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Modeling of integrated lighting system based on coloured and white LEDs for performances improvement

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LED technology offers new opportunities for lighting in the form of dynamic light sources. The authors of this article have analyzed an integrated LED system in terms of improving their overall performance, based on its modeling and simulation. An original methodology for determining the optical, electrical and thermal characteristics of coloured and white LEDs, using specialized software, was proposed. The operational optimization of LED-based lighting system, with special attention to the influence of thermal effect over the integrated system, was conducted. It was studied the reliability of the LED system in order to analyze the extension of its life duration. Based on the results obtained from the simulation of the analyzed LED system, the authors have highlighted a very good agreement between the numerically modeled and the literature-based experimentally determined electrical, optical and thermal characteristics for the two operating modes (forward mode and reverse mode) and cooling modes (with heat sink and without heat sink), respectively.

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1. Introduction

Lighting systems with LEDs provide help in reducing energy consumption and obtaining a light emission as close to the user's needs.

Recent researches on LED lighting systems consider the optimization of emitted luminous fluxes and, particularly, the dynamic control of the new generation RGBW LED system [1-4]. Intelligent dynamic control may be the best option for modeling and optimization of an efficient optical lighting system, requiring fine precision in terms of light quality [5-7].

Development of LED lighting system widely led to increased attention on their lifetime and mainly on the thermal effect that occurs during their operation [8-10]. This leads to an increased instability of the LED, followed by a decrease in its brightness due to excessive heat [11-15]. For this reason, a thermal management based on heat sink system for LEDs was implemented [16, 39-41]. It is worth noticing that thermal effects on LEDs can reduce their life expectancy by 20-30%, which represents 8.000 - 15.000 hours; this is an essential factor of increased costs associated with LED lighting system [17]. Regarding LED applications, it is considered the increase of their reliability and operation at relatively high temperatures, such as 80-90 °C, without affecting their optical performance [18].

Fig. 1 represents an integrated LED structure, where these specific components can be observed: heat sink, LED driver, optical assembly and the LEDs with their corresponding chips.

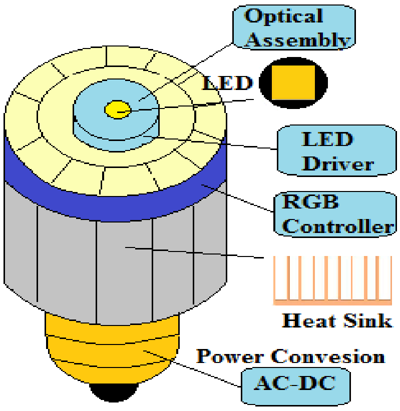

Fig. 1. Anatomy of an integral LED lamp

The objective of this article is to present a detailed methodology of an integrated LED lighting system, which is composed of four types of LEDs, namely red, green, blue and white [19, 20]. The authors studied and simulated the behaviour of the LEDs depending on their operating temperature and on direct/reverse current [21].

The authors approached the characteristics and performances of the LED system from two points of view:

- as electrical, optical or thermal models, highlighting the specific electrical, optical or thermal characteristics and performances, separately for each LED (RGBW) [22-24].
- as complex models through the characteristics and overall performance of integrated LED system.

This approach was only partially presented in the literature [25], not being shown from the perspective of a unifying vision, as we sought to achieve in the present article.

This study proposes an analysis of the integrated LED system optimization based on its electrothermal and optical modeling, respectively, taking into account: 1) "reverse characteristics" and 2) the influence of "junction temperatures" over optical power. Using the junction temperature dependence, there were obtained by numerical simulation some essential parameters characterizing the LED system, namely: 1) total power, and 2) optical efficiency (energy to electric light conversion efficiency). It was concluded that system performances decrease only when its cooling conditions get worse; therefore it is necessary to emphasize the thermal management.

The results of the simulations were compared and verified against experimental measurements obtained in the literature [26-31]. It was found a very good concordance between the values numerically modeled by authors and the experimental data of electrical, optical, and thermal characteristics, respectively the overall optical efficiency for the integrated LED system.

2. State of the art

2.1. Electrical, optical and thermal properties of the LEDs. Integrated LED systems

Development of LED lighting has led to a thoroughgoing study of both theoretical and experimental aspects, enabling electrical, optical and thermal performance improvements for increasingly complex applications.

Jia Wang and Wei Dongying from the Academy of Computer and Communications Engineering at the Polytechnic University of Tianjin, China, presented in the paper „The intelligent system for LED lighting based on STCMCU”, an intelligent dimming system based on LED lamps, as well as the hardware and software design for such a system [28].

A. Thorseth, J. Thomsen, W. Dam-Hansen, in the paper „Characterization, Modeling and Optimization of Light-Emitting Diode Systems” [29], studied and characterized LED systems considering their operating parameters, correlated with the quality of light. Particularly, emphasis is given to thermally control of the effect, in terms of interdependence between them and light quality. It is stressed the thermal effect and the control regarding interdependence between them and light quality.

Nilesh Yadav, Nirvesh Mehta and Jaspalsinh Dabhi, in their work on „Design Review and Theoretical Model of Thermoelectric” [30] present the development of certain mathematical models for evaluating the performance of a heat sink system for a LED lighting system, based on thermoelectric properties.

András Poppe, Gábor Farkas and György Horváth, in their work „Electrical, thermal and optical characterization of power LED assemblies” [31], are examining the optical and electrical parameters of the LEDs based on junction temperature. Thermal management plays an important role in the case of power LEDs, which requires both physical measurements and simulation tools. There is also presented a method of electrothermal and optical simulation and at both LED-level and system-level.

2.2. LED systems technologies and their implementation in applications

The implementation of LED systems in applications has been studied by different authors, one of the major problems being the correlation of these energy-efficient applications to environment-friendly photovoltaic systems.

Chih-Hsuan Tsue, Wen-Shing Sun and Chien-Cheng Kuo, in their work „Hybrid sunlight / LED illumination and renewable solar energy saving concepts for indoor lighting” [32], studied a hybrid method for using sunlight together with a LED lighting system for interior connected to PV panels.

Ankit R Patel, Ankit A Patel, Mahesh A Patel and Dhaval R Vyas, in their work „Modeling and Simulation of Photovoltaic based LED Lighting System” [33], analyzed the efficiency of LED lighting systems powered by photovoltaic systems with the purpose of identifying the optimal configurations for different applications.

Mahrous Elsamman and MK Metwally, in the work „Modeling and simulation control of the power conditioning for LED street light” [34], analyze and propose a complex system consisting of a photovoltaic panel, a system of energy storage, a LED lamp, a heat sink system and a controller that can manage the well-functioning of a complex system.

2.3. Reliability of the LEDs

The failure of any LED system/component not only takes into account the connection type (serial or parallel) but also its electronic, thermal and optical management respectively. While some LED systems will fail in a direct way, others may experience low parameters, meaning they will not produce an acceptable amount of light or its quality will decrease. A complete characterization of a LED system’s lifespan must consider the possibility of an instant failure of the system’s components or the LED itself. However, in the present there is no standard or well-defined method to perform such characterization. Consequently, understanding failure, lifetime and reliability is very important for evaluating LED systems [35].

3. The methodology for LEDs characterization

3.1. General approach

The methodology for the characterization of LEDs followed their performances using 1) electrical modeling,

2) thermal modeling 3) optical modeling 4) integrated LED system modeling. The results are based on numerical simulation of the LEDs using specialized software, namely LUMILEDS (https://www.lumileds.com) for electrical, thermal and optical modeling of each LED independently and WEBENCH / Texas Instruments software (http://www.ti.com/webench) for the integrated system, respectively. The structure of the integrated LED system proposed for analysis in this article is shown in Fig. 2; in practice, this system is represented by an LED lamp that can be used for different applications according to the specific characteristics of the controller (i.e. residential / street / medical / museum lighting). Therefore, the LEDs can be analyzed based on different common semiconductor materials (see Table 1). There are also presented the specific characteristics of these materials, used in electrical and optical modeling of the LEDs.

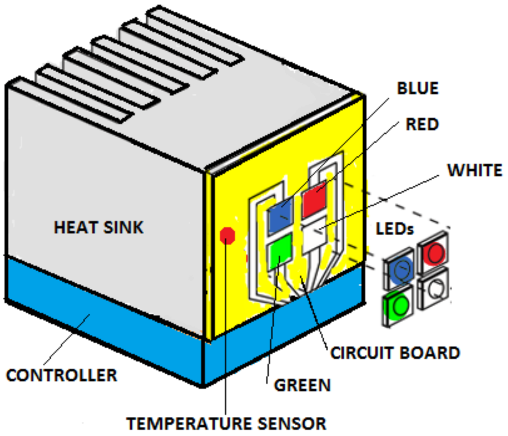

Fig. 2. LED system design, proposed by authors

Table 1. LEDs characteristics for usual semiconductor materials

Semiconductor materials	Wavelength (nm)	Colour [-]	U_F * [V]
GaInN	450nm	White	4.0
SiC	430 – 505 nm	Blue	3.6
GaAsP	605 – 620 nm	Red	1.8
AlGaP	550 -570 nm	Green	3.5

* U_F represents the forward voltage

3.2. Electrical modeling and simulation of LEDs

Establishment of the electrical characteristics for each type of LED (white, blue, green and red) was performed taking into account their performance dependence on the junction temperature. In Fig. 3 the I-V characteristics of the studied LEDs for the forward currents, obtained by numerical simulation using the LUMILEDS software, are presented. It is remarked that the white and the blue LEDs support relatively high currents compared with the red and green LEDs. This explains the preferential use of the white / blue LEDs together with the green / red LED, depending on the applications.

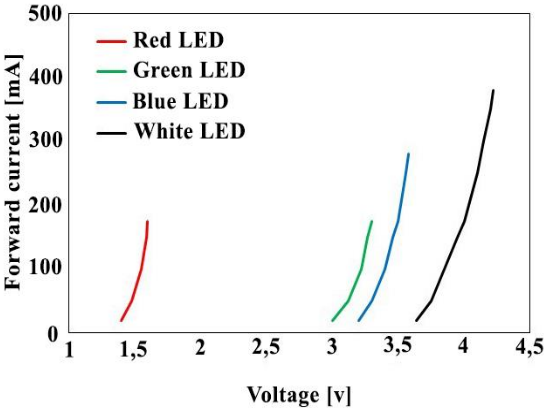

Fig. 3. I-V characteristics depending on the junction temperature (Tj = 83 ˚C)

3.3. Thermal modeling and simulation

Part of the total electrical energy entering the system is converted into light radiation (25%); the rest is converted into heat (75%) and represents the system losses. It is estimated that these percentages may vary depending on the light output and the LED type. System losses are characterized by the thermal power obtained using the relation (1):

$$P_{thermic} = P_{imput} - P_{light} \tag{1}$$

where: $P_{thermic}$ – thermal power [W], P_{input} – input power [W], P_{light} – LED emission power [W]. P_{input} is given by relation (2), where (V_i) and (I_i) represent the LEDs voltage and input current, respectively,

$$P_{imput} = V_i \cdot I_i \tag{2}$$

Emission power of LED (P_{light}) is obtained by relation (3):

$$P_{light} = \left(P_{imput} \cdot \eta_{driver}\right) \cdot \eta_{LED} \tag{3}$$

where: η_{driver} – driver efficiency [%], η_{LED} – LED efficiency. One of the most important parameters is the temperature of the LED junction. It can not be measured directly, but can be determined if the following parameters are known: SPT (solder point temperature), R_{th} (LED thermal resistance measured in ^{0}C/W) and P_{th} (thermal power, expressed in Watts).

$$T_j = T_{sp} + R_{th} \cdot P_{th} \tag{4}$$

Junction temperature variation has a negative effect on the LED; the optimization of thermal power using a heat sink system must be taken into account. With the help of LUMILEDS software it was analyzed the junction temperature influence on the radiative flux for the four studied types of LED. The simulation results are presented in Fig. 4 and can be used to dimension the heat sink system of the LED to improve its performance.

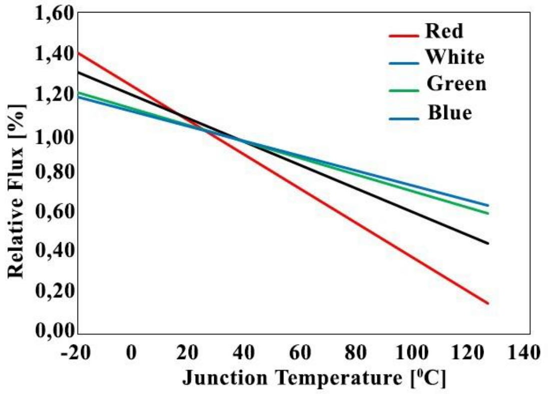

Fig. 4. Relative Flux depending on the junction temperature normalized to 25 ˚C

3.4. Optical modeling and simulation

Optical modeling involves both a theoretical analysis of the LED system in terms of optical performance, and its simulation in order to assess the quality of the emitted light. Regarding the light quality analysis, a number of quality features should be taken into account, namely: 1) the normalized intensity of the light spectrum, 2) spectral luminous flux and 3) the colour temperature for different types of LEDs. These features will be discussed next. For a LED, the spectral luminous flux (I_V) depends on the wavelength (λ), according to relationship (5):

$$I_V(\lambda)=683.002\,V(\lambda)I(\lambda) \tag{5}$$

where V (λ) represents the light sensitivity of the eye, and I (λ) is the luminous intensity, which is defined according to IEC standards (see Fig. 5).

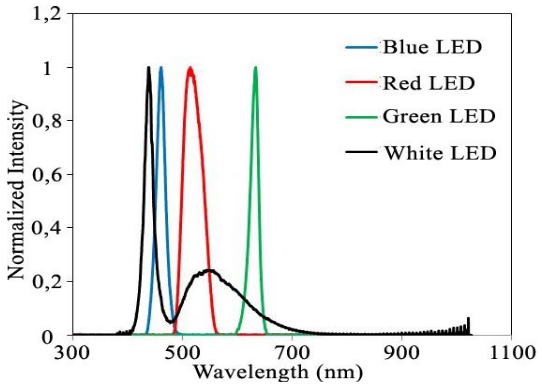

Fig. 5. Normalized intensity of a RGBW LED system

For a LED, the net quantity of light perceived is defined by integral luminous flux on visible. It is calculated using the relation (6):

$$\Phi_V=\int_0^{2\pi}\int_0^{\pi}\int_{390nm}^{730nm} I_V(\lambda,\theta,\varphi)\sin(\theta)\,d\lambda\,d\theta\,d\varphi \tag{6}$$

where θ and φ are the spherical coordinates around the light source. An important characteristic of a LED is the luminous efficiency, which can be described as the ratio of luminous flux and electrical power. This can be calculated with relationship (7):

$$\eta_0=\frac{\Phi_V}{\Phi}=\frac{\int V(\lambda)I(\lambda)d\lambda}{\int I(\lambda)d\lambda}\left[\frac{lm}{W}\right] \tag{7}$$

In Fig. 5 and Fig. 6 the authors obtained, by numerical simulation with LUMILEDS, the quality characteristics of the studied LEDs, i.e. the normalized luminous spectral intensity and the luminous spectral flux.

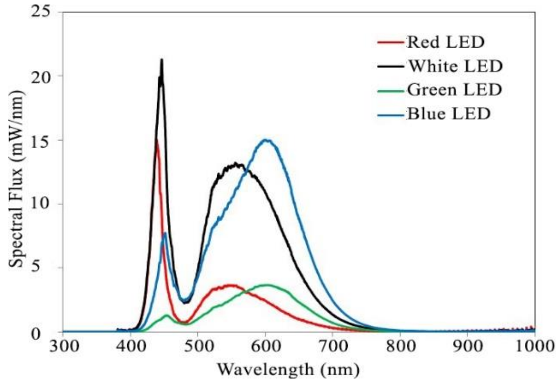

Fig. 6. Spectral power distribution of the used RGBW LED system

The authors also examined the influence of the temperature on the characteristics of the studied LEDs. On this basis, their real characteristics were determined, namely: 1) the emergent luminous flux and 2) the optical efficiency.

Optical efficiency η_o luminous flux Φ_v may refer to a single LED, a lamp or a lighting system. Regarding the optical modeling and simulation studied by authors, the optical efficiency refers to individually analyzed RGBW LEDs, for two cases: without heat sink (Fig. 7) and with heat sink (Fig. 8).

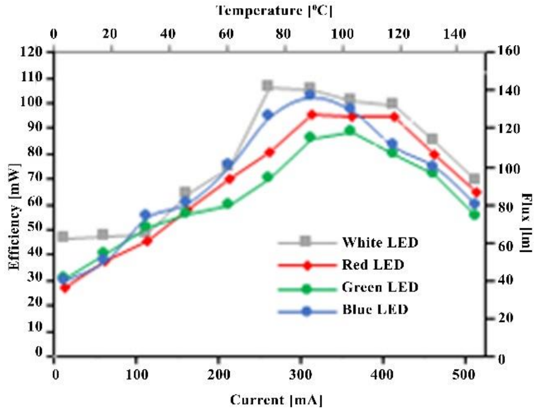

Fig. 7. Efficiency vs current for White, Red, Green, and Blue LEDs input current (without heat sink)

The simulation results indicate good performances for the analyzed LEDs, identified by higher values of the luminous flux in the case of heat sink LEDs (Fig. 9). By placing the heat sink system, there were obtained high quality optical parameters, as well as a possible prolongation of the nominal operating duration of the LEDs. Optimization and thermal management of lighting system / LEDs can be seen as an important factor in their design and operation.

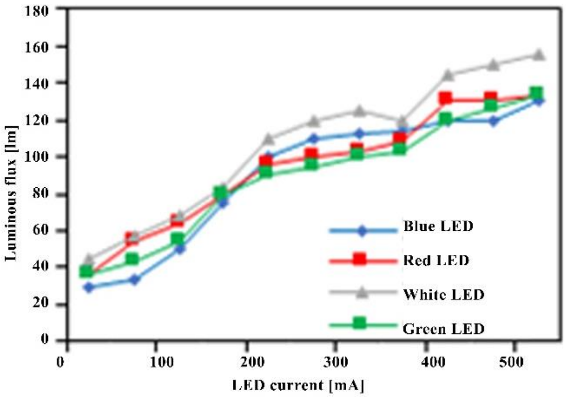

Fig. 8. Luminous flux dependind on the LED current (with heat sink)

4. Electrical and optical performances of an integrated/complex LED system depending on temperature

4.1. Thermoelectric analysis of the integrated LED system

The proposed integrated system was modeled and simulated using the WEBENCH / Texas Instruments software in order to verify its behaviour and performance. The experimental results based on literature were compared with the simulated ones. The characteristics of the LEDs depend on their internal temperature, which is the sum of the ambient and excess temperatures, due to thermal phenomena. Taking into account the self-heating effects occurring in the integrated LED, the usage of electrothermal model was required for its analysis. The LED system is based on two functioning modes, namely: without heat sink and with heat sink. Parameters that describe the electric and optical model of the considered system were obtained through numerical modeling, while thermal parameters taken into account were obtained through a calculation method (see Chapter 3.3). Fig. 9 and Fig. 10 describe the numerically modeled characteristics and the experimental ones of the forward-mode-built system, depending on the junction temperature (dotted line represents the experimental results and the continuous line represents results by numerical modeling).

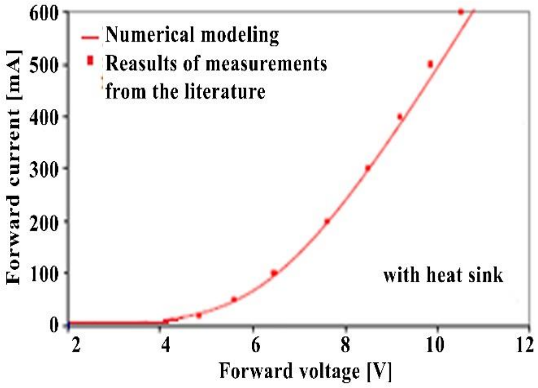

Fig. 9. Current-voltage characteristics of the forward biased LEDs at different cooling conditions (with heat sink)

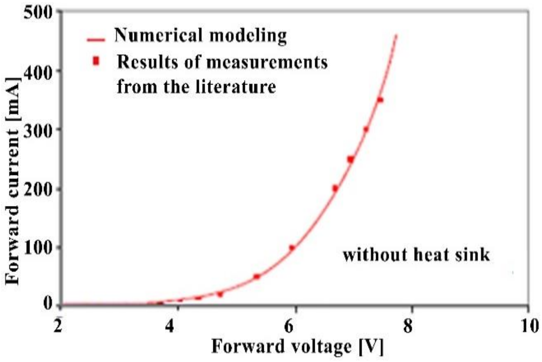

Fig. 10. Current-voltage characteristics of the forward biased LEDs at different cooling conditions (without heat sink)

As expected, the case without heat sink yielded some considerably higher internal temperatures. Fig. 11 and Fig. 12 present an electrothermal analysis of the integrated LED system. It was studied temperature (both junction and case) dependence on "forward current" for the two cooling modes. The obtained heat difference is significant between these two modes, case temperature dictating the flow through the system. By increasing the internal temperature of the integrated LED system, it is revealed a decrease of the forward current. These excesses above ambient temperature (Ta = 25 °C) differ substantially between them.

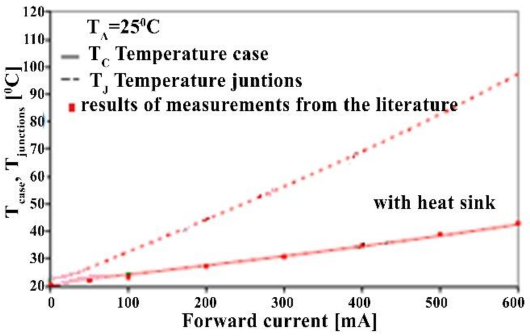

Fig. 11. Dependences of the internal and case temperatures on the forward current at different cooling conditions (with heat sink)

As can be observed, there is a very good agreement between the experimental and numerical modeled characteristics of the analyzed system, for the two cooling modes considered.

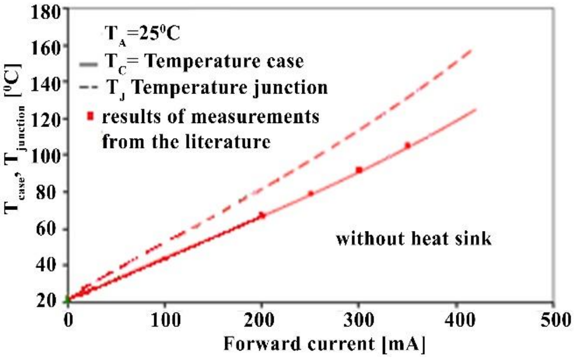

Fig. 12. Dependences of the internal and case temperatures on the forward current at different cooling conditions (without heat sink)

4.2. Optical analysis of the integrated LED system

For the integrated system, it was studied the lighting dependence on forward current, considering the two modes, in order to establish its optical performances.

In Fig. 13 is shown the dependence of lighting system and its correlation with experimental data based on the forward current. The values obtained by numerical modeling and the experimental ones, respectively, were processed for both modes of the system. The following issues must be specified: 1) continuous line refers to the case without heat sink, while the dashed line is considering the heat sink case; 2) points represent experimental values obtained in the literature. The analysis in Fig. 15 shows the following: 1) an increase in forward current determines an increase of the light emission of the investigated system; 2) the lack of the heat sink results in an internal temperature increase, leading to an inefficient lighting system.

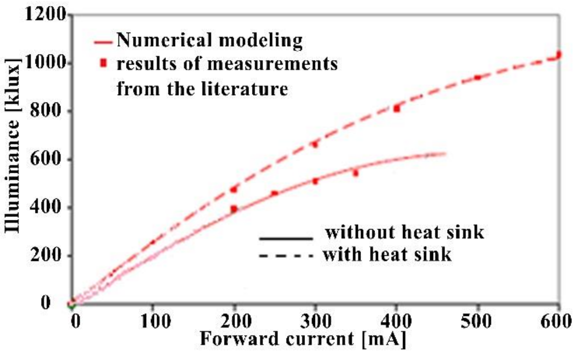

Fig. 13. Numerical modeling and experimental dependences of illuminance of the investigated diodes on the forward current at different cooling conditions

4.3. Energy and power analyzes of the integrated LED system

The types of LED system studied in the literature are characterized only for the forward mode (the most used in applications), reverse mode being nearly absent. However, in the study of LED system power supply it is necessary to analyze both modes. Fig. 14 and Fig. 15 show the current-voltage characteristics for the LED system reverse biased, in the two cases: 1) without heat sink, 2) with heat sink.

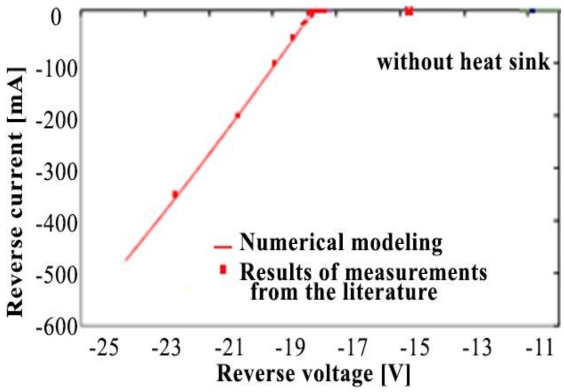

Fig. 14. Reverse characteristics of the LED lamps operating without heat sink

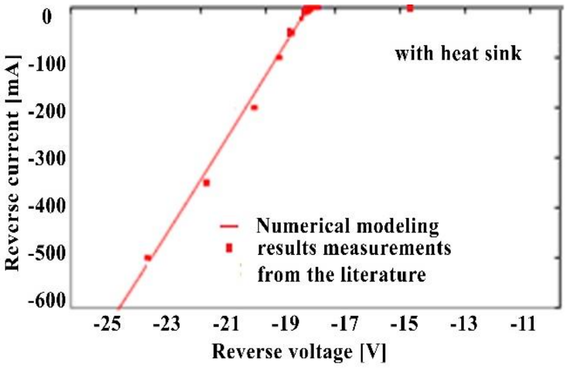

Fig. 15. Reverse characteristics of the LED lamps operating with heat-sink

It is remarked from the analysis of these figures that, in case of heat sink functioning, the LED lighting system withstands relatively high currents and voltages compared to the case without heat sink. Also, as in the "forward current" case, the "reverse current" lighting system manifests a strong influence of current-voltage characteristic from the internal temperature.

Fig. 16 and Fig. 17 show the dependence of the junction temperature on the total system power. In the two figures, the continuous line corresponds to the forward mode, while the dashed line corresponds to the reverse mode.

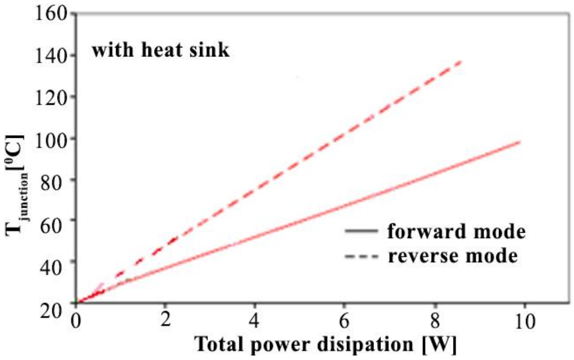

Fig. 16. The dependence of internal temperature Tj of the investigated diodes on the total power P dissipated in the LED

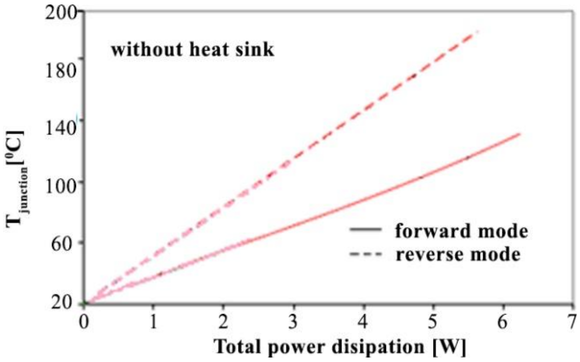

Fig. 17. The dependence of internal temperature T_j of the investigated diodes on the total power P dissipated in the LED

The junction temperature dependences on the total power obtained for the two operating modes of the system differ between them. At the same amount of total power for "the way forward", the system yields a lower value of the internal temperature compared to "reverse mode". The obtained characteristics for the analyzed system allow the establishing of its performance and integration into various LED lighting applications.

An important issue in optimizing the LED lighting system is the intelligent control [36]. This refers to a series of control strategies on: learning experience, intelligent control, able to manage a LED lighting system, can be achieved using algorithms implemented in different programming platforms.

4.4. Reliability analysis

The thermal conditions strongly influence light emission, respectively electrical conditions for the LEDs operation. At the same time, they lead to the losses decrease by dissipated heat.

The influence of temperature on the lighting system could be determined by the degradation curve based on two methods, presented in the document called *Lumen degradation lifetime estimation method for LED light sources,* available on the site ENERGY STAR [37]:

a) The least squares method is based on the eq. (8)

$$\Phi(t) = B\exp(-\alpha t) \tag{8}$$

where t – is the operation time in hours, $\Phi(t)$ – is the normalized relative average luminous flux, B – is the projected initial constant derived by the least-squares-curve fit, and α - is the decay rate constant (hours $^{-1}$) derived by the least-squares-curve fit.

b) The maintenance method of luminous flux for life duration is based on the eq. (9)

$$L_p = \frac{\ln\left(\frac{B}{p}\right)}{\alpha} \tag{9}$$

where, L_p is lumen maintenance life expressed in hours and p is the percentage of initial lumen output that is maintained [%].

The simulation of reliability characteristics was achieved using the tool TM-21 Calculator developed by ENERGY STAR [38, 42-44].

The degradation curve of the lumen maintenance [%] depending on life duration [hours] for four values of test (stress) temperature is represented in Fig. 18. The simulated values were introduced in the Excel environment, and the degradation curve was obtained.

The failure of the LEDs lighting system and reduction of the lumen flux is connected with the test temperature. According with Fig. 18, at a test temperature of 140 °C, the lumen flux reaches at 60% from the total value of lumen flux; it corresponds to an operation duration of 22,000 hours. In this way the life duration of the system is reduced by roughly 15,000 hours in the temperature range of 80-140 °C [45].

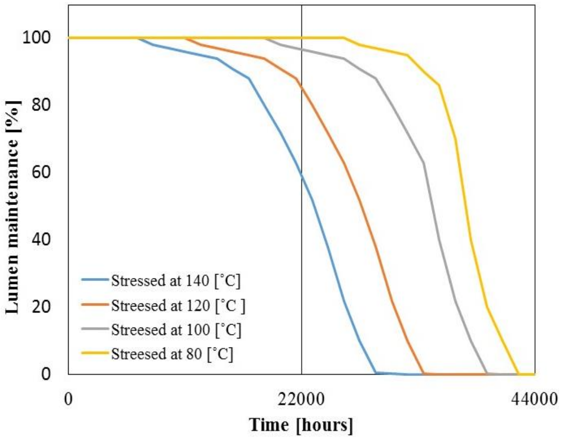

Fig. 18. The degradation curve of lumen maintenance life [%] depending on life duration (hours) for four values of test (stress) temperature

5. Conclusions

In the present article, the integrated LED lighting systems were studied from the point of view of a complex characterization based on electrical, optical and thermal performances, useful both for the implementation of new applications and control techniques, and for further developments.

By modeling and numerical simulation of electrothermal and optical characteristics associated with the analyzed LED system, there were obtained useful information, based on two major issues: 1) the improvement of thermal management for the increase of luminous flux of the system, reduction of operation temperature and decrease of losses by dissipated heat, and 2) the reliability analysis of the LEDs for extension of the system life duration.

Research in this area includes analysis and applications of the LED lighting systems, along with the use of photovoltaic systems in order to achieve hybrid lighting systems.

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