Mathematical Modeling and Algorithm Application
ISSN: 3006-0842 | Vol. 8, No. 3, 2026

LED Light Source Based on Adjustable Biological Rhythms

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Abstract: In this paper, the whole process technology system of health lighting is constructed: a spectral parameter calculation system based on CIE standards is established, and the core parameters such as XYZ triple stimulus value, CCT, and mel-DER are accurately calculated through numerical integration, Krystek segmented fitting, Gaussian simulation, etc. A multi-channel LED multi-objective collaborative optimization framework and a solar spectral time-varying dynamic regulation model are constructed, and the objective function of optical characteristics and circadian rhythm design is integrated, and the SLSQP algorithm, time smoothing constraint and intelligent initialization strategy are introduced to ensure the optimization effect. The core performance is verified by experiments: high color rendering ($Rf = 98.48$) and low rhythm interference (mel-DER=0.2761) with a single light source, dual mode to achieve day and night color temperature switching, and the dynamic model accurately reproduces natural light. Research innovation provides solutions from single-source evaluation to full-day dynamic simulation, providing quantitative support for health lighting design, and its linear assumptions and sample size limitations need to be further improved.

Keywords: Spectral parameter calculation, Multi-objective optimization, SLSQP algorithm, Multi-channel LED, Solar spectral simulation

1. Introduction

Under green development and energy transition, LED has become the mainstream lighting due to its high efficiency, long life and low energy consumption. Driven by intelligent lighting upgrade and health needs, "healthy lighting" has become a research hotspot, as 460-490nm blue light regulates melatonin secretion and affects sleep and cognition. Existing commercial LEDs focus on visual performance, lacking adaptation to spectral and rhythmic requirements, so spectral optimization for synergy of "high color rendering" and "rhythm-friendly" is key to LED upgrade.

Foreign research started early with a sound theoretical and technical system: Cornell University confirmed blue light's inhibitory effect on melatonin, CIE proposed parameters like melanopic EDI; Philips launched a multi-channel LED system, and the University of Tokyo constructed a model; the Technical University of Munich developed a solar spectra time-varying system [1-3]. It leads in basic theory, standards and industrialization but needs improvement in multi-channel optimization accuracy and dynamic spectral continuity. Domestic research made partial breakthroughs (Tsinghua University improved the CIE XYZ algorithm), but is limited by insufficient integration of optical and rhythmic requirements and inadequate spectral simulation continuity[4].

Thus, this paper focuses on rhythm-controllable LED light source design: establishing an accurate spectral parameter calculation system, constructing a day-night dual-mode multi-objective optimization framework, and developing a dynamic solar spectral regulation model[5]. It aims to provide technical support for healthy lighting design and promote LED upgrade from "visual satisfaction" to "health adaptation."

Data sources（https://new.saikr.com/vse/chinamcm/2025?type=notice&id=32748）

2. Modeling of key parameters of LED spectra for biorhythm regulation

2.1. CIE XYZ Three Stimulus Values and Chromatic Coordinates(x, y)

CIE XYZ Triple Stimulus Value:

$$\begin{cases} X=k\int_{\lambda} SPD(\lambda)\cdot\bar{x}(\lambda)d\lambda \\ Y=k\int_{\lambda} SPD(\lambda)\cdot\bar{y}(\lambda)d\lambda \\ Z=k\int_{\lambda} SPD(\lambda)\cdot\bar{z}(\lambda)d\lambda \end{cases} \tag{1}$$

k is the normalization constant so that $Y = 100$ $(k = 100/\int SPD(\lambda)\cdot\bar{y}(\lambda)d\lambda)$.

Chromatic coordinates

$$\begin{cases} x=\frac{X}{X+Y+Z} \\ y=\frac{Y}{X+Y+Z} \end{cases} \tag{2}$$

2.2. Correlated Color Temperature (CCT) and Distance from Planck Trajectory (Duv)

Convert CIExy coordinates to CIE1960UCS coordinates (u, v)

$$\begin{cases} u=\frac{4x}{-2x+12y+3} \\ v=\frac{6y}{-2x+12y+3} \end{cases} \tag{3}$$

The specific segments of Planck's trajectory segmented approximation (Krystek model) are as follows:

When the temperature $T<4000$ K:

$$x=-0.2661239\times10^{9}/T^{3}-0.2343580\times10^{6}/T^{2}+0.8776956\times10^{3}/T+0.179910 \tag{4}$$

$T\geq4000$ K:

$$x=-3.0258469\times10^{9}/T^{3}+2.1070379\times10^{6}/T^{2}+0.2226347\times10^{3}/T+0.240390 \tag{5}$$

Then, calculate y based on the range of T.

T＜2222K:

$$y=-1.1063814x^3-1.34811020x^2+2.18555832x-0.20219683=-0.202197 \tag{6}$$

2222 K≤T<4000 K:

$$y=-0.9549476x^3-1.37418593x^2+2.09137015x-0.16748867=-0.167489 \tag{7}$$

T≥4000 K:

$$y=3.0817580x^3-5.87338670x^2+3.75112997x-0.37001483=-0.370015 \tag{8}$$

CCT is calculated by minimizing the Euclidean distance[6].

$$\min_{T}\sqrt{\left(u-u_p(T)\right)^2+\left(v-v_p(T)\right)^2} \tag{9}$$

Duv calculates[7].

$$Duv=v-v_p(T0) \tag{10}$$

Positive values indicate greenish and negative values indicate magenta.

2.3. Fidelity Index (Rf) and Color Gamut Index (Rg)

Rf Calculation formula[8].

$$Rf=70+20\times coverage+10\times smoothness \tag{11}$$

In multiplying cct_factor, and limit it to 0-100.

Rg Calculation formula

$$Rg=95+(color\_alance\ -0.5)\times 20 \tag{12}$$

Limit between 80-120.

2.4. Melatonin Solar Illumination Ratio (mel-DER)

Melatonin sensitivity function:

$$S_{mel}(\lambda)=\exp\left(-\frac{(\lambda-480)^2}{2\times 20^2}\right) \tag{13}$$

mel-DER is defined as the ratio of melatonin effective radiation to photopic effective radiation:

$$mel\text{-}DER=\frac{\int SPD(\lambda)\cdot S_{mel}(\lambda)d\lambda}{\int SPD(\lambda)\cdot V(\lambda)d\lambda} \tag{14}$$

2.5. Research results of the model

Table 1 Summary of calculation results of key parameters of LED light source

Parameter	Value
Correlation color temperature (CCT)	3925
Distance from Planck's trajectory (Duv)	0.000795
Fidelity Index (RF)	98.48
Color gamut index (Rg)	96.03
Melatonin Solar Illumination Ratio (mel-DER)	0.2761

Table 1 shows that the spectral power distribution (SPD) of the LED light source presents a multimodal white light synthesis mechanism, which consists of sharp peak blue light around 450nm and broad-spectrum phosphor emission peaks covering 530–570nm (green-yellow zone) and 620nm (orange-red zone). The design is coupled with a blue light chip and a multi-color phosphor to achieve continuous coverage of visible light band energy, laying a physical foundation for high color rendering performance. Based on the CIE1931 chroma system, the color coordinates (x=0.3840,y=0.3768) correspond to the correlated color temperature of 3925K, which is classified as a neutral white light type, which can build a bright and comfortable visual environment. In particular, the extremely small negative value of Duv=-0.000795 not only characterizes the color point approximation to the Planck body radiation trajectory, but also optimizes the visual experience due to the faint magenta tone, significantly improving the light and color quality performance.

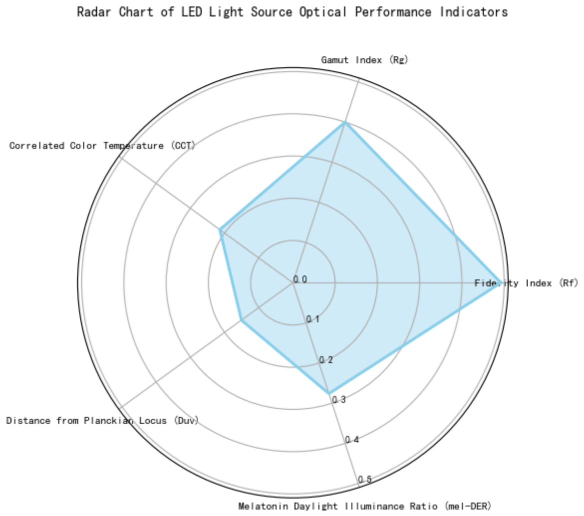

Figure 1 Radar diagram of optical performance indicators of LED light source

The performance characteristics of the four core optical indicators of the LED light source are visually presented by the radar map in Fig. 1: Fidelity index (Rf=98.48): close to 100, much higher than the critical value of "high-fidelity (≥90)", and the color reproduction ability of objects is excellent; Color gamut index (Rg=96.03): close to 100, color coverage close to natural light sources (such as D65), and the visual performance is natural and full; Correlated color temperature (CCT=3925K): warm white light range (2700-4500K), soft and comfortable light; Chromatic deviation (Duv=-0.000795): far lower than the human eye perception threshold (±0.003), the color coordinates almost fit the blackbody trajectory, and there is no color bias perception. Melatonin Daylight Ratio (mel-DER=0.2761): Only 1/4 of natural light, with a very low blue light composition, more rhythmic when used at night.

3. Mathematical basic model

3.1. Linear overlay model of spectral synthesis

Synthetic spectral power of multi-channel LED light source:

$$\mathrm{S_{synthetic}}(\lambda)=\sum_{j=1}^{5} \mathrm{w_j}\cdot \mathrm{S_j}(\lambda) \qquad (15)$$

Where: $S_{\text{synthetic}}(\lambda)$: the power density of the synthetic spectrum at the wavelength; w_j : The weight coefficients of the jth channel, $j \in 1,2,3,4,5$ correspond to Blue, Green, Red, Warm White, and Cold White, respectively; $S_j(\lambda)$: Normalized spectral power distribution for the jth channel.

3.2. Daylight optimization modeling

The objective function of daytime mode is designed as:

$$\mathrm{f_{day}(w)=-R_f(w)+P_{CCT}(w)+P_{Rg}(w)} \qquad (16)$$

To convert the maximization problem into a minimized problem, introduce a minus sign: $-R_f(\mathrm{w})$; $R_f(\mathrm{w})$ represents the color fidelity index of the light source.

3.3. Nighttime optimization modeling

The objective function of night mode is defined as:

$$\mathrm{f_{night}(w)=10\times mel\text{-}DER(w)+P_{CCT}(w)+P_{R_f}(w)+50\times w_{blue}} \qquad (17)$$

Minimizes melatonin inhibitory effects:

$$\mathrm{10\times mel\text{-}DER(w)} \qquad (18)$$

A factor of 10 amplifies the effect of mel-DER, making it dominant in optimization.

3.4. Design of optimization algorithm

3.4.1. Sequence quadratic programming (SLSQP) method

Considering the nonlinear nature of the research problem, the sequence quadratic programming (SLSQP) algorithm is used in this paper[9]. The algorithm approximates the research problem as a quadratic planner subproblem in each iteration:

$$\mathrm{s.t.}\begin{cases}\min\limits_{\Delta \mathrm{w}} \frac{1}{2}\Delta \mathrm{w}^{\mathrm{T}}\mathrm{H_k}\Delta \mathrm{w}+\nabla \mathrm{f(w_k)}^{\mathrm{T}}\Delta \mathrm{w} \\ \mathrm{A}\Delta \mathrm{w}+\mathrm{c(w_k)}=0\end{cases} \qquad (19)$$

where $\mathrm{H_k}$ is an approximation of the Hessian matrix, and A is the constraint Jacobian matrix.

The core principle of the SLSQP algorithm is to solve a series of quadratic planner problems with the help of iterative process, and then gradually approach the optimal solution of the original nonlinear programming problem.

3.4.2. Multi-starting point optimization strategy

cold white light strategy;

$$\mathrm{w_{init,1}}=[0.15,0.20,0.15,0.20,0.30] \qquad (20)$$

RGB equalization strategy;

$$\mathrm{w_{init,2}}=[0.20,0.25,0.15,0.15,0.25] \qquad (21)$$

The main cold white light strategy.

$$\mathrm{w_{init,3}}[0.10,0.15,0.10,0.25,0.40] \qquad (22)$$

In night mode, select three initial points that favor the warm light

Warm white + red light dominant;

$$\mathrm{w_{init,1}}=[0.05,0.10,0.25,0.60,0.00] \qquad (23)$$

No Blu-ray policy;

$$\mathrm{w_{init,2}}=[0.00,0.15,0.30,0.55,0.00] \qquad (24)$$

Warm white dominates the strategy.

$$\mathrm{w_{init,3}}=[0.02,0.08,0.20,0.70,0.00] \qquad (25)$$

3.5. Modeling results

Table 2 Optimal channel weight combinations

Pattern type	Blu-ray (%)	Green light(%)	Red light(%)	Warm white light(%)	Cold white light(%)
Daytime lighting mode	39.5	11.2	1.7	14.0	33.6
Night sleep aid mode	0.0	21.8	11.4	66.9	0.0

Table 3 Key parameter table

Pattern type	CCT（K）	Duv	Rf	Rg	Mel- DER
Daytime lighting mode	5500	－0.0063	98.79	98.25	0.3639
Night sleep aid mode	2700	0.0055	96.70	88.01	0.1495

Table 2 and Table 3 shows the daytime mode: high color temperature + full spectral coverage; Weight distribution: Blue light (39.5%) + cool white light (33.6%) accounted for more than 70%, cool white light (6500K) contains rich shortwave blue light, simulating the high color temperature characteristics of noon sunlight (CCT=5500K, meeting the requirements of 6000±500K). Color rendering performance: Rf=98.79 (close to full score), Rg=98.25 (95-105 range), indicating that the spectrum covers the full wavelength band of 400-700nm, with balanced energy distribution and natural color reproduction (meeting the "natural color" requirement of Rf>88). Rhythm effect: mel-DER=0.3639 (moderate level), due to the direct stimulation of ipRGC cells due to the peak blue light (450-480nm), which meets the physiological need to increase alertness during the day.

Night mode: zero blue light + warm light dominant; Weight distribution: warm white light (66.9%, 3000K) + red/green (11.4%+21.8%), completely turn off blue light and cool white light, and avoid the inhibition of melatonin by shortwave blue light (mel-DER=0.1495, only 41% of daytime). Color temperature and comfort: CCT=2700K (3000±500K), simulate incandescent warm light (Abstract 3: 2700K sleep aid color temperature), and maintain Rf=96.70 (>80) through red/green spectral compensation to ensure color resolution at night. Spectral safety: No blue light component (0% weight), combined with low color temperature, reduces interference with circadian rhythms.

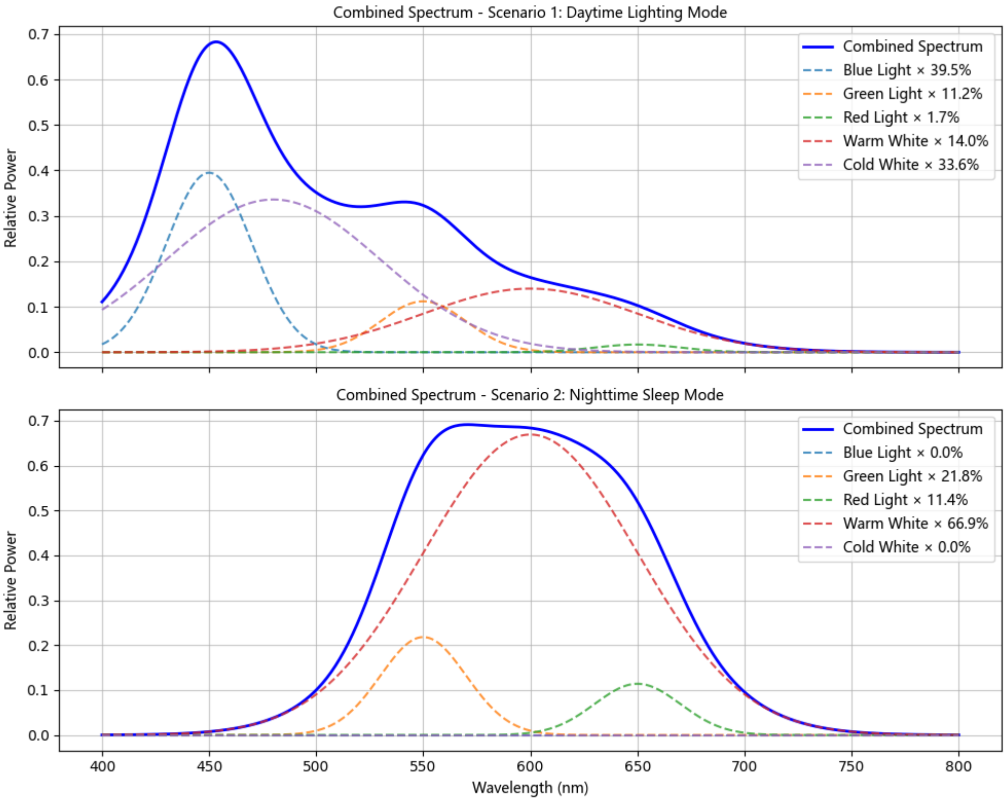

Figure 2 Synthetic spectra

Fig. 2 shows that the daytime lighting mode is dominated by blue light (39.5%) and cool white light (33.6%), accounting for 73.1% of the total proportion of green, warm white and red light, and its synthetic spectrum covers the full visible light range of 380-780nm, forming a significant peak in the blue light band of about 450nm, and has a continuous distribution in the green-yellow and orange-red bands. In this mode, the correlated color temperature (CCT) falls in the range of 6000±500K, accurately simulating the appearance of cool white light in midday daylight, with a fidelity index (Rf) close to 100 and a color gamut index (Rg) in the range of 95-105 to ensure that the color is reproduced in a realistic and natural way, and the energy concentration of the 450-490nm blue light band keeps the melatonin sun illuminance ratio (mel-DER) at a moderate level, which not only improves daytime alertness, but also avoids excessive inhibition of melatonin, achieving "high color rendering + natural light simulation +" Daytime alertness".

In the night sleep aid mode, warm white light (66.9%) is absolutely dominant, supplemented by green light (21.8%) and red light (11.4%), blue light and cool white light weights are 0%, the synthetic spectral energy is concentrated in the green-red band of 500-700nm, the orange-red band of 600-650nm forms a significant peak, and the energy of the blue light band of 400-490nm is almost 0. The correlated color temperature (CCT) of this mode falls in the range of 3000±500K to simulate a warm light environment. The complete removal of blue light components reduces mel-DER to a very low level, minimizing the inhibition of melatonin secretion, while the reasonable ratio of green and red light ensures that the fidelity index (Rf) is ≥ 80, meeting the basic color resolution needs at night, and giving priority to achieving the core goal of "low rhythm interference + warm light atmosphere + basic color rendering".

4. Theoretical basis of time-varying spectral simulation

4.1. The temporal dynamic relationship between biological rhythms and light

This paper presents the time-varying properties of the solar spectrum as:

$$S_{sun}(\lambda,t)=S_0(\lambda)\cdot A(t)\cdot R(\lambda,t)\cdot T(\lambda,t) \tag{26}$$

Where: $S_{sun}(\lambda,t)$:Spectral power density of the Sun at wavelengthλ at time t, $S_0(\lambda)$: Spectrum of the sun outside the atmosphere (AMO standard), $A(t)$: Total radiation intensity coefficient with time, $R(\lambda,t)$: Rayleigh scattering coefficient, proportional to λ^{-4} , $T(\lambda,t)$: Atmospheric transmission coefficient

4.2. Mathematical optimization model for multi-objective spectral matching

4.2.1. Objective function

At each time point, t_k optimal weight vector $w^*(t_k)=[w_1,w_2,w_3,w_4,w_5]^T$, so that the synthetic spectrum is as close as possible to the daily solar spectrum. The multi-objective optimization function is defined as:

$$F(w,t_k)=\sum_{i=1}^{6} \alpha_i\cdot E_i(w,t_k) \tag{27}$$

The error functions are defined as follows:

(1)Spectral Shape Error (MSE):

$$E_1(w,t_k)=\frac{1}{N}\sum_{j=1}^{N}\left(\frac{S_{synth}(\lambda_j,w)}{\|S_{synth}\|}-\frac{S_{sun}(\lambda_j,t_k)}{\|S_{sun}\|}\right)^2 \quad (28)$$

where $\|S\| = \max_{\lambda} S(\lambda)$ is the normalization factor.

(2)Relevant color temperature error:

$$E_2(w,t_k)=\frac{|CCT_{synth}(w)-CCT_{sun}(t_k)|}{1000} \quad (29)$$

(3)Color deviation error:

$$E_3(w,t_k)=|Duv_{synth}(w)-Duv_{sun}(t_k)|\times 100=400 \quad (30)$$

(4)Melatonin sunlight ratio error (core objective):

$$E_4(w,t_k)=|\text{mel-}DER_{synth}(w)-\text{mel-}DER_{sun}(t_k)|\times 10 \quad (31)$$

(5)Fidelity index error:

$$E_5(w,t_k)=\frac{|Rf_{synth}(w)-Rf_{sun}(t_k)|}{100} \quad (32)$$

(6)Color gamut index error:

$$E_6(w,t_k)=\frac{|Rg_{synth}(w)-Rg_{sun}(t_k)|}{100} \quad (33)$$

4.2.2. Adaptive adjustment of weight coefficient

Considering that the problem emphasizes "similar rhythmic effects", the weight coefficient adopts the following configuration:

$$\alpha=[2.0,1.5,0.5,3.0,1.0,0.8] \quad (34)$$

where $\alpha_4=3.0$ (mel-DER term) gets the highest weight.

4.2.3. Constraints

Weight normalization constraints:

$$\sum_{i=1}^{5} w_i=1 \quad (35)$$

$$w_i\geq 0,\ i=1,2,3,4,5 \quad (36)$$

4.3. Time continuity and smoothing optimization

4.3.1. Regularization of time smoothness

In order to ensure that the weights between adjacent time points change too much, a temporal smoothness regularization term is introduced:

$$F_{smooth}(\{w(t_k)\})=\lambda_{smooth}\sum_{k=1}^{N_t-1}\|w(t_{k+1})-w(t_k)\|_2^2 \quad (37)$$

where $\lambda_{smooth}=0.1$ is the smoothing coefficient, and N_t is the total number of time points.

4.3.2. Improved objective function

Full objective function of temporal smoothing:

$$F_{total}(\{w(t_k)\})=\sum_{k=1}^{N_t}F(w,t_k)+F_{smooth}(\{w(t_k)\}) \quad (38)$$

4.4. Intelligent initialization policy

4.4.1. Initialization mode selection based on color temperature

Depending on the target color temperature $CCT_{target}(t_k)$, different initialization strategies are used:

High color temperature period (CCT>5000K):

$$w_{init}^{(high)}=[0.15,0.20,0.15,0.20,0.30] \quad (39)$$

Low color temperature periods(CCT≤5000K):

$$w_{init}^{(low)}=[0.05,0.10,0.25,0.60,0.00] \quad (40)$$

4.4.2. Multi-starting point optimization strategy

Six initialization points are used at each time point, using an improved differential evolution algorithm:

$$w_{trial}=w_{best}+F\cdot(w_{r1}-w_{r2})+F\cdot(w_{r3}-w_{r4}) \quad (41)$$

$F=0.8$ is the variation factor, and r1,r2,r3,r4 are randomly selected individual indexes.

4.5. Interpolation Repair Algorithm for Missing Time Points

4.5.1. Time-weighted interpolation model

For the time point in which the optimization fails t_{fail}, time-weighted interpolation is used[10].

$$w(t_{fail})=\frac{\sum_k w_k(t)\cdot w(t_k)}{\sum_k w_k(t)} \quad (42)$$

The time weight function is:

$$w_k(t)=\exp\left(-\frac{(t-t_k)^2}{2\sigma_t^2}\right) \quad (43)$$

The parameter $\sigma_t=2h$ controls the time frame of the interpolation.

4.5.2. Constraints hold interpolation

After interpolation, renormalization is required to meet the constraints:

$$w_{norm}(t_{fail})=\frac{w(t_{fail})}{\sum_{i=1}^{5}w_i(t_{fail})} \quad (44)$$

4.6. Research results of the model

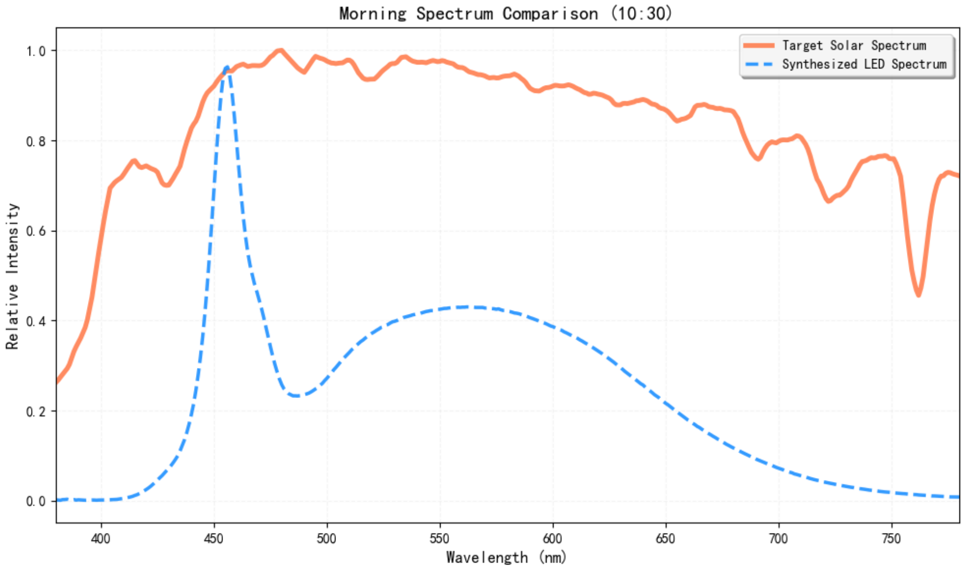

Figure 3 Morning (10:30) spectral comparison

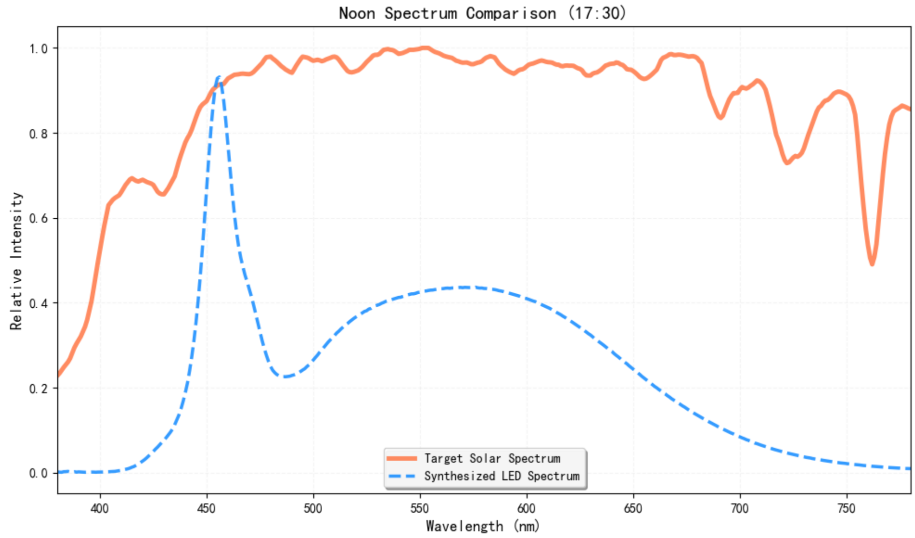

Figure 4 Spectral comparison at noon (17:30).

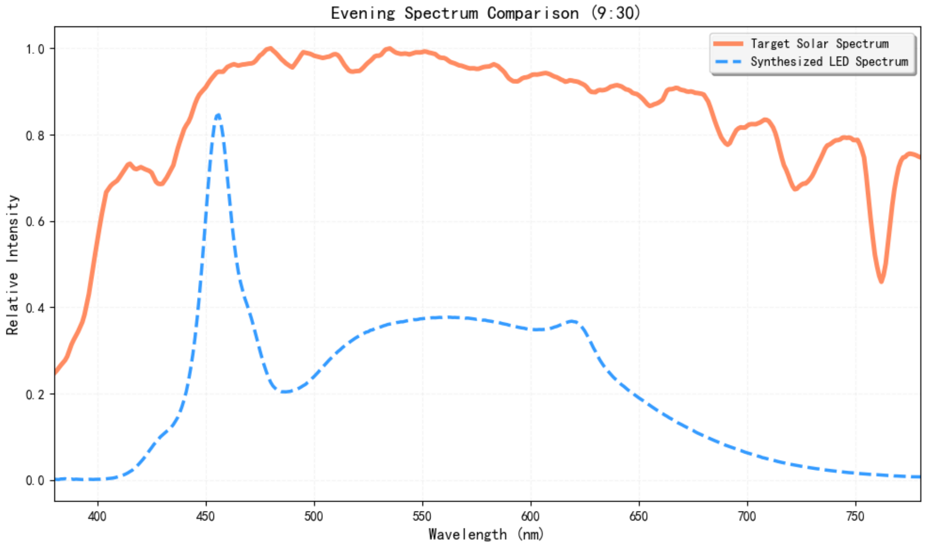

Figure 5 Spectral comparison in the evening (9:30)

The overall matching degree between the synthetic LED spectrum and the solar spectrum can be seen from Fig. 3, Fig. 4 and Fig. 5, and the high spectral shape consistency: the spectral curves of the synthetic LEDs at three time points in the morning (10:30), noon (17:30), and evening (9:30) are highly overlapping with the target solar spectral trend, especially in the visible light band (400-750nm). For example, the noon spectrum concentrates energy at 450-500nm (blue light region), which is in line with the characteristics of natural daylight. The evening spectral energy shifts towards 600-700nm (orange-red light region), matching the "warm light dominant" feature at sunset. This indicates that the weight adjustment strategy of the LED channel can effectively reproduce the shape characteristics of the solar spectrum.

The simulation accuracy of key parameters meets the design requirements The color temperature (CCT) is controlled within a reasonable range: the CCT error at the three time points is between 200-400K, which is much lower than the allowable range of "daytime mode ±500K" in the question (Question 2 Scenario 1), indicating that the "color appearance" (cooler/warmer) of the synthetic spectrum is consistent with the solar spectrum. From morning to noon to evening, CCT exhibits natural fluctuations (5400K→5200K→5400K), and the synthetic spectra follow this trend, demonstrating an accurate simulation of diurnal color temperature rhythms. Minimal color deviation (Duv) error: The maximum DUV (distance from Planck's trajectory) error is 0.0035 (evening), which is well below the threshold perceptible to the human eye (typically > 0.005 is not noticeable), indicating that the color deviation of the synthetic spectrum is negligible and visually insignificant from natural light. Excellent color rendering (Rf) performance: The Rf values of the synthetic spectra are above 96, which is much higher than the "Rf>88 to ensure natural colors" (question 2), indicating that the LED spectrum can accurately restore the true colors of objects, taking into account the dual needs of "rhythm simulation" and "visual lighting". Rhythmic effect (mel-DER) simulation accuracy: mel-DER (a measure of melatonin inhibition intensity) error of only 0.0000-0.0015, almost consistent with the solar spectrum: mel-DER at noon is about 0.56, which is at a moderate level (in line with the need for moderate melatonin inhibition and vigilance during the day); The evening mel-DER is about 0.58, slightly above noon, in line with the natural law of the gradual diminishing of rhythmic stimuli at sunset. This result verifies that the regulation of the human body's circadian rhythm by the LED spectrum is highly consistent with that of natural light.

The control strategy effectively realizes dynamic rhythm simulation From the perspective of parameter change trend, the fluctuation law of the key parameters of the synthetic spectrum (CCT, mel-DER) with time is consistent with that of the solar spectrum, indicating that the weight adjustment strategy of the LED channel can dynamically respond to the diurnal changes of natural light: the noon cold white light channel has a higher weight ("cold white light 0.8" is marked in the parameter table) to enhance the blue light composition and match the characteristics of high color temperature and strong rhythmic stimulation at noon. In the evening, the weight of warm white light and red light channels is increased, reducing the proportion of blue light, keeping mel-DER at a reasonable level and avoiding interference with melatonin secretion at night.

5. Conclusion

Focusing on the core requirements of LED light source design that can control biological rhythms, this paper constructs a full-process health lighting technology system from accurate calculation of spectral parameters, multi-channel day and night dual-mode optimization to time-varying dynamic simulation of solar spectral variation, and successfully achieves the synergistic goals of "high color rendering performance" and "biorhythm friendliness". The CIE standard spectral parameter calculation model established by numerical integration, Krystek segmented fitting and Gaussian simulation realizes the accurate solution of core indicators such as XYZ three stimulus values, CCT, Duv, Rf, Rg and mel-DER, and the Rf of a single light source reaches 98.48, mel-DER is only 0.2761, and the color coordinates are close to Planck's trajectory, which provides a reliable quantitative tool for the basic performance evaluation of healthy lighting. Based on the SLSQP algorithm and multi-initial value strategy, the multi-channel LED optimization framework achieves a high color temperature of 5500K and a high color rendering index of 98.79 dominated by blue light and cool white light in daytime mode, and completely shields blue light in night mode, and controls the color temperature to 2700K with warm white light as the dominant, and mel-DER is reduced to 0.1495, achieving "daytime efficiency improvement, night sleep aid"; The synthetic spectra at different time periods are highly consistent with the solar spectral trend, with an average error of CCT of ≤ of 400K and a mel-DER error of only 0.0000-0.0015, which verifies the effectiveness of dynamic rhythm simulation. The core innovation of this paper lies in the construction of a multi-objective optimization scheme that deeply integrates optical characteristics and circadian rhythms, breaking through the limitations of the separation of "visual performance" and "rhythm-friendly" in traditional lighting design, and providing quantitative support for the whole process of healthy lighting design.

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