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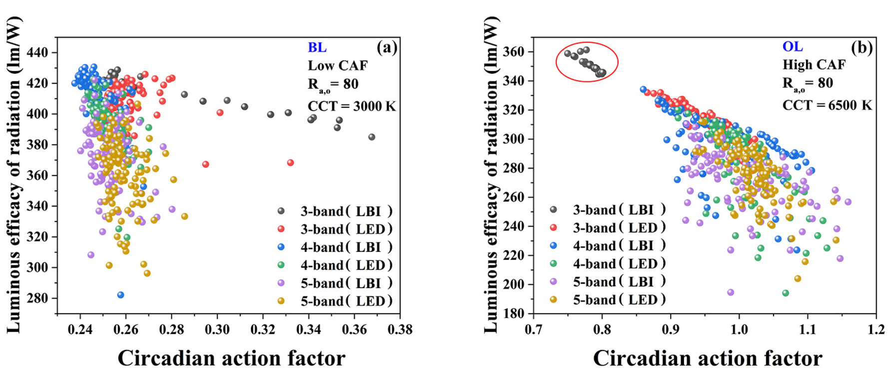
Shuo-Di Lei
Bi-Jing Liu
Yang Gao
Xiao-Ya Dong
Yu-Jia Gong
Jian Xu
Yun-Xin Xu
Dong Wang
Zi-Quan Guo, *Member, IEEE*
Ting-Zhu Wu
Chen-Liang Zhou
Zong-Jian Cai
Yi-Jun Lu
Zhong Chen



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Investigation on Circadian Action and Color Quality in Laser-Based Illuminant for General Lighting and Display

Shuo-Di Lei,[1] Bi-Jing Liu,[1] Yang Gao,[1] Xiao-Ya Dong,[1] Yu-Jia Gong,[1] Jian Xu,[2] Yun-Xin Xu,[3] Dong Wang,[1] Zi-Quan Guo,[1] *Member, IEEE*, Ting-Zhu Wu,[1] Chen-Liang Zhou,[4] Zong-Jian Cai,[5] Yi-Jun Lu,[1] and Zhong Chen[1]

[1]Fujian Engineering Research Center for Solid-State Lighting, Department of Electronic Science, Xiamen University, Xiamen 361005, China
[2]Lab of New Energy Materials and Devices, School of Physics and Electronic Information, Henan Polytechnic University, Jiaozuo 454000, China
[3]Xiamen Leedarson Lighting Group Corporation Ltd., Xiamen 361006, China
[4]Department of Computer Science, University of British Columbia, British Columbia V6T 1Z4, Canada
[5]Fuzhou SkyUnion Digital Corporation Ltd., Fuzhou 350000, China

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Abstract: In this work, the genetic algorithm is employed to optimize both circadian action factor (CAF) and color quality of laser-based illuminants (LBIs) with three, four, and five spectral bands to disclose its possible use in two common white lighting applications, i.e. bedroom lighting and office lighting. Comparing all LBIs at a correlated color temperature (CCT) of 3000 K and a color rendering index of 80, the CAF of four-band LBIs reaches a minimum of 0.238 and maintains at a possibly highest luminous efficacy of radiation (LER) of 422 lm/W among all cases. The performances of white LBIs are also compared with those of white light-emitting diodes (LEDs). The results demonstrate that, under the same conditions of color rendering and color temperature, both four-band LBIs and four-band LEDs exhibit the largest circadian tunability of about 4.7, while four-band LBIs possess much higher LER at the same time compared with four-band LEDs. In addition, for the display application, the investigation on the optimal circadian tunability as a function of color gamut at two CCTs (3000 K and 6500 K) is also performed. We believe that this study can serve as a useful guidance for the application of LBIs in both the healthy general lighting and display.

Index Terms: Laser-based illuminant, circadian action, color quality.

1. Introduction

Solid-State lighting is one of the most promising lighting technologies in the 21st century, and has become the dominant technology for the general lighting [1]. The solid-state lighting technology based on light-emitting diodes (LEDs) and laser diodes (LDs) has gained widespread attention [2],

[3]. In recent years, LEDs are replacing conventional incandescent lamps due to several well-known advantages, such as color-tunable property, long lifespan, compact size, and high luminous efficacy among others [4], [5]. However, there still exist many serious problems in LEDs which can not be completely addressed [6], [7]. For example, LEDs generally exhibit a decrease in the power efficiency at high current densities, so-called as the efficiency droop [8], which hinders the rapid development and application of solid-state lighting. Therefore, many researchers have turned to study the potential use of LDs for their applications in general lighting and display fields. Previous studies have shown that various coloured LD combinations, denoted as laser-based illuminants (LBIs) here, can generate the pure white light as well as LED-phosphor combinations [9], and the color rendering of LBIs can also reach a level of LEDs [10].

With increasing living standards, people are not satisfied with only high luminous efficacy and good color quality of the artificial light, they are getting more and more concerned about whether the artificial light applied in general lighting or display is healthy or not to human body due to its long use in the daily life of people. Previously, the traditional general lighting or display mainly focuses on its photometric and colorimetric properties [11], [12], such as luminous efficacy of radiation (LER), correlated color temperature (CCT, T_c), color coordinates, Commission Internationale de L'Eclairage (CIE) color rendering index (CRI, R_a), and color gamut among others. The CRI is the current standardized parameter for describing the color rendering properties of light source although existing some deficiency for LEDs and LBIs with narrow bandwidths. The CCT is a scale to measure the color temperature of a light source. Besides, the healthy lighting or display also considers the influence of the artificial light on the human body, denoted as the circadian effects [13], [14]. The behavior of all living beings generally follows a regular change in a cycle of 24 hours, denoted as the circadian rhythm attributed to a third type of photoreceptor called as intrinsic photosensitive retinal ganglion cells [15]. These cells play a key role in the formation and release of melatonin, cortisol and other hormones. The melatonin secretion is suppressed during the daytime but becomes active at night [16]. Several parameters are proposed to quantitatively evaluate this circadian action, one of which is called as circadian action factor (CAF). Under the same luminance level (because the luminance will also affect the melatonin secretion too), the white light with low CAF means reducing melatonin suppression and promoting sleep in the bedroom at night. Instead, the white light with high CAF means making people more exciting and improving working efficiency in the office during the daytime [16]. T. Wu *et al.* have studied the improvement on the circadian performance of virtual reality headsets [17]. Q. Dai *et al.* have carried out the optimization of solid-state lighting spectra to achieve beneficial and tunable circadian effects [18]. In their studies, they have proposed a parameter called as the CAF tunability, to describe the tunability from the lowest CAF to the highest CAF for the white light sources, especially the white LEDs and LBIs.

Till now, there are quite a lot of research studies on the improvement of color rendering and LER for LBIs [10], [19], but those referring to circadian effects are rarely reported. The difference in performances on circadian effects between LBIs and LEDs still remains unknown. Therefore, in this study and for the general lighting application, we theoretically and comprehensively investigate the spectral optimization on CAF and LER, both of which are only determined by the spectral power distribution of LBIs and LEDs, at a fixed CRI of 80 (acceptable color rendering) or 90 (excellent color rendering) and under two CCTs (3000 K and 6500 K, related to two common lighting scenarios) for LBIs and LEDs by using the general genetic algorithm (GA). We calculate and compare the maximum CAF tunability (defined by the ratio of highest CAF at 6500 K to lowest CAF at 3000 K) of different types of LBIs and LEDs after the optimization. For the display application, we also investigate their optimal CAF tunabilities as a function of color gamut, described by the ITU-R Recommendation BT. 2020 (Rec. 2020) [20].

2. Experimental Details

In this study, non-visual and visual parameters mainly include CAF, LER, CCT, CRI, color distance (D_{uv}, in the CIE 1960 UCS color system), and color gamut defined by Rec. 2020.

For the general lighting, as well known, the standardized CRI is inadequate to evaluate the color rendering property of spiky and discrete white LBI spectrum [21], so we also consider some other color rendering indices for the supplement [16], such as the special CRI of strong red (R_9), Illumination Engineering Society of North America (IES) TM-30 color fidelity index (R_f) [22], IES TM-30 color gamut index (R_g) [22], and CIE 224:2017 color fidelity index ($R_f^{'}$, different from TM-30 R_f) [23].

The spectral optimizations are carried out in consideration of two common lighting scenarios, i.e. bedroom lighting (3000 K CCT, close to standard A light source) and office lighting (6500 K CCT, close to standard D65 light source). For the display application, we also take these two CCTs into account. Ignoring the influence of luminance level which is also related to melatonin secretion, for bedroom lighting, the CAF is required to be as low as possible to promote melatonin secretion, while for office lighting, it is desirable to make CAF as high as possible to suppress this secretion.

Prior to optimization, a model for describing the LBI spectrum is urgently needed. Considering that the LD spectrum is extremely narrow (its full-width at half-maximum, FWHM, is generally $\leq$ 2 nm) and nearly symmetric, the simple Gaussian function is employed and written as

$$P(\lambda, \lambda_n, w_n) = e^{-k(\frac{\lambda-\lambda_n}{w_n})^2} \tag{1}$$

where λ is the wavelength, λ_n the peak wavelength, w_n the FWHM, and k the constant. This model is also applicable for LED chip or quantum dots, although their spectra are a little bit asymmetric [21]. Thus, the spectrum of white LBIs and LEDs with N bands, $S(\lambda)$, is written as

$$S(\lambda) = \sum_{n=1}^{N} H_n P(\lambda, \lambda_n, w_n) \tag{2}$$

where H_n is the relative peak height. The band number in LBIs is selected from 3 to 5 in this current work. While the band number is larger than five, it is beneficial for increasing the color rendering property, but is adverse to both luminous efficacy and cost as well as increasing the device complexity.

For the general lighting application, a nonlinear program based on genetic algorithm (GA) is designed through MATLAB software to achieve the minimum (Min.) or maximum (Max.) CAF with an acceptable CRI scored at 80 and 90, and possibly highest LER. The GA is based on the biological evolution process, and is capable of solving this current optimization problem. However, the GA is easy to fall into local optimum during the solving process because it will converge prematurely. Of course, we are desired to obtain the global optimal solution instead of local optimal solution to the best of our abilities, so we solve this problem by setting random initial values and letting the program run multiple times, and seek out the optimal one from a great amount of sub-optimal results. The objective function in the GA program (seen in Fig. 1) is formulated as,

$$F(\lambda_1, \ldots, \lambda_n; w_1, \ldots, w_n; H_1, \ldots, H_n) = \text{Min. or Max. CAF} \tag{3}$$

The FWHM of single LD is smaller than 2 nm, while that of single LED is several tens of nanometers. Therefore, for comparing with LEDs, we set up two FWHMs for each band in the GA program, as 0.1–2 nm for LBIs and 10–40 nm for LEDs, respectively. The λ_n is ranging from 430 nm to 670 nm in the visible light and the H_n is varying from 0 to 100%. The CCT tolerance (ΔT) is regarded as 10 K, and the color distance in the CIE 1960 UCS color system between the artificial light and the standard one is kept within 0.01, i.e. $D_{uv} \leq 0.01$, to make sure that the artificial light is close enough to the standard one in the white color.

For the display application, similarly, we aim at searching for the Min. or Max. CAF by the GA program after meeting certain conditions, including the fixed color gamut defined by Rec. 2020. Above two CCTs (3000 K and 6500 K), the same CCT tolerance (10 K), $D_{uv} \leq 0.01$, and LER $\geq$ 300 lm/W are regarded as limited conditions, too. For the general lighting application, we do not limit the condition of LER $\geq$ 300 lm/W because we want to study the relationship of LER vs. CAF.

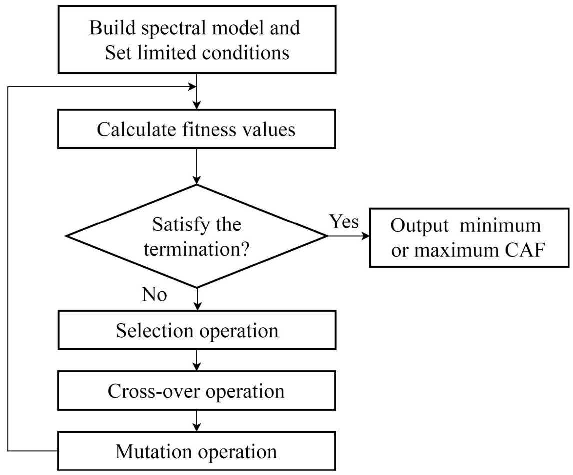

Fig. 1. The flow chart of GA program in this present work.

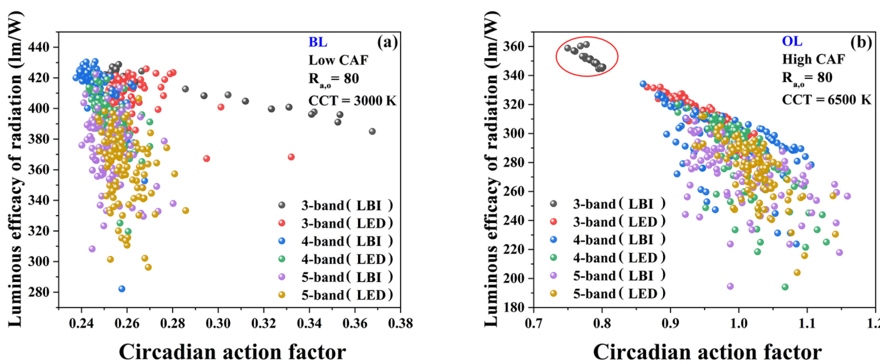

Fig. 2. A number of scatters corresponding to parts of sub-optimal solutions of LER and CAF at (a) 3000 K for bedroom lighting and (b) 6500 K for office lighting.

3. Results and Discussions

3.1 Optimization for the General Lighting

Figs. 2(a) and 2(b) plot a number of scatters corresponding to a few parts of sub-optimal solutions of LER and CAF while the GA program runs multiple times. As can be observed, at a lower CCT, it is easier to achieve a much higher LER value, and as the color temperature increases, LER values corresponding to the 3-band, 4-band, and 5-band models all descend, indicating a trade-off relationship between CAF and LER under the same conditions of CRI and CCT. In comparison of LBIs and LEDs in the 4-band and 5-band models, overall, LBIs are much easier to achieve a lower CAF at 3000 K and a higher CAF at 6500 K than LEDs, and maintain at a higher LER at the same time. In the 3-band model, due to extremely narrow FWHM of each spectral band in LBIs and fewer spectral bands, under all constraints of R_a, D_{uv}, and ΔT, it is hard to optimize CAF while ensuring satisfied color quality in the white light simultaneously, which becomes very obviously at 6500 K CCT, as shown in Fig. 2(b), and it looks vary strange compared to other two models. For 5-band model in LBIs, it can achieve relatively lower or higher value of CAF compared to others, but it does not perform well on LER. The 4-band model in LBIs provide the best performances in achieving both the lowest and highest CAF as well as highest possible LER. Considering both the

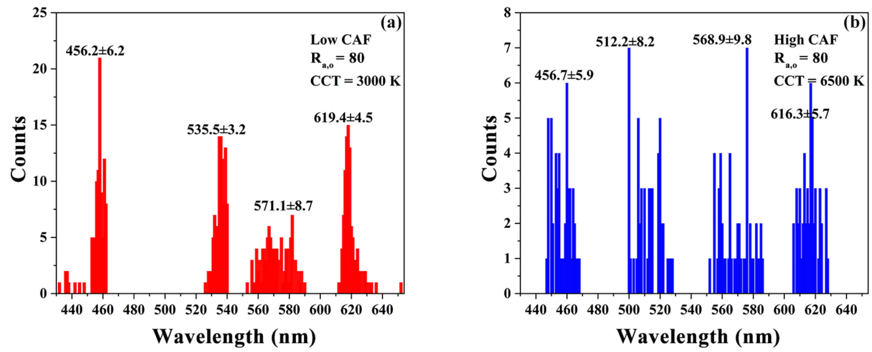

Fig. 3. The peak wavelength distribution with LER $\geq$ 300 lm/W when optimizing CAF and LER in the 4-band LBIs at (a) 3000 K and (b) 6500 K CCT.

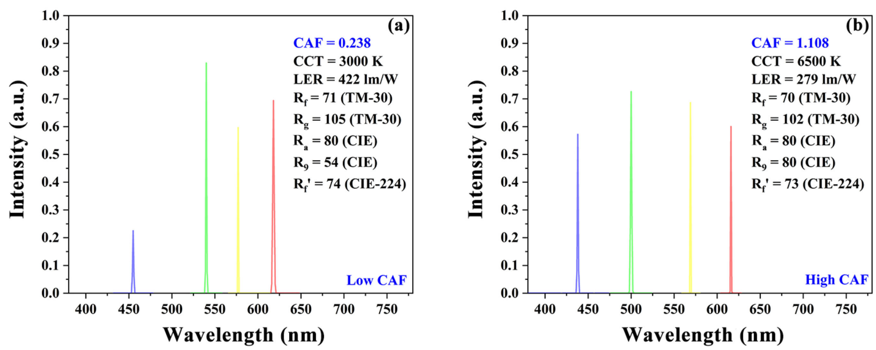

Fig. 4. Two representative optimal spectra corresponding to the (a) lowest and (b) highest CAF.

LER and CAF, we finally conclude that the 4-band LBIs exhibit the best performances among all the analyzed cases.

Then, in the following parts, we will mainly analyze the 4-band model in LBIs. Shown in Figs. 3(a) and 3(b) the peak wavelength distribution with LER $\geq$ 300 lm/W when optimizing CAF and LER in the 4-band LBIs. As can be seen, the peak wavelength distribution is regular when optimizing and obtaining the lowest or highest CAF. Comparing Figs. 3(a) and 3(b), it is clearly noticed that the averaged peak wavelength behaves differently in the cyan-green region (500–540 nm), but it is roughly the same in the blue, yellow-orange, and red regions. We have presented these wavelength values (the average value and the standard deviation) for each spectral band in Figs. 3(a) and 3(b), and can be used as a reference for selecting LDs in the future experiments for the achievement of the lowest or highest CAF and the highest possible LER at $R_a = 80$.

We have presented two representative optimal spectra in Fig. 4 corresponding to the (a) lowest and (b) highest CAF, while considering CIE R_a as the primary parameter for illustrating the color rendering, with other parameters such as IES R_f, IES R_g, CIE $R_f^{'}$, and CIE R_9 as the supplement. As can be clearly observed, at a CCT of 3000 K, the CAF of 0.238 turns out to be the lowest with a high LER of 422 lm/W, with the corresponding peak wavelength combination of 455 nm (blue), 540 nm (green), 577 nm (orange), and 618 nm (red) for each band. Likewise, we obtain the highest CAF of 1.108 at the CCT of 6500 K with a LER of 279 lm/W, and the corresponding peak wavelength combination has become 438 nm (blue), 500 nm (green), 569 nm (yellow), and 616 nm (red), respectively. Other color rendering indices, including IES R_f, IES R_g, CIE $R_f^{'}$, and CIE R_9 in Figs. 4(a) and 4(b) also indicate that studied LBIs would properly render the colors of objects.

TABLE 1
A Comparison of CAF and LER Between the LBIs and LEDs With Different Types at $R_a = 80$. Some Data are Collected From Our Previously Published Works [16], Where p Denotes the Phosphor

Type	CAF_t	CAF_{bl}	LER_{bl} (lm/W)	CAF_{ol}	LER_{ol} (lm/W)
LBI (RYGB)	4.66	0.238	422	1.108	279
LED (RYGB)	4.68	0.242	413	1.128	206
LED (RGB)[8]	4.16	0.247	408	1.028	294
LED (RG_pB)[8]	3.83	0.270	371	1.033	245
LED (R_pG_pB)[8]	3.82	0.272	367	1.038	236
LED ($R_pG_pB_p$)[8]	3.63	0.291	311	1.056	236

TABLE 2
A Comparison of CAF and LER Between the LBIs and LEDs With Different Types at $R_a = 90$

Type	CAF_t	CAF_{bl}	LER_{bl} (lm/W)	CAF_{ol}	LER_{ol} (lm/W)
LBI (RYGB)	3.60	0.280	407	1.007	297
LED (RYGB)	3.33	0.294	384	0.981	290
LED (RGB)	2.79	0.320	385	0.892	321
LED (RG_pB)	3.01	0.320	340	0.965	290
LED (R_pG_pB)	2.96	0.337	344	0.997	269
LED ($R_pG_pB_p$)	2.96	0.340	273	1.007	237

Between LBIs and LEDs, we compare their lowest CAF at 3000 K for the bedroom lighting (CAF_{bl}) and the highest one at 6500 K for the office lighting (CAF_{ol}) at a CRI of 80, as detailedly listed in Table 1. The LBIs and LEDs with four discrete spectral bands are denoted as RYGB, corresponding to red (R), yellow (Y), green (G), and blue (B) color, respectively. We introduce a parameter, as the CAF tunability (CAF_t), to indicate the tunability of circadian action from low CAF at low CCT (3000 K) to high CAF at high CCT (6500 K) in this comparison, as

$$CAF_t = \frac{CAF_{ol}}{CAF_{bl}} \tag{4}$$

As can be noticed in Table 1, the CAF_t turns out to be the largest for the LBIs ($CAF_t = 4.66$) and the LEDs ($CAF_t = 4.68$) with four bands among all cases, indicating that the 4-band models in LBIs and LEDs both show the largest CAF tunability. But for LBIs, at the same time, RYGB also exhibits the lowest CAF and the highest LER at the CCT of 3000 K, implying that this type of solid-state lighting has the most potential in both the promotion of melatonin secretion (indicated as low CAF) and the energy saving (related to high LER). In addition, Table 2 has listed a comparison of CAF and LER between the LBIs and LEDs with different types at $R_a = 90$. As can be observed, the 4-band models in LBIs have shown the largest CAF tunability ($CAF_t = 3.60$) with the highest LER at the low CCT of 3000 K. Combing the analyses of Table 1 and Table 2, we conclude that the 4-band models in LBIs have demonstrated the largest CAF tunability among all analyzed cases. At the same time, their CAFs are the lowest at a CCT of 3000 K, indicating that RYGB LBIs have the most potential in the healthy lighting at $R_a = 80$ and $R_a = 90$.

3.2 Optimization for Display Application

Realizing wide color gamut display has become the development direction of the new generation of display technology [25], [26]. Highly saturated colors coming from LEDs, LDs, quantum dots, and rare-earth phosphors with relatively narrower FWHMs are propitious for realizing wide color gamut display [27], [28]. In the display technology, the healthy issues corresponding to the light emission in the display have drawn great attention of people, so it is necessary to consider the influence of circadian effects on people while achieving the wide color gamut display at the same time.

The area ratio (A) can be used to describe the color gamut which compares the triangular area surrounded by chromaticity coordinates of RGB of the display with the triangular area of

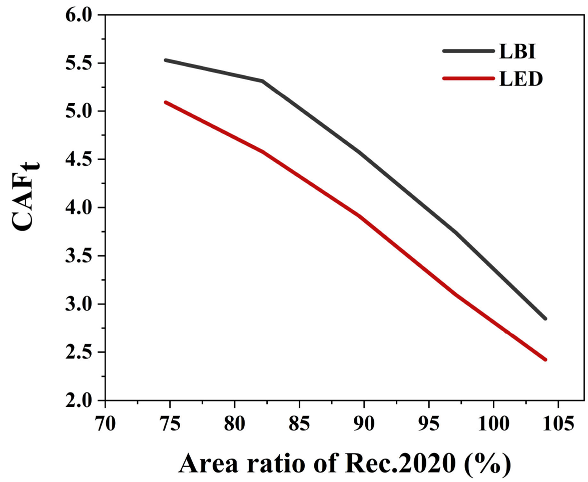

Fig. 5. The optimal circadian tunability as a function of color gamut for the RGB LEDs and the RGB LBIs.

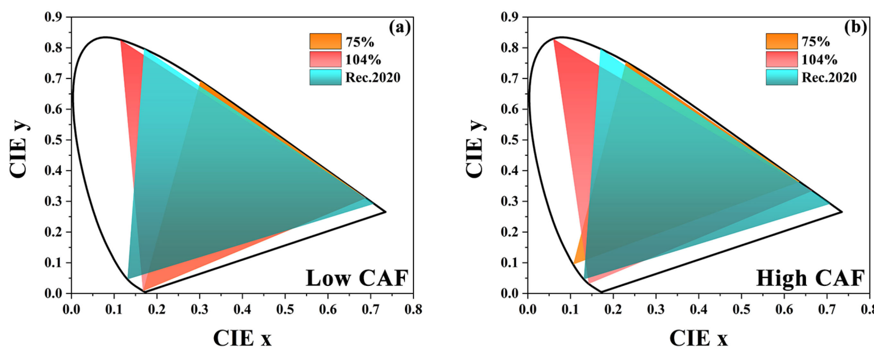

Fig. 6. Three triangles corresponding to 75%, 104%, and standard of Rec. 2020 in the cases of (a) low CAF and (b) high CAF.

the standard one, as $A = S_{display}/S_{standard}$. The triangle area can be calculated from CIE 1931 XYZ chromaticity coordinates of RGB colors according to the following formula [29], as

$$S = \frac{R_x(G_y - B_y) + G_x(B_y - R_y) + B_x(R_y - G_y)}{2} \tag{5}$$

where the subscript x and y stand for chromaticity coordinates in the CIE 1931 XYZ color system, and R, G, and B represent red, green, and blue color, respectively. Although there is another calculation method for color gamut as the coverage ratio, but for simplicity we only adopt area ratio in this current work [20]. Recently, the Rec. 2020 is a widely accepted standard for describing the color gamut. In this paper, we only employ the area ratio of Rec. 2020 as the primary metrics for the calculation of color gamut. The goal has become searching for the maximum CAF tunability, CAF$_t$, at several fixed color gamuts under those constraints of two CCTs (3000 K and 6500 K), the same CCT tolerance (10 K), $D_{uv} \leq 0.01$, and also LER $\geq$ 300 lm/W.

We compare the maximum CAF$_t$ of RGB LEDs and RGB LBIs under different area ratios of Rec. 2020 (from 75% to 104%) in Fig. 5. The 75% Rec. 2020 is equivalent to 100% National Television Standards Committee, another well-known standard for the calculation of color gamut. Fig. 6 shows three triangles corresponding to 75%, 104%, and the standard of Rec. 2020. Both CAF$_t$ values of RGB LEDs and RGB LBIs decrease with the increasing area ratio of Rec. 2020, and the value of

CAF_t of RGB LBIs is a little higher than that of RGB LEDs (the averaged value is 4.40 for RGB LBIs, but 3.82 for RGB LEDs). From 75% to 104% of area ratio in Rec. 2020, the CAF_t of RGB LBIs decreases from 5.53 to 2.84 and the CAF_t of RGB LEDs decreases from 5.10 to 2.42. This result indicates the superiority of RGB LBIs in the circadian tunability while applying in the wide color gamut display application.

4. Conclusion

In summary, based on the GA optimization, we have investigated the optimal circadian tunability for both LEDs and LBIs respectively applied in the general lighting and wide color gamut display. Some results are concluded as follows: 1) both RYGB LEDs and LBIs show the maximum circadian tunability of about 4.7 among all cases, including three-band, four-band, and five-band LEDs and LBIs. However, the four-band LBIs exhibit lower CAF at the 3000 K CCT as well as much higher LER than four-band LEDs, indicating the great potential of the LBIs for both energy-saving and healthy lighting. 2) For wide color gamut display application, RGB LBIs have shown greater circadian tunability than RGB LEDs, when the area ratios of Rec. 2020 and other conditions are fixed.

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