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Simultaneous optimization of circadian and color performance for smart lighting systems design

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ABSTRACT

We present in this work a method to design lighting sources that can be adapted to different temperatures of color and, simultaneously, with a tunable circadian character. We obtained an acceptable range of tuning in both parameters compared to the bibliography. This kind of lighting source has potential applications particularly in building lighting, but also in farming or agriculture. At the same time, we have shown the possibilities of multiobjective optimizations in the lighting industry. The optimization has been developed using the Genetic Algorithm and multiobjective merit functions. The lighting source is able to work under two different regimes regarding the circadian effect, with a design based on a combination of two monochromatic and two white Lighting Emitting Diodes (enough for controlling the circadian character and the color performance at the same time). A prototype, which can be manually or automatically controlled, has been also implemented and evaluated, with a performance in terms of color coordinates very close to the daylight, showing a modulation of the Circadian Efficacy of Radiation between 6% and 16%, and a Color Rendering Index above 80%.

1. Introduction

Lighting is a key parameter for building functionality, sustainability and comfort. In order to perform their tasks in a safe and comfortable way, occupants need lighting that provides adequate visibility without causing discomfort [1]. By designing quality lighting conditions, it is also possible to achieve efficiency and energy saving. Very similar to acoustic building design, lighting design can have either positive or negative effects, particularly in the spaces where the occupants spend a lot of time [2].

In the case of humans and other living organisms, light not only provides visual information, but also affects their physical, physiological and psychological behaviors. This is due to the presence of melatonin, a ubiquitously molecule present since the origin of life, from bacteria to mammals [3]. The suppression or activation of melatonin regulates the endogenous circadian clock, with 24-h cycles adapted to daylight. Melatonin also plays a key role in seasonal photoperiodic regulation in animals [4]. In addition to natural daylight, humans are nowadays also exposed to a considerable amount of artificial light. Thereby, artificial light can affect the timing of the circadian clock causing sleep alterations. These phenomena are called “non-visual biological effects of light” [6,5]. Usually, non-visual effects are considered as harmful or detrimental. However, we can take advantage of these effects in different environments such as schools, hospitals, farming or agriculture. Thus, speaking about healthy lighting, we should focus not only on humans, but also on animals and plants [7].

While the research on visual effects of light has a long history, the field of non-visual effects of light is somehow recent. The effect of light on the production of melatonin was discovered in 1980 [8], whereas the third type of photoreceptors in the retina of mammals (denoted as intrinsic photosensitive retinal ganglion cells, ipRGCs) was discovered by Berson in 2002 [9]. Further researches shown that ipRGCs are mainly sensitive to the blue-green zones of the spectrum (with a maximum of sensitivity around 480 nm) [10]. Coinciding with the research on non-visual effects of light, lighting sources based on white Light-Emitting Diodes (LEDs) have overtaken incandescent and fluorescent lighting types over the last decade. This is due to many advantages such as low power consumption, small size and reduced heat radiation [11–13]. Some previous works are focused on the design of LED-based lighting systems oriented to different designs. Thus, for example, there are available artificial lighting designs optimized for a high vision

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performance in terms of color temperature or color rendering capability [14–16]. We also can find many examples, especially in the recent years, able to keep good vision performance whereas the circadian effect is minimized [12,13,17–19]. Commonly, the design is made after a single objective optimization, trying to maximize or minimize only one quality factor. There also exist some examples of designs that can be adapted to different objectives along the day or along the year [20]. Moreover, and regarding to the circadian effects, the literature reports lighting systems designed for a high circadian effect (called "Blue Enriched White Light", understanding that the blue light is responsible of the non-visual effects) [21], as well as lighting systems with a low circadian effect (called "Blue Depleted White Light", or even "Blue-free light") [22].

In this work, we show that there is still room for further improvements in lighting designs. Our aim is the development of a smart lighting system based on a multiobjective optimization, able to achieve a good performance both in the visual aspects as well as in the non-visual effects, by taking advantage of high and low circadian effects. The lighting system, composed of four kind of LEDs driven by different currents, can be adapted to different color temperatures (i.e. providing visual comfort) but it is also able to allow a tunable circadian effect, with two different regimes of circadian effect. Thus, our lighting system can be adapted to different tasks in indoor environments, such as increasing the attention, reducing the sleep alterations, or even affecting to the seasonal perception of animals and plants in order to increase the production in agriculture and farming, and it can be combined with any kind of control system. The color and circadian characteristics of the source could be change manually (e.g. by the final user), or it can be combined with an automatized system, depending on a sensor or a timetable, for example. Although introducing this lighting system is the main novelty of this work, we also want to show the possibilities of multiobjective optimization in the lighting industry. Our intention is also to detail the different steps that should be carried out in a complete multiobjetive design of a lighting system.

The structure of this paper can be summarized as follows. In Section 2 we introduce some definitions used to describe the quality of light spectra. In Section 3 we explain the optimization method, showing the main results. The features of a prototype based on our design are evaluated in Section 4. Finally, we summarize in Section 5 the main conclusions of this work.

2. Theory

2.1. Circadian and visual radiometric quantities

Traditionally, the characterization of Lighting Systems has been made in terms of the Correlated Color Temperature (CCT, the temperature of the black body whose perceived color is closer to a given spectrum) and the coordinates in a color space (known as the tristimulus values RGB, corresponding to the CIE standard observer color matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$). Thus, any spectral distribution $S(\lambda)$ can be projected in a chromaticity diagram using the tristimulus values, *XYZ* (see Fig. 1). For example, the *XYZ* values for the black-body emission spectra define the Planckian locus on the chromaticity diagram. This leads to a new variable, the Correlated Color Temperature (CCT), which is widely used in the industry since it allows describing a spectral distribution with only one parameter [17]. There are many other quantities from the point of view of indoor lighting, such as Color Rendering Index (CRI), which reveals the ability of a spectral distribution to reproduce faithfully the true color of an object. On the other hand, since the discovery of the sensitivity of ipRCGs to blue-rich light, different functions have been proposed to quantify the circadian effect of a given spectrum [17,23]. Thus, the Circadian Efficacy of Radiation (CER) is defined as

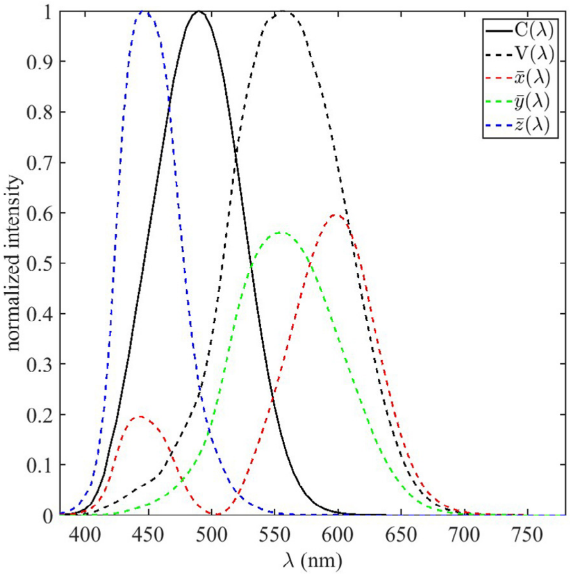

Fig. 1. Normalized Circadian Action Factor, normalized photopic eye-sensitivity and the CIE standard color matching functions (normalized to the maximum).

$$\mathrm{CER} = \frac{\int_{380\mathrm{nm}}^{780\mathrm{nm}} S(\lambda)C(\lambda)d\lambda}{\int_0^\infty S(\lambda)d\lambda}, \tag{1}$$

being $C(\lambda)$ the circadian spectral sensitivity function. In addition, another useful parameter is the Circadian Action Factor (CAF), defined as,

$$\mathrm{CAF} = \frac{\int S(\lambda)C(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda}, \tag{2}$$

with the integrals defined between 380 and 780 nm. Fig. 1 also shows the photopic eye-sensitivity $V(\lambda)$ and the circadian action spectrum $C(\lambda)$), with peaks at 555 nm and 490 nm respectively.

Note that Eq. (1) is defined between 0 and 1, whereas Eq. (2) is a ratio and, therefore, it can take value over 1. It is also notorious that a high value of CAF does not show the total amount of circadian potential of a spectral distribution. In this sense, CER (that is, the amount of light in the circadian region) is more suitable for the aims of this work in order to characterize the circadian potential of a spectral distribution. On the other side, regarding the color quality, we choose to work with the CCT parameter, since it allows to describe easily the color characteristic and the proximity to the ideal white (the black body spectral emission). In addition, CCT is widely used to describe the spectral behavior for final users. In the following sections, we will describe the use of CCT and CER as merit functions for our multiobjective optimization.

2.2. Spectral characterization of LEDs

For the experimental implementation of the smart lighting system, we have different kind of LEDs available, all of them from CREE, Inc [24]. We have a simple set-up for LEDs characterization, shown in Fig. 2. Each LED is driven by an electrical current source (PROMAX, FA-363C). At a fixed distance of the LED we have a GRIN lens, collecting the light into an optic fiber and guiding it up to an optical spectrometer (RGB Photonics, Smini). We also use a 250 mm diameter integrating sphere (Admesy, AC-AIS-250-01) for the radiant power characterization.

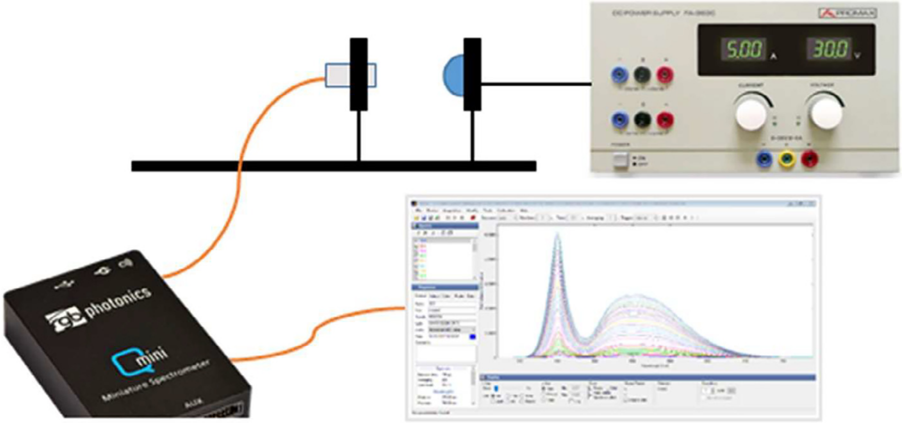

Fig. 2. Schematic measurement setup for the spectral characterization of LEDs.

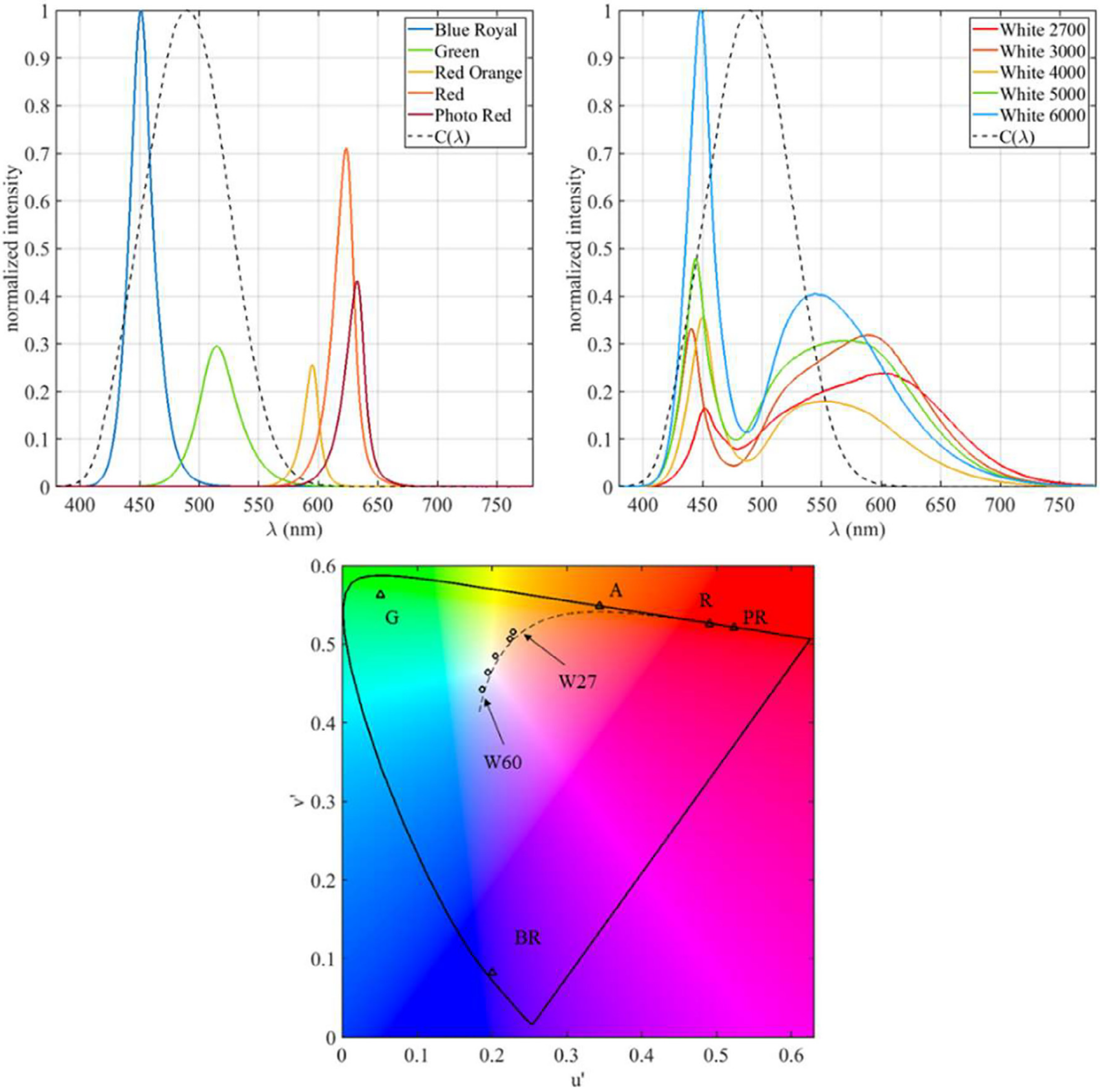

Fig. 3. Up: Spectra of the monochromatic LEDs for different currents (left) and spectra of the white LEDs driven at 1 A (right). Dotted curves show the Circadian Action Factor $C(\lambda)$. Down: Color coordinates of the monochromatic (triangles) and white (circles) LEDs.

Fig. 3 shows the Measured spectra of the studied LEDs. As can be seen, we have five monochromatic LEDs (from blue to red) and five white LEDs with different color temperatures, from 2700 K to 6000 K. As we will see, we use only some of these LEDs in the final design of our lighting system. We think, however, that it could be useful for the reader to see a comparison between these

LEDs, in order to understand our election, explaining what kind of parameters could be interesting for our goals. The plots in Fig. 3 also show the circadian action function $C(\lambda)$. It is important to note that, among the monochromatic LEDs, only the Blue Royal and the Green LEDs have significant optical power within the circadian region. This fact will be important for the election of the suitable LEDs. In addition, the emission peak of the Blue Royal matches the blue peak of the white LEDs, whereas part of the emission of the Green LED falls in the region with minimum emission of the white LEDs. Thus, whereas Blue royal and Green LEDs give us circadian action, the Blue Royal LED is redundant when is combined with white LEDs. Moreover, the emission of Green LEDs is close to the gap in the white spectra below 500 nm (indeed, it is the only LED able to emit close to this region), and therefore, it can help to smooth the final spectrum. For all these reasons, the Green LED becomes very useful for our aims. In the case of the white LEDs, a higher color temperature implies a higher bluish component. The spectral curves of the white LEDs are not as smooth as the theoretical spectral curves of the black body. This fact affect to the CRI of lighting systems based on white LEDs. Thus, we can see in Table 1 that the CRI parameter of this white LEDs falls below 80, which represent a bad performance in terms of color rendering.

Following the definitions in Section 2.1, and due to the results shown in the following sections, we focus in the use of two monochromatic LEDs plus two white LEDs. Regarding the monochromatic LEDs, we choose the Red and the Green LEDs, corresponding with two of the three color matching functions. The first one is placed on the reddish extreme of the spectrum (i.e., with low circadian effect), whereas the Green LED gives us circadian action and is not redundant with white LEDs spectra. As we have previously explained, we can discard the Blue LED, since the white LEDs have a significant peak at this wavelength. On the other hand, the selected white LEDs correspond to the minimum (reddish) and maximum (bluish) color temperature (2700 K and 6000 K, respectively). In other words, they present the lower and the higher circadian factor, as can be seen in Table 2. Thus, we try to get a soft and continuous spectrum based on the white LEDs, able to be adapted to different color temperatures, and at the same time, able to induce different circadian activity using the three monochromatic LEDs. In any case, if the reader is interested in replicate our results, it is possible to test the performance with different combinations of LEDs. In our case, the best results have been obtained with the four mentioned LEDs.

Once we have selected the most suitable LEDs, we study the dependence of the spectral emission with the electrical current. Beginning with the monochromatic LEDs, we see that there is a small shift of the emission peak, but it is always lower than 10 nm. Thus, we can disregard this effect. At the same time, the spectral shape remains unaltered. Fig. 4 (left) collects the maximum peak of emission for the monochromatic LEDs at different currents. As can be seen, the behavior is not linear. We obtain similar results with the white LEDs.

Finally, in order to know the driven current needed to get a certain amount of power, we normalize the maximum optical power for each LED. Fig. 4 (right) shows the four curves. A polynomial fit for each curve gives us the numerical behavior of each LED. For two of them we need up to a third order for a better fitting. The fitting equations are,

$$I_r = 371.39 \times P_r^2 + 615.87 \times P_r + 5.90$$

$$I_g = 846.98 \times P_g^3 - 500.80 \times P_g^2 + 648.10 \times P_g - 11.46$$

$$I_{60} = 441.77 \times P_{60}^2 + 533.72 \times P_{60} + 8.16$$

$$I_{27} = 395.62 \times P_{27}^3 - 133.11 \times P_{27}^2 + 736.62 \times P_{27} + 5.42 \qquad (3)$$

where I denotes the driving current (in mA), P denotes the normalized power, and the subscripts r, g, *60* and *27* stand for Red, Green, White 6000 and White 2700 respectively.

Once we have selected and characterized the most suitable LEDs for our assembly, we can face the optimization and design of the Smart Lighting system.

2.3. Functions of merit

We will perform a multi-objective optimization based on a combination of the four selected LEDs with two main goals. As we have mentioned, we have two main objectives: to control the color performance and to change the circadian action, both at the same time. Thus, regarding to the color performance, we look for spectra close to the curves of the black body for different temperatures. As it is known, CCT has become a standard in lighting industry for describing the color characteristics of white sources, since it is easy to understand by the final user [17]. On the other hand, we will try that the light source can work in two different regimes, i.e. with a high circadian emission as well as with a low circadian emission, regardless the color temperature. The result of the optimizations is a set of weights for each LED, which need to be translated to electrical current using Eq. (3). Finally, and although it is not considered by the optimizations, we will evaluate other characteristics, such as the color coordinates or the CRI of the light source for the different working regimes.

Any optimization requires of criteria defining the goodness of the results. These criteria are expressed as a mathematical function, called merit function. The objective of our optimization algorithm is to look for a global minimum in this merit function. Since we have a multi-objective optimization, we will define a merit function for each objective, and a global merit function (as a linear combination of both partial merit functions) for the global optimization. The first merit function is the distance between the color coordinates of the emitted spectrum and the spectrum of the black body at a certain temperature, using the root mean square. Thus, given a black body emission curve (normalized) at a certain temperature, $B_T(\lambda)$, and a certain normalized emission spectrum designed for the color temperature T, $S_T(\lambda)$, the first merit function will be

$$f_{CCT} = \frac{1}{N_T}\sum_T \frac{[CCT(S_T(\lambda)) - CCT(B_T(\lambda))]^2}{CCT(B_T(\lambda))} \qquad (4)$$

Table 1
CRI, CAF, CER, uv coordinates and maximum luminous flux for the White LEDs evaluated in this work.

	2700 K	3000 K	4000 K	5000 K	6000 K
CRI	85.60	73.60	73.00	76.00	70.00
CAF	0.49	0.45	0.72	0.61	0.81
CER	0.25	0.24	0.35	0.34	0.37
u	0.23	0.22	0.19	0.20	0.19
v	0.34	0.34	0.31	0.32	0.29
Luminous Flux (lm)	218	249	266	284	284

Table 2
Characterization parameters of the monochromatic LEDs.

	Blue Royal	Green	Amber	Red Orange	Red	Photo Red
Wavelength (nm)	450	515	595	620	630	660
FWHM (nm)	20	40	15	20	20	20
U	0.20	0.05	0.34	0.49	0.52	0.57
V	0.05	0.37	0.37	0.35	0.34	0.34
CAF	7.32	1.12	0.02	0.01	0.01	0.01
CER	0.58	0.70	0.02	0.01	0.01	0.00
Luminous Flux (lm)	30	327	188	220	177	90

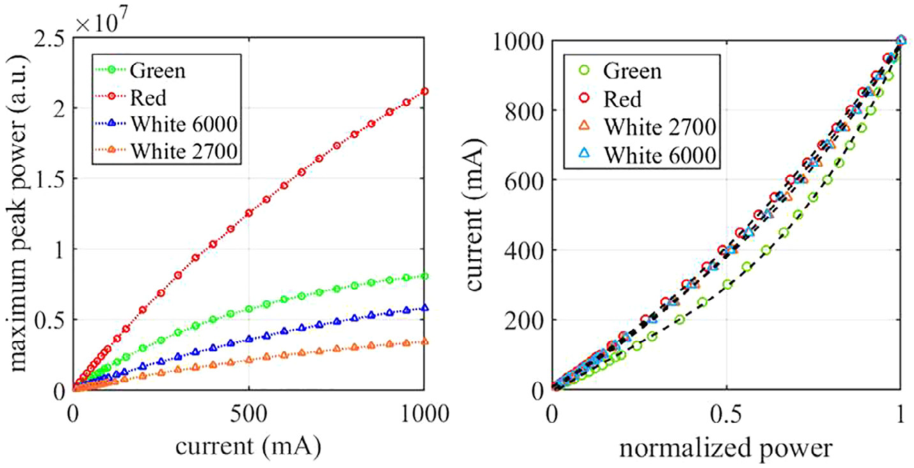

Fig. 4. Left: Optical power of the selected monochromatic LEDs at different currents. Right: Electrical current versus optical power normalized to the maximum of each LED.

where N_T is the number of temperatures used in the optimization. The second merit function takes into account the circadian amount of radiation of the spectral distribution using Eq. (1), and it will depend on the working regime (Low or High circadian effect). We choose to use CER to describe the circadian effect, and thus the two merit functions will be,

$$f_{CER}^{Low} = \frac{1}{N_T}\sum\nolimits_T CER_T ; f_{CER}^{High} = \left(1 - \frac{1}{N_T}\sum\nolimits_T CER_T\right) \tag{5}$$

with *CER* defined in Eq. (1). The global merit function will also depend on the working regime. If we are looking for a low circadian effect, we will simply use,

$$f_T^{Low} = f_{CCT} + f_{CER}^{Low} \tag{6}$$

which is minimum when both f_{CCT} and f_{CER} are minimum. On the contrary, if we are looking for a high circadian effect at a given temperature, we will use

$$f_T^{High} = f_{CCT} + f_{CER}^{High}, \tag{7}$$

being minimum when both f_{CCT} and $(1 - f_{CER})$ are minimum, since Eqs. (1 and 5) are defined between 0 and 1. As we have mentioned, the result of the optimization will be a set of weights for each LED, equivalent to the normalized power in Eq. (3). Note that similar results can be obtained using CAF instead of CER, since CER depends only on the evaluated spectrum, regardless the $V(\lambda)$ function.

3. Optimizations

In this section we present some of the optimizations performed for the realization of this work. For reasons of clarity, we will show the process leading to the final design, starting from the simplest configuration. All the optimizations were performed using a Genetic Algorithm (GA), starting from a random population. The solutions evaluated by the algorithm consist on the relative weight of each LED in a certain assembly of LEDs, which leads to the driven current of each kind of LEDs. The final spectra are obtained adding the different LED spectrum balanced by the relative weight. We have used the MATLAB Genetic Algorithm Toolbox, running in a Personal Computer under Windows Operating System. In order to avoid stagnation, we perform a 1000-iterations optimization, and the resulting solution is used again as a seed for a second 1000-iterations process. The complete process needs around 15 min for a complete optimization.

3.1. Use of white and monochromatic LEDs

As a first attempt, we show the different performances of two sets of LEDs, the first of them consisting on 5 white LEDs with different CCT objectives(from 2700 K up to 6000 K), and the second one consisting on a set of 5 monochromatic LEDs (Blue Royal, Green, Amber, Red Orange and Red), all of them described in Fig. 3. The monochromatic assembly has been used in lighting since the development of the first efficient LEDs [12,13,17]. Moreover, white LEDs, as well as different combinations of monochromatic and white LEDs, are widely used in the current development of indoor lighting [18,23]. In our case, the spectra obtained after the optimization are plotted in Fig. 5. These spectra were obtained using the relative weights obtained by the optimizations, using each one of the assemblies (only the 5 white LEDs and only the 5 monochromatic LEDs), using the merit function in eq. (4) relative to CCT. This kind of optimization can be easily found in the literature, and we show it in order to compare the standard procedure with our final results. The most appreciable difference is the softness obtained with the white LEDs and the spiked curves obtained with the monochromatic LEDs. This can be also shown with the CRIs: whereas for the set of white LEDs, the CRI of each

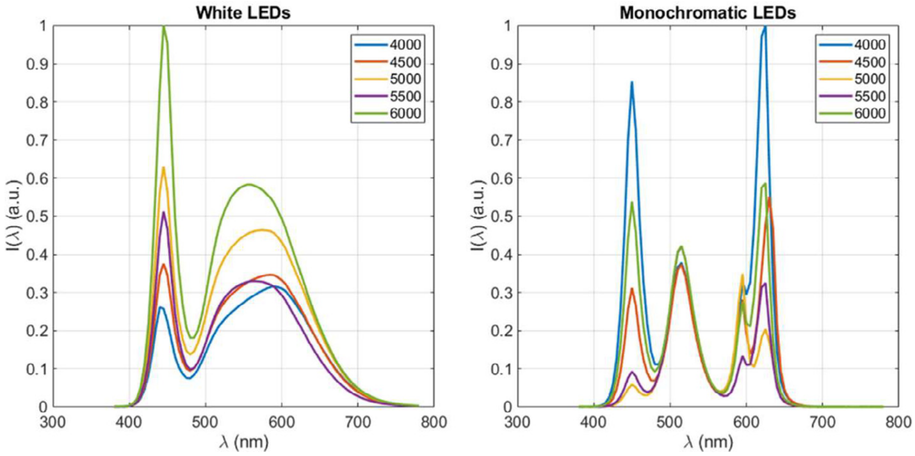

Fig. 5. Spectra obtained with the two set of LEDs (only the five white LEDs on the left, and only the five monochromatic LEDs on the right), using a CCT-based function of merit. Each curve correspond to a different CCT objective (in Kelvin).

spectrum are between 76 and 78, for the monochromatic set we obtain CRIs between 44 and 69, which indicates a low performance of the monochromatic assembly in terms of color rendering. However, the white set shows a strong handicap, since it does not allow to efficiently covering the circadian region of the spectrum. Thus, for example, with the white set we obtain CAFs between 0.48 and 0.65, whereas with the monochromatic set we obtain CAFs between 0.75 and 0.90 (although we do not have taken into account circadian parameters in the merit function of this optimization).

For these reasons, in the following optimizations, we will use a set of LEDs combining white and monochromatic LEDs, in order to obtain soft spectra with good circadian performance (we will refer to this assembly as ''Whites + RG''). Specifically, we will use the white LEDs with 2700 K and 6000 K (the lowest and highest temperatures) and the Green and Red monochromatic LEDs. Particularly, the Green LED allows us to play with the circadian component of the spectrum. In a first stage, we perform again an optimization based on CCT. Fig. 6 gathers all the results, as well as a comparison with previous results. As we can see, the obtained spectra present an acceptable level of softness. Compared to both assemblies (white LEDs and monochromatic LEDs), this mixed combination of LEDs presents a better performance in terms of color reproducibility with a CRI always above 80 (even much better than the whites LEDs assembly), although this parameter was not included in the optimization. Regarding the circadian parameters, the monochromatic assembly reaches the highest performance, both with CAF and CER, and the white LEDs assembly reaches the lowest performance. This indicates that the circadian performance of the Whites + RG assembly could be adapted to be increased or decreased, allowing a certain degree of modulation, and allowing at the same time the better performance in terms of color rendering. Thus, the Whites + RG assembly seems to be a good candidate for indoor lighting, and we will carry out further optimizations following this idea.

Up to this point, the results presented in this section are comparable to those published in the bibliography. In the next section we present an alternative which can increase the performance and applicability of smart lighting systems.

3.2. Multi-objective optimizations

At this point, we begin with the multiobjective optimizations, which is the main contribution of this work. Starting with the Whites + RG assembly, we attempt to obtain a light source able to adapt the spectrum to different CCT, and as the same time, to work with two different regimes of circadian effect: low CER and high CER. Thus, we will use the merit functions defined in Eqs. (6 and 7). The results are shown in Fig. 7. As we can see, the high CER regime is obtained increasing the green component in the spectrum, whereas for the low regime the green component is reduced, increasing the relative weight of the blue component. We obtain a variation above 10% in the CER parameter, achieving a good performance with the reproducibility of colors with CRI above 80 (which is a good level, in agreement with the bibliography).

As we have seen in Fig. 7, the optimization with CCT and CER objectives is able to reach a good performance in terms of CCT, modulation of CER and even CRI (although this last parameter was not included in the optimization). Table 3 shows the relative weight of each LED at the desired CCT for the two different regimes of work. As can be seen, the White 2700 LED shows a small modulation, compared with the rest of the LEDs. Moreover, taking into account the calibration shown in Fig. 3, we see that the total emission of the White 2700 LED is very low, compared to the others. For this reason, we change the number of LEDs of each type. After different attempts, we find that the distribution shown in Table 4 shows a good performance, as we will see. This combination of LEDs constitutes the unit cell used in the following optimizations. Thus, using this unit cell, we obtain the results shown in Fig. 8, where we can see that the sharpness of the spectra has been reduced, which contributes to an improvement of the CRI performance.

Based on the unit cell detailed in Table 4, we perform again the optimization with the same configuration (two consecutive optimizations with 1000 iterations each one), with the merit functions defined by Eq. (6 and 7). The results are plotted in Fig. 8, where we can evaluate again the lighting performance of the light source. As we can see, the spectra in both regimes of work are quite soft, indicating a good color rendering behavior. In fact, we can see that CRI is always above 80 with a maximum value of 92, which is a good result. It should be noted, however, that the CRI performance has not been included in the optimization. The plot of the circadian effect also shows the modulation of the CER parameter, with a good differentiation between both regimes. Aimed by these good results, we consider the possibility of testing a prototype based on our results, as we will see in the next section.

4. Experimental implementation

In order to test our final design, we have implemented a prototype of the smart lighting system. Firstly, we need to obtain the

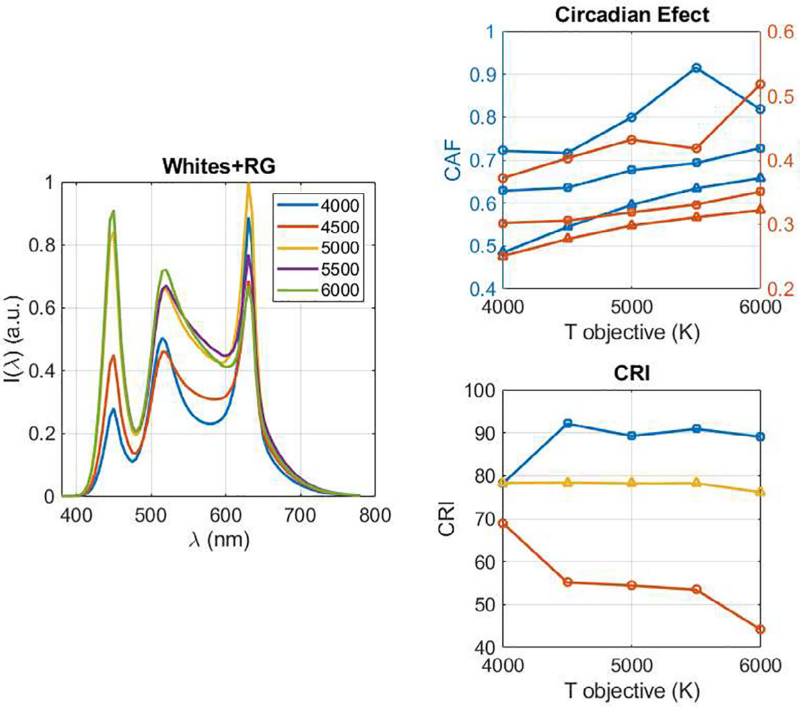

Fig. 6. Left: Spectra of Whites + RG combo for each CCT objective. Bottom right: CAF (blue) and CER (orange) for the assemblies of monochromatic LEDs (circles), white LEDs (triangles) and Whites + RGB LEDs (squares), compared to the black body performance (dashed lines). Top right: CRI for the assemblies of monochromatic LEDs (circles), white LEDs (triangles) and Whites + RGB LEDs (squares). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

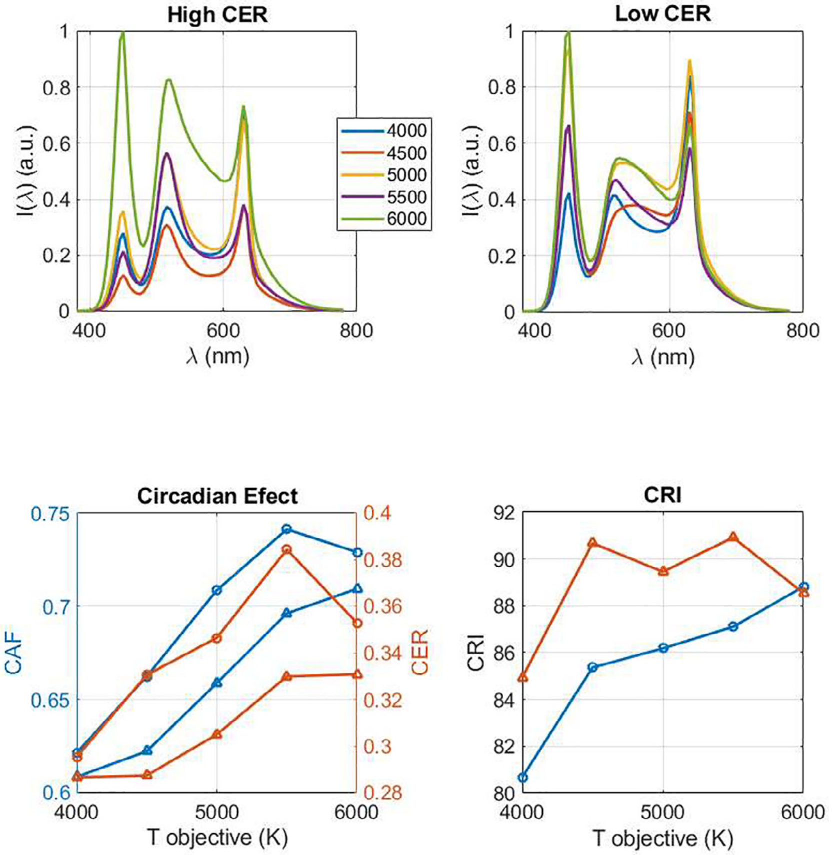

Fig. 7. Multiobjective optimizations with the Whites + RG combo, taking into account the CCT and the CER (high and low performance). Upper row: spectra for high CER (left) and low CER (right). Lower row, left: CAF, CER and CRI for high CER (circles) and low CER (triangles).

Table 3
Relative weight of each different LED with the Whites + RG combo.

High CER	White 2700	White 6000	Green	Red	CCT (K)
	0.62	0.20	0.43	0.75	4000
	0.48	0.06	0.42	0.37	4500
	0.56	0.30	0.75	0.72	5000
	0.67	0.12	0.83	0.31	5500
	0.95	0.95	0.79	0.57	6000
Low CER					
	0.82	0.32	0.38	0.85	4000
	0.77	0.59	0.09	0.65	4500
	0.83	0.89	0.22	0.83	5000
	0.61	0.63	0.36	0.51	5500
	0.60	1.00	0.26	0.56	6000

Table 4
Number of LEDs of each type in the unit cell used in the final design.

Type	Number of LEDs
White 2700	5
White 6000	2
Green	2
Photo Red	1
Total	10

current intensities for each kind of LED in the unit cell. We present in Table 5 the relative weights of each LED in the two regimes of work for the different CCT objectives. Using these weights in Eq. (3), we obtain the current for each LED, plotted in Fig. 9. We can see some trends in these electrical currents. Thus, the main difference between both regimes is that in the low CER configuration, the Green LED keeps a low level, whereas in the high CER configuration the Red LED reaches a high relative weight. The relative weight of the white LEDs in the low CER is balancing between the White 2700 and the white 6000 when the CCT objective is increased.

Once we have obtained the electrical currents, we define the spatial distribution of the LEDs. The luminaire is based on the replication of a unit cell, made up with the five LEDs selected in our optimizations. The location of the different LEDs in the unit cell tries to homogenize the emission of the different kind of LEDs after a diffusive screen. The prototype is designed to work with a maximum illuminance of 1000 lx, which implies to use at least 3 unit cells. Fig. 10 shows different views of this prototype. The final implementation of this lighting system could include a control sys-

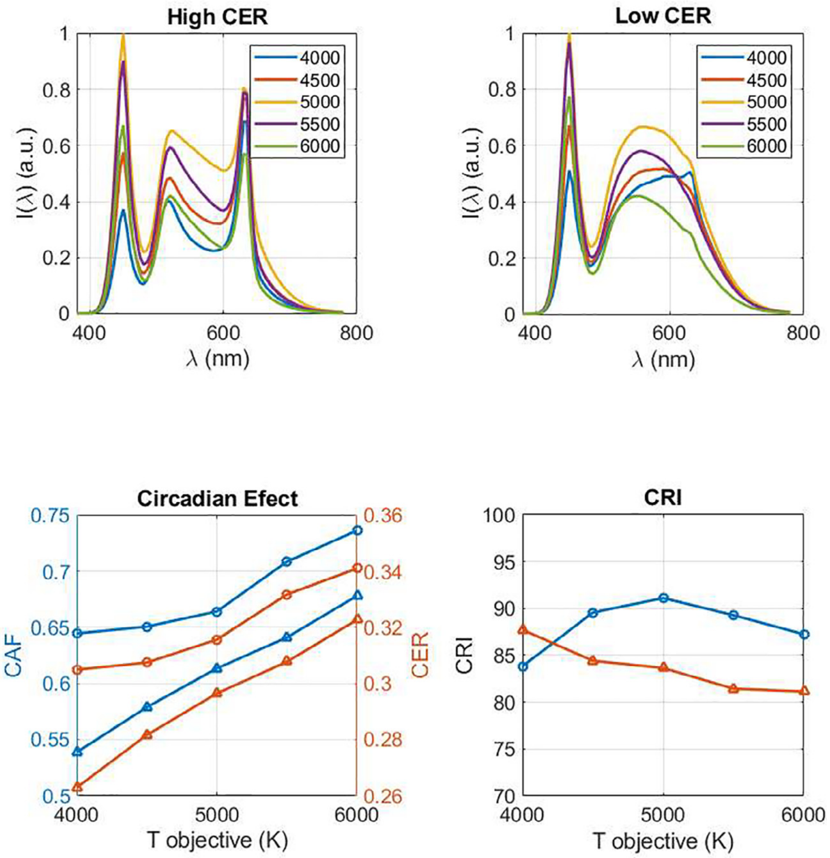

Fig. 8. Similar to Fig. 7, using the unit cell formed by 5 White 2700 LEDs, 2 White 6000 LEDs, 2 Green LEDs and 1 Photo Red LED. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Relative weight of each different LED for the unit cell of the final design.

High CER	White 2700	White 6000	Green	Red	CCT (K)
	0.14	0.19	0.28	0.94	4000
	0.19	0.31	0.27	0.97	4500
	0.31	0.55	0.24	0.80	5000
	0.14	0.55	0.30	1.00	5500
	0.05	0.44	0.22	0.78	6000
Low CER					
	0.95	0.30	0.01	0.35	4000
	0.90	0.54	0.00	0.12	4500
	1.00	0.94	0.05	0.20	5000
	0.74	1.00	0.00	0.05	5500
	0.41	0.87	0.04	0.13	6000

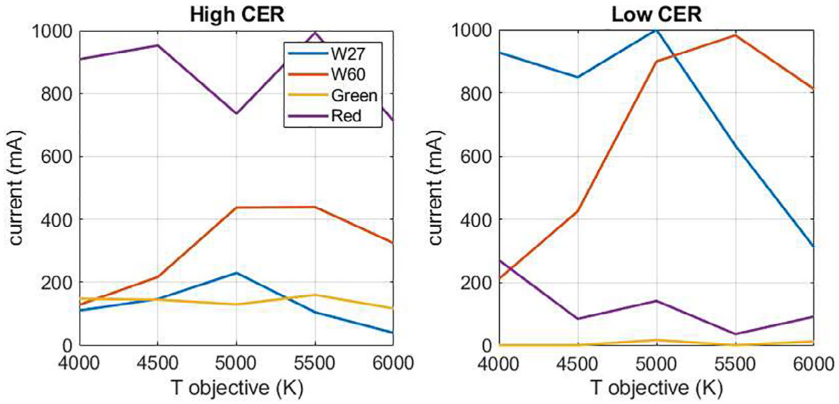

Fig. 9. Electrical current for each kind of LED in the unit cell, as a function of the CCT, for the two regimes of work.

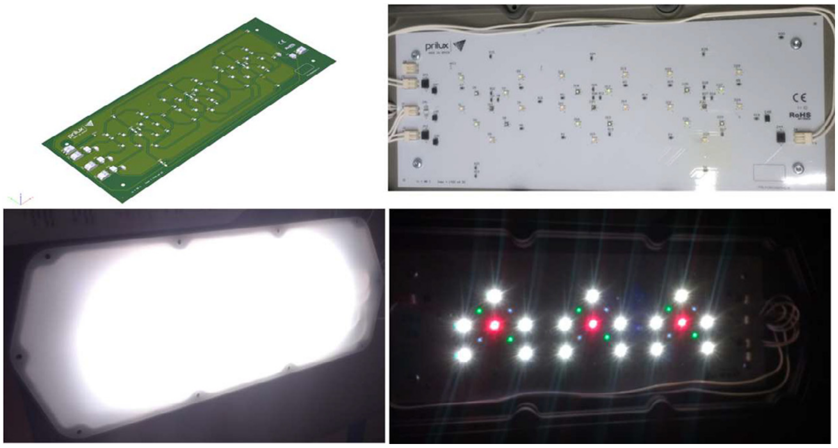

Fig. 10. Prototype of smart lighting system; (a) electronic design; (b) actual implementation with three unit cells; (c) performance after the diffusive screen; (d) aspect when the diffusive screen is removed.

tem depending on an automatized method (for example, depending on a timetable, or responding to a sensor), or it can be also controlled by the final user. In addition, and based on the characteristics of the selected LEDs, it is possible to estimate the energy performance of the luminaire. Table 6 shows the expected luminous flux and the luminous efficacy (in lm/W) in both regimes for the different CCT objectives. As can be seen, these two parameters are comparable to the most recent available LED-based lighting sources [26–29].

The actual performance of the prototype is shown in Fig. 11. We can see that the color coordinates of each spectra fall very close to the Planckian locus, in the white region of the CIE map, and very close to the black body emission with the objective color temperatures. At the same time, we show the CER modulation between both regimes for each CCT objective, expressed as a percentage. We obtain a modulation between 6% and 16%, which constitutes enough difference for long-day lighting. Although it can seem a low modulation range, these values fall between the limits of achievable modulations [25], and apparently low CER modulations can produce notable effects after long-term exposures such as a full working day. In addition, the experimental CRI values reach levels between 80 and 92 for the whole range of regimes and temperatures.

For summarizing, we have presented a lighting system able to be adapted to different color temperatures and with a tunable circadian character. The system can be controlled manually or it can be combined with an automatized system. At the same time, we have shown the possibilities of multiobjective optimizations in the lighting industry. This point is, to some extent, the major novelty of this work, and represents a clear advantage with respect to single objective optimization strategies. Traditionally, lighting sources have been designed attending only to one main parameter (the color temperature or the circadian action, for example). In our case, we have choose CCT as a parameter indicating the color performance, and CER for the circadian description. We have seen that we are able to define two regimes of work regarding the circadian effect. Moreover, the design is based on a combination of monochromatic and white LEDs. Based on this design, we have implemented a first prototype, showing a performance close to the design, as well as excellent color qualities.

5. Conclusions

The industry of lighting is developing scientific and technological improvements, since white LEDs were invented. To date, the design of lighting systems are based, principally, in the optimization of one parameter (sometimes is the color performance, some other times is the circadian effect, or even the color rendering capability). Traditionally, the circadian effects are treated as a kind of harmful radiation, although it can have beneficial effects on different fields. In addition, the lighting systems consist usually on a set of only white LEDs, or monochromatic LEDs. Only in a few reported papers we find a combination of white and monochromatic LEDs, using the white ones as a basis for the color performance and serving the monochromatic LEDs for slightly conform the spectra. We present in this work a complete design of a lighting system able to tune simultaneously the circadian character and the color performance. We have explained the different steps needed to perform this design, from the election of LEDs up to obtaining the driving currents of the system. As a result, we have presented a lighting source able to be adapted to different lighting environments, with a tunable temperature of color and, simultaneously, able to allow two different regimes of circadian action. We also have shown the possibilities allowed by multiobjective optimizations for lighting systems design. The description of the visual effects of our lighting design is based on color temperatures, which is the main parameter used in the industry for describing the quality of the light. As merit function for the non-visual effects, we have choose CER as parameter for describing the circadian aspect. Moreover, this system is based on the use of two kind of white LEDs (with color temperatures of 2700 K and 6000 K, respectively) and two monochromatic LEDs (at 515 nm and 630 nm). This combination of LEDs is enough to control the circadian character as well as the color performance of the source. A prototype based on this design has been also implemented and evaluated. The performance of the prototype, in terms of color coordinates, is very close to the daylight, showing a modulation of CER parameter between 5% and 20%. The CRI performance of the system is above 80%, maintaining a good luminous efficacy. This prototype can be combined with any kind of control system, either manual or automatic.

Some advantages of this source can be outlined, compared to other systems. First, we can make use of the circadian radiation, being able to define two different working regimes (low and high circadian action), and understanding how the circadian component can be also modulated and utilized. In addition, color rendering ability shows good performance, similar to standard sources. Lastly, we have shown that multiobjective optimizations can be used in tuning lighting systems. The results shown in this work open the way to new studies and developments. On one hand, we need to perform a thorough evaluation of our lighting system in real environments, taking into account perception aspects. On the other hand, the method shown in this work can be applied in multitude of designs of interest for the lighting industry. In this sense, this study can contribute to the development of healthy and efficient lighting systems for the realization of natural colors.

Table 6
Estimated luminous flux (in lm) and efficacy (in lm/W) for the final design with 3 unit cells.

High CER	CCT (K)	Luminous flux (lm)	Luminous efficacy (lm/W)
	4000	1830	95
	4500	2194	95
	5000	2847	97
	5500	2515	99
	6000	1759	100
Low CER			
	4000	3823	89
	4500	3926	92
	5000	5076	94
	5500	4150	96
	6000	2971	99

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

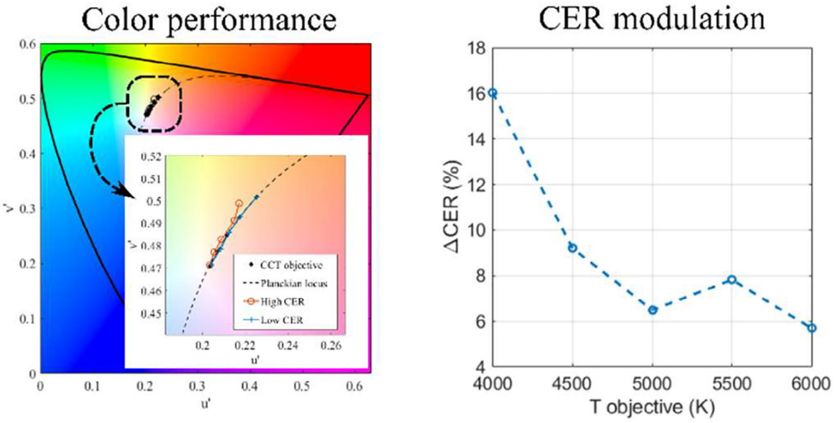

Fig. 11. Experimental performance of the prototype. Right: CIE uv map; Left: CER modulation, expresed as a the difference in percentage.

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