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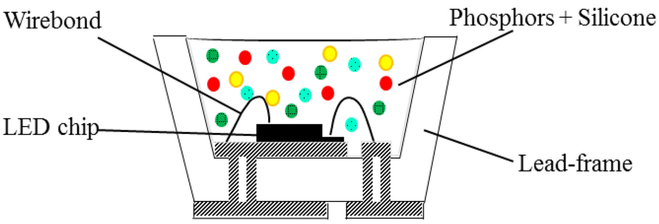

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Blue Light Hazard Optimization for High Quality White LEDs

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Abstract: With the advanced formulation of new phosphors and latest progress in packaging design, technologies to obtain the higher color quality and healthier white LEDs are investigated. The luminescent properties were characterized by the spectrum power distribution (SPD) and IES TM-30-15. By engineering the SPD of white LEDs using advanced phosphor formulation and package design, we developed light sources that present qualities closest to daylight with higher color rendering index, better spectral continuity, and more nature color comparing to typical Ra80 LED on the market. It offers benefits that are not available in normal LED light sources, including minimized the potential blue hazard, improved color perception without drastically scarifying lumen efficiency, and reliability. The specific mechanism and relevant parameters of achieving high-quality white LEDs are investigated and analyzed in this paper.

Index Terms: White LEDs, high CRI, IES TM-30-15, blue light hazard, circadian rhythm.

1. Introduction

White light-emitting diodes (LEDs) as a new generation of solid-state light devices show many advantages owing to the high luminous efficiency, low energy consumption, environmental friendliness, and high reliability. After the past decade of fast improvement in LEDs efficiency and cost, attention has shifted recently to the value of LED light to human and society [1]–[3]. Currently, two approaches are widely applied to create white light LEDs: (1) packaging multi-color LEDs such as the red, green, and blue LED chips together to produce devices known as RGB LEDs [4]; (2) using blue LEDs to excite multi-color phosphors such as yellow or green and red phosphors to produce devices known as phosphor-conversion LEDs [5]. Compared with RGB LEDs, phosphor-conversion LEDs are cost-effective and don’t require complex control circuits, leading to a large market share [6]. However, it also has several issues to address, notably visual experience and photobiological safety. These issues put forward with more challenges to phosphor materials and the LEDs packaging technology.

A LED light source for good visual experience is one that exhibits quality closest to daylight or incandescent light which is used as reference light source with high fidelity, wide color gamut and high saturated color. The colors and texture of objects can be viewed more accurately, as they would be seen under natural sunlight. The corresponding spectrum is smooth, proportional, and balanced, but is ideally attuned to human sensitivity. It contains only the wavelengths in the visible range and ideally without ultraviolet (UV) or infrared (IR) radiation. This makes it both vivid color and efficient, as energy is not wasted producing unnecessary heat (IR), UV radiation, or unbalanced amounts of light in different parts of the spectrum [7].

Regarding the photobiological safety, many studies have shown that LEDs do not exhibit greater risk for the blue-light hazard than traditional light sources (e.g., incandescent light, fluorescent light) in typical use cases because photophobic responses limit exposure to bright sources [8], [9], and the risk seems rather significant for specific population (as very young infants [10]) or particular occupational situations [11]. On the other hand, manufacturers have confirmed that some LEDs are capable of posing a Risk Group 2 (RG2) hazard for general population at domestic illuminance [12]. Blue light damage is caused by a breakdown in the photochemical synergy between the pigment epithelium and the rod and cone photoreceptors, when a photosensitizer absorbs photon energy of a specifc wavelength [8]. The pigment epithelium plays several essential functions for maintaining photon absorption and visual transduction [13]. The study demonstrates [14] that the photodamage to pigment epithelium cells in this test system was not only due simply to the high photon energy of short-wavelength blue-violet light, but that this apoptotic cell death represents blue-light phototoxicity specifcally mediated by the photosensitizer A2E. A2E (N-retinylidene-N-retinylethanolamine) is a key photosensitive fluorophore that mediates lipofuscin phototoxicity. It is excited by blue light with maximum absorption at around 440 nm. Study further proves that blue-light phototoxicity to pigment epithelium cells appears to be concentrated in a narrow band of wavelengths centered on 435 nm ± 20 nm [14]. However, the luminescence range of the blue light chip typically overlaps this wavelength range, so the amount of blue light irradiated by a white LED light source can raise some concern. Thus, a number of safety standard and reference documents are available to provide support in the understanding the technical definitions and test procedures. IEC/EN 62471:2006 [15], [16] is a method to make an evaluation of the photobiological safety of lamps and lamp systems. New standard EN 60598-1:2015 "Luminaires–Part 1: General requirements and tests" has extended the photobiological safety requirement [17]. In addition, according to standard IEC/TR 62778 [18] and EN 60598-1: 2015 standards, TÜV Rheinland has established a method to make an evaluation of the retinal blue light hazard ratio of LEDs: the ratio of light in the range from 415 nm–455 nm compared to 400 nm–500 nm shall be less than 50%.

However, in addition to high-energy blue light (415–455 nm) which is hazard to human eyes, there is a low energy blue-turquoise light (465–495 nm) which exhibits vastly different effects on the eyes. More recent research has also indicated that the blue-turquoise light plays an essential role in non-visual physiologic functions, which affect the regulation of human's circadian rhythm [19]–[22]. Maintaining appropriate blue-turquoise light in spectrum can promote natural energy, alertness, focus, and overall performance during day time; on the other hand, reducing blue-turquoise light which inhibits the production of melatonin can assist better sleep at night [23].

In this work, the white light LEDs concerning visual comfort, low blue hazard and circadian rhythm have been reported. Utilizing advanced formulation of new phosphors and latest progress in packaging design, we attempted to engineer the spectra power distribution of LEDs which exhibit qualities closest to daylight with high CRI, continuous and balanced spectrum in the visible emissions range. Furthermore, two methods have been utilized to minimize the ratio of high energy blue to total blue light. We established a method to quantify the continuity of spectrum and the blue light hazard ratio of a light source. The phosphorescence properties and the mechanism of achieving high quality white LEDs is also investigated and reported in this paper.

2. Experiment

2.1 Package Design

Two formulation and package design approaches are experimented, aiming to achieve higher color quality and reduced blue-hazard white LEDs, respectively. The first approach is to use dual blue chips of different wavelengths (450 and 470 nm) to excite phosphors (DBE LED). The other approach is to use a long wavelength (465 nm) blue LED to excite phosphors (LBE LED). Samples of both

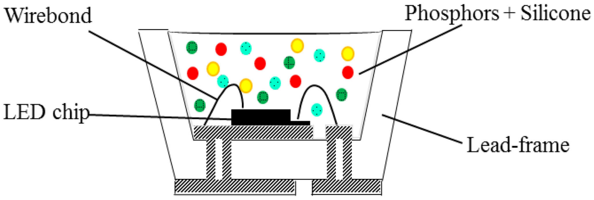


Fig. 1. The structure of a white phosphors-coated LED.

DBE and LBE were produced and compared at a fixed CCT of 5000K which located at the CIE chromaticity coordinates of (0.345, 0.356).

The white LEDs packaging processes were performed by the following steps. First, the LED chip or chips were die-attached onto the cavity of 2.8*3.5*0.7 mm SMD lead-frame with the thermally conductive adhesive. Then electrodes of LED chip were bonded onto the lead-frame with Au alloy wires for electrical interconnection. Stoichiometric amounts of the cyan ($BaSi_2N_2O_2:Eu^{2+}$), yellow-green ($Lu_3Al_5O_{12}:Ce^{3+}$), Red ($(Ca,Sr)SiAlN_3:Eu^{2+}$) phosphors and silicone were mixed together in a plastic cup. Phosphors to silicone ratio was 2:3 by wt. %. The coating amount of the phosphor gel is about 0.0021 g in a cavity of 2.8*3.5*0.7 mm SMD lead-frame. The mixture was injected into the cavity and dispensed on top of the LED chips for white light conversion, and was dried in an oven. Fig. 1 shows a cross-section of a white phosphor–coated LED structure. We conducted the design of experiment (DOE) by selecting suitable chip size and wavelength to match the phosphor formulation and mixing ratio to optimize the targeted performance and parameters.

2.2 Measurement

The photoluminescence measurements (PLE) were carried from the UV to VIS spectra region by EVERFINE LED300E and EVERFINE HAAS-2000. The packages are characterized under 0.5 W driving power at 25 °C case temperature. SPD, lumen output, CRI were measured, while color fidelity (R_f), color gamut (R_g), the spectral continuity (C_s), and the high-energy blue light ratio (B_r) were calculated. Finally, the data were analyzed against the design and the phosphor formulations were optimized for targeted lighting applications. Test data from both DBE and LBE LED approaches were obtained and compared.

3. Results and Discussion

3.1 Photoluminescence Properties and CRI

As shown in Fig. 2, the emission spectra of DBE and LBE LEDs are designed and measured to emulate the 5000K CCT mixed reference illuminant (a blend of CIE D Series and Planckian Radiation reference source) [24]. The DBE has little ups and downs in radiant energy while LBE has an obvious blue peak. But both follow the reference spectrum better than the standard Ra80 LED does, therefore they can present the actual color of the objects more closely to the reference source. In order to quantify the continuous spectrum characteristics, we introduce the concept of spectral continuity. In the visible light wavelengths in the range of 400–700 nm [8], the continuity of spectrum (C_s) is obtained by calculating the spectral power distribution weight ratio of the test source to the reference source.

$$C_s = 1 - \frac{\left|\sum_{\lambda=400}^{700} (Y_R(\lambda) - Y_T(\lambda)) * \Delta\lambda\right|}{\sum_{\lambda=400}^{700} Y_R(\lambda) * \Delta\lambda} \times 100\% \quad (1)$$

Where C_s is the spectral continuity, $Y_T(\lambda)$ and $Y_R(\lambda)$ are the spectral power distribution weighting functions of the test and reference sources, respectively. $\Delta\lambda$ is the bandwidth in nm. The greater the C_s value is, the better the continuity is. The reference illuminant's continuity is 100%. All spectral

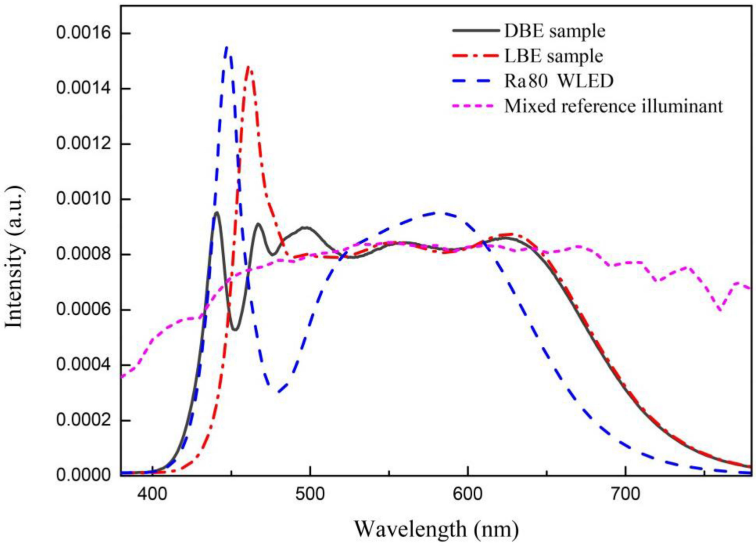


Fig. 2. Emission spectra of three light sources at 5000K CCT.

calculations are based on brightness normalization. Using the definition of Eq. (1), the sample's spectral continuity is calculated to be 84.0% for DBE, 78.4% for LBE and 64.2% for standard Ra80 LED, showing that the DBE and LBE LEDs have more continuous and smoother spectral. They can produce more abundant and broader range of colors than Ra80 LED. Meanwhile, the greater the spectral continuity of the test source, the better the performance of R_f and R_g. The difference of continuity results from the sophisticated phosphors recipe and the optimal match of LED power and wavelength to phosphors. Particularly, the cyan and deep red are typically missing on the Ra80 LEDs with typically using a yellow phosphor only. The mechanism of phosphor-converted white LED light is based on proportional mixing of the primary colors or multi-colors emissions. In a LED light source, a portion of light has been absorbed by the phosphors and the rest is passing through the phosphors. It can be seen from Fig. 3 that the light energies in the range of 400–470 nm absorbed by the phosphors is used to excite electrons to a higher energy level. Then these electrons at the excited state fall back to ground states to emit photons. The broadband emission spectra of DBE and LBE LEDs are composed of cyan ($BaSi_2N_2O_2:Eu^{2+}$), yellow-green ($Lu_3Al_5O_{12}:Ce^{3+}$), and Red ($(Ca,Sr)SiAlN_3:Eu^{2+}$) and blue (GaN LED) emissions. Among them, the cyan ($BaSi_2N_2O_2:Eu^{2+}$) [25] and red ($(Ca,Sr)SiAlN_3:Eu^{2+}$) [26] emission peaks are located at 496 and 635 nm, respectively, which is assigned to the allowed $4f^6 5d$ to $4f^7$ transition of Eu^{2+} ions; a broad yellow-green ($Lu_3Al_5O_{12}:Ce^{3+}$) emission peak is observed with the maximum at 545 nm, which ascribed to the electron transitions from the lowest crystal-splitting component of $5d^1$ level (2D) to the $4f^1$ ground state ($2F^{5/2}$ and $2F^{7/2}$) of Ce^{3+} ions [27], respectively. Thus the polychromatic light emitted by phosphors mixed with the transmitted blue light to create white light [28].

All color metrics of a light source can be calculated from its SPD. The Color Rendering Index (CRI) offers a quantitative measure of a light source's ability to reproduce a particular set of colors of objects accurately compared to an ideal or natural light source. The less these combined differences in color appearance, the higher the CRI. There are two types of CRI. One is general CRI which is named as Ra while the other is special CRI which is named as Ri. Two types of CRI can be obtained using equations given by International Commission on Illumination as follows [29]:

$$\mathrm{Ra} = \sum_{i=1}^{8} \mathrm{Ri} * 1/8 \tag{2}$$

$$\mathrm{Ri} = 100 - 4.6 * \Delta \mathrm{Ei} \ \ (\mathrm{i} = 1 \text{ to } 15) \tag{3}$$

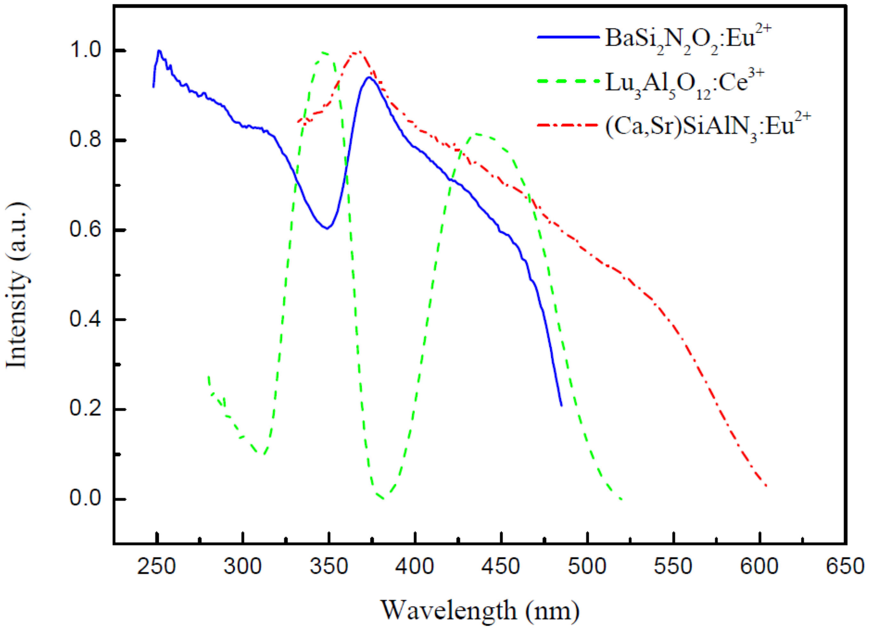


Fig. 3. Excitation spectra of three phosphors.

TABLE 1
The R1-R15 Particular Parameters of Three Light Sources

LED	Ra	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
DBE	96.7	99	97.8	95.5	96.5	98.6	96.2	95.3	94.7	91	94.2	97.5	94.8	99.2	97.5	97.7
LBE	93	96.7	94	92.1	87.7	93.4	92.6	87.5	89.7	96.6	87.7	92	75.3	95.8	95.9	93.5
Ra80	80	80.1	84.8	88.3	82.6	81.4	80	85.3	67.3	5.3	64.2	82.8	62.5	80.7	93.5	74.9

Ra and Ri refer to the average value of the R1 to R8 and the particular value of each 15 test color, respectively. ΔEi is the chromaticity coordinate value difference between standard light and reference light source on CIE 1964 $U^*V^*W^*$. All Ri ($i = 1$ to 15) parameters of three light sources are calculated using Eq. (2-3) and listed in Table 1. Meanwhile, the corresponding colors of R1 - R15 are shown in Fig. 4. The DBE sample has a Ra as high as 96.7 while the LBE has a Ra of 93. The Ri of DBE is consistently above 90 from R1 though R15. In comparison, the R12 (saturated blue) of LBE drops down to 75, while it's R4, R8, and R10 also are scored under 90. However, their color rendering abilities are far superior to standard Ra 80 LED (e.g., R9 as low as 5.3). High CRI LEDs can render the most authentic colors in the objects we see, and it is more suitable for lighting applications such as in schools, museums, hospitals and photography scenes.

3.2 IES TM-30-15 Analysis

CRI can provide significant information on color fidelity. However, one issue with CRI as a measurement is that it only defines a small set of colors. Averaged CRI doesn't convey information about specific colors. Furthermore, CRI can't fully meet user preference to the color. The Illumination Engineering Society has developed a scientifically objective measurement standard

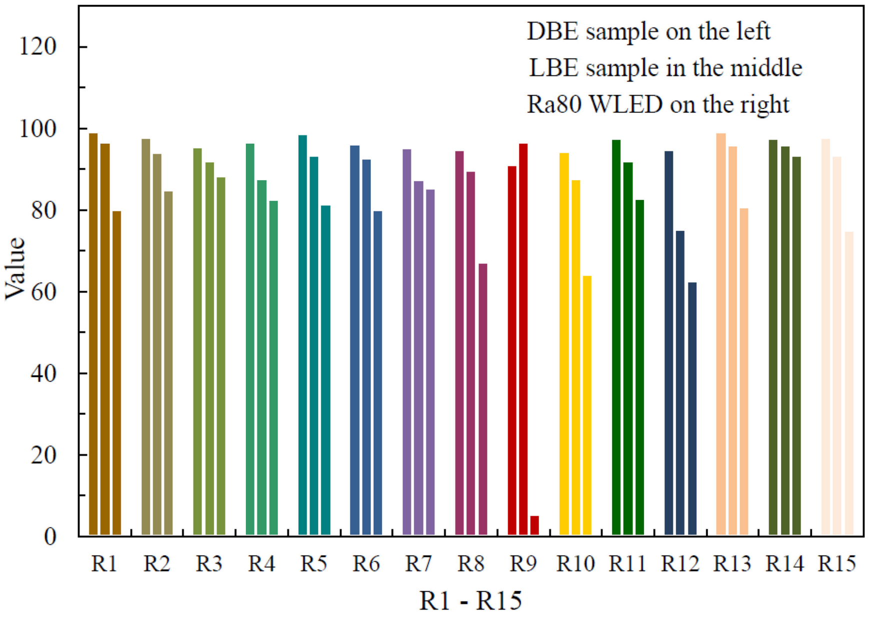


Fig. 4. Comparison of the R1-R15 values of three light sources.

(TM-30-15) to address these issues. In TM-30-15, two-metric concept are introduced: the color fidelity R_f which is similar to CRI but based on 99 color samples, and the color gamut R_g which attempts to measure color saturation. Furthermore, it has been shown in a National Institute of Standards of Technology study that color saturation of certain colors can be related to user preference [30], [31].

The color fidelity R_f and color gamut R_g values for three testing LED samples are calculated based on SPD data and compare with the population database. In Fig. 5, the grey dots represent the color rendition coordinates for some reference sources stored in a library database. The shaded areas approximating combinations that are not possible for sources on the blackbody locus (light gray) or not classified as white light (dark gray). DBE, LBE and Ra80 are shown as the red, yellow and blue dots, respectively. The DBE sample has excellent naturalness of appearance in the objects (R_f 93), and reveals the better color space uniformity and superior color attractiveness (R_g 98). By contrast, the LBE sample has a slightly lower R_f 83 and R_g 93 values, which are similar to the Ra80 LED, but their color distortion graphics are quite different. In Fig. 6, the color vector and color distortion graphics show shift information of hue and saturation between the test sources (red line) with the reference sources (black or white circle). The DBE sample under-saturates green and yellow slightly without hue shift. In the LBE sample, besides that the green push towards blue, it under-saturates yellow-green while oversaturates blue. In the Ra80 LED, cyan and magenta are shifted to blue and yellow, and it under-saturates red and cyan-green, while over-saturates yellow-green, violet and blue.

In an ideal world, lighting would be best to have R_f 100, and R_g 100, but, in reality, real light source is hard to achieve this target, It's up to users and designers to choose light sources that not only have acceptable color fidelity but also a reasonable gamut index. In the majority of general lighting applications, like hospitals or classrooms, require high color fidelity. Public may prefer them to be natural. However, the specific scenes, such as a theme park or merchandise retail, might be better served with a boost in saturation that makes the colors of the goods more vibrant and eye-catching.

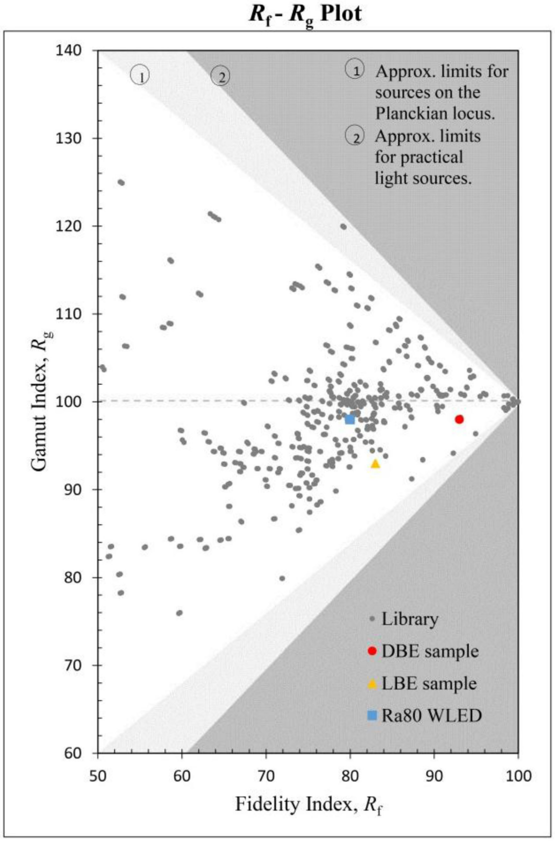
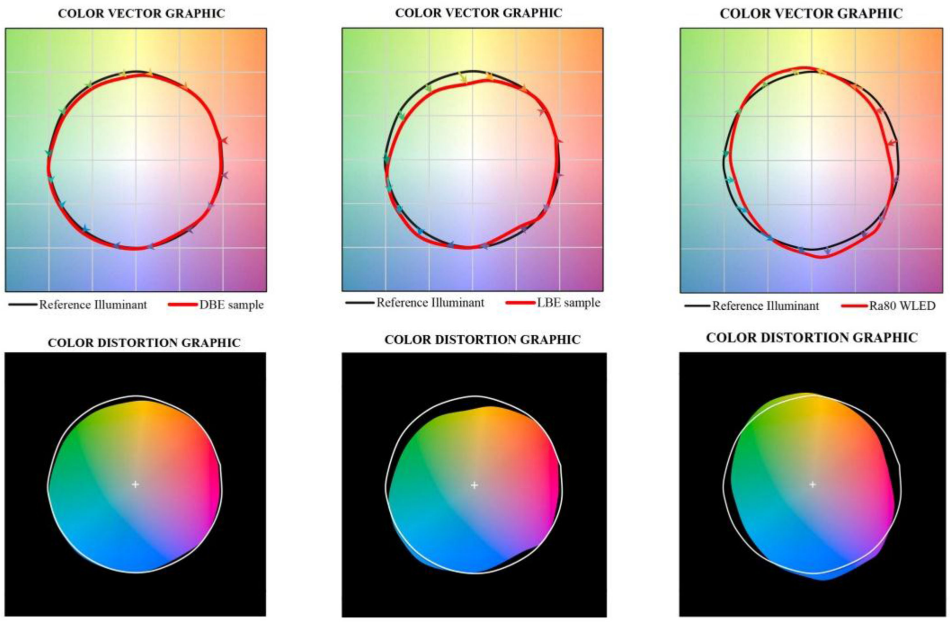


Fig. 5. Two dimensional color rendition plot of R_f versus R_g for three light sources.

3.3 Blue Light Hazard Ratio and Circadian Rhythm

Although light is essential to vision and color perception, light exposure can also cause retinal disorders such as age-related macular degeneration (AMD) through absorption of photon energy. Being in the most energetic portion of the visible spectrum, blue light has the greatest potential to induce the photochemical damage. The level of photochemical damage therefore has close relationship with blue content in SPD, the CCT, and luminance of light sources [32]. There is a strong linear correlation between retina damage potential and CCT, because of the increase in blue spectral energy as CCT increases. The blue hazard of a light source could be reduced by optimizing low-wavelength blue component of SPD at the same CCT and equal lumen output. Considering that blue light is still a necessity for color perception and circadian functions, properly balancing the band(s) of blue light is critical.

The two approaches discussed earlier have been designed to compare the blue light ratio in SPD. In the DBE sample, the high energy blue light (415–455 nm) ratio has been decreased by filling the missed spectral of the blue-turquoise light (465–495 nm) that stimulate ipRGC response. IpRGC responds to blue light and sends a melatonin suppression signal to the brain. In the LBE sample, we shifted the blue chip wavelength to the long blue light (465 $\pm$ 2 nm) which is away from the high energy blue light (435 $\pm$ 20 nm), although this approach sacrifices slightly the CRI quality when comparison to the DBE. In order to quantify the blue light hazard of LEDs, we defined the blue light hazard ratio of spectral power distribution by combining the methods used by IEC/EN 62471 and TÜV Rheinland. We limit the major damage in the 415–455 nm blue light range as TÜV Rheinland used and according to the research [14] by Kirk Smick *et al.,* but adopted the blue light hazard weighting function used by IEC/EN 62471 standard. The blue light hazard ratio of spectral



DBE LED LBE LED Ra80 LED

Fig. 6. Comparisons of the color vector and color distortion graphics of three light sources.

TABLE 2
Data of Testing Parameters of Three Light Sources

Symbol	CCT	Power	C_s	Ra	R_f	R_g	B_r	Efficacy
	K	W	%	--	--	--	%	lm/w
DBE LED	5000	0.5	84.0	97.1	93	98	34.5	119
LBE LED			78.4	92.1	83	93	19.1	110
Ra 80 LED			64.2	80	80	98	56.2	146
Reference (Mixed)			100	100	100	100	35.8	--

power distribution, B_r, is therefore defined as:

$$B_r = \frac{\sum_{\lambda=415}^{455} Y_T(\lambda) * B(\lambda) * \Delta\lambda}{\sum_{\lambda=400}^{500} Y_T(\lambda) * \Delta\lambda} * 100\% \tag{4}$$

Where $Y_T(\lambda)$ is the spectral power distribution weighting function of a test source, B(λ) is the blue light hazard weighting function, Δλ is the bandwidth in nm. It is suggested that the lower the B_r the safer to human eye. Used Eq. (4), the blue light hazard ratio (B_r) of the DBE LED is 34.5% while the LBE sample reaches 19.1%, which are superior to the reference source (35.8%). By contrast, the B_r of the normal Ra80 LED is 56.2%, which is much higher than reference source and test LEDs. The testing parameters of the three types of LEDs are tabulated and compared below in Table 2. DBE LED has a well-balanced performance with great color quality, high lumen efficiency, and good eye safety. It can be applied to all applications in the general lighting. The LBE LED has the lowest blue ratio B_r at the expense of color fidelity R_f and color gamut R_g. This light source can be used in applications where healthy lighting requirement are emphasized, such as eye-protection desk lamp, educational or school lighting. Moreover, it is also available for the applications of display and backlight.

4. Conclusion

This paper reports the progress of white LEDs development especially targeting to achieve the higher color quality and eye-safety white LEDs. Both dual blue chip (DBE) and single long wavelength blue chip (LBE) to excite multiple phosphor approaches were developed by considering the lighting characteristics of color rendition, photobiological safety and circadian rhythm. Five characteristics of CRI, color fidelity R_f, color fidelity R_g, continuity of spectrum C_s and blue light hazard ratio B_r are combined to better evaluate the high quality LEDs. The DBE LED exhibits qualities closet to daylight with continuous and balanced spectrum and thus better color fidelity and color gamut. In the meantime, they contain lower blue hazard ratio and thus safer to human eyes, when compared to the normal Ra80 LED; while the LBE LED shows the lowest blue hazard ratio and can be used in special eye safety concern environment.

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