Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2018, № 2 (90)
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

INSTRUMENT-MAKING AND INFORMATION-MEASURING SYSTEMS

ПРИЛАДОБУДУВАННЯ ТА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНІ СИСТЕМИ

UDC 621.38

STABILIZATION OF LEDs THERMAL CONDITIONS BY THERMOELECTRIC MODULES OF COOLING

Volodymyr Zakordonets; Natalija Kutuzova

Thernopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary*. It is suggested to use the thermoelectric cooling modules (TCM) to stabilize the LED thermal mode. The thermoelectric cooling system has several advantages over other systems, such as: high reliability and absence of moving parts, compactness and low weight, low inertia and noiselessness of operation. The cooling system operates due to the temperature difference between the hot and cold TCM surfaces. The thermal mathematical model of the thermoelectric cooling system is constructed. The system of equations including the stationary heat conductivity equation, the thermogeneration equation, and the cold generating equation is solved. The temperature of the heterojunction of the LED is calculated, depending on its power, the total thermal resistance of the cooling system, the ambient temperature and the cold productivity of TCM. The analytical dependences of the temperature of the heterojunction on the current supply of TCM at various LEDs and at various values of the thermal resistance of the cooling system are obtained. With the given thermal power of LED and the thermal resistance of the cooling system, an optimal value of the TCM supply current is found, in which the temperature of the heterojunction of the LED reaches its minimum. At current value that is close to the optimal, the thermoelectric cooling system allows to achieve lower value of the temperature of the heterojunction in comparison with the traditional one. It has been shown that the use of TCM makes it possible to reduce the temperature of the heterojunction of the LED to the values that are lower than the ambient temperature. This is especially actual under the condition of the temperature of the medium is close to the critical temperature of the heterojunction. It has been shown that the efficiency of using the TCM decreases with the increasing of LED power, ambient temperature and total thermal resistance of the cooling system. When analyzing the efficiency of the cooling system, it should be guided not only by the parameters of the TCM, but also by the parameters of the entire LED cooling system as a whole.*

Key words: *LED, heterojunction, thermal conditions, thermal resistance, thermalstabilization, thermoelectric modules of cooling, radiator.*

Received 16.04.2018

Statement of the problem. Modern semiconductor light sources have an efficiency of converting electrical energy into light close to 30 % [1, 2]. Thus, almost 70 % of the supplied energy is converted into heat. In terms of increasing the power of the light emitting diodes (LED) traditional stabilization system are not coping with providing adequate thermal regimes. If the thermal power is not removed, excessive heating of the LED results in the degradation of light characteristics and reduces its lifetime. In addition, increased temperatures will reduce the light intensity and luminous flux.

Corresponding author: Volodymyr Zakordonets; e-mail: wladim21@gmail.com

To improve the efficiency of thermal stabilization of high-power LED active means of heat sink: fans, liquid cooling, thermoelectric cooling, etc. are used. Thermoelectric cooling systems have several advantages in comparison with other systems, such as: high reliability and no moving parts, compact size and light weight, low inertia and no noise. The use of thermoelectric cooling modules (TCM) provides the heat sink system with cooling function, i.e. makes it possible to reach the temperature of the LED heterojunction lower than the ambient temperature. This problem becomes especially relevant in the conditions when the temperature environment becomes equal to or more than the temperature of the LED heterojunction.

Analysis of the latest researches and publications. The problem of stabilization of the LED thermal conditions has already been concerned in several papers. Particularly, in [3, 4] the problems of ensuring the thermal conditions of LED Lamp were discussed. Special attention is paid to the problem of minimizing the thermal resistance when using different models. The innovative technologies of LED cooling using jet blowing were concerened. However, the thermal mathematical model was not created and heat calculations were not carried out. In [5] due to the well-known formulas of thermal engineering and experimental observations of temperature conditions, the methods of selecting an effective radiator and air flow rate are developed. Thus, for the intensification of heat exchange of the radiator with external environment fan blowing is used. In [6] theoretical analysis of the LED thermal conditions with remote radiator and traditional cooling was carried out. Overheating temperature of the LED heterojunction, depending on its capacity and parameters of the heat conductor and radiator is calculated. However, thermoelectric thermal stabilization mode was not considered.

The objective of this paper is to develop the mathematical thermal model of LED thermoelectric cooling system and to calculate on its basis the overheating temperature of the heterojunction LED, depending on its power, the thermal resistance of the cooling system and the cooling capacity of the TCM.

Statement of the task. To determine by theoretical analysis the analytical relationship between the LED power, the thermal resistance of the cooling system, the cooling capacity of TCM and the temperature of the LED heterojunction, providing the rational choice of the LED circuit to ensure the required luminous flux and lifetime.

Results of the investigations. It is known that LED generates heat power

$$P_t = (1-\eta_e)U_f I_f , \tag{1}$$

where I_f and U_f is the direct current and direct voltage of LED, ηe is its quantum efficiency.

It is obvious that TCM must absorb the power not smaller than the thermal LED power, because, otherwise, the thermal conditions stabilization becomes impossible. If TCM absorbs excess power, its cold surface will produce condensed water resulting in short circuit. The only possible way use effective TCM use is the application of the electronic unit, which can adjust the power depending on the temperature of the LED heterojunction.

Let us assume that the thermal power of the LED is completely absorbed by the cold surface of TCM

$$P_t = P_c , \tag{2}$$

and from the hot surface due to the radiator heat capacity P_h is removed. To calculate the LED thermal conditions the method of electrothermal analogy [7] is used. The scheme of the stabilization system of the LED thermal conditions equipped with TCM IS shown in Figure 1. In the scheme each element is characterized by its thermal resistance. In particular, Θ_{js} is thermal resistance between the heterojunction and the contact pad, $\Theta_{sc}=\Theta_{hr}$ – thermal resistance between the contact pad and the cold surface of TCM and between the hot surface of the TCM and the radiator, Θ_{ra} is the thermal resistance between the radiator and the environment, $\Delta T=T_h-T_c$ is the temperature difference between hot and cold surfaces of the TCM due to the Peltier effect.

The thermal diagram corresponds to the equation of thermal equilibrium:

$$T_j = T_a + P_c \cdot \left(\Theta_{js} + \Theta_{sc}\right) + P_h \cdot \left(\Theta_{hr} + \Theta_{ra}\right) - \Delta T\ . \tag{3}$$

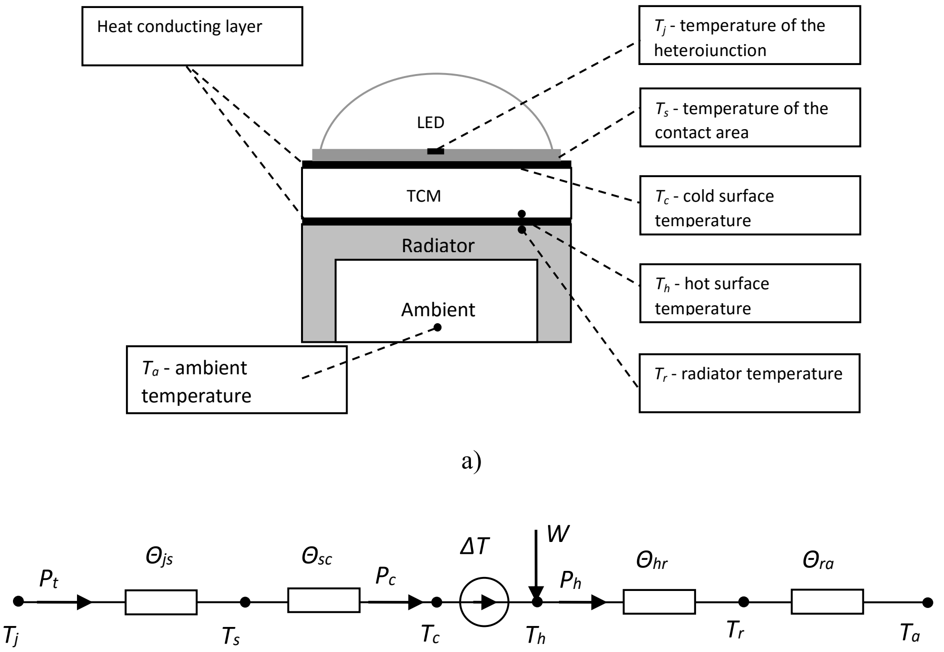
Thermal power absorbed by the TCM (refrigeration) is determined by [8, 9]:

$$P_c = \alpha T_c I - \frac{1}{2} I^2 R - \kappa \Delta T\ , \tag{4}$$

and from the hot surface due to the radiator the heat power P_h is removed

$$P_h = \alpha T_h I + \frac{1}{2} I^2 R - \kappa \Delta T \tag{5}$$

where α is the coefficient of differential thermopower, κ is the thermal conductivity, R is the resistance ofa semiconductor material of the TCM branches, T_c, and T_h is the temperature of hot and cold surfaces of TCM, and I is the current of the TCM power supply.



a)

b)

Figure 1. Schematic representation of the stabilizing system of the thermal mode of the LED with the TCM and the radiator (a) and its thermal scheme (b). Here T_j is the temperature of the LED heterojunction, T_s is the temperature of the contact pad, T_c and T_h is the temperature of the cold and hot surfaces of the TCM respectively, T_r is the radiator temperature, T_a is the envirinment temperature, ΔT is the temperature difference between the hot and cold surfaces of the TCM

Power generated on the TCM hot surface is larger than the power absorbed by the cold surface on the magnitude of the cost of electricity power sources

$$P_h = P_c + W\,. \tag{6}$$

The power W is consumed for performing the work of moving charge against the potential difference which occur according to Seebeck law in the thermoelectric curcuit, and Joule heat loss:

$$W = P_h - P_c = \alpha I \Delta T + I^2 R\,. \tag{7}$$

The TCM efficiency is determined by the cooling coefficient [10]:

$$\varepsilon = \frac{P_c}{W}\,. \tag{8}$$

From the equation of thermal equilibrium for the overheating temperature of the LED heterojunction we define:

$$\Delta T_j = T_j - T_a = P_c \cdot (\Theta_c + \Theta_h) + (\alpha I \Delta T + I^2 R) \cdot \Theta_h - \Delta T \tag{9}$$

where $\Theta_c=\Theta_{js}+\Theta_{sc}$, and $\Theta_h=\Theta_{hr}+\Theta_{ra}$ are thermal resistances from the hot and cold surfaces of TCM,

$$\Delta T = \frac{1}{\kappa} \cdot \left(\alpha T_c I - \frac{1}{2} I^2 R - P_c \right), \tag{10}$$

temperature differential.

In the formula (9) the first summand describes the increase of the LED heterojunction temperature during the thermal power transfer generated by the LED and the module itself. The last two summands determine the influence of TCM on the temperature of the LED heterojunction. Cooling is provided by the temperature difference between hot and cold surfaces of TCM. As the result, the efficiency of thermoelectric cooling system depends exactly on the mutual correlation of these summands values.

The temperature of the LED heterojunction is determined by its capacity, thermal resistance of the cooling system, environment temperature and TCM operation mode. Control of module operation is performed by changing the amount of current supply. While developing and operating the thermoelectric cooling system it is important to select optimal current with efficient cooling.

Analysis of the obtained results

Let us consider the impact of TCM supply current on the efficiency of thermal stabilization of the LED heterojunction under given values of power and thermal resistance of the system. As the semiconductor light source we choose modern LED XLamp CMA1516 matrix which parameters are given in Table 1 [11].

Table 1

Parameters of LED XLamp CMA1516

Maximum current, *A*	Maximum voltage, *V*	Maximum power, *W*	Light Flux, *lm*	Thermal resistance LED $\Theta_{j\text{-}s}$, *K/W*	The area of thermal contact, *mm²*
1.05	39	41	1400-4800	0.4	*251*

The LED power can be controlled within wide limits by varying the voltage or current. It is obvious that the maximum LED power should be less than maximum TCM cooling capacity. For the given LED matrix the maximum thermal capacity equals:

$$P_{t\ \max} = (1-\eta_e)U_{f\ \max} I_{f\ \max} = 0.75 \cdot 39 \cdot 1.05 = 30\ W.$$

TCM model is be chosen taking into account thermal power, dimensions and requirements to the temperature conditions of LED operation. The characteristics of commercial *TCM TB-161* [12] with the following parameters: maximum current $I_{max}=5{,}7\ A$ maximum voltage $U_{max}=18{,}3\ V$, maximum cooling capacity at zero temperature difference $P_{c,max}=66.3\ W$, the maximum temperature difference at zero cooling capacity $\Delta T_{max}=70\ K$ were used during calculations.

The use of thermoelectric modules is always associated with the use of a certain radiator designed to dissipate not only the heat emitted by the LED, but also Joule heat, generated in the thermal element during the electric current passage through it. The thermal resistance of modern radiators equipped with fans is $\Theta_{ra}=0{,}3\div0{,}6\ K/W$. The best samples with heat pipes reach the values of $\Theta_{ra}=0{,}1\ K/W$. Liquid cooling systems are still more efficient. Their thermal resistance is $\Theta_{ra}=0{,}1\div0.01\ K/W$, but they are too large and difficult to be installed into the lighting system.

The analysis of the derived dependences is carried out by numerical methods. Figure 2 shows the graphical dependence of the overheating temperature of the LED heterojunction on TCM current at different values of LED thermal power.

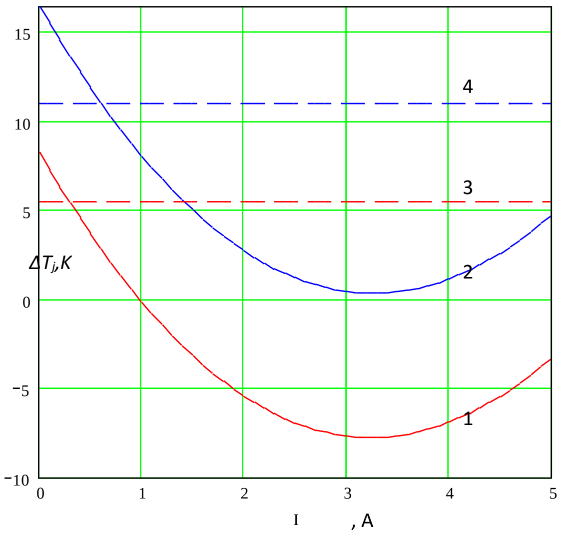


Figure 2. The dependence of the overheating temperature of the LED heterojunction from the current of TCM at different values of the power of the LED and with thermal supports $\Theta_c=0.6\ K/W$, $\Theta_h=0.2\ K/W$. Solid lines 1 and 2 at $P_c=10\ W$, and $P_c=20\ W$, respectively. Dashed lines 3 and 4 are at the same power and thermal support, but without TCM

Minimums of lines $\Delta T_j(I)$ correspond to operation modes with maximum efficiency of the cooling system, the one that produces the lowest temperature of the heterojunction. It is obvious that the currents close to the efficient thermoelectric cooling system make it possible to get the lower temperature values than the traditional one. Dashed lines in the figure define out temperature dependences for the cooling system without the TCM calculated by the formula (7) for the same values of thermal resistance.

The dependence of the overheating temperature of the heterojunction on the TCM current at various values of the thermal resistance from the hot side of the TCM is shown in Figure 3.

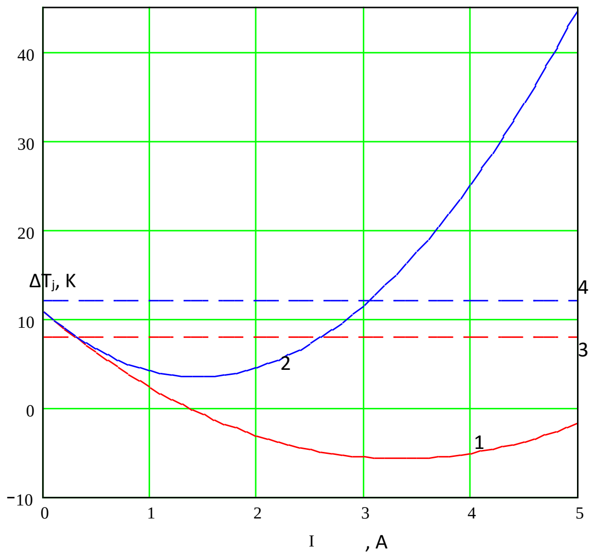


Figure 3. The Dependence of the overheating temperature of the heterojunction on the current of the TCM at the power of the LED $P_c=10\ W$ and at different values of the thermal resistance from the hot side of the TCM. The solid lines 1 and 2 are at $\Theta_h=0.2\ K/W$ and $\Theta_h=0.6\ K/W$, respectively. Dashed lines 3 and 4 are at the same power and thermal supports, but without of TCM

It is obvious that with the growth of value Θ_h the cooling efficiency worsens and the location of the minimums of $\Delta T_j(I)$ dependences is shifted towards the lower values of current. At certain relations between the power of TCM and LED the temperature of the heterojunction towards the environment temperature decreases and sometimestowards to the lower than the temperature of the environment. This is especially important in case when the environment temperature is close to the critical temperature of the LED heterojunction.

The dependence of the temperature difference from the TCM current at different LED power is presented in Figure 4.

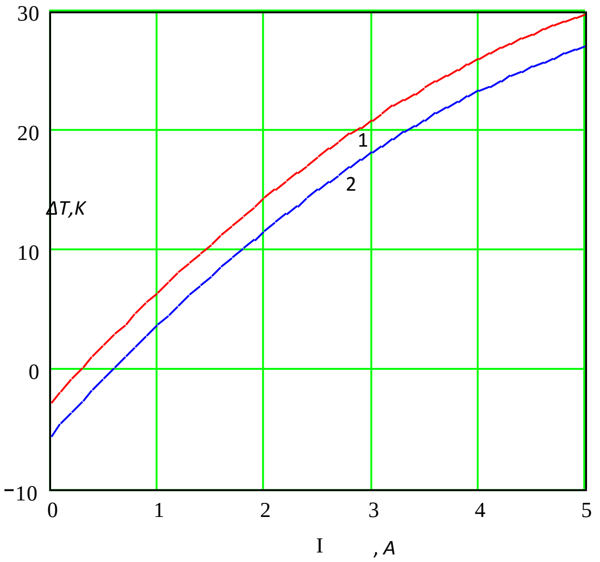


Figure 4. The Dependence of the temperature difference on the current of the TCM at different powers of LEDs. Line *1* is at $P_c=10\ W$, line 2 at $P_c=20\ W$

It follows from the graph that with the increase in the current the differential temperature between hot and cold surfaces of TCM increases. Besides, it depends on the heat load. Particular, while increasing the LED thermal power the temperature differential decreases, and vice versa, while reducing the power it increases.

The value of the thermal resistance of the cooling system is significantly influenced by the TCM operation mode and capacity of the heat load. If the temperature of the LED heterojunction equals to the environment temperature or becomes lower, the thermal resistance of the system will be zero, or even negative.

Conclusions. In conditions when the environment temperature is close to the critical temperature of the LED heterojunction, it is offered to use a thermoelectric cooling modules (TCM) in order to stabilize the thermal conditions.

At the given thermal LED power and the thermal resistance of the cooling system there is an optimal value of the TCM supply current when the temperature of the LED heterojunction reaches the minimum. At currents close to optimal the thermoelectric cooling system makes it possible to get lower temperatures for the heterojunction than the traditional one.

At the optimal ratio between the capacity of TCM and LED the thermoelectric cooling system reduces the temperature of the LED heterojunction to the temperatures lower than the environment temperature. The efficiency of TCM use is reduced by increasing the thermal power of the LED and the total thermal resistance of the cooling system.

While analyzing the efficiency of the cooling system we should take into account not only the TCM parameters, but the parameters of the whole LED cooling system, in general, the total thermal resistance of the cooling system, heat load and the TCM operation mode.

References

1. Nikiforov S. Temperatura v zhizni i rabote svetodiodov. S. Nikiforov, Komponenty i texnologii, 2005, no. 9, p. 140 – 146 [In Russian].
2. Gonin M. Spasitel'naya proxlada, ili teplootvod dlya moshhnyx svetodiodnyx matric. M. Gonin, Novosti e'lektroniki+svetotexnika, 2013, no. 2 [In Russian].
3. Polishhuk A.A. Obespechenie teplovogo rezhima svetodiodnyx lamp pri razrabotke svetotexnicheskix ustrojstv. A.A Polishhuk, Sovremennaya e'lektronika, 2006, no. 3, p. 42 – 45 [In Russian].
4. Staroverov K. Sistemy oxlazhdeniya dlya svetodiodov. K. Staroverov, Novosti e'lektroniki, 2008, no. 17, p. 21 – 23 [In Russian].
5. Lotar Noe'l'. Oxlazhdenie i regulirovanie temperaturnyx rezhimov svetodiodov, Lotar Noe'l', Poluprovodnikovaya svetotexnika, 2010, no. 3, p. 13 – 15 [In Russian].
6. Zakordonets V. Theoretical analysis of thermal conditions and ways of led temperature stabilization. Volodymyr Zakordonets, Natalija Kutuzova. Visnik TNTU. T. : TNTU, 2016, no. 4 (84), p. 105 – 112.
7. Belyaev N.M. Metody teorii teploprovodnosti. Ch.1. N.M. Belyaev, A.A. Ryadno, M.: Vyssh. shk., 1982. 327 p. [In Russian].
8. Anatychuk L.I. Termoelementy i termoe'lektricheskie ustrojstva. Kiev : Naukova dumka, 1979. 768 p. [In Russian].
9. Bulat L.P., Buzin E.V. Termoe'lektricheskie oxlazhdayushhie ustrojstva. SPb. : SPbGUNiPT, 2001. 41 p. [In Russian].
10. Shostakovskij P. Sovremennye resheniya termoe'lektricheskogo oxlazhdeniya. P. Shostakovskij, Komponenty i texnologii, 2009, no. 12, p. 40 – 46 [In Russian].
11. http://www.cree.com/led-components/media/documents/ds-CMA1516.pdf.
12. http://kryothermtec.com/ru/standard-single-stage-thermoelectric-coolers.html.

Список використаної літератури

1. Никифоров, С. Температура в жизни и работе светодиодов. [Текст] / С. Никифоров // Компоненты и технологии. – 2005. – № 9. – С. 140 – 146.
2. Гонин, М. Спасительная прохлада, или теплоотвод для мощных светодиодных матриц. [Текст] / М. Гонин // Новости электроники+светотехника. – 2013. – № 2.
3. Полищук, А.А. Обеспечение теплового режима светодиодных ламп при разработке светотехнических устройств. [Текст] / А.А Полищук // Современная электроника. – 2006. – № 3. – С. 42 – 45.

4. Староверов, К. Системы охлаждения для светодиодов. [Текст] / К. Староверов // Новости электроники. – 2008. – № 17. – С. 21 – 23.
5. Лотар, Ноэль. Охлаждение и регулирование температурных режимов светодиодов. [Текст] / Ноэль Лотар // Полупроводниковая светотехника. – 2010. – № 3. – С. 13 – 15.
6. Zakordonets, V. Theoretical analysis of thermal conditions and ways of led temperature stabilization [Text] / Volodymyr Zakordonets, Natalija Kutuzova // Вісник ТНТУ. – Т. : ТНТУ, 2016. – № 4 (84). – С. 105 – 112.
7. Беляев, Н.М. Методы теории теплопроводности. Ч.1. [Текст] / Н.М. Беляев, А.А. Рядно. – М. : Высш. школа, 1982. – 327 с.
8. Анатычук, Л.И. Термоелементы и термоэлектрические устройства. [Текст] / Анатычук Л.И. – Киев : Наукова думка, 1979. – 768 с.
9. Булат, Л.П. Термоэлектрические охлаждающие устройства. [Текст] / Л.П. Булат, Е.В. Бузин. – СПб.: СПбГУНиПТ, 2001. – 41 с.
10. Шостаковский, П. Современные решения термоэлектрического охлаждения. [Текст] / П. Шостаковский // Компоненты и технологии. – 2009. – № 12. – С. 40 – 46.
11. http://www.cree.com/led-components/media/documents/ds-CMA1516.pdf.
12. http://kryothermtec.com/ru/standard-single-stage-thermoelectric-coolers.html.

УДК 621.38

СТАБІЛІЗАЦІЯ ТЕПЛОВОГО РЕЖИМУ СВІТЛОДІОДІВ ТЕРМОЕЛЕКТРИЧНИМИ МОДУЛЯМИ ОХОЛОДЖЕННЯ

Володимир Закордонець; Наталія Кутузова

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Для стабілізації теплового режиму LED запропоновано використовувати термоелектричні модулі охолодження (TCM). Термоелектрична система охолодження має ряд переваг у порівнянні з іншими системами, а саме: високу надійність і відсутність рухомих частин, компактність і невелику вагу, малу інерційність і безшумність роботи. Система охолодження працює за рахунок виникнення перепаду температур між гарячою і холодною поверхнями TCM. Побудовано теплову математичну модель термоелектричної системи охолодження. Розв'язано систему рівнянь, яка містить стаціонарне рівняння теплопровідності, рівняння термогенерації та рівняння генерації холоду. Розраховано температуру гетеропереходу LED залежно від його потужності, загального теплового опору системи охолодження, температури навколишнього середовища та холодопродуктивності TCM. Отримано аналітичні залежності температури гетеропереходу від струму живлення TCM різних потужностях LED та при різних значеннях теплового опору системи охолодження. При даній тепловій потужності LED та тепловому опорі системи охолодження знайдено оптимальну величину струму живлення TCM, при якому температура гетеропереходу LED досягає мінімуму. При струмах, близьких до оптимального, термоелектрична система охолодження дозволяє отримувати нижчі значення температури гетеропереходу ніж традиційна. Показано, що застосування TCM дає можливість зменшити температуру гетеропереходу LED до значень, нижчих температури навколишнього середовища. Це особливо актуально в умовах, коли температура середовища близька до критичної температури гетеропереходу. Показано, що ефективність використання TCM знижується при збільшенні потужності LED, температури навколишнього середовища й сумарного теплового опору системи охолодження. При аналізі ефективності роботи системи охолодження слід керуватися не лише параметрами TCM, а й параметрами всієї системи охолодження LED у цілому.*

Ключові слова*: світлодіод, гетероперехід, тепловий режим, тепловий опір, термостабілізація, термоелектричний модуль охолодження, радіатор.*

Отримано 16.04.2018