Enhance the Photosynthetic and Color Performances of Multi-Primary White Light-Emitting Diodes for the Indoor Farming

Mengxiao Zhuo, Qiyao Li, Bingui Lv, Mingkai Huang, Xiaoting Xue, Xiao Zheng, Yi Lin, Bijing Liu, Xinqin Liao, Ziquan Guo, *Member, IEEE*, and Zhong Chen

***Abstract*—The GaN-based white light-emitting diodes (LEDs) increase the possibility of realizing an ideal spectrum for the growth of plants. At the same time, high photosynthetic action of white LEDs is very crucial for the plant lighting to increase the crops productivity in the indoor artificial lighting plant factory. In this paper, via designing a non-linear program (NLP) based on the common genetic algorithm (GA), we are capable of conducting the comprehensive spectral optimization for realizing high photosynthetic action of multi-primary white LEDs (from three-primary to five-primary) under three different correlated color temperatures (CCTs, 2700 K, 4500 K, and 6500 K, respectively) while taking the color rendering performances, such as Commission Internationale de l'Eclairage (CIE) color rendering index (CRI, R_a), two special color rendering indices (R_9 and R_{12}) and Illuminating Engineering Society of North America (IES) TM-30 (R_f and R_g), and color quality scale (CQS, Q_a) into account. In addition, these mentioned performances are compared among different primary numbers, CCTs, and spectral bandwidths in the multi-primary LEDs. Finally, we believe that the obtained relevant results presented here could provide a useful guidance for the achievement of high photosynthetic and excellent color performance lighting for the indoor farming.**

***Index Terms*—Genetic algorithm, indoor farming, light-emitting diodes, photosynthetic.**

I. Introduction

RECENTLY, the indoor artificial lighting plant factory has been proposed to guarantee the quality, safety, and ecological environment of agricultural products [1]. The research results have demonstrated that the most important wavelength ranges for most plants on the earth belong to 400 nm–500 nm (blue B) and 600 nm–700 nm (red R), which are basically related to the maximum light absorption by main components of most of existing plants. Therefore, blue and red emissions could be used to improve the photosynthesis of plants [2], [3].

Owing to several common advantages including small size, long lifespan, fast response, spectral adjustment, energy saving, environment friendliness, etc., GaN-based light-emitting diodes (LEDs) are replacing conventional white light sources, namely by incandescent lamps, fluorescent lamps, and high-intensity discharged (HID) lamps, applied in several lighting and display fields, such as general lighting, automotive lighting, plant lighting, micro-LED display, and so on [4], [5]. It is easy to meet a variety of demands in the diverse lighting applications by changing the spectrum or spectral power distribution (SPD) of white LEDs [6], [7].

The primary figures of merit for describing the photosynthesis and photo-pigmentation performances of white LEDs generally include: photosynthetic luminous efficacy of radiation (PLER, K_p, plm/W), photosynthetic luminous efficacy (PLE, plm/W), photosynthetic illuminance (PIL), photosynthetic action factor (PAF), photosynthetic photon flux (PPF), etc. In addition to the photosynthesis and photo-pigmentation performances, the visual and color performances of LEDs, such as luminous efficacy of radiation (LER, K), luminous efficacy (LE), Commission Internationale de l'Eclairage (CIE) color rendering index (CRI, R_a), of the artificial light sources are also crucial for the indoor lighting. In other words, there is a fundamental trade-off relationship between the photosynthetic and color performances [8], [9]. Previously, the four-package white LEDs have exhibited excellent photosynthetic performances (PLER = 469 plm/W and PLE = 169 plm/W) and good visual and color performances (LER = 271 lm/W, LE = 98 lm/W, and CRI = 86) at 10000 K correlated color temperature (CCT, T_c) for blue-enriched white LEDs [8]. In addition, Wu et al. performed the analyses of six-primary plant-growth light sources in achieving the maximum photosynthesis efficiencies with enhanced color qualities previously [9]. Cao et al. investigated the phosphor-converted white LEDs for plant lighting based on a single blue LED chip (450 nm) and two blue LED chips (450 nm + 470 nm) separately by optical simulation [10]. In their works, the average CRI, the special color rendering index (CRI-9, R_9, saturated red light and CRI-12, R_{12}, saturated blue light) were considered as the main evaluating parameters of LED light sources on the plant growth

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The authors are with the Fujian Engineering Research Center for Solid-state Lighting, Department of Electronic Science, School of Electronic Science and Engineering (National Model Microelectronics College), Xiamen University, Xiamen 361005, China (e-mail: 838268762@qq.com; qiyaoli9826@163.com; 2676774730@qq.com; 1602014150@qq.com; 35320192200253@stu.xmu.edu.cn; 35320192200278@stu.xmu.edu.cn; 314309646@qq.com; 444802635@qq.com; liaoxinqin@xmu.edu.cn; zqguo@xmu.edu.cn; chenz@xmu.edu.cn).

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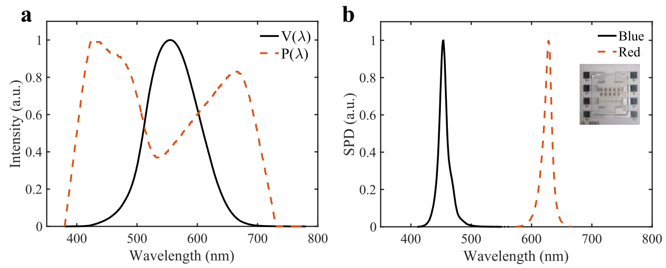

Fig. 1. (a) The photosynthetic and visual spectral sensitivity curves. (b) The experimental SPD of LEDs (normalized). Inset: the photograph of LEDs consisted of six blue InGaN-based LEDs (averaged peak wavelength: 454 nm, FWHM: 14 nm) and ten red AlGaInP-based LEDs (averaged peak wavelength: 628 nm, FWHM: 15 nm) fabricated by *Xiamen Hualian Electronics Co., Ltd.*

[10]. Liu et al. designed and optimized luminescent spectrum of LEDs (QLEDs) based on quantum dot (QD) materials according to the photosynthetic action spectrum (PAS) of plants [11]. In the calculation, three- or four-band QLEDs have shown better photosynthetic parameters than those of conventional light sources. Deng et al. proposed the ultra-stable red-emitting phosphor-in-glass (PiG) for superior high-power artificial plant growth LEDs [12]. This PiG is proven to be a potential alternative to serve as the color converter for high-power plant light sources owing to their excellent optical, thermal, and chemical stabilities.

Till now, there are few works that have been reported previously on a comprehensive investigation and comparison of photosynthesis and photo-pigmentation performances for multi-primary (such as three-primary, four-primary, and five-primary) white LEDs possibly applied in the plant lighting.

Based on previous works from our research group [7], [9], [13], in this current work, we carry out the spectral optimization study on increasing both photosynthetic and color performances of multi-primary (MP) white LEDs containing multiple InGaN-based and AlGaInP-based LEDs. The non-linear program (NLP) based on the common-use genetic algorithm (GA) is well designed on the Matlab platform to solve this multi-objective optimization problem. In order to simulate the spectra of three-primary, four-primary, and five-primary LEDs, for simplicity, the simple *Gaussian* function is adopted.

II. Theory

In this section, some strongly related parameters for the photosynthetic and color performances in this study are particularly introduced for a better understanding to readers.

A. Photosynthetic Action Factor, PAF

Similar to the definition of luminous efficacy of radiation (LER), the photosynthetic efficacy of luminous radiation (PLER K_p) can be defined as the ratio of photosynthetic luminous flux to radiant flux, which can be simply expressed by [8]

$$K_p = \frac{K_{pm} \int_{380nm}^{780nm} P(\lambda) S(\lambda) d\lambda}{\int_{380nm}^{780nm} S(\lambda) d\lambda} \tag{1}$$

where λ is the wavelength; *P(λ)* is the normalized photosynthetic action spectrum (as shown in Fig. 1(a)); $K_{pm} = 683$ plm/W is the maximum PLER; *S(λ)* represents the SPDs of white light from MP-LEDs.

Then, the photosynthetic action factor (PAF) can be expressed by [8]

$$PAF = \frac{K_{pm} \int_{380nm}^{780nm} P(\lambda) S(\lambda) d\lambda}{K_m \int_{380nm}^{780nm} V(\lambda) S(\lambda) d\lambda} \tag{2}$$

where *V(λ)* is the normalized CIE photopic spectral sensitivity function (also shown in Fig. 1(a)); $K_m = 683$ lm/W is the maximum LER.

B. Spectral Model

The normalized SPD of a single LED with relatively narrow bandwidths (10 nm–40 nm) fits fairly well with the *Gaussian* function

$$S_{\mathrm{i}}(\lambda, \lambda_0, \Delta\lambda) = \mathrm{e}^{-4\ln(2)\frac{(\lambda-\lambda_0)^2}{\Delta\lambda^2}} \tag{3}$$

where λ, λ_0, and Δλ are wavelength, peak wavelength, and full-width at half maximum (FWHM), respectively. Therefore, according to above expression, the SPD of MP-LEDs contains *N* primary colors can be expressed as

$$S(\lambda, \lambda_0, \Delta\lambda) = \sum_{i=1}^{N} a_i S_i(\lambda, \lambda_0, \Delta\lambda) \tag{4}$$

where a_i is the relative intensity of primary color varying within the range of (0, 1). Here, the number of primary colors *N* is taken from three to five, namely three-primary, four-primary, and five-primary white LEDs.

C. Non-Linear Program Based on GA

In this part, we briefly introduce the procedure of multi-objective spectral optimization on the photosynthetic, visual, and color performances. The common genetic algorithm (GA) which is based on the biological evolution process is used for solving these multi-objective optimizing problems [13]. It searches for the maximum or minimum values randomly by mutation and crossover among population members. We adopt the GA for this spectral optimization because it is most widely applied in the optimization works [14]. A non-linear program (NLP) on the Matlab platform based on GA is designed thereby. Fig. 2 shows the flow chart of this NLP. The objective function (*F*) in this NLP can be written by

$$F = \text{Maximum PLER (under constrained conditions)} \tag{5}$$

Prior to carrying out the spectral optimization, some limitations or constrained conditions are set as: (a) the representative CCT is set as 2700 K (warm white light), 4500 K (neutral white light), and 6500 K (cold white light), respectively. (b) The tolerance of CCT is about 10 K. (c) The color distance (D_{uv}) between standard light sources (u_0, v_0) and studied MP-LEDs (*u*, *v*) in the color space of CIE 1960 UCS is kept within 0.01 (i.e., $D_{uv} \le 0.01$). (d) The FWHM of MP-LEDs is restricted to a range of 10 nm–40 nm, matching well with most primary LEDs.

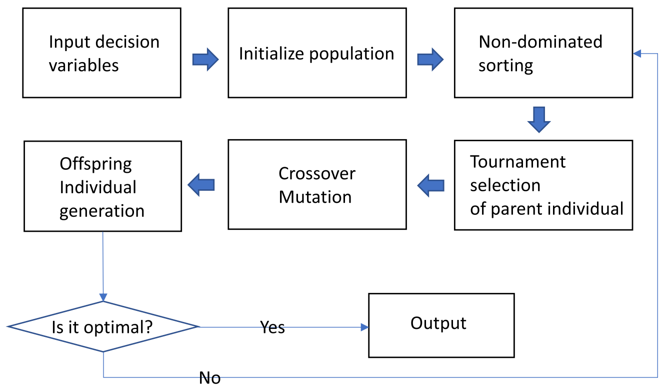

Fig. 2. The flow chart of this current program based on GA.

At present, for simplicity, the FWHM is fixed as 30 nm for all primary LEDs. At last, the performances are also compared under various FWHM values of 20 nm, 30 nm, and 40 nm, respectively. (e) The CIE color rendering property is constrained as $R_a \geq 60$. We also calculate other color rendering metrics, such as CIE special color rendering index (CRI-9 and CRI-12), Illuminating Engineering Society of NorthAmerica (IES) TM-30 R_f and R_g [15], color quality scale (CQS, Q_a) [16], for the supplement to CIE CRI due to its deficiency in the evaluation of color rendering performances for LEDs [15], [16].

III. Experimental

A spectral measurement of InGaN-based blue LEDs and AlGaInP-based red LEDs is performed. The MP-LED samples (with the primary number N of 2) are fabricated by *Xiamen Hualian Electronics Co., Ltd*. Inset of Fig. 1(b) shows the photograph of such type of MP-LEDs. These MP-LEDs are consisted of six blue InGaN-based LEDs (with chip size of about 922.9 μm $\times$ 497.1 μm) and ten red AlGaInP-based LEDs (with chip size of about 337.1 μm $\times$ 362.9 μm). In this packaging structure, the transparent silicone gels are used for the protection of these LEDs from water and oxygen in order to increase the reliability of devices.

The spectral measurement is carried out by using a comprehensive spectral measurement system (Spectro-320e, Instrument Systems Inc.) connected to an integration sphere (ISP-500, Instrument Systems Inc.). During the spectral measurement, these LED samples attached on heatsink are temperature-controlled by a TEC device (Keithley-2510, Keithley Inc.). At the same time, they are power supplied by two source meters (Keithley-2611 and Keithley-2400, Keithley Inc.). Fig. 1(b) shows two measured normalized emission SPDs corresponding to InGaN-based (peak wavelength of 454 nm, FWHM of 14 nm) and AlGaInP-based LEDs (628 nm, 15 nm), respectively. The calculated PAF and PLER for this experimental SPD shown in Fig. 1(b) are 4.40 and 565.6 plm/W, but poor CRI and super-high CCT are -162 and exceeding 25000 K due to lack of green color component in the emitting white SPDs. However, green and other color components are also propitious for the growing of plants [2]. It means that to achieve better photosynthetic, visual, and color performances, the number of primary LEDs should be more than two.

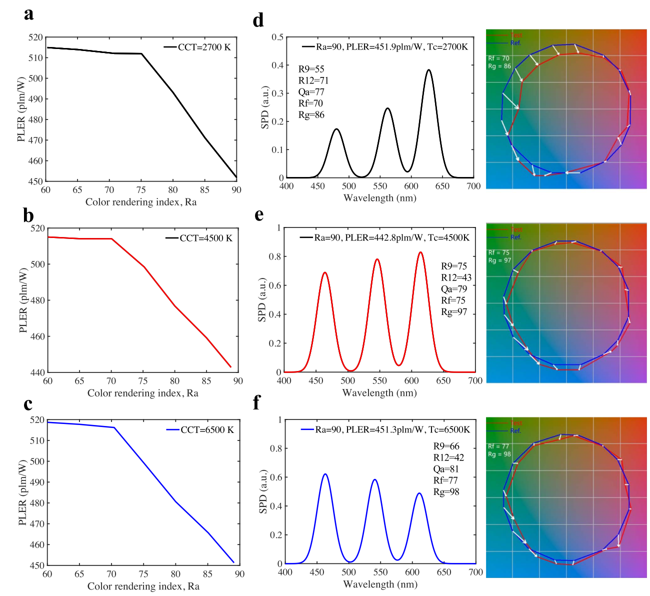

Fig. 3. For three-primary LEDs: (a)–(c) CRI versus PLER under various CCTs of (a) 2700 K, (b) 4500 K, and (c) 6500 K, respectively. (d)–(f) The corresponding SPDs and relevant parameters under various CCTs of (d) 2700 K, (e) 4500 K, and (f) 6500 K, respectively. In addition, we also plot the IES TM-30 icon and distortion.

IV. Results and Discussion

A. Photosynthetic and Color Performances for Three-Primary LEDs

Fig. 3(a)–(c) demonstrate the maximum PLER versus CRI under three various CCTs (2700 K, 4500 K, and 6500 K, respectively). From Fig. 3(a)–(c), we can clearly notice that there is a fundamental trade-off relationship between the photosynthetic and color performances. That is to say, as CRI increases, PLER value decreases under these three CCTs. Particularly to note that, while CRI is lower than 70, the optimal PLER values are nearly the same. However, at low CCT of 2700 K, CRI is lower than 75, and PLER is nearly unchanged. At the same time, when CRI is equal to 60, the maximum PLER for three-primary LEDs is about 514.9 plm/W (2700 K), 515.0 plm/W (4500 K), and 518.7 plm/W (6500 K), respectively. When CRI increases from 60 to 90, the decrement of PLER is about 63.0 plm/W (2700 K), 72.2 plm/W (4500 K), 67.4 plm/W (6500 K), respectively. Fig. 3(d)–(f) display the optimal SPDs for three-primary LEDs under various CCTs at a CRI of 90. A comparison among three CCTs indicates that the PLER values are higher for warm white light (2700 K) and cold white light (6500 K) than for neutral white light (4500 K), implying that warm white light and cold white light are more propitious for obtaining both high photosynthetic and color performances than neutral white light, but their differences are relatively small. From Fig. 3(d)–(f), it is obvious to note that the optimal wavelengths behave differently under three studied CCTs. As the CCT decreases from 6500 K to 2700 K, the optimal wavelengths all shift towards longer wavelength to ensure high photosynthetic performances at a fixed CRI. In addition, CRI-9 (R_9), CRI-12 (R_{12}), and other parameters for three-primary LEDs are not high enough, especially the values of CRI-9 and CRI-12, and can be found in Fig. 3.

TABLE I
SEVERAL OPTIMAL RESULTS BY NLP INCLUDING CCT, PAF, PLER, LER, CQS, IES-TM-30 SCORES, CRI, D_{uv}, CORRESPONDING WAVELENGTH, AND OTHERS

CCT(K)	D_{uv}	LER(lm/W)	PLER(plm/W)	PAF	R_a	Q_a	R_9	R_{12}	R_f	R_g	Wavelength (nm)
2690	0.0064	322.7	451.9	1.40	90	77	55	71	70	86	480+562+628
4490	0.0063	349.2	442.8	1.27	90	79	75	43	75	97	464+546+614
6490	0.0023	333.4	451.3	1.35	90	81	66	42	77	98	463+541+611
2690	0.0063	177.3	485.1	2.74	90	80	96	82	72	116	441+527+595+670
4508	0.0057	230.6	482.4	2.09	90	87	93	90	81	110	444+519+588+663
6510	0.0054	235.9	489.8	2.08	90	89	86	89	85	107	447+513+583+659
2704	0.0062	244.8	479.1	1.96	93	88	100	87	88	98	430+489+559+609+661
4499	0.0062	273.8	477.4	1.74	95	92	95	95	93	99	438+488+550+603+665
6492	0.0048	266.8	483.2	1.81	95	95	95	88	92	100	449+491+536+587+649

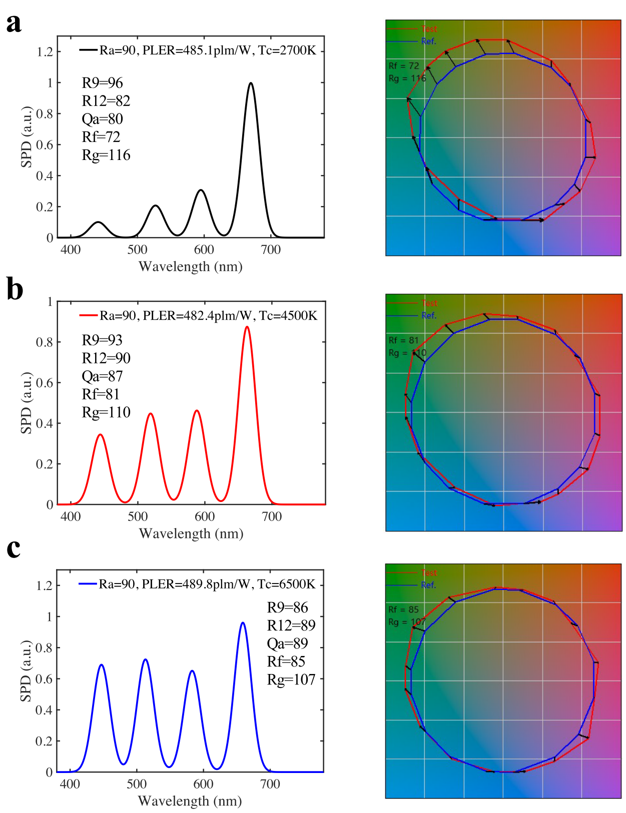

Fig. 4. For four-primary LEDs: the optimal SPD of LEDs and relevant parameters under various CCTs of (a) 2700 K, (b) 4500 K, and 6500 K, respectively. In addition, we also plot the IES TM-30 icon and distortion.

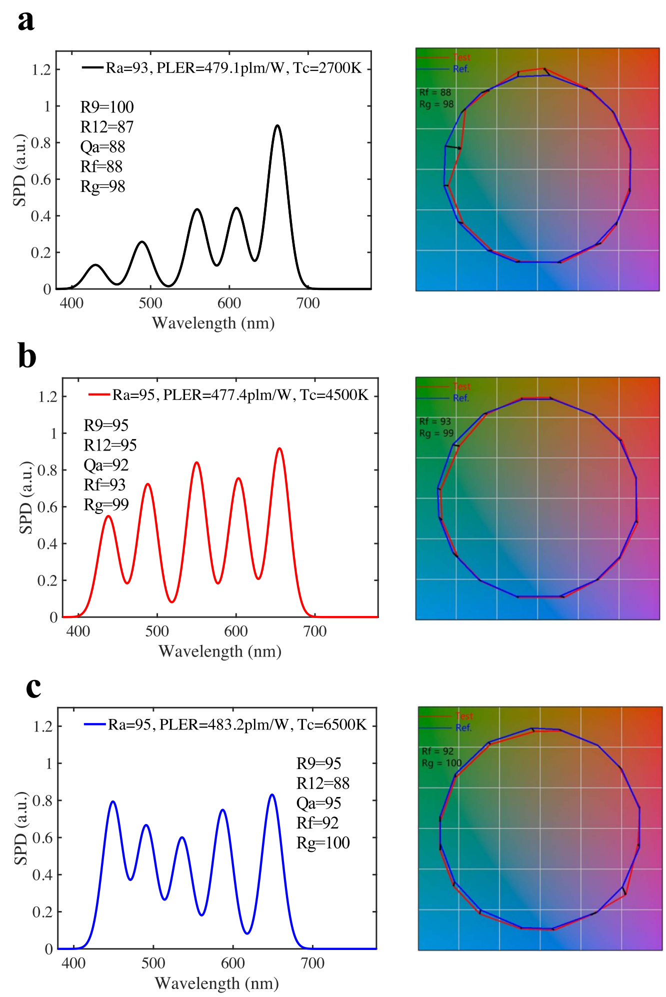

Fig. 5. For five-primary LEDs: the optimal SPD of LEDs and relevant parameters under various CCTs of (a) 2700 K, (b) 4500 K, and (c) 6500 K, respectively. In addition, we also plot the IES TM-30 icon and distortion.

Reasons for the low CRI-9, CRI-12 and other parameters in three-primary LEDs are attributed to the narrow spectral FWHM of LEDs, which may induce the incomplete natural colors that can cover all wavelengths.

B. Photosynthetic and Color Performances for Four- and Five-Primary LEDs and the Comparison

Fig. 4(a)–(c) illustrate the optimal SPDs as well as photosynthetic and color performances for four-primary LEDs under the CCTs of (a) 2700 K, (b) 4500 K, and (c) 6500 K, respectively. The IES TM-30 icon and distortion can also be found in these figures. The PLER values for three studied CCTs are 485.1 plm/W for 2700 K, 482.4 plm/W for 4500 K, and 489.8 plm/W for 6500 K, respectively. Their other parameters are also found in Fig. 4. Fig. 5(a)–(c) show the optimal SPDs as well as photosynthetic and color performances for five-primary LEDs under the CCTs of (a) 2700 K, (b) 4500 K, and (c) 6500 K, respectively. The PLER values for three CCTs are 479.1 plm/W for 2700 K, 477.4 plm/W for 4500 K, and 483.2 plm/W for 6500 K, respectively. These PLER values are a little lower than those of four-primary LEDs. Obviously, the decaying is about 6.6 plm/W for 6500 K, 5.0 plm/W for 4500 K, 6.0 plm/W for 2700 K, respectively. The decaying is the smallest for 4500 K CCT among three.

These results can be found in Table I, including CCT, PAF, PLER, LER, CQS, IES-TM-30 scores, CRI, D_{uv}, corresponding

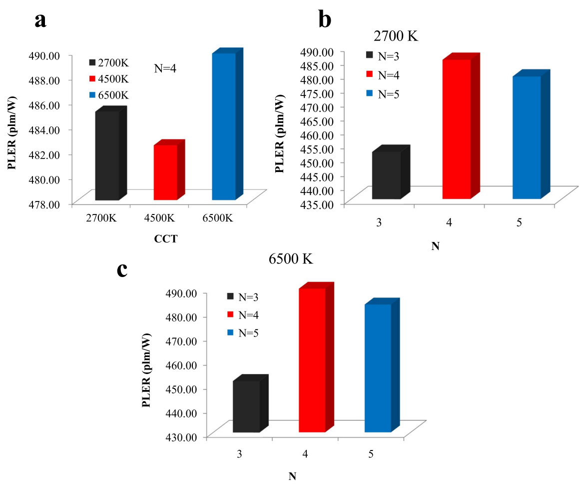

Fig. 6. A comparison of (a) PLER for various CCTs for four-primary LEDs, and PLER for three- to five-primary LEDs at (b) 2700 K and (c) 6500 K CCT.

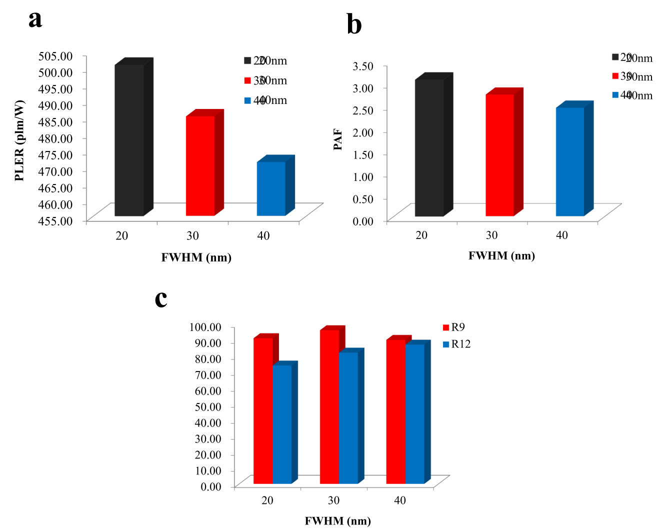

Fig. 7. The optimal values of (a) PLER, (b) PAF, and (c) CRI-9 (R_9) and CRI-12 (R_{12}) versus FWHM of MP-LEDs.

wavelength, and others. It can be easily noted that for $N = 4$, with increasing CCT, the corresponding wavelengths for blue LEDs have red-shifts, while blue-shifts for green, orange, and red LEDs. For $N = 5$, similarly, the corresponding wavelengths for blue LEDs have red-shifts, while blue-shifts for yellow, orange, and deep-red LEDs. But the wavelengths for cyan LEDs are changed slightly (488 nm∼491 nm).

Fig. 6 compares the PLER values under (a) different CCTs and various primary numbers ($N = 3{\sim}5$) for (b) 2700 K CCT and (c) 6500 K CCT, respectively. From Fig. 6(a), it can be clearly observed that, the PLER is the highest for warm white and cold white four-primary LEDs, and the SPDs related to 4500 K CCT own the lowest PLER values in all three cases. From Fig. 6(b), (c), in comparison of three, four, and five-primary LEDs, four-primary LEDs have shown the highest PLER values, whereas five-primary LEDs possess the best color rendering performances. Adding one primary color will increase the cost and device complexity, so we want to suggest that four-primary LEDs are the most suitable for high demands of excellent photosynthetic and color performances in the indoor farming application.

In addition, Fig. 7 shows (a) PLER, (b) PAF, and (c) CRI-9 and CRI-12 values under different spectral bandwidths or FWHMs ($\Delta\lambda$) from 20 nm to 40 nm. It is obvious to notice that the narrower spectral bandwidths are more propitious for increasing photosynthetic performances but would partly sacrifice color rendering performances, such as CRI-9 and CRI-12. In addition, one point to mention is that, in our work, we mainly focus on the PLER optimization, but not on PAF optimization. The PAF results are corresponding to the optimal PLER.

Obviously, a linear decaying can be shown as

$$PLER = -1.4657 \times \Delta\lambda + 529.63 \quad (6)$$

with the coefficient of determination R^2 value of 0.9989 indicating an excellent linear fitting. This simple linear expression can be used to predict the optimal values of PLER under different spectral bandwidths for four-primary LEDs with good color rendering properties without repeatedly running above optimization programs, thus saving more time.

V. Conclusion

In summary, via the well-known genetic algorithm, we perform a spectral optimization study on enhancement of photosynthetic, visual, and color performances of MP-LEDs. The MP-LEDs, including three-primary, four-primary, and five-primary LEDs, are compared in these above performances. The results could be concluded as follows: (a) the warm white light and cold white light are more propitious for both increasing the photosynthetic and color performances than the neutral white light; (b) the four-primary LEDs have shown the highest PLER values, whereas five-primary LEDs possess best color rendering performances. In the future, according to simulation results, the experimental verification should be done for promoting the plant growth in the indoor farming. The well thermal management and optical design for achieving multiple-primary LED-based arrays with good stability and good optical uniformity applied in the indoor farming are also urgently needed. In addition, this study can be expanded to other types of white LEDs, such as emerging QLEDs or phosphor-type LEDs, possibly applied in the indoor plant lighting in the future. The phosphor-type LEDs have lower costs than MP-LEDs, and have been extensively applied in the indoor lighting fields, and are beneficial for excellent color rendering properties. Future studies would focus on the improvement of photosynthetic performances in the phosphor-type LEDs.

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