Optoelectronics and optoelectronic devices

The influence of temperature and current on the spectral and luminous characteristics of high-power LEDs

A.M. Minyaylo[1], D.V. Pekur[1*], Yu.E. Nikolaenko[2], O.M. Kamuz[1]

[1]*V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Department of Optoelectronics, 41 Prosp. Nauky, 03680 Kyiv, Ukraine*
[2]*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Institute of Atomic and Thermal Energy, 37 Beresteiskyi Avenue, 03056 Kyiv, Ukraine*
[*]*Corresponding author e-mail: demid.pekur@gmail.com*

Abstract. This article aims to investigate the influence of temperature and drive current on the spectral and photometric characteristics of high-power Chip-on-Board (COB) LEDs. An analysis of variations in luminous flux, correlated color temperature (CCT), and color rendering index (CRI) is presented, accompanied by the development of analytical models describing their behavior. To achieve an accurate mathematical representation, a regression analysis method is proposed, enabling the formulation of precise theoretical dependences of luminous flux and CCT on the operating temperature and current of LEDs. The obtained results provide a scientific foundation for designing the energy-efficient lighting systems with stabilized photometric characteristics, suitable for industrial, biomedical, and photobiological applications. Furthermore, the findings offer promising opportunities for real-time prediction of temperature-induced degradation in LED performance.

Keywords: LED, luminous flux, correlated color temperature, color rendering index.

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1. Introduction

In the modern world, light-emitting diode (LED) light sources are gradually replacing traditional lighting technologies [1] due to their numerous advantages, including high energy efficiency [2], long operational lifetime [3], environmental safety [4], and the ability to support compact lighting device configurations. LEDs play a crucial role in residential and industrial lighting, automotive illumination systems [5], display technologies [6], biomedical systems [7, 8], horticultural lighting [9, 10], optical communication systems [11, 12], emergency lighting [13], and lighting systems powered by renewable energy sources [14]. Consequently, there is a growing interest in exploring the physical and technical aspects of LED operation, particularly under intensive usage and external disturbances.

One of the key aspects affecting the reliability and efficiency of high-power LEDs is the thermal stability of their electro-optical characteristics [15]. During operation, LEDs generate a significant amount of heat, which necessitates effective thermal exchange with the surrounding environment. Non-uniform temperature distribution and overheating of the active region of the LED lead to reduced quantum efficiency of emission, degradation of semiconductor layers, alteration of the spectral composition of light, and, ultimately, decreased luminous efficacy and shifts in colorimetric parameters. Therefore, the thermal stability of the spectral properties of LEDs is critically important for maintaining lighting quality in museum exhibits, precision and medical lighting, color recognition systems, machine vision, and controlled photobiological applications.

The use of high-power LEDs in systems with stringent spectral stability requirements (namely, biological illumination, color correction, medical phototherapy devices, hyperspectral imaging systems, and optical sensors) demands an in-depth understanding of the physical mechanisms underlying temperature-induced changes in spectral characteristics. This is particularly relevant for Chip-on-Board (COB) LEDs with a high density of semiconductor die placement [16], resulting in substantial thermal loads and heightened sensitivity to thermal dissipation conditions. COB modules are frequently operated close to their thermal and electrical limits, resulting in a decrease in luminous efficacy and total luminous flux.

The spectral efficiency of LEDs, which characterizes the ability of a light source to effectively convert electrical energy into optical radiation [16] at specific wavelengths, directly depends on the bandgap width of the semiconductor material, the temperature dependence of recombination mechanisms, the properties of phosphor coatings (in the case of white LEDs), and the electrical drive method. An increase in temperature leads to the following phenomena, namely, redshift of the emission spectrum, broadening of the spectral band, changes in the amplitude profile of emission, a decrease in short-wavelength emission intensity, an overall reduction in spectral efficiency, and deviations from nominal chromaticity coordinates [17].

The efficiency of LED light sources is a multifactorial parameter influenced by both intrinsic properties of semiconductor materials and external operating conditions. Among the key factors affecting luminous efficiency, one can mention the junction temperature of the *p-n* region [18], thermal dissipation efficiency, spectral characteristics of emission, electrical operating mode (current, voltage), optical system design, and the degree of material degradation during operation. These complex interdependences render the analytical modeling of luminous flux as a function of temperature as a challenging task, particularly for lighting systems subjected to variable or unstable thermal conditions. This underscores the need to develop adaptive models capable of predicting the influence of temperature and electrical operating conditions to ensure the reliability and stability of the luminous characteristics of LED sources.

Thermal influence on LED performance is not only instantaneous but also accumulative [19]. Under prolonged thermal loading, degradation processes become activated within the crystal active region, accompanied by the formation of thermally induced defects and a decrease in the stability of semiconductor heterostructures. Accurate analysis and modeling of the temperature behavior of LEDs requires consideration of a range of interrelated processes: electrophysical (charge carrier migration, non-radiative recombination), optical (changes in spectral emission parameters and filtering effects), thermodynamic (variations in thermal conductivity, thermal expansion), and chemical (material degradation, contact oxidation).

At the same time, for practical engineering implementation, it is essential to develop generalized mathematical models for describing the dependence of key spectral and luminous parameters on crystal temperature and other influencing factors. In particular, the application of two- or multi-parameter regression models [20–22], built upon statistical processing of experimental data that accounts for the effects of temperature and operating current, opens avenues for developing adaptive control algorithms and degradation prediction systems for LED technologies. The study of thermal stability of spectral properties, especially under fluctuating thermal loads, remains highly relevant not only for LED systems but also for other classes of photonic devices, namely cholesteric liquid crystal materials, which exhibit temperature-dependent optical properties [23, 24].

Modern microcontrollers with enhanced computational capabilities, integrated into energy-efficient LED drivers [25], are capable of effectively implementing these models in real time. This enables intelligent control of lighting modes considering the thermal dynamics and cumulative effects. As a result, the reliability, stability, and energy efficiency of LED lighting systems can be significantly improved, particularly under conditions of variable thermal loading.

This study aims to perform a comprehensive experimental and theoretical investigation of the influence of temperature and electrical operating regimes on the spectral and photometric parameters of high-power LEDs, specifically, luminous flux, correlated color temperature, and color rendering index. The ultimate goal is to establish a scientific foundation for designing energy-efficient LED light sources with predictable photometric characteristics for use in efficient lighting, spectrometry, and photobiological applications.

2. Methodology and results of experimental studies

To investigate the influence of temperature on the luminous flux, correlated color temperature (CCT), and color rendering index (R_a) of high-power LEDs, an experimental procedure was developed combining spectrometric analysis with precise thermal control.

The objects of the study were high-power Chip-on-Board (COB) LED modules Samsung SPHWHAHDNM231ZR3D4, which provide intense broadband emission and are characterized by a high packing density of semiconductor dies. These light sources are thermally sensitive due to the limited area of the active surface and the challenges associated with heat dissipation from the central region. For the experiments, COB module samples with a nominal color temperature close to 5000 K and a maximum rated power of 225 W were selected. The physical dimensions of the modules are 28×28×1.7 mm.

To analyze the dynamic changes in the electro-optical parameters of the COB modules under various thermal conditions, a controlled thermal load procedure was implemented using a Binder MK 53 climate chamber. To maintain a stable and controllable thermal regime, the LED modules were mounted on a massive copper heat sink and placed inside the Binder MK 53 chamber, which allowed for heating or cooling within the range –30 °C…+40 °C with a step of 10 °C. Additional temperature measurements were performed using a thermocouple and monitored *via* a multichannel temperature measurement system (YF500). Particular attention was paid to isolating the light source from convective airflows and ambient lighting to prevent distortion of spectral data.

Spectral characteristics were recorded using a high-precision Everfine-2000 spectroradiometer, which operated within the visible range (380…780 nm) with the aid of a specially designed aperture system. The device is equipped with an optimized optical input geometry that minimizes stray reflections and ensures accurate light capture. This configuration enabled high spectral resolution and measurement stability even under intense optical radiation.

Thanks to the high luminous flux generated by the COB modules, it was possible to use a short integration time (up to 20 ms at each measurement point), which minimized the influence of illumination fluctuations and system noise. Each measurement was repeated three times, and the results were statistically averaged to enhance accuracy and reduce random errors.

Upon completion of the measurement series under controlled temperature conditions, the acquired spectra were processed and compared with reference measurements recorded at 20 °C using an Instrument Systems CAS-140CT spectroradiometer and a 2-meter integrating sphere with an internal high-diffusivity coating. This setup ensured measurement uncertainty close to 1% and enabled accurate registration of absolute emission parameters across the temperature range. The comparison allowed for reliable identification of spectral peak shifts, changes in spectral shape, and, subsequently, the determination of variations in chromaticity coordinates and changes in the color rendering index.

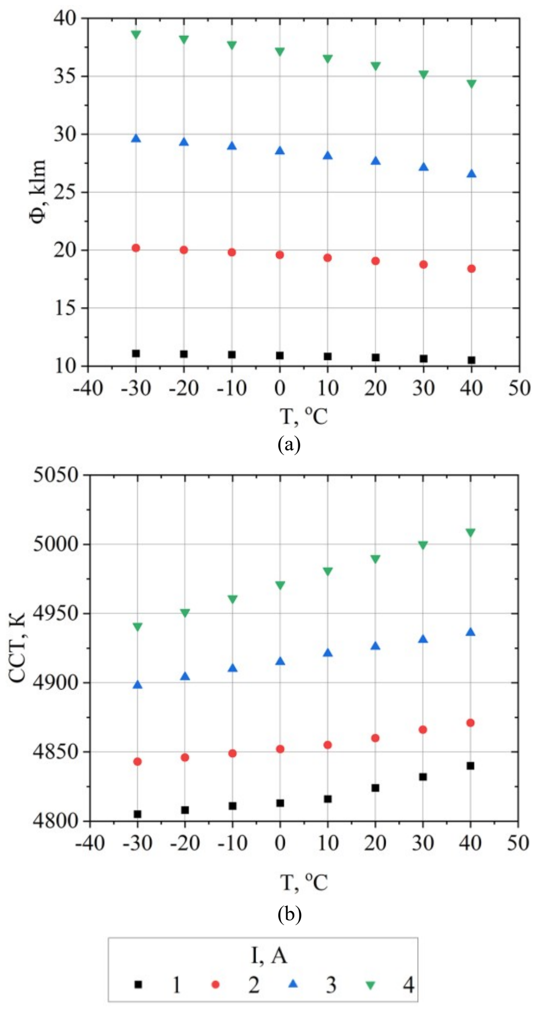

Fig. 1. Dependence of luminous flux (a) and correlated color temperature (b) on temperature at different drive currents.

The results of the study demonstrated that within the range –30 °C…+40 °C and for drive currents ranging from 1 to 4 A, the maximum deviations of the measured parameters were as follows:

- luminous flux – an increase by a factor of approximately 3.67, from 10,513 lm (at 1 A and +40 °C) to 38,635 lm (at 4 A and –30 °C);
- correlated color temperature – variation of approximately 204 K, with extreme values of 4805 K (at 1 A and –30 °C) and 5009 K (at 4 A and +40 °C);
- color rendering index (R_a) – deviation of about 2 units, remaining within the range of 69.5 to 71.6 across all conditions.

Fig. 1a illustrates the variation in luminous flux (Φ) with temperature at different drive currents, while Fig. 1b presents the dependence of correlated color temperature (CCT) on both temperature and drive current.

The found changes in the color rendering index were minimal and, in most cases, within the margin of measurement error [26]. Nevertheless, a general trend was observed: a slight improvement in CRI with increasing current and temperature. At higher currents, the radiation intensity increases, which enhances the probability of radiative recombination in the long-wavelength emission bands of the phosphor. In addition, non-radiative heating contributes to a slight shift of the emission peak toward the red band due to bandgap narrowing in the LED chip and changes in the phosphor's conversion efficiency. These processes lead to a better spectral coverage of the red component, which improves the color rendering index. Given the marginal nature of these variations, the construction of analytical dependences or mathematical models for CRI is deemed impractical within the scope of this experimental series.

3. Development of an analytical model based on experimental data: accuracy and applicability

Analytical modeling of the dependence of luminous flux in a COB-type LED module on temperature and drive current is a key step toward understanding the degradation patterns of its parameters and enabling the development of engineering-level predictive systems. The obtained experimental data were used to construct an approximating function that describes the nonlinear behavior of luminous flux under combined thermal and electrical stresses.

The measured electro-optical parameters of the COB module were structured into an array of value pairs:

- ambient temperature (from –30 °C to +40 °C, in 10 °C increments);
- drive current (from 1 to 4 A, in 1 A increments);
- corresponding luminous flux (Φ, in lumens) and correlated color temperature (CCT, in Kelvins).

In total, two datasets were compiled for training, each containing 32 measurement points. For each pair of parameters (T_i, I_i), the associated luminous Φ_i and correlated color temperature CCT_i were recorded. These training datasets were deemed suitable for regression analysis techniques [27].

Given the nonlinear dependence of both luminous flux and CCT on temperature and current, as well as their interaction, a second-order model was selected, specifically a bivariate quadratic regression. This type of model provides an optimal balance between descriptive accuracy and computational stability. It accounts for: quadratic temperature dependence (T^2), which reflects thermally induced loss mechanisms; quadratic current dependence (I^2), representing self-heating effects at high currents; interaction term ($T{\cdot}I$), capturing the coupled nature of electrothermal phenomena; linear dependences (T, I); constant term, representing the base level of luminous flux.

The choice of a second-order polynomial model also helps to avoid overfitting, which is typical for higher-order models when applied to relatively small datasets.

The general form of the analytical models is given by the equations:

$$\Phi(T,I) = a_1T^2 + a_2I^2 + a_3TI + a_4T + a_5I + a_6\,, \qquad (1)$$

$$\mathrm{CCT}(T,I) = a_1T^2 + a_2I^2 + a_3TI + a_4T + a_5I + a_6\,, \qquad (2)$$

where $\Phi(T, I)$ – luminous flux, lm; $\mathrm{CCT}(T, I)$ – correlated color temperature, K; T – ambient temperature, °C; I – drive current, A; a_1–a_6, b_1–b_6 – regression coefficients to be determined.

These functions (1) and (2) describe a second-order surface in the variable space of T and I, enabling the representation of key physical effects with high accuracy. The model parameters were determined using the least squares method. For this purpose, the training datasets were organized in the form of a feature matrix X and a target vector y:

$$X = \begin{bmatrix} T_1^2 & I_1^2 & T_1I_1 & T_1 & I_1 & 1 \\ T_2^2 & I_2^2 & T_2I_2 & T_2 & I_2 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ T_n^2 & I_n^2 & T_nI_n & T_n & I_n & 1 \end{bmatrix},\quad y = \begin{bmatrix} \Phi_1 \\ \Phi_2 \\ \vdots \\ \Phi_n \end{bmatrix}$$

$$X = \begin{bmatrix} T_1^2 & I_1^2 & T_1I_1 & T_1 & I_1 & 1 \\ T_2^2 & I_2^2 & T_2I_2 & T_2 & I_2 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ T_n^2 & I_n^2 & T_nI_n & T_n & I_n & 1 \end{bmatrix},\quad y = \begin{bmatrix} \mathrm{CCT}_1 \\ \mathrm{CCT}_2 \\ \vdots \\ \mathrm{CCT}_n \end{bmatrix}$$

Solving the system of equations to determine the coefficient vector $\vec{a} = [a_1,\ldots,a_6]^T$:

$$\vec{a} = \left(X^TX\right)^{-1}X^Ty\,.$$

A similar procedure was applied to determine the coefficients vector $\vec{b}$ of the model describing the correlated color temperature $\mathrm{CCT}(T, I)$. The calculations were performed in the Python environment using the NumPy and scikit-learn libraries. Insignificant terms, whose statistical contribution was below the accepted threshold, were excluded from the final model to improve its robustness and interpretability. As a result of the computations, the following equations were obtained for the luminous flux and correlated color temperature:

$$\Phi(T,I) = 11.195\cdot T + 8747.3\cdot I - 0.17234\cdot T^2 - $$
$$-17.508\cdot T\cdot I - 9.04 + 2188.8\,, \qquad (3)$$

$$\mathrm{CCT}(T,I) = 0.1765\cdot T + 25.93\cdot I + 0.00188\cdot T\times T + $$
$$+5.313\cdot I\cdot I + 0.1614\cdot I\cdot T + 4783.2\,. \qquad (4)$$

The evaluation of the relative deviation between experimental and modeled values is performed using the relative error (δ):

$$\delta = \frac{\left|A_{\mathrm{exp},i} - A_{\mathrm{model},i}\right|}{A_{\mathrm{exp},i}}\cdot 100\%\,, \qquad (5)$$

where $A_{\mathrm{exp},i}$ are the experimental values and $A_{\mathrm{model},i}$ are the calculated (modeled) values. For the computed values of Φ and CCT, the relative error δ did not exceed 1%. These values are below the typical level of metrological uncertainty for photometric measurements, which generally does not exceed 2% for Class A laboratory-grade equipment. Therefore, the constructed models can be considered reliable within the experimental range.

Additionally, to provide a quantitative measure of approximation quality, the coefficient of determination R^2 was calculated. This coefficient represents the proportion of the variance in the experimental data that is explained by the model:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(A_{\mathrm{exp},i} - A_{\mathrm{model},i}\right)^2}{\sum_{i=1}^{n}\left(A_{\mathrm{exp},i} - \overline{A}\right)^2}\,, \qquad (6)$$

where $\overline{A}$ is the sample mean.

The obtained coefficient of determination R^2 was 0.9994 for the luminous flux and 0.995 for the correlated color temperature, indicating a high level of agreement between the model and the experimental data. This confirms that the approximating functions are sufficiently accurate for use in engineering analysis and automated control systems.

Fig. 2 presents a comparison between the modeled results and the experimental data.

The developed analytical model for the temperature dependence of luminous flux and correlated color temperature of the LED COB module not only confirms theoretical understanding of the influence of temperature and current on electro-optical characteristics but also offers practical value across a wide range of engineering applications. The model can be integrated into the design, control, and performance evaluation processes of LED systems, particularly under variable or harsh thermal environments.

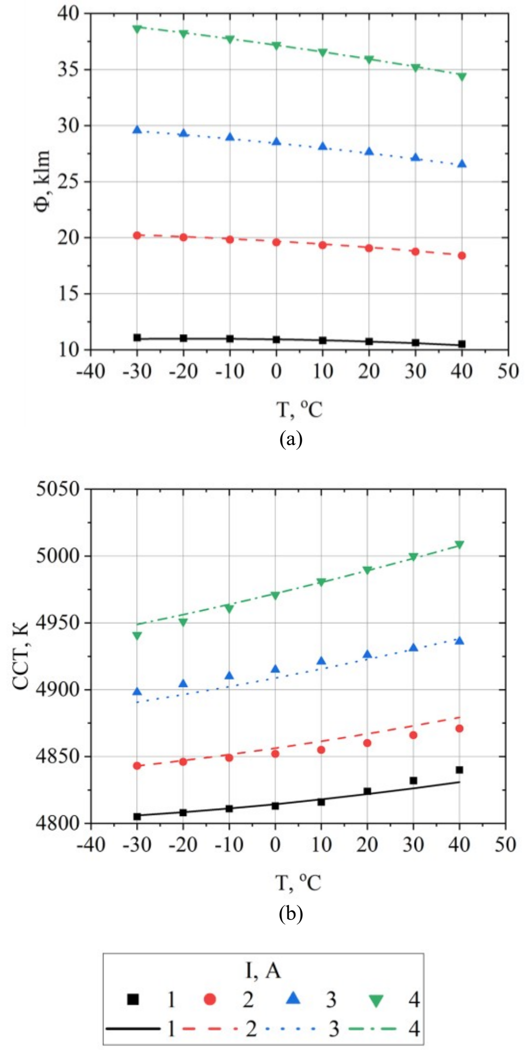

Fig. 2. Comparison of experimental data (geometric markers) with model predictions obtained using equations (3) and (4) (lines) for luminous flux (a) and correlated color temperature (b) as functions of temperature at various drive currents.

The model enables high-accuracy real-time prediction of luminous flux $\Phi(T, I)$ under ambient or operating temperature fluctuations. This is especially relevant for energy-efficient applications where temperature changes dynamically throughout the day or seasonally, namely in street lighting, industrial facilities, transportation systems, and greenhouse environments.

By enabling the prediction of light source behavior without the need for repeated measurements, the model allows engineers to:

- select optimal drive current settings to maintain target illumination levels;
- compensate for luminous losses through current adjustment;
- perform pre-design estimations of lighting levels under dynamically changing operating conditions.

One of the key advantages of the proposed model is its analytical form, which is suitable for implementation in microcontroller-based or digital control systems. It can be embedded in LED driver firmware to enable adaptive current regulation based on real-time temperature data, ensuring a stable light output.

Due to its computational simplicity, the model can be efficiently implemented in environments with limited processing capabilities (*e.g.*, STM32, AVR, ESP32), as well as in visual programming platforms for control systems such as MATLAB/Simulink or LabVIEW.

4. Conclusions

This study presents a comprehensive experimental and theoretical investigation of the influence of temperature on the electro-optical characteristics of high-power LED COB modules. A series of precise laboratory measurements of luminous flux were performed under various temperature and current conditions to develop an analytical model that describes the behavior of key module parameters (luminous flux and correlated color temperature) under varying thermal loads and electrical drive conditions.

Based on the experimental data, a second-order two-parameter model was constructed, accounting for the individual effects of temperature and current as well as their interaction. The proposed model, formulated as a quadratic regression, demonstrated a strong correlation with the experimental results, with a maximum relative error close to 1% and coefficients of determination R^2 of 0.9994 for luminous flux and 0.995 for correlated color temperature. The model enables highly accurate prediction of luminous flux variation within the investigated temperature range, facilitating its integration into engineering calculations and control systems.

The analytical formulation of the model enables seamless integration into embedded microcontroller systems for real-time control of LED performance. Its computational efficiency makes it particularly attractive for resource-constrained applications, such as adaptive street lighting, industrial illumination, and intelligent greenhouse lighting systems.

The presented methodology supports the development of thermally adaptive LED drivers and can serve as a foundation for implementing temperature-compensated feedback control algorithms, ensuring consistent photometric output in dynamic environments.

The findings highlight the practical utility of regression-based empirical modeling as a fast and effective alternative to complex numerical thermal simulations, particularly during early-stage design and prototyping of solid-state lighting systems.

Thanks to its high accuracy and versatility, the developed model provides a valuable foundation for further optimization of high-power LED lighting systems in both high-tech and industrial applications.

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Authors and CV

Anastasiia M. Minyailo, Leading engineer of the Department of Optoelectronics at the V. Lashkaryov Institute of Semiconductor Physics. Authored 12 scientific publications. Her current research interests: smart lighting, phytolighting, optical simulations and measurements.
E-mail: miniailo.anastasiia@gmail.com,
https://orcid.org/0009-0007-7926-9131

Demid V. Pekur, PhD in Telecommunications and Radio Engineering, Deputy Head of the Department of Optoelectronicsat the V. Lashkaryov Institute of Semiconductor Physics. Authored more than 90 publications and 7 patents for inventions. His research interests include development of advanced high-power LED lighting systems, creation of lighting systems with wide functionalities, and development of perspective optoelectronic devices.
https://orcid.org/0000-0002-4342-5717

Yurii E. Nikolaenko, Doctor of Engineering. Leading Fellow of the Heat-and-power Engineering Department at the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute". He is the author of more than 350 scientific publications. His research interests include heat removal from electronic components by using heat pipes.
E-mail: y.nikolaenko@kpi.ua,
https://orcid.org/0000-0002-3036-5305

Oleksandr M. Kamuz, Doctor of in Physics and Mathematics, Senior Research Fellow at the Department of Optoelectronics, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Authored more than 250 publications and 6 patents for inventions. His research interests include photoinduced modification of II–VI and III–V semiconductors, development of integrated optical and waveguide laser systems, diagnostics of photophosphor materials for white LED applications, and creation of advanced optoelectronic tools for light-matter interaction studies.
E-mail: kamuz_a_m@ukr.net,
https://orcid.org/0000-0001-8785-8576

Authors' contributions

Minyaylo A.M.: formal analysis, validation, investigation.
Pekur D.V.: formal analysis, investigation, data curation, visualization, writing – original draft, writing – review & editing.
Nikolaenko Yu.E.: conceptualization, investigation, validation, writing – original draft.
Kamuz O.M.: investigation, data curation, visualization.

Вплив температури та струму на спектральні та світлові параметри потужних світлодіодів

А.М. Міняйло, Д.В. Пекур, Ю.Є. Ніколаєнко, О.М. Камуз

Анотація. Стаття спрямована на дослідження впливу температури та струму електроживлення на спектральні та світлотехнічні параметри потужних світлодіодів типу СОВ. Проведено аналіз зміни світлового потоку, корельованої колірної температури та індексу кольоропередачі, а також побудовано аналітичні моделі, що описують їх поведінку. Для точного математичного опису запропоновано використовувати метод регресійного аналізу, який дозволяє з високою точністю формувати теоретичні залежності світлового потоку та корельованої колірної температури від температури та струму експлуатації світлодіодів. Отримані результати формують наукове підґрунтя для проектування енергоефективних систем освітлення зі стабілізованими фотометричними характеристиками, придатними для промислових, біомедичних і фотобіологічних застосувань. Більше того, ці результати відкривають перспективи прогнозування температурної деградації світлодіодів у режимі реального часу.

Ключові слова: світлодіод, світловий потік, корельована колірна температура, індекс кольоропередачі.