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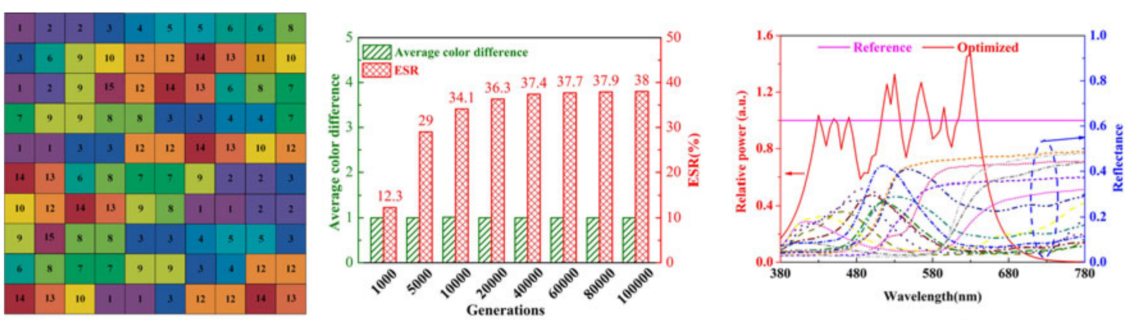

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Energy-Saving Light Source Spectrum Optimization by Considering Object's Reflectance

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Abstract: When an object is illuminated, part of the incident light is absorbed by the object that does not contribute to the illumination. If the light source's spectrum can be optimized by decreasing the light energy along the absorbed wavelengths, substantial energy can be saved. In this study, a spectrum optimization method by means of a genetic algorithm to minimize the light energy along the absorbed wavelengths while maintaining the light quality of the light source was proposed. Under the constraint that the color differences of the object illuminated by the optimized illuminant and the reference illuminant do not exceed specified levels, maximum energy saving ratio (ESR) is achieved for various reference illuminants. It is found that through the proposed method effectively saving the energy, for a monochromatic object, the ESR can reach 49.5% with barely recognizable color difference, whereas for a polychromatic object, the ESR can reach 55.2% with an acceptable color difference for each patch of the object.

Index Terms: Sources, spectrum optimization, energy saving, reflection, color rendering index.

1. Introduction

Lighting contributes significantly to the world's total energy consumption [1]. According to the *Buildings Energy Data Book*, lighting consumed about 20.2% of the commercial building energy in the United States in 2010 [2]. Therefore, there is an urgent need to develop strategies to minimize the lighting electricity to realize energy-saving sustainable buildings [3], [4]. For energy-saving reasons, many studies have been carried out [5] that involved adjusting light source spectra for different illumination applications [6], [7]. The object information that the human eye perceives depends on the light reflected from the surface of the object [8]. Thus, when illuminating, only the light reflected by an object is necessary and useful for the illumination, while the absorbed light is a wasteful energy loss. Most light sources, including energy-saving, white light-emitting diodes [9]–[11], emit large amounts of light energy at various wavelengths [12]–[14]. At certain wavelengths, the light is mostly absorbed by the target objects; thus, the light energy at such wavelengths is

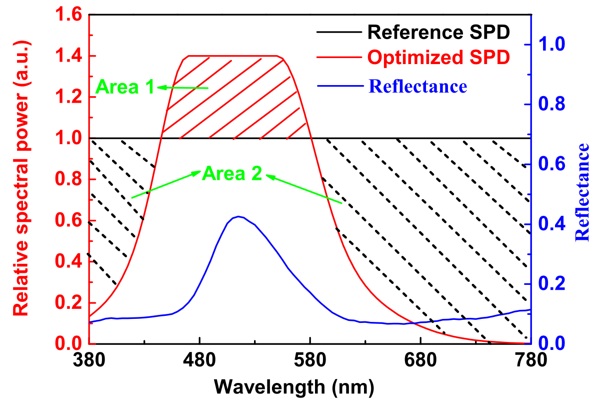

Fig. 1. Spectrum optimization based on reflectance. (Area 1 is the energy brought by strengthening the light energy in the high reflectance region; Area 2 is the energy brought by decreasing the light energy in the low reflectance region).

wasted. It has been proved that spectral tunable light sources can realize energy savings by not emitting unnecessary (absorbed) wavelengths and by minimizing the energy wasted by absorption at surfaces [15]; those authors also demonstrated that colored test spectral power distributions (SPDs) can reduce energy consumption by up to 44% while maintaining very little difference in the perceived color of objects illuminated by the test SPDs versus standard illumination sources.

However, the previous study tried to reduce energy consumption of the light source by simply increasing bandwidth of the spectrum [15]. An easy and effective spectrum optimization method is needed to achieve the lowest energy consumption potential (highest energy saving potential) and an acceptably small difference in perceived color when compared to standard illumination. Therefore, the problem of how to optimize the source spectrum needs to be further studied.

More importantly, the subjects of previous research have been monochromatic objects [15]. However, most actual objects in commercial buildings are polychromatic. Energy-saving light source spectrum optimization for polychromatic objects have not yet been systematically analyzed and need to be discussed deeply.

In this paper, spectrum optimization based on genetic algorithm was proposed to optimize the light source's spectrum for achieving maximum energy saving ratio (ESR). Two constraints were made, one is the luminance of the object under illumination by the optimized illuminant and reference illuminant are equal, the other is the color differences of the object illuminated by the optimized illuminant and the reference illuminant do not exceed specified levels. The monochromatic objects and a polychromatic object prototype consisting of 15 kinds of color quality scale (CQS) samples were optimized separately. Based on this, influences caused by color differences, reference illuminants, and illumination objects are analyzed separately.

2. Problem Statement

When an object is illuminated by a light source, light reflected by the object is related to the SPD of the light source and the reflectance of the object. The SPD of the reflected light can be given by [16]

$$S'(\lambda) = S(\lambda) \cdot R(\lambda) \tag{1}$$

where $S'(\lambda)$ is the SPD of reflected light, $S(\lambda)$ is the SPD of the light source, and $R(\lambda)$ is the reflectance of the object.

To human eye, the light energy in the low reflectance regions is relatively unimportant for illumination. Therefore, it is feasible to save lighting energy by decreasing the light energy at the absorbed wavelengths while maintain the radiance of the reflected light. As shown in Fig. 1, the reflectance

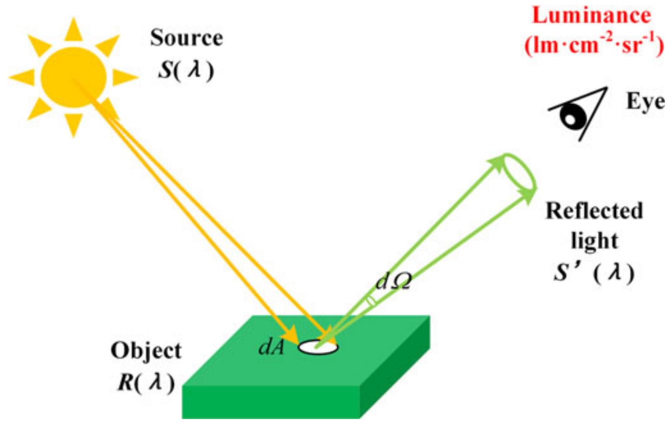

Fig. 2. Illumination model. (The reflected light enters the sensor and the eye at a vertical angle. dA is the unit projected area of the source. $d\Omega$ is the unit solid angle reflected by the object.)

of an object from 480 nm to 580 nm is higher than the remaining wavelength range, which implies that the light falling into this range will be highly reflected and other light will be mostly absorbed. The radiance of the object illuminated by the reference SPD and optimized SPD is equal, while the optimized SPD consumes less energy, the saved energy could be expressed as the area difference between Area 1(solid crosshatching) and Area 2 (dashed crosshatching).

The light energy in the above description is represented by radiance, while for human eyes, luminance, which considers the human eye's visual response to different wavelengths, is more meaningful for illumination than radiance [16], [17]. As shown in Fig. 2, only when the luminance of the object under the two sources is equal can the above energy saving function be reasonable and faithful [15]. Therefore, we optimized energy-saving light source spectrum for monochromatic and polychromatic objects by taking the luminance into consideration, the details are discussed later.

3. Energy Saving Assessing

For general illuminating, luminance and color difference are key parameters. Color difference between illumination by the optimized light source and the reference light source of the object, is defined as ΔE^*_{ab} by the Commission Internationale de l'Eclairage (CIE) [19]. For observers, $\Delta E^*_{ab} = 1$ is considered to be a barely recognizable difference; $\Delta E^*_{ab} = 10$, which is considered to be a noticeable—but also potentially acceptable-color difference [20]. If an optimized light source can be used instead of a reference light source, the luminance of the object under two sources should be equal, and the color differences between two sources should be acceptable [21]. Then, the saved energy can be calculated by subtracting the radiant flux of the optimized SPD from that of the reference SPD. Here, we assess the energy saving properties of the optimized light source for monochromatic object and polychromatic object, respectively.

3.1 Energy Saving Ratio for Monochromatic Object

The radiant flux of the light source can be calculated by integrating the total area under the SPD curve [18]. As shown in Fig. 1, the radiant flux of a light source can be expressed as

$$P = \int_{380}^{780} S(\lambda) d\lambda \tag{2}$$

where P is the radiant flux, whose unit is Watts, and can assess the power consumption of a light source. $S(\lambda)$ is the SPD of the light source.

The luminance of the object can be calculated by

$$L = \frac{\phi}{dA \cdot d\Omega} = \frac{1}{dA \cdot d\Omega} \cdot 683 \frac{\text{lm}}{\text{W}} \cdot \int_{380}^{780} S'(\lambda) \cdot V(\lambda) d\lambda \tag{3}$$

where ϕ is the luminous flux of the reflected light, dA is the unit projected area of the source, $d\Omega$ is the unit solid angle reflected by the object, $S'(\lambda)$ is the SPD of the reflected light, and $V(\lambda)$ is the photopic vision function, which has a maximal value of unity at 555 nm. The maximal luminous flux of a light source is 683 lm/W [18].

The ratio of the saved radiant flux of the optimized light source to that of the reference is expressed as a percentage that indicates the ESR of the optimized light source. when SPDs of optimized light source meets the constraint that the reflected luminance under the optimized (L_{opt}) and reference light sources (L_{ref}) is equal, and meets the constraint that the color differences under two light sources are acceptable, the saved energy (radiant flux) can be obtained by subtracting the radiant flux of the optimized light source from that of the reference light source. Consequently, the ESR of the optimized light source can be calculated as

$$\text{ESR} = \frac{P_{ref}(\lambda) - P_{opt}(\lambda)}{P_{ref}(\lambda)} = 1 - \frac{\int_{380}^{780} S_{opt}(\lambda) d\lambda}{\int_{380}^{780} S_{ref}(\lambda) d\lambda} \tag{4}$$

where $P_{ref}(\lambda)$ is the radiant flux of the reference light source, $P_{opt}(\lambda)$ is the radiant flux of the optimized light source, $S_{ref}(\lambda)$ is the SPD of the reference light source, and $S_{opt}(\lambda)$ is the SPD of the optimized light source.

3.2 Energy Saving Ratio for Polychromatic Object

In theory, a polychromatic object can be divided into a vast number of small patches, where each patch represents one monochromatic sub-object. Here, for theoretical analysis, each patch is assigned a random value selected from 15 kinds of CQS samples, which are typical highly saturated colors and previously defined by Ohno [21]. An object prototype is shown in Fig. 3.

When the polychromatic object is illuminated by an optimized light source and a reference illuminant separately, the color difference of each patch on the object can be calculated [21]. Here, we suppose the lighting surface of the light source is large, so color patches on the object have equal reflection angle of reflection and incidence. Therefore, same CQS samples on the object have equal color difference under the light source. We use an average color difference to describe the color characteristic of the object under the two sources. The average color difference can be expressed as

$$\langle \Delta E^*_{abi} \rangle = \frac{1}{n} \sum_{i=1}^{n} \Delta E^*_{abi} \tag{5}$$

where $\langle \Delta E^*_{abi} \rangle$ is the average color difference of the object under two sources, n is the number of CQS patches on the object, i is the serial number of the patch, and ΔE^*_{abi} is an color difference between illumination by the optimized light source and the reference illuminant of the i_{th} patch on the polychromatic object.

Since the object consists of many patches, the luminance of the object is the sum of the individual luminance values reflected by each of the patches. The luminance of the reflected polychromatic object can be expressed as

$$\sum L = \sum_{i=1}^{n} L_i = \sum_{i=1}^{n} \left(\frac{1}{dA \cdot d\Omega} \cdot 683 \frac{\text{lm}}{\text{W}} \cdot \int_{380}^{780} S(\lambda) \cdot R_i(\lambda) \cdot V(\lambda) d\lambda \right) \tag{6}$$

where $\sum L$ is the luminance of the object, L_i is the reflected luminance of the i_{th} patch on the object, and $R_i(\lambda)$ is the corresponding reflectance.

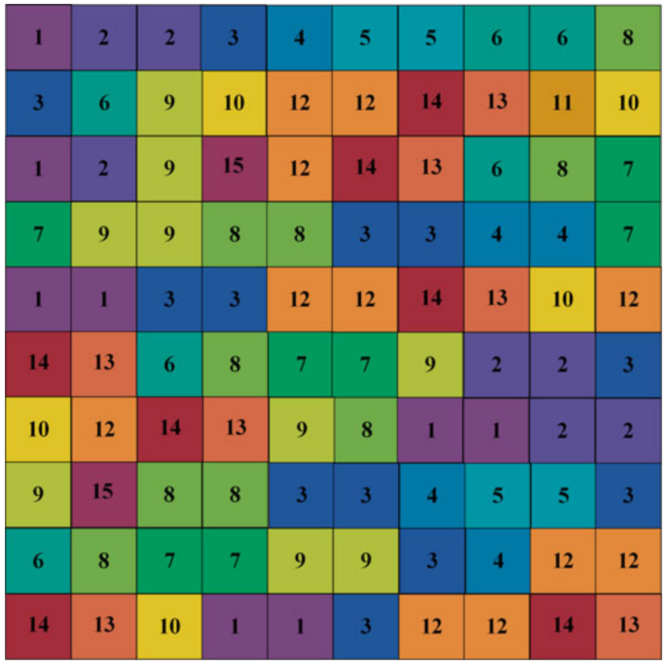

Fig. 3. Object consisting of 10 $\times$ 10 CQS samples.

Thus, when SPDs of optimized light source meets the constraint that the luminance of the object under illumination by the optimized ($\sum L_{opt}$) and reference light sources ($\sum L_{ref}$) is equal, and meets the constraint that the color differences under two light sources should be acceptable, the ESR of the optimized light source can be calculated as (4).

4. Spectral Optimization Methods

Optimizing spectra with the highest ESR and acceptable average color difference is a complex nonlinear programming (NLP) problem. The genetic algorithm (GA) is proved for having faster global convergence and higher computational efficiency than other optimization methods includes ant colony algorithm, particle swarm algorithm, especially for complex NLP problems [22], [23]. The penalty function approach is generic and applicable to many types of constraint [24]. Therefore, we adopted a genetic algorithm (GA) with penalty functions to realize the energy-saving spectrum optimization for monochromatic and polychromatic objects separately [7].

4.1 For Monochromatic Object

To ensure that the color difference of the object under the two sources is acceptable for observers, the color difference of the object are constrained to be no more than certain values. The NLP can be expressed as

$$\begin{cases} \text{Maximize} & f(\vec{x}) = ESR \\ \text{Subject to} & \Sigma L_{opt} = \Sigma L_{ref} \\ & \Delta E^*_{ab} \leq \text{K} \end{cases} \tag{7}$$

where $f(\vec{x})$ is the objective function, $\sum L_{opt} = \sum L_{ref}$ is the equality constraint, $\Delta E^*_{ab} \leq$ K is the inequality constraint, and the spectrum vector $\vec{x}$ that meets the constraints is defined as the feasible solution. K is the upper limit for the color difference of the object. In addition, as the spectral curves of practical illuminants are continuous, the SPD curve of optimized light source is constrained 5% variation at a 5 nm wavelength interval.

4.2 For Polychromatic Object

As shown in Fig. 3, the polychromatic object used in this study consists of 100 color patches, each of whose color values was randomly selected from 15 possibilities of CQS samples. First of all, to ensure certain illumination quality of each patch on the object, the color difference of each color patch under the optimized and reference illuminants is restricted to $\Delta E^*_{abi} \leq 10$ ($i = 1, 2, \ldots 100$), which is considered to be a noticeable—but also potentially acceptable—color difference for observers [15]. In addition, to assess the color performance of the whole object, the average color difference of the polychromatic object should be should be taken into account. Therefore, the NLP can be expressed as

$$\begin{cases} \text{Maximize} & f(\vec{x}) = ESR \\ \text{Subject to} & \sum L_{opt} = \sum L_{ref} \\ & \Delta E^*_{abi} \leq 10, i = 1, 2, \ldots 100 \\ & \langle \Delta E^*_{abi} \rangle \leq K' \end{cases} \tag{8}$$

where $f(\vec{x})$ is the objective function, $\sum L_{opt} = \sum L_{ref}$ is the equality constraint, $\Delta E^*_{abi} \leq 10$, $\langle \Delta E^*_{abi} \rangle \leq K'$ is the inequality constraint, and the spectrum vector $\vec{x}$ that meets the constraints is defined as the feasible solution. The upper limit for the average color difference of the polychromatic object $\langle \Delta E^*_{abi} \rangle$ is set to K'.

5. Results and Discussions

5.1 Monochromatic Object

The spectral resolution in computations is 5 nm. Since the color differences of the optimized illuminants refer to the reference illuminants, in order to ensure the final color quality of the optimized illuminants, the reference illuminants should also have high color quality. Therefore, five light sources are used as reference illuminants in this analysis, including standard illuminant A (incandescent lamp), standard illuminant D65 (natural daylight), equal-energy radiator (standard illuminant E), illuminant C, and illuminant D50. The five illuminants have very high color quality scales (higher than 90). Spectra of the reference illuminants from 380 nm to 780 nm are shown in Fig. 4, [19].

Here, the reference illuminant is the equal-energy radiator, and the reflectance is that of the 7th kind of CQS sample. We first optimized the spectra under the constraint that $\Delta E^*_{ab} \leq 1$ (a barely recognizable difference). Fig. 5(a) shows that the ESR rises as the number of generations increases. It is found that after 1000 generations, color difference can be constrained to be no more than 1. Moreover, the ESR of the energy-saving spectrum increases from 23.9% to 49.5% as the number of generations increases from 1000 to 100 000, indicating that more and more energy is saved during the 100000-step evolution process. Therefore, the ESR is stable after 100 000 generations, and the following simulation results are all obtained after 100 000 generations.

The optimized spectrum obtained the simulations is shown in Fig. 5(b). It is also found that after 5000 generations of evolution with the GA, the optimized spectral power with high reflectance increases, while the spectral power with low reflectance decreases sharply. The decreased area is much larger than the increased area, which means that energy is saved. Therefore, an energy-saving spectrum can be achieved by our spectrum optimization. A real energy-saving light source with the optimized spectrum can be fabricated using monochromatic LEDs [25]. Since the spectral optimization should achieve little color difference compared with reference illuminant, and achieve highest ESR, the optimized spectrum tends to be a little irregular after computation.

In addition, influences on ESR by reflectance of the target objects were analyzed under the constraint of $\Delta E^*_{ab} \leq 1$. Fifteen kinds of CQS samples were utilized as the illumination objects [21].

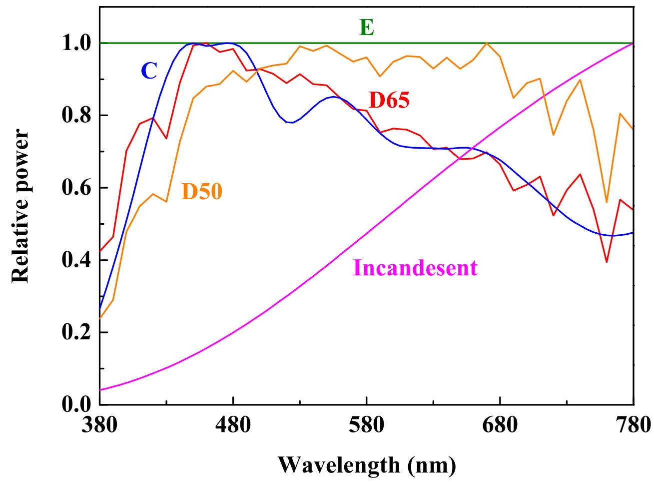

Fig. 4. Reference illuminants.

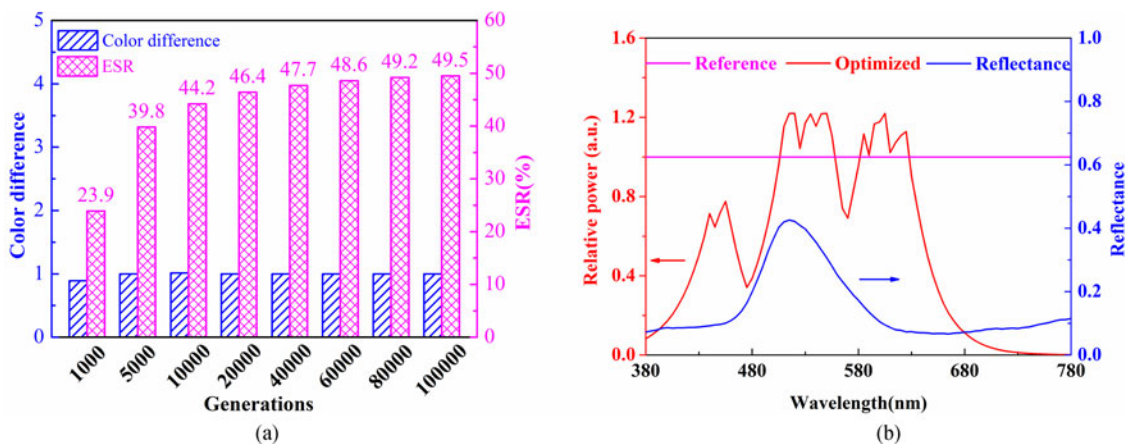

Fig. 5. Optimized results. (a) ESR as a function of increasing genetic algorithm generations. (b) Optimized spectrum after 100000 generations.

As shown in Fig. 6(a), although the reflectance of the CQS samples is different, energy-saving spectra can be obtained by our optimization. Moreover, since the ESR varies from 46.0% to 63.3% corresponding to different CQS samples, it is concluded that the reflectance influences the energy-saving potential of the final optimized illuminants. The 15 kinds of CQS samples were grouped according to the presence of three major components in their spectral reflectance factors: peak, plateau and inclination [15], as shown in Fig. 6(b). The reflectance falls into 5 types, plateau, peak and plateau, peak, peak and incline, and plateau and peak. The corresponding maximum ESRs are 63.3, 46.3, 54.4, 60.2, 52.6, respectively. Therefore, the plateau type of reflectance shows the maximum energy saving potential.

Further simulations were carried out with different reference illuminants. When the simulations are restricted to satisfy $\Delta E^*_{ab} \leq 1$, the ESRs of the 7th CQS sample are shown in Fig. 7 after 100000-step evolution process. It is found that energy-saving spectra can be obtained by our optimization for a variety of different references; the ESR varies from 44.3% to 57.4%. The difference between the ESRs of these five reference illuminants is large. Therefore, the energy-saving potential very dependent upon the spectra of the reference illuminants.

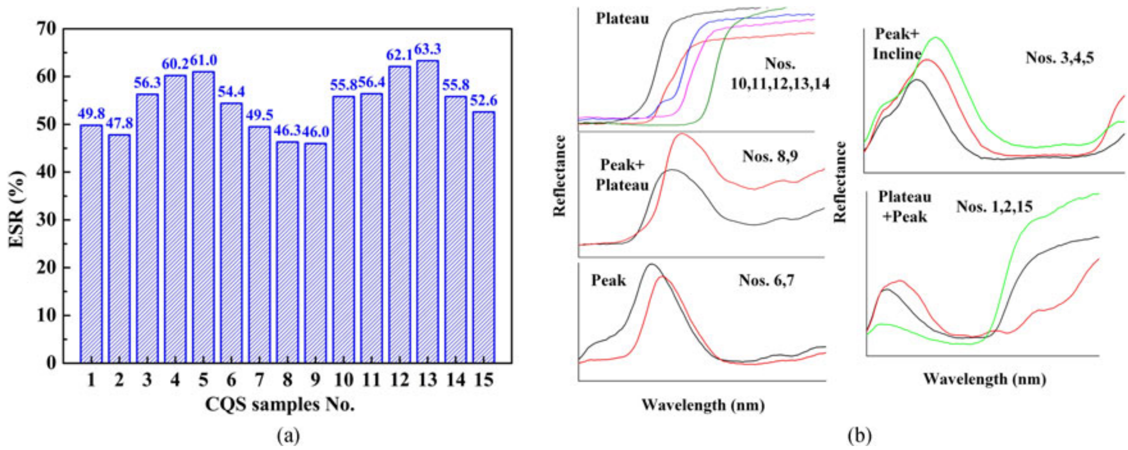

Fig. 6. ESR and CQS samples. (a) ESR corresponding to different kinds of CQS samples. (b) Five reflectance types.

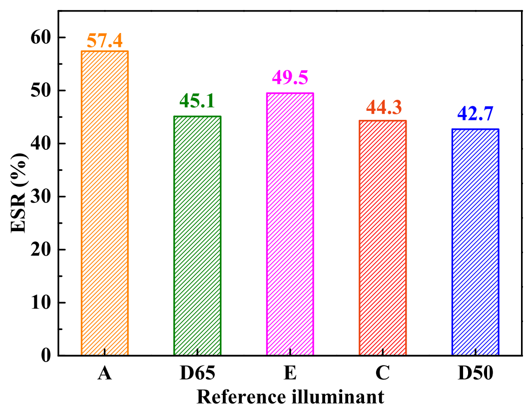

Fig. 7. ESR for different reference illuminants.

5.2 Polychromatic Object

In this section, the reference illuminant also is the equal-energy radiator. Based on the restriction to each color patch, energy-saving spectra for polychromatic objects are optimized when the constraints of average color difference K' are 1 and 5. After evolution of the GA for 100000 generations, Fig. 8 shows the actual color differences of 15 kinds of CQS color patches when the average color difference is 1 and 5. Firstly, it is found that all the color differences of 15 kinds of CQS color patches are under the constraints of $\Delta E^*_{abi} \leq 10$ ($i = 1, 2, \ldots 15$), regardless of variation in the average color difference; this indicates that all of the CQS color patches in the object can be well constrained by our optimization. Secondly, the individual color difference of the 15 kinds of CQS color patches are much larger under the average color difference of 5.

Fig. 9(a) shows that the ESR rises with the increasing generations of the GA. It is found that after 1000 generations, the average color difference can be constrained to be no more than 1. What is more, the ESR of the energy-saving spectra increases from 12.3% to 38.0% as the number of generations increases from 1000 to 100 000, indicating that ESR is stable after 100 000-step evolutionary process. Therefore, the following simulation results are obtained after 100 000 generations. The optimized spectrum obtained the simulations is shown in Fig. 9(b). Since the reflectance of different CQS samples varies greatly, and the optimized spectrum tends to be irregular after computation.

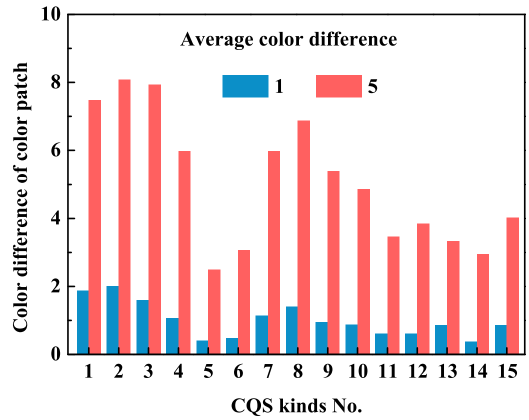

Fig. 8. Color differences of 15 kinds of CQS color patches when the average color difference is 1 or 5.

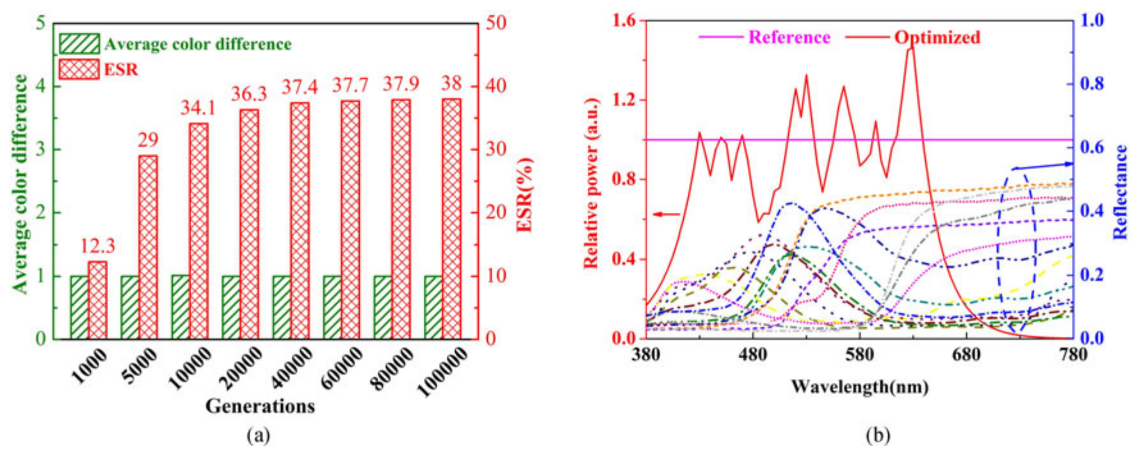

Fig. 9. Optimized results (a) ESR as a function of increasing genetic algorithm generations. (b) Optimized spectrum after 100 000 generations.

Fig. 10 shows that with an optimized energy-saving light source and reference illuminant, the ESR rises as the average color difference increases. It is found that there is high energy-saving potential for polychromatic objects. In particular, when the average color difference is 1, the ESR of the optimized energy-saving spectra is 38.0%. When actual average color difference increases from 1 to 5 in steps of 1, the ESR gradually rises to 50.6%. Therefore, the energy-saving potential depends very strongly on the average color difference. To obtain higher illumination quality, the ESR of the optimized spectra will decrease. In addition, when the average color difference is under the constraint of ACD $\leq$ 1, 2, 3, 4, 5, based on the data of Fig. 10, the maximal color differences are calculated as 2.0, 3.1, 5.0, 6.5, and 8.0, respectively.

Further simulations were carried out under different reference illuminants. When the simulations are restricted to satisfy $\langle \Delta E^*_{abi} \rangle \leq 1$, the ESRs of the polychromatic object are shown in Fig. 11, which demonstrates that energy-saving spectra can be obtained by our optimization for many different references. The difference between the ESRs of these five reference illuminants is large, varying from 28.5% to 52.2%. Therefore, the energy-saving potential is highly dependent on the spectra of the reference illuminants. Since there is little color difference between the optimized spectra derived from different reference illuminants, they have the nearly the same color characteristics as the references. It is advisable to use the spectrum with the highest ESR for energy-saving illumination.

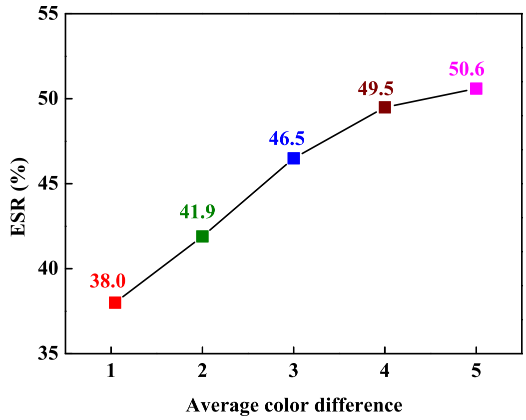

Fig. 10. ESR increasing as a function of the average color difference.

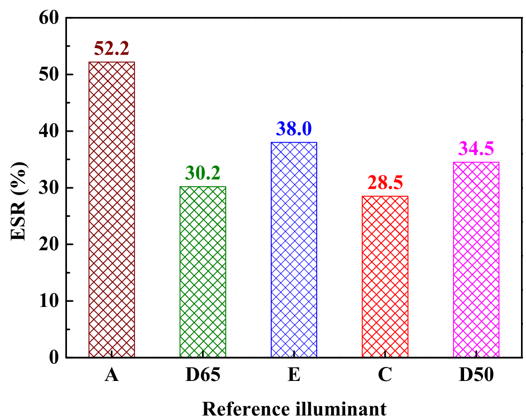

Fig. 11. ESR in the case of different references.

6. Conclusion

In this work, subject to the condition that equal luminance of the object under illumination by either the optimized or the reference illuminant, we propose an effective ESR to quantify the saved energy of the optimized illuminant compared to that of the reference illuminant. Then, under color difference constraints, a spectrum optimization method is used to maximize the ESR. By means of a vast number of simulations, energy-saving spectra were obtained for monochromatic objects and polychromatic objects. It was shown that for a monochromatic object, the ESR can be as high as 49.5% with barely recognizable color differences. In addition, the ESR varies from 46.0% to 63.3% in the case of different CQS samples, and the ESR varies from 44.3% to 57.4% in the case of different reference illuminants. For polychromatic objects, it was shown that the ESR can reach 50.6% with an acceptable color difference for each color patch of the object, referring to illuminant E. The ESR rises from 38.0% to 50.6% with average color difference increments from 1 to 5, and varies from 28.5% to 52.2% depending on the choice of reference illuminant.

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