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Design and Simulation of Low Circadian Action Micro-LED Displays with Four Primary Colors

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Received: 8 April 2020; Accepted: 5 May 2020; Published: 8 May 2020

Abstract: Nowadays, displays are ubiquitous in our daily lives. Long-time exposure to a display's unnatural light could influence the user's circadian rhythm, especially at night. Here, we propose a four-color micro-light-emitting diode (LED) display to achieve low circadian action for nighttime uses. Specifically, we evaluate the RGBW-type (red, green, blue, and white) and RYGB-type (red, yellow, green, and blue) micro-LED displays in terms of circadian effect and color gamut coverage. With the addition of an extra white subpixel, it was found that the circadian effect at night can be reduced dramatically, but the color gamut remains unchanged. However, with an additional yellow subpixel, both the circadian effect and color gamut were found to improve. Finally, we simulated the circadian illuminance of real image contents for different displays. In comparison with existing liquid crystal displays, organic LED displays, and RGB (red, green, blue) micro-LED displays, the proposed four-primary-color micro-LED displays can significantly reduce the circadian effect at night.

Keywords: circadian action; micro-LEDs; four primary colors

1. Introduction

Displays have become ubiquitous in our daily lives; their applications include large-size TVs, desktop monitors, notebook computers, pads, smartphones, and near-eye displays such as virtual reality and augmented reality. Presently, the liquid crystal display (LCD) and the organic light-emitting diode (OLED) display are two dominating technologies [1], while the micro-LED display is emerging and has potential to become a disruptive technology [2]. To produce three primary colors, two types of light source have been commonly employed: 1) red, green, and blue emitters (i.e., RGB sub-pixels) and 2) color conversion using GaN-based blue LEDs to pump yellow phosphor [3], green and red inorganic phosphors [4], or quantum dots [5–9]. However, a general concern is that the produced color is quite different from that of sunlight. For example, the natural sunlight from blackbody radiation exhibits a continuous, broadband spectrum, while the displayed colors are RGB concentrated, with a narrow and strong peak at the blue wavelength. Therefore, it is worth investigating whether watching such an unnatural light source for a long time would cause any health problem.

In this paper, we first discuss the influence of blue light (or high-energy photons) on our bodies. Next, we propose a new design of four-color micro-LED displays. The introduction of an extra color (or subpixel) can strongly reduce the circadian effect at night compared to the three-primary-color micro-LED displays. Our design also performs much better than the existing LCDs and OLED displays.

2. Influence of Blue Light

How the blue light influences our circadian rhythm has been studied intensively [10–12]. Under ambient light, the intrinsically photosensitive retinal ganglion cells (ipRGCs) innervating the suprachiasmatic nucleus (SCN) can affect melatonin secretion, which in turn alters the circadian rhythm [13]. According to experiments on light-induced melatonin suppression, the action spectrum of the circadian effect with a peak at blue wavelength has been proposed [14,15], as plotted in Figure 1. From this curve, we can see that blue light with a wavelength of 450–460 nm has the strongest influence. There are several parameters we can use to quantify this effect, including circadian action factor (CAF), circadian luminous efficacy (CLE), circadian efficacy of radiation (CER), and circadian illuminance (CIL). They all quantify how much light perceived by human eye can contribute to the circadian effect. From Equations (1)–(3), it can be seen that they are quite related. Here, LER stands for the luminous efficacy of radiation, LE is luminous efficacy, and VIL is visual illuminance. If we take CAF as an example, usually at daytime, we would need a larger CAF value, while we would need a smaller CAF value to follow the circadian rhythm at nighttime.

$$\mathrm{CAF}\,(\mathrm{blm}\cdot\mathrm{lm}^{-1}) = \mathrm{CER}\,(\mathrm{blm}\cdot\mathrm{W}^{-1})\,/\,\mathrm{LER}\,(\mathrm{lm}\cdot\mathrm{W}^{-1}) \tag{1}$$

$$\mathrm{CLE}\,(\mathrm{blm}\cdot\mathrm{W}^{-1}) = \mathrm{LE}\,(\mathrm{lm}\cdot\mathrm{W}^{-1}) \times \mathrm{CAF}\,(\mathrm{blm}\cdot\mathrm{lm}^{-1}) \tag{2}$$

$$\mathrm{CIL}\,(\mathrm{blx}) = \mathrm{CAF}\,(\mathrm{blm}\cdot\mathrm{lm}^{-1}) \times \mathrm{VIL}\,(\mathrm{lx}) \tag{3}$$

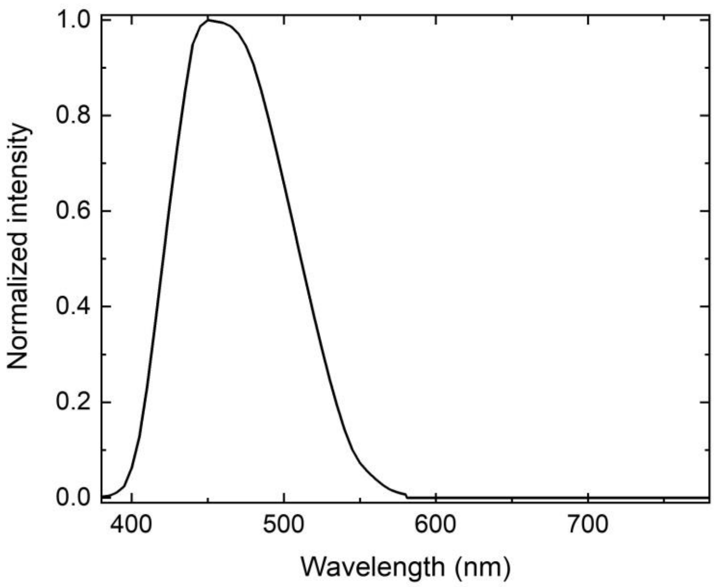

Figure 1. Circadian action spectrum. Data replotted from [14].

This influence is important to human beings because nowadays, it is a common problem for those who watch screens at night for a long time to have a hard time falling asleep. A recent work was devoted to evaluating the circadian properties of some LCDs and OLED displays [16]: It was found that while displaying the same content, LCDs have a slightly lower circadian effect than OLEDs. To further reduce the circadian effect, many have proposed the use of an even shorter wavelength because a shorter blue wavelength overlaps less with the circadian action spectrum [16,17]. However, this approach raises another concern regarding whether short blue wavelengths are safe to the human eye.

Some literatures have report that blue light can make retinal cells release some chemicals that are harmful to other cells [18]. Some other works have shown that high-energy blue light may cause a common eye disease called age-related macular degeneration, though in these studies, only in vitro experiments or in vivo (in rats) experiments were performed [19]. However, there is no direct evidence that the high-energy blue photons emitted from a display cause human eye disease for two reasons. First, the blue light emitted from a display panel is weak compared to indirect sunlight and room lighting. Second, the environment in our eyes is very sophisticated, and several protection mechanisms exist in the cells in human eyes [20].

From above justifications, the potential hazard of the high-energy photons from a display panel is not a real concern compared to the circadian effect. Therefore, the question of how to minimize a display's circadian effect at night is more crucial. In fact, many existing products offer such functionalities, such as the night shift mode in Apple's products, blue filter mode in Samsung's products, and reader mode in many monitors. All these modes simply shift the white point from D65 (correlated color temperature (CCT) = 6504 K) to a lower CCT white point (for example, 3000 K) by adjusting the spectral ratios between the RGB colors. For micro-LED displays, similar strategies can be applied as well. However, here we propose a new four-color approach to achieve better performance by utilizing the self-emissive and narrow emitting bandwidth properties of micro-LEDs.

3. Four-Color Micro-LED Displays

To fulfill low circadian action, here, we propose a four-color micro-LED display. As Figure 2 depicts, such a display consists of four subpixels. In addition to the traditional RGB subpixels (Figure 2a), another subpixel, which can be a yellowish white pixel or a yellow pixel (Figure 2b), was added in our design to further mitigate the circadian effect. Previously, RYGB-type (red, yellow, green and blue) four-primary-color displays have been proposed to enlarge the color gamut of LCDs [21,22], and RGBW-type (red, green, blue, and white) displays have been demonstrated to boost display brightness [23]. Here, our proposed four-color displays mainly targets reducing the circadian effect.

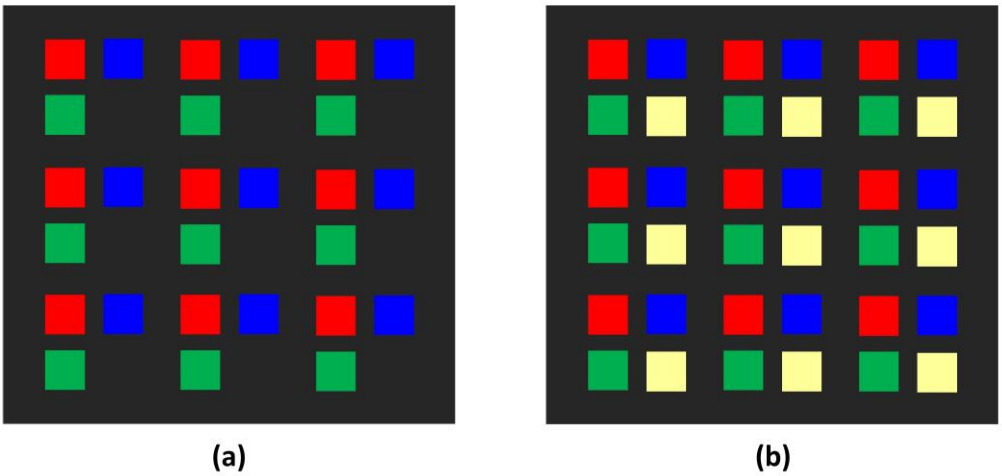

Figure 2. An example of pixel arrangements of (**a**) three-color micro-light-emitting diode (LED) displays and (**b**) four-color micro-LED displays.

To obtain a yellow subpixel, we could use a yellow micro-LED chip directly or a phosphor-converted blue micro-LED with complete down-conversion. On the other hand, a yellowish white subpixel could be realized by designing a phosphor-converted blue pixel with incomplete down-conversion. For both RGBW and RYGB four-color micro-LED displays, a lower circadian effect and a wider color gamut are desirable. Rec. 2020 is a color space specifying various aspects of ultra-high-definition televisions with a wide color gamut [24]. Here, we used CAF as the indicator of the circadian effect and calculated the color gamut coverage (CGC) in Rec. 2020 standard, specifically by:

$$\text{CAF} = \frac{K_c \int S(\lambda)C(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda}, \tag{4}$$

$$\text{CGC} = \frac{A_{display} \cap A_{standard}}{A_{standard}}, \tag{5}$$

where $A_{display}$ is the color gamut area of the display, $A_{standard}$ is the color gamut area of the color standard, K_c is a normalization constant that ensures CAF = 1 for the International Commission on

Illumination (CIE) standard daylight illuminant D65, $S(\lambda)$ is the spectral power distribution of the mixed white light, $C(\lambda)$ is the circadian action function, and $V(\lambda)$ is the photopic eye sensitivity function. Our objective was to optimize the CAF for a 3000 K white point, which is quite close to the white point of commercial displays at night modes.

As for the input micro-LED spectra, we adopted the measured spectra of RGB micro-LEDs from PlayNitride (one of the leading micro-LED manufacturers) [25], as shown in Figure 3a. In calculations, the line shape of each spectrum remained the same, but the peak wavelength was allowed to shift within a small range. The yellow micro-LED was assumed to have the same spectral power distribution as the red micro-LED for simplicity. More specifically, the range of the peak wavelength for each micro-LED was [420, 490], [490, 560], [560, 610], and [610, 670] for the blue, green, yellow, and red micro-LEDs, respectively. For the yellow phosphor spectra, we found that the spectra of some commercially available phosphors (Figure 3b) could be fitted with asymmetric Gaussian function as:

$$S_G(\lambda, \lambda_0, \Delta\lambda_1, \Delta\lambda_2) = \begin{cases} e^{-4\ln 2 \frac{(\lambda-\lambda_0)^2}{\Delta\lambda_1^2}} & (\lambda < \lambda_0); \\ e^{-4\ln 2 \frac{(\lambda-\lambda_0)^2}{\Delta\lambda_2^2}} & (\lambda \geq \lambda_0), \end{cases} \tag{6}$$

where λ_0 is the central wavelength and $\Delta\lambda_1$ and $\Delta\lambda_2$ are fitting parameters. From fittings of some phosphor spectra, $\Delta\lambda_2/\Delta\lambda_1$ was set to be 2.5. Similar to the yellow micro-LED chip, the central wavelength of the yellow phosphor spectra was assumed to be in the range of [540, 610]. Different full width at half maximum (FWHM), defined as $(\Delta\lambda_1 + \Delta\lambda_2)/2$, was also considered, including 40, 60, 80, 100, and 120 nm, in order to study the trend.

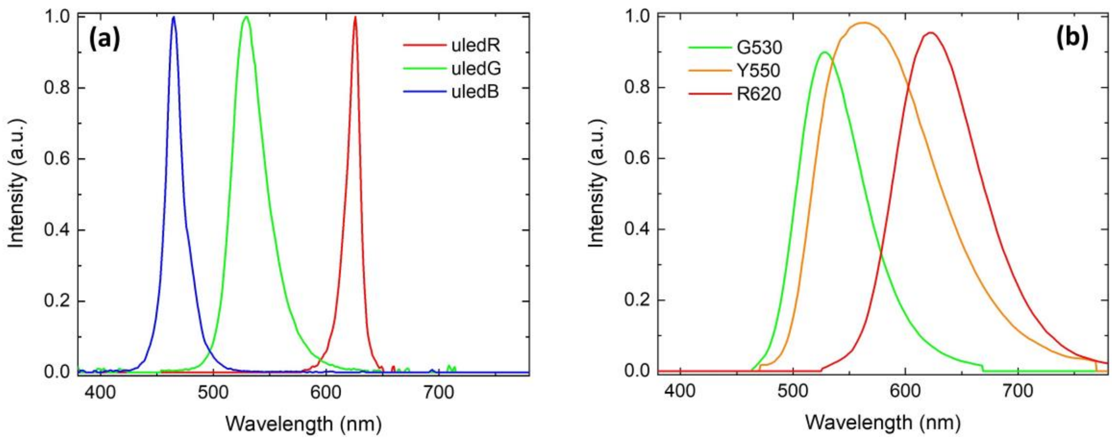

Figure 3. (**a**) Measured RGB (red, green, and blue) micro-LED spectra from PlayNitride [25]. (**b**) Spectra of some commercial phosphors.

Since the objectives (CAF and CGC) were purely dependent on the spectra, we could simulate them through our homemade MATLAB code. During the optimization process, four algorithms (genetic algorithm, particle swarm optimization, differential evolution, and adaptive simulated annealing) were utilized interchangeably to obtain global optimal solutions. For multi-objective optimizations, the intrinsic tradeoffs among objectives created a unique geometry termed Pareto front, where each individual on the geometry demonstrated an optimal solution that had at least one objective outperforming the others.

3.1. RGBW-Type Micro-LED Displays

The result plotted in Figure 4 shows that there is a tradeoff between the CGC and the CAF. It is also worth mentioning that the introduction of the 3000 K white subpixel should not influence the color gamut such that the highest CGC is the same for all the cases. Interestingly, compared to RGB-type micro-LED displays, the RGBW-type micro-LED displays can achieve a much lower CAF. As the bandwidth of the phosphors gets narrower, the CAF is lower when the color gamut remains the same. This may be somewhat contradictory to expectations at first glance because one may think a continuous spectrum would be more natural and should exhibit a lower CAF. However, the action spectrum mainly focuses on the blue and cyan colors. When the bandwidth of yellow color gets narrower, the ability to tailor the spectrum is higher, which enables a better design to reduce the overlapping with the action spectrum. Given that the CAF of a 3000 K blackbody radiator is around 0.43, an 87% Rec. 2020 RGB-type micro-LED display would have a higher CAF (~0.49). However, by using yellow phosphors whose bandwidth is as broad as 120 nm, the CAF can be reduced to ~0.33, which corresponds to a 33% decrease in comparison with the RGB-type.

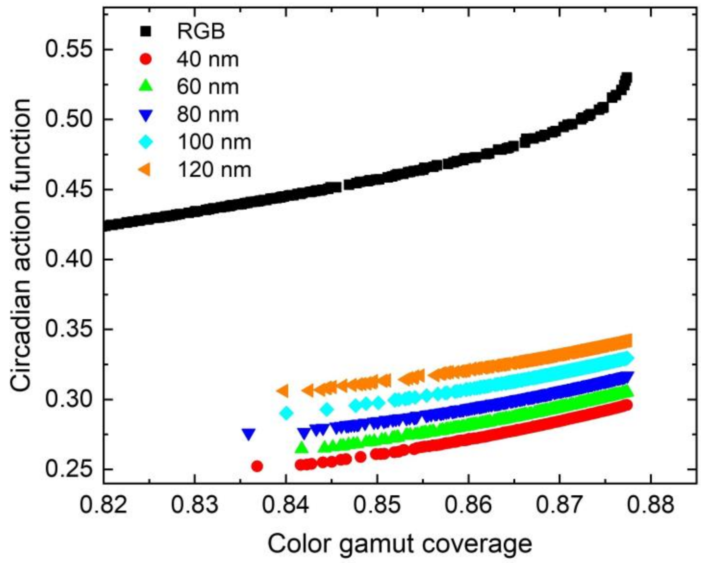

Figure 4. Pareto front of red, green, blue, and white (RGBW)-type micro-LED displays.

An advantage of the systematic optimization is that the parameter preference, as well as the correlations between each input parameter and each objective, can be studied. As an example, here we investigated a quite realistic case where the FWHM of the yellow phosphor was 60 nm. Figure 5 shows the relationship between the objectives (CGC and CAF) and the central wavelengths of RGB micro-LEDs and the yellow phosphors. As noticed, for all the optimal solutions, the central wavelengths of red and green micro-LEDs and the yellow phosphor stayed almost the same at around 639 nm, 518, and 567, respectively. The central wavelength of the blue LED became the determining factor of both CGC and CAF, where a longer blue wavelength led to a larger CGC but also a larger CAF.

3.2. *RYGB-Type Micro-LED Displays*

In comparison with RGBW-type micro-LED displays, the RYGB-types could achieve a wider CGC because four primary colors were used. The Pareto front is plotted in Figure 6. Similarly, there was a tradeoff between CGC and CAF, and the RYGB-type micro-LED displays could achieve a much lower CAF than the RGB-type. As the bandwidth of phosphors got narrower, CAF could achieve a lower value while CGC could be larger. By comparing to the cases with phosphors, it could be seen that the CGC of pure micro-LEDs could achieve a much higher value because the bandwidth of yellow micro-LED was much narrower than that of the yellow phosphor. We need to point out that in our simulations, we assumed the yellow micro-LED had the same line shape as the red one, but this assumption may not hold in real cases. However, when the line shape of yellow LED was broadened, we can see from Figure 6 that the maximum CGC decreased and the minimum CAF increased.

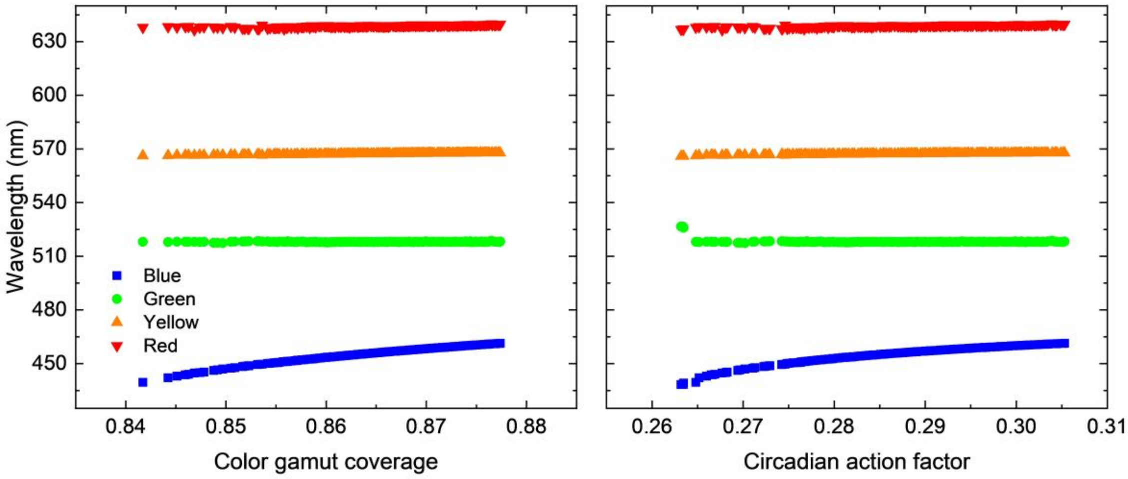

Figure 5. Correlations between objectives (color gamut coverage (CGC) and circadian action factor (CAF)) and the central wavelengths of RGB micro-LEDs and the yellow phosphors, where the bandwidth of the yellow phosphor was 60 nm (RGBW-type).

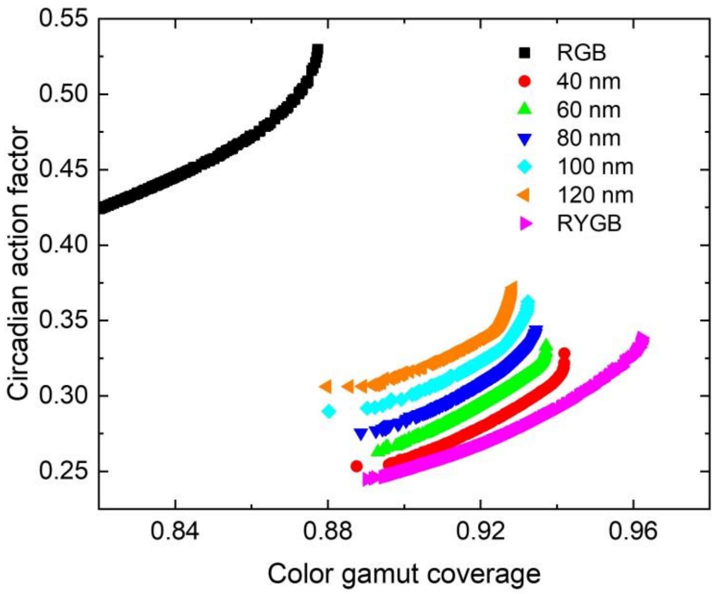

Figure 6. Pareto front of red, yellow, green, and blue (RYGB)-type micro-LED displays. In the plot, RYGB denotes the case with yellow micro-LED chips.

For comparison with the RGBW-type, we explored the parameter preference and the correlations between each input parameter and each objective for the case where the FWHM of the yellow phosphor was 60 nm. Figure 7 depicts the relationship between the objectives (CGC and CAF) and the central wavelengths of RGB micro-LEDs and yellow phosphors. In this case, the central wavelength of the green micro-LED stayed almost the same (around 516 nm), and that of the blue LED still exhibited the same trend as in the RGBW-type. However, the yellow and red central wavelengths were also varied to achieve a larger CGC.

3.3. Performance Comparison between an RGB-Type and an RYGB-Type Micro-LED Displays

Once we had obtained a set of optimal solutions, we could study their performance in detail. For example, we compared the performance of an optimized RGB-type micro-LED display with an optimized RYGB-type micro-LED display whose yellow subpixels comprised yellow micro-LED chips. Detailed peak wavelengths and performance are listed in Table 1. The addition of yellow subpixels enlarged the CGC by ~5% in Rec. 2020 color space and decreased the CAF to almost one half, as compared to the RGB-type micro-LED display. The optimized spectra of these two displays for a 3000 K white point are plotted in Figure 8a. In the RYGB case, the spectrum of 3000 K white point was mainly contributed by the red, yellow, and blue subpixels in order to decrease CAF. In addition to the optimized white point, other mixed colors also exhibited a decreased CAF. For instance, for a 4000 K white point on the blackbody locus, the CAF of the RYGB-type was ~40% lower compared to that of the RGB-type. Their corresponding spectra are depicted in Figure 8b. Again, the spectrum of 4000 K white point was mainly contributed by the red, yellow, and blue subpixels. The details of their color gamut are shown in Figure 8c. The introduction of yellow pixel mainly enlarged the CGC in green, yellow, and amber wavelengths.

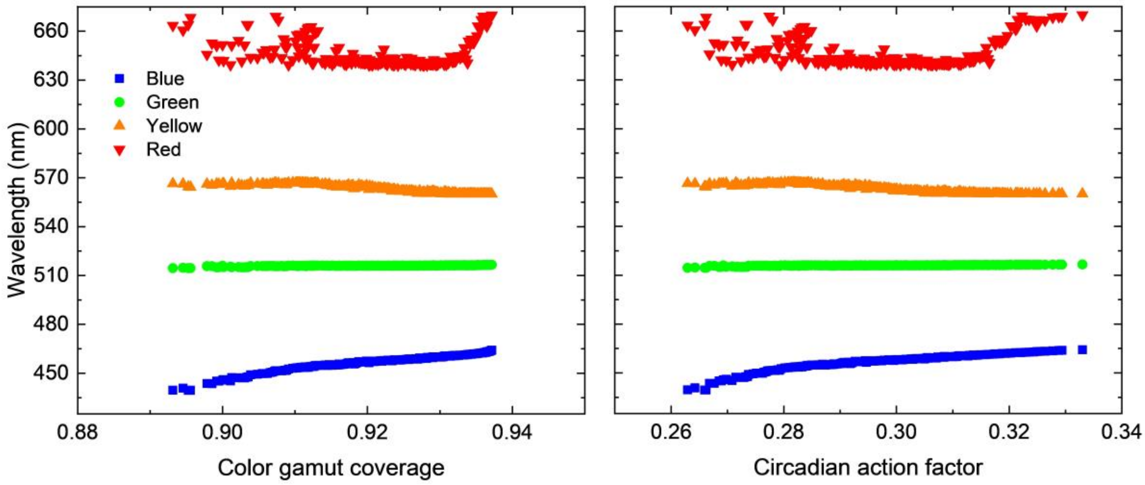

Figure 7. Correlation between objectives (CGC and CAF) and the central wavelengths of the RGB micro-LED display and the yellow phosphors, where the bandwidth of the yellow phosphor was 60 nm (RYGB-type).

Table 1. Central wavelengths and performance of two micro-LED displays.

Type	Peak Wavelength (nm)				CGC	CAF (3000 K)	CAF (4000 K)
	R	Y	G	B			
RYGB	639.8	567.7	515.3	449.5	0.928	0.277	0.437
RGB	640.0	-	520.2	461.6	0.876	0.517	0.711

Thus far, we have demonstrated how the RYGB-type reduced the CAF for the designed white point and another white point. Nevertheless, the ultimate goal was to achieve a lower circadian effect for complete images or displayed contents. To evaluate the circadian effect of different displayed contents at night for different types of displays, four websites under blue-filter mode were captured, and their circadian actions were evaluated for an LCD (iPhone 8 plus), an OLED display (Galaxy S8), the optimized RGB-type micro-LED display, and the optimized RYGB-type micro-LED display (as listed in Table 1).

In our calculations, we assumed that the illuminance of a certain image for different displays was the same. Because illuminance and circadian illuminance are only related to the spectra of a display, we were thus able to simulate the corresponding circadian illuminance for different displays. The simulated results are listed in Table 2. Please note that for a certain image, every display showed the same image content, including perceived colors and brightness. This means that for a certain website, even if the illuminance of all different displays is the same, the circadian illuminance can vary a lot. From Table 2, it can be seen that for all the websites, the RGB micro-LED display showed the highest circadian illuminance. The LCD and the OLED display provided a similar circadian illuminance, though one that was lower than that of the RGB micro-LED display. This was understandable because from the Pareto front, we knew that there was a tradeoff between CGC and CAF. With a much smaller CGC, the LCD and OLED display could achieve a smaller circadian effect. However, intriguingly, the RYGB micro-LED did achieve a much lower circadian effect than all other displays. For all these images, the RYGB micro-LED display could realize a 35%~37% lower circadian illuminance to the RGB micro-LED display.

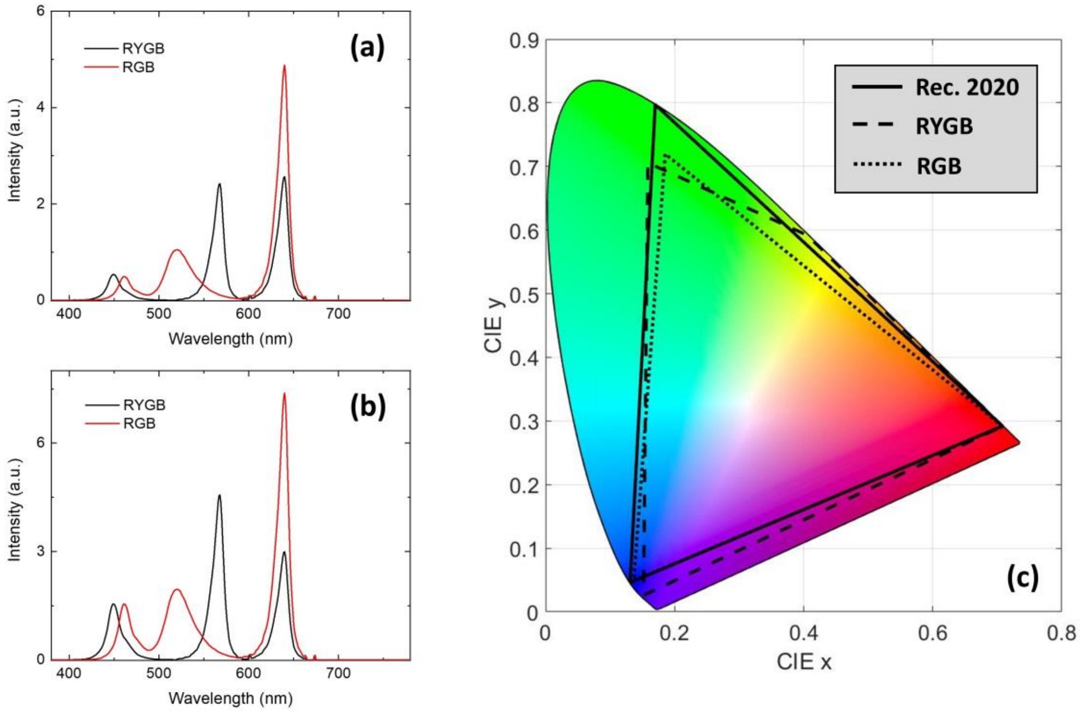

Figure 8. The spectra of an optimal RGB-type and an optimal RYGB-type micro-LED displays for (**a**) the 3000 K white point and (**b**) the 4000 K white point, as well as (**c**) the corresponding color gamut of these two displays in International Commission on Illumination (CIE) 1931 color space.

Table 2. Comparison of the circadian illuminance for different displays.

Website		Zhihu	Twitter	YouTube	Google
Circadian illuminance (blx)	LCD	36.4	27.6	19.9	33.4
	OLED	38.8	29.4	21.2	35.6
	RGB micro-LED	44.0	33.3	24.3	40.6
	RYGB micro-LED	28.5	21.6	15.4	26.0
Illuminance (lx)		57.3	43.8	34.6	54.5

4. Conclusions

We investigated how a display's blue light affects the user's circadian rhythm. We evaluated the performance of two types of four-color micro-LED displays: RGBW and RYGB. Our results indicated that the new RYGB-type micro-LED display helps to reduce the circadian effect at night. The introduction of additional yellow subpixels not only offers a better night-shift mode than simply rearranging the RGB ratios in traditional displays but also widens the color gamut of micro-LED displays. This strategy may also apply to other emissive displays such as OLEDs.

Author Contributions: Methodology, Z.H. and G.T.; writing—original draft preparation, Z.H.; writing—review and editing, Z.H. and S.-T.W.; supervision, Y.-F.L. and S.-T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by a.u.Vista, Inc.

Conflicts of Interest: The authors declare no conflict of interest.

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