Investigation on Circadian Regulation of Four-Primary LED Display Differed in People by GA

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***Abstract*—The concept of human-centric lighting is gradually emerging. People no longer only consider the lighting function of light, but also begin to pay attention to the comfort and health of light. In this article, we perform an investigation on the circadian regulation of four-primary light-emitting diode (LED) based displays for the people with various ages from 1 year old to 100 years old. The double-Gaussian function is used to mimic the spectral power distribution of monochromatic LED. The main figures of merit of LED display performance are color gamut of Rec. 2020, luminous efficacy of radiation, correlated color temperature (CCT), and also non-visual parameters, such as circadian stimulus and melanopic efficacy of luminous radiation provided by Commission Internationale de l'Eclairage (CIE) standard. Then, the genetic algorithm is adopted for performing the spectral optimization of four-primary LED display while many constraint conditions are set, such as CCT values (2700 K and 6500 K), CCT tolerance, and color distance ($D_{uv} < 0.01$) in the CIE 1960 UCS color space. Related results of visual and non-visual characteristics are also compared with those of three-primary LED displays. This work would pave a way for the development of healthy four-primary LED display in consideration of various ages of people.**

***Index Terms*—Light-emitting diode display, double Gaussian function, genetic algorithm, circadian regulation.**

I. Introduction

SINCE the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs), the healthy lighting based on light-emitting diode (LED) has garnered increasing attention from industry and community. The GaN-based LED, as a high efficiency lighting device, has been extensively applied in many lighting and display fields, such as general lighting, visible light communication, plant lighting, road lighting, and mini- or micro-LED display [1], [2], because it possesses many advantages such as high efficiency, long lifespan, energy savings, spectral tunability, and fast response [3], [4], [5], [6].

Currently, there are many approaches for realizing the full-color display by using LEDs. Among them, one method is that red (R), green (G), and blue (B) LEDs are integrated onto the same substrate [6]. The other promising technique is that quantum dots or rare-earth phosphors are employed as down-conversion materials for generating red and green emission in the full-color display. The quantum dots with ~100 nm particle size are generally used in micro-LED display, and rare-earth phosphors with ~10 um particle size can be used in mini-LED display [6]. The latter technique possesses relatively low cost and reduces the massive transferring times and bad pixel repairing issues, and has attracted great interest from industry and community. For LED display, abundant blue light is still a critical issue that needs to be paid attention to. Blue light has been verified to be harmful for human healthy, mainly on blue light hazard to human eyes as well as disturbing the circadian rhythms of humans. In general, the circadian rhythm is associated with five common photoreceptor cells, such as S-cones, M-cones, L-cones, rods, and ipRGCs [7]. Most of them are sensitive to the light in blue wavelength range. Therefore, it is significant to optimize spectral power distributions (SPDs) of LED display for different scenario applications such as daytime working and nighttime relaxation as well as sleeping.

Many previous published works are dedicated to make the emitting light become more healthy and increase visual and non-visual performances of lighting devices in the lighting and display fields [8], [9], [10], [11], [12], [13], [14]. Among them, Wu et al. proposed a fullerene derivative blending strategy to suppress the blue light hazards caused by the indoor organic photovoltaic devices, reduce the blue light hazard efficacy, and improve their overall device performances [10]. Ke et al. compromised the circadian performance and color gamut Rec. 2020 for achieving the healthy LED displays. However, they did not consider the age effects during the circadian tuning process [11]. He et al. designed low circadian action micro-LED displays with four primary colors. But they did not consider the high circadian action in the daytime, and also lacked the discussion on the age of different people [12]. Chaopu et al. studied the change of blue light hazards and circadian effects of LED backlight displayer with color temperature and age. However, they did not make an optimization on LED spectra [13]. Wu et al. previously designed an evaluation system for quantitatively evaluating the circadian

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performance of smartphone-based virtual reality displays based on non-visual parameters, such as circadian action factor and circadian illuminance [14]. So far, there are rare works on the spectral optimization of four-primary LED display on achieving wide color gamut and tunable non-visual performance.

In this context, the four-primary LED display technology offers several significant advantages over the traditional three-primary (RGB) technology. The inclusion of an additional primary color, typically yellow (Y), allows for a broader color gamut, thus providing more accurate and vivid color reproduction. This expanded gamut is particularly beneficial in applications requiring high color fidelity, such as medical imaging, professional photography, and cinema displays. Furthermore, the four-primary system enables better control over the SPD, allowing for more precise adjustments to minimize blue light hazards and optimize circadian benefits. This makes the four-primary LED technology more adaptable to varying lighting conditions and users' needs, promoting both visual comfort and health.

In this paper, the common genetic algorithm (GA) is used to find out optimal values that describing visual and non-visual characteristics of four-primary LED display. The FWHMs of four primary colors are set as 15 nm (blue, B), 25 nm (green, G), 15 nm (yellow, Y), and 15 nm (red, R) according to experimental results from spectrometers and some references [15], [16], [17], [18]. Narrower spectral bandwidth of LED is more beneficial for the realization of wider color gamut and large circadian tunability [11]. The double-Gaussian functions are adopted to model the SPD of four-primary LED displays [19]. Section II provides the related theory and procedure of optimization as well as spectral modelling by using double-Gaussian function. Section III presents the results and discussions. The last section shows the brief conclusion of this current work.

II. Theory and Optimization

A. Introduction of Related Parameters

1) Melanopic Efficacy of Luminous Radiation and Circadian Stimulus: In order to evaluate the circadian performance of LED display, melanopic efficacy of luminous radiation (MELR, K_{M}) and circadian stimulus (CS) are employed. The MELR can be defined by

$$K_M = \frac{\int_{380nm}^{780nm} M(\lambda)\, S(\lambda)\, d\lambda}{K_m \int_{380nm}^{780nm} V(\lambda)\, S(\lambda)\, d\lambda} \tag{1}$$

where $M(\lambda)$ is the normalized spectral sensitivity of ipRGC photoreceptors to optical radiation incident at the cornea, $V(\lambda)$ is the normalized Commission Internationale de l'Eclairage (CIE) photopic spectral sensitivity function, $S(\lambda)$ is the spectral power distributions of white light, and $K_{\mathrm{m}} = 683$ lm/W is the maximum value of luminous radiation of efficacy (LER, K). Fig. 1(a) shows the spectral sensitivity curves of $M(\lambda)$ and $V(\lambda)$ in (1).

The optical transmittance of human eyes would become differently for different ages of people. Fig. 1(b) shows the optical transmittance of human eyes for different ages (A) at each wavelength, namely by τ (λ, A). Thus, the parameter of MELR in consideration of peoples' ages can be given by the following formula

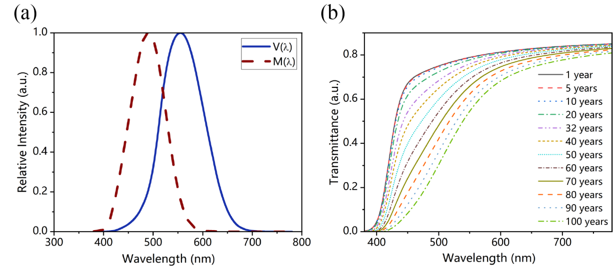

Fig. 1. (a) The spectral sensitivity curves of $M(\lambda)$ and $V(\lambda)$. (b) The optical transmittance of human eyes (from 1 year old to 100 years old).

$$K_{M,A} = \frac{\int_{380nm}^{780nm} M(\lambda)\, S(\lambda)\, \frac{\tau(\lambda,A)}{\tau(\lambda,32)} d\lambda}{K_m \int_{380nm}^{780nm} V(\lambda)\, S(\lambda)\, \frac{\tau(\lambda,A)}{\tau(\lambda,32)} d\lambda} \tag{2}$$

where τ (λ, 32) is the spectral transmittance of human eyes at 32 years old (which is treated as the age of standard observers).

The circadian stimulus is expressed by [20]

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_a}{355.7}\right)^{1.1026}} \tag{3}$$

where CL_{a} is called as circadian light. The light with CS $>$ 0.35 (half of the maximum value of CS $= 0.7$) is helpful for the increasing performance of entertainment and working efficiency in the daytime, while the light with CS < 0.1 is helpful for the relaxation and sleeping in the nighttime.

2) Color Gamut Standard of Rec. 2020: The color gamut coverage (G_{c}) typically measures the range of colors that a display device or light source can reproduce, and it can be generally expressed as a percentage. The formula for color gamut coverage is expressed as [21]

$$G_c = \frac{A_{test} \cap A_{std}}{A_{std}} \times 100\% \tag{4}$$

where A_{std} is the triangular area of color gamut standard, A_{test} is the triangular area of a tested display. Currently, the most popular standard for color gamut is Rec. 2020 color gamut, which exhibits the widest among many color gamut standards, such as Digital Cinema Initiatives Protocol 3 (DCI-P3), sRGB, Adobe RGB, National Television Standards Committee (NTSC), Rec. 709, and Rec. 2020. Here, Rec. 2020 color gamut standard will be used in this present work for demonstrating the color quality of tested display.

B. GA-Based Optimization Procedure

This work mainly focuses on four-primary LED-based displays. Fig. 2(a) shows the emission SPDs of LEDs with four different colors (blue, green, yellow, and red) which are experimentally obtained from a spectrometer (Spectro-320e, Instrument Systems Inc.). The peak wavelength of LED is 422 nm, 450 nm, 510 nm, 570 nm, 580 nm, 620 nm, and 638 nm, respectively.

A Gaussian shape of LED spectra can be observed from Fig. 2(a). The spectral power distribution (SPD) of four-primary

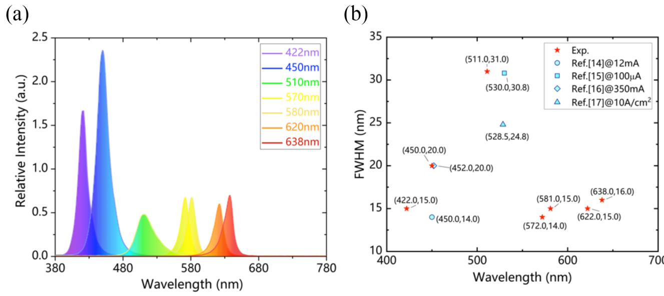

Fig. 2. (a) The emission spectral power distributions (SPDs) of four different colors (blue, green, yellow, and red) LEDs. These SPD data were obtained from experimental measurements by using a spectrometer. (b) The FWHM values and their wavelengths of four-primary LEDs from experiments acquired by spectrometers and some references.

LEDs can be modelled by double-Gaussian function [21]. Fig. 2(b) shows the FWHMs of four-primary LEDs in the experiments acquired by spectrometers and some references [15], [16], [17], [18]. We can notice that the FWHM of blue, green, yellow, and red LED is within 14∼20 nm, 25∼31 nm, 14∼15 nm, and 15∼16 nm, respectively. Although the presented data are a few, they could also indicate the real experimental FWHM values of LEDs. Thus, in the optimization procedure, the FWHM of blue, green, yellow, and red color is set as 15 nm, 25 nm, 15 nm, and 15 nm, respectively, accompanied fairly well with the above experimental and reference data. The peak wavelength of blue, green, yellow, and red color is set as 430∼499 nm (B), 500∼549 nm (G), 550∼599 nm (Y), and 600∼650 nm (R), respectively.

A non-linear program based on genetic algorithm (GA) has been designed. The objective function in this study is written by $F = \text{Max. MELR}$ (or Min. MELR). The penalty functions in the GA program are as CCT $= 2700$ K (for night-time relaxation) and 6500 K (for daytime working), with a CCT tolerance of 10 K; the color distance in CIE 1960 UCS color space is provided as $D_{\text{uv}} < 0.01$; the Rec. 2020 color gamut is from 90% to 100%, meeting high demands of wide color gamut of designed LED display devices.

III. Results and Discussion

Here, we discuss obtained optimal results of this present work. Fig. 3(a)–(b) shows MELR values acquired from 300 total results (those are sub-optimal results for running each GA program) versus Rec. 2020 for low MELR at 2700 K CCT and high MELR at 6500 K CCT, and also MELR values versus LER for low MELR and high MELR. One can see a clear linear boundary in each figure. The points on the linear boundary correspond to the best solution for each color gamut condition (mainly as 90∼100% Rec. 2020). It can be observed that the MELR would increase for obtaining low MELR at 2700 K and decrease for obtaining high MELR at 6500 K, implying that the circadian tunability (defined by the ratio of high MELR at 6500 K to low MELR at 2700 K) of a four-primary display would decrease with increasing color gamut. For the LER, when the CCT is 2700 K, while achieving the low MELR, the lowest MELR value changes

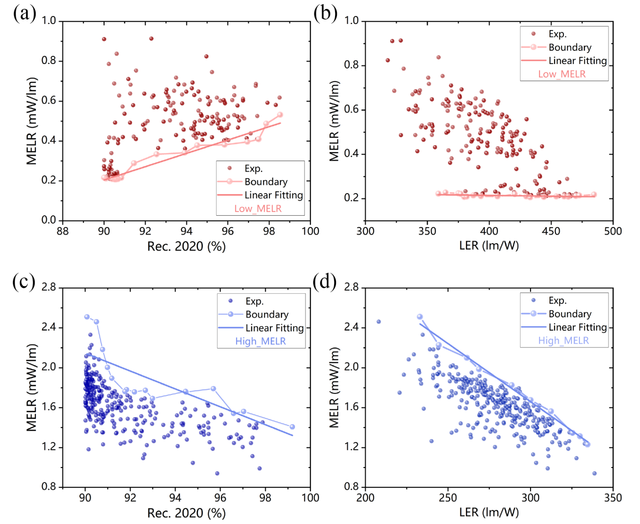

Fig. 3. When the Rec. 2020 color gamut is 90%∼100%, (a) MELR vs. Rec. 2020 at 2700 K, (b) MELR vs. LER at 2700 K, (c) MELR vs. Rec. 2020 at 6500 K, (d) MELR vs. LER at 6500 K.

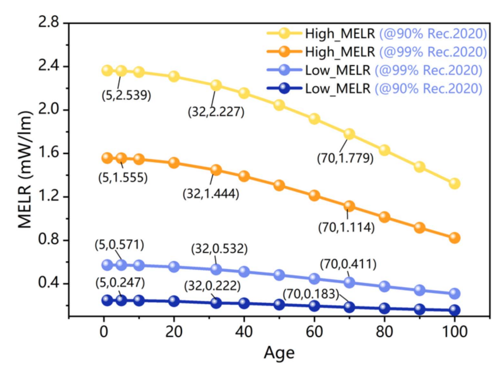

Fig. 4. The optimal MELR values (low and high) of four-primary LED display with Rec. 2020 of about 99% and 90%. One can observe that the MELR value decreases with the age of people.

a little with the increasing LER. Thus, we can readily choose the optimal data point with the highest LER and lowest MELR. However, when CCT is 6500 K, there is a trade-off relationship between LER and MELR. Therefore, we shall fully consider the compromise among LER, MELR, and Rec. 2020 at the same time.

After carefully selecting the best solutions at 2700 K and 6500 K CCT for the people's age of 32, the SPDs for the other ages from 1 year to 100 years can be deduced. Fig. 4 shows the optimal results of MELR at Rec. 2020 of 90% and 99% for different ages of people. It can be noted that the MELR value decreases with the age of people. For example, when the color gamut of display is 99% Rec. 2020, the low MELR is 0.571 for 1 year old, while it is 0.532 for 32 years old, and 6.83% decrease can be found. It is 0.411 for 70 years old, and thus 28.02% decrease can be found while compared with 1 year old. Similar analysis can be done on other three curves, and similar results can be found. It means that the same light in the four-primary display would induce different circadian regulation for different people with different ages. Due to that low MELR light is beneficial for

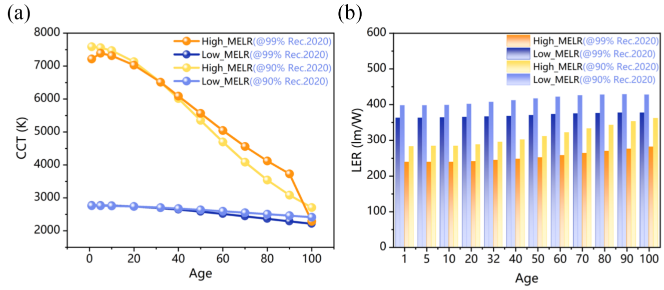

Fig. 5. (a) CCT and (b) LER changes with the increasing age for high and low MELR at the color gamut of 90% Rec. 2020 and 99% Rec. 2020.

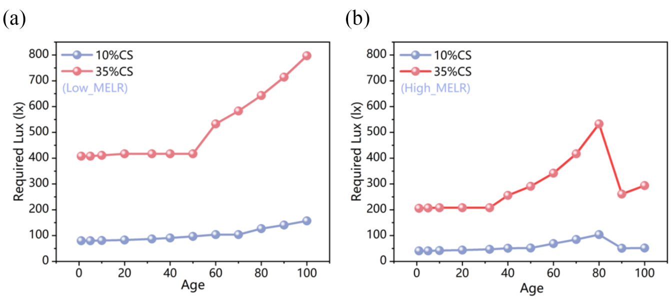

Fig. 6. The required illuminance (lux) as a function of age of people for (a) low MELR light and (b) high MELR light when CS = 0.1 and CS = 0.35.

relaxation, and high MELR light is better for increasing working performance, elderly people are more easily to relax than the younger people under the same light from display, while the younger people can acquire more alertness by the artificial light [23], [24]. The related values are listed in Tabs. S1-S4 in detail.

Fig. 5(a) and (b) show the CCT and LER change with the increasing age of people for high and low MELR under the color gamut of 90% Rec. 2020 and 99% Rec. 2020. It can be noticed that the CCT decreases with the increasing age of users. The CCT calculated from the SPD with low MELR changes slightly with the age, whereas the CCT changes greatly with the age for high MELR light. This fact is owing to different light proportions in the total LED spectra, especially for the blue component which greatly affects CCT (as seen in Figs. S1 and S2, supplementary information). In addition, between two different color gamut conditions, small difference of CCT can be found for the younger people, while large deviation of CCT for elderly people. There is not big different in the LER for different ages, and LER is higher for low MELR light than the high MELR light. LER would increase with the age of people.

Then, we would quantitatively discuss and analyze how the illuminance of four-primary LED display affects the circadian regulation of people with different ages by using figure of merit as CS. Fig. 6(a) and (b) show the required illuminance (lux) as a function of age based on above optimal SPDs when CS = 0.1 and 0.35 respectively. From this figure, it can be found that the required lux increases with the age of people. The elderly people need more lux than the younger people for arriving at the same circadian stimulus.

In addition, we also compare the circadian performance of three-primary LED display and four-primary LED display in

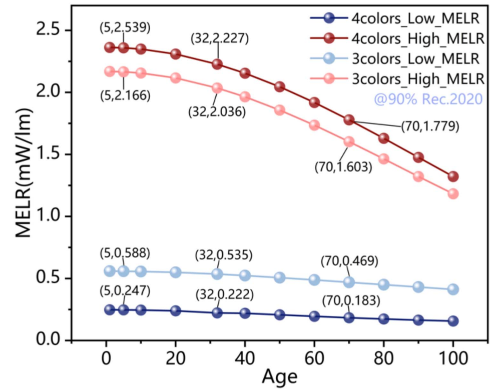

Fig. 7. The MELR values as a function of age for three-primary LED display and four-primary LED display at color gamut of 90% Rec. 2020.

this work. Fig. 7 shows the MELR values as a function of age for three-primary LED display and four-primary LED display at the color gamut Rec. 2020 of 90%. It can be seen that the four-primary LED display has larger circadian tunability (defined as the ratio of high MELR at 6500 K to low MELR at 2700 K) than three-primary LED display, thus possessing greater potentials in tuning the circadian rhythms of people. For example, at the age of 32, the circadian tunability is 10.032, while it is 3.806 for three-primary LED display. The comparison of CCT and LER can be found in Fig. S3. The LER for three-primary LED display is lower than four-primary LED display. Thus, in consideration both the visual and non-visual performance, four-primary LED display surpasses three-primary LED display. However, the CCT is not different between them.

IV. Conclusion

In this paper, we conduct an investigation on the circadian regulation of four-primary LED display with wider color gamut for different ages of people. First, the double-Gaussian function is used to mimic emission spectra of four-primary LEDs. Then, the melanopic luminous efficacy of radiation (MELR) and circadian stimulus (CS) are mainly used to evaluate the circadian performance of four-primary LED display. The genetic algorithm is used to achieving the compromise of color gamut and MELR for the standard observers at the age of 32. Then, the SPDs of other ages of people are deduced, and related analyses are performed. We believe that this work is helpful for guiding the spectral design of four-primary LED display for tuning the circadian rhythm in the future in consideration of different people with various ages.

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