambda)$ are the theoretical limits of light source efficacy at each wavelength. For example monochromatic light at 450 nm has luminous efficacy of only 26 lm/W (theoretical limit). For real light sources including LEDs, the luminous efficacy of radiation, K, is calculated from its spectral power distribution $S(\lambda)$ by

$$K \text{ [lm/W]} = \frac{K_m \int_0^\infty S(\lambda)\, V(\lambda)\, d\lambda}{\int_0^\infty S(\lambda)\, d\lambda}, \quad \text{where } K_m = 683 \text{ [lm/W]}$$

The spectral power distribution of white LEDs should be designed to have high luminous efficacy. For comparison, the total efficacy (lumens per electrical power including ballast losses) of traditional light sources is summarized in Figure 6 (taken from Ref. 9). Within a lamp type, the higher-wattage sources are generally more efficient than the lower-wattage sources. High-pressure sodium, metal halide, and fluorescent lamps are the most efficient white light sources.

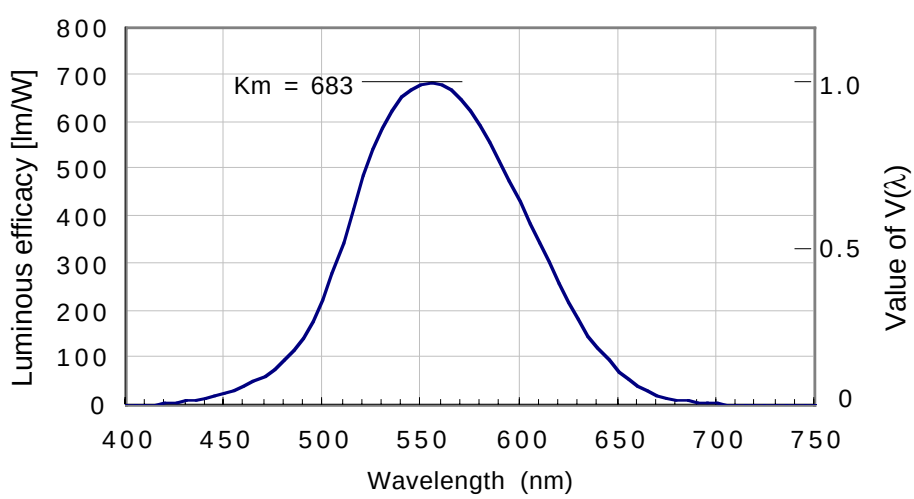


Figure 5. Luminous efficacy of monochromatic radiation, $K(\lambda)$.

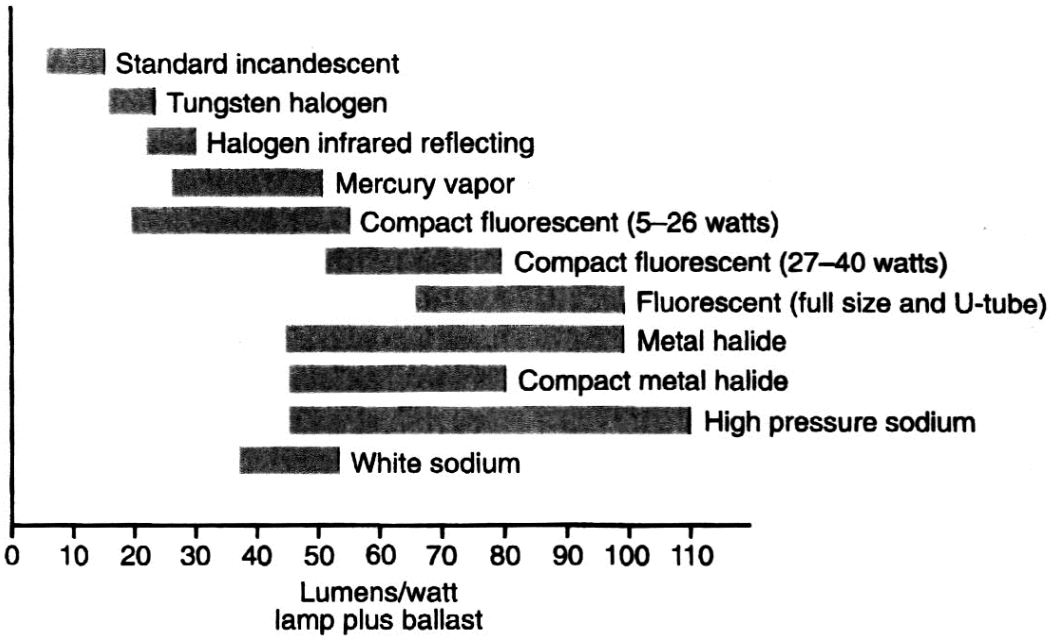
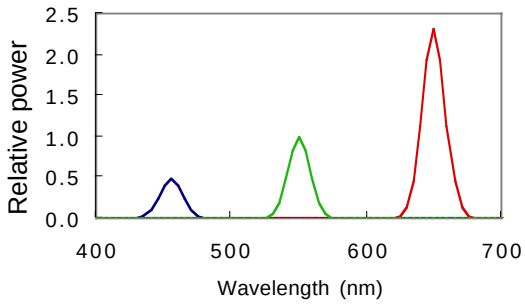


Figure 6. Efficacy of traditional light sources (from Ref. 7)

Application to White LED design

From the information given above, when the spectral power distribution of a light source is given, one can calculate chromaticity coordinate, CCT, CRI, and the luminous efficacy of radiation. The CRI (R_a) of the two-chip white LED shown in Figure 4 is calculated to be only about 4. Two-chip white LEDs in any wavelength combinations can never produce an R_a value acceptable for general lighting. Three-chip white LEDs can produce much better color rendering but the choice of the peak wavelengths is critical. Figure 7 shows the results of a simulation of three LEDs at peak wavelengths of 450 nm, 550 nm, and 650 nm, with their relative power adjusted to create white color of 4000 K. Each LED is a model using a Gaussian function [10], with half-bandwidth of 20 nm. In this case, CRI (R_a) is only 37 with luminous efficacy of 228 lm/W (theoretical maximum). R_a=37 would not be acceptable for use in general lighting, except for limited outdoor use.

Figure 8 shows the result of a simulation to produce the same white color from another combination of three LEDs, with peak wavelengths of 459.7 nm, 542.4 nm, and 607.3 nm. With this combination, R_a=80 with luminous efficacy of 400 lm/W (theoretical maximum) is achieved. If the efficiency of the LED chips is 20 %, the total efficacy would be 80 lm/W, which is comparable to typical fluorescent lamps. R_a=80 is acceptable for general lighting including indoor applications. This is only a demonstration, and is not necessarily the best result. There may be other combinations with even better results. As shown by this, the selection of wavelengths makes big differences in performance of white LEDs. In real cases, as the efficiency of LEDs differ at different wavelengths, selection of wavelengths is restricted. Using more sophisticated simulation analyses with restrictions applied, optimum designs of white LEDs using



x	0.3792
y	0.3736
CCT[K]	4011
Δuv	0.001
R_a	37
Efficacy [lm/W]	228

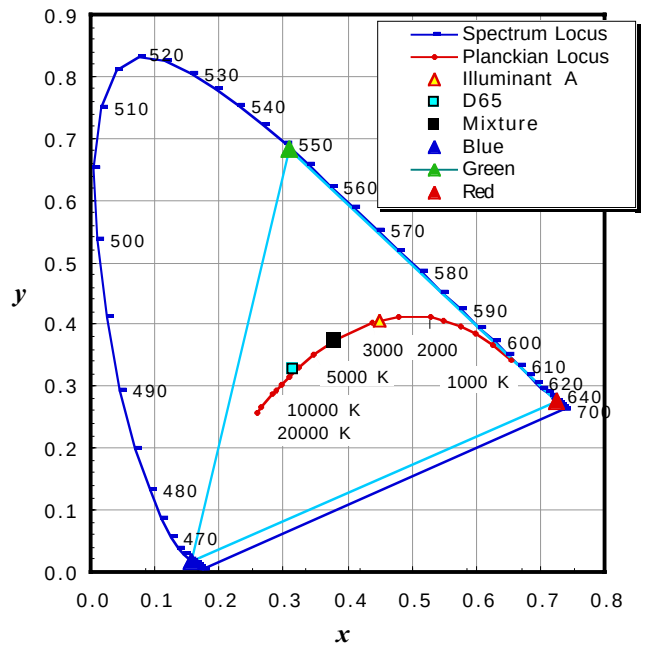
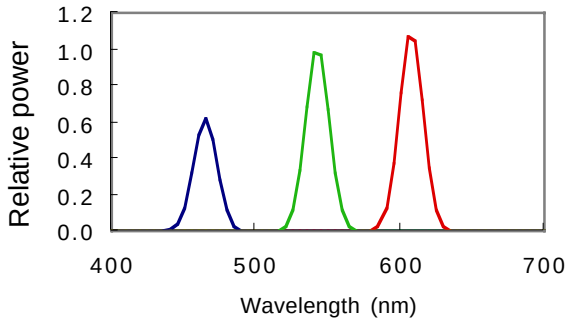


Figure 7. Simulation of a three-chip white LED – poor example



x	0.3812
y	0.3795
CCT[K]	4011
Δuv	0.001
R_a	80
Efficacy [lm/W]	399

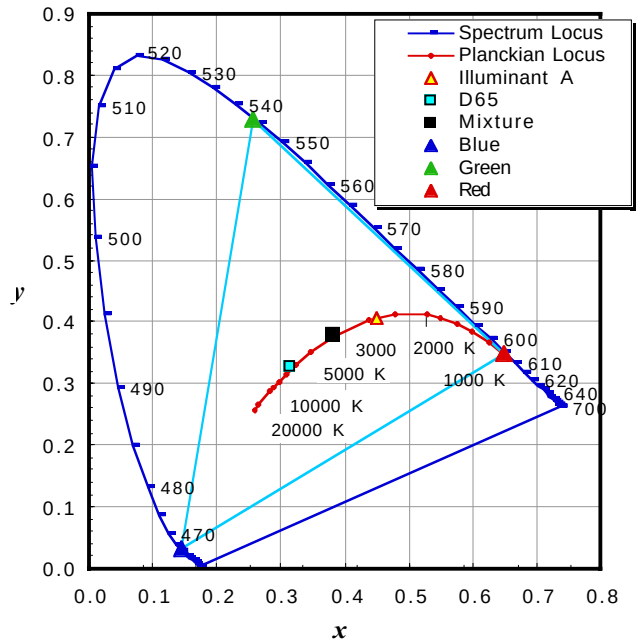


Figure 8. Simulation of a three-chip white LED – good example.

available color LEDs for any desired CCTs can be made. Using four chips should give even better color rendering than three chips. Phosphor type white LEDs will need different approaches for simulation but can be evaluated in the same manner.

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