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Electro-optical characteristics of an innovative LED luminaire with an LED matrix cooling system based on heat pipes

D.V. Pekur[1], V.M. Sorokin[1], Yu.E. Nikolaenko[2], V.P. Kostylyov[1], V.S. Solntsev[1], V.V. Ponomarenko[1]

[1]*V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine,*
41, prosp. Nauky, 03680 Kyiv, Ukraine,
E-mail: demid.pekur@gmail.com, vsorokin@isp.kiev.ua
[2]*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute",*
37, prosp. Peremohy, 03056 Kyiv, Ukraine,
E-mail: y.nikolaenko@kpi.ua

Abstract. Widespread use of energy-saving LED lighting systems powered by renewable energy sources, solar energy in particular, will contribute to the improvement of global ecology. One of the structural elements of such lighting systems is LED luminaire. The authors of this article perform a first ever experimental study of electro-optical characteristics of the basic version of a compact high-power LED luminaire for indoor use. The particular feature of this lighting device is that its cooling system for the LED light source is based on heat pipes and concentric cooling rings. Such design allows ensuring the required cooling efficiency of the LED matrix. The revealed trends in optical and electrical parameters during temperature stabilization indicate that the proposed cooling system is highly efficient in maintaining normal thermal conditions of LED light sources with a power of up to 140.7 W and a luminous flux of up to 15083 lm. The results on determining spatial distribution of luminous flux of these luminaires indicate that they may be used for lighting large rooms with high ceilings. Scaling the basic modular design version of the cooling system allows increasing the power of the LED light source up to 600 W.

Keywords: energy-saving lighting, LED, LED matrix cooling, air cooling, heat pipe.

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1. Introduction

One of the ways to improve ecology is to reduce energy consumption and the use of fossil fuels while at the same time expanding the use of renewable energy sources. One of the effective renewable energy sources is solar energy. Many cities have a high concentration of large premises requiring continuous high-quality artificial lighting (including during the daytime), such as industrial production halls, shopping malls, office buildings, classrooms, *etc*. Lighting of such premises with environmentally friendly solar energy has a significant energy-saving potential that could benefit the environment, but this reserve mostly remains untapped to this date. To use renewable energy sources for powering these lighting systems, it is necessary to develop and implement combined energy-saving LED lighting systems.

One of the structural elements of this lighting system is LED luminaire. LED light sources are small and have high light efficiency values [1]. Moreover, the simultaneous use of two or more types of LEDs allows changing the color characteristics of the light by controlling their brightness. To date, LEDs are unrivalled leaders among artificial light sources [2]. LED technologies have been developing rapidly and over recent years, the capability of individual light emitting devices has increased significantly, which greatly widened their application scope. Most LED luminaires, however, cannot perform reliably without ensuring that the light-emitting semiconductor structures maintain the required operation temperature [3], which must not exceed the peak allowable temperature values for the corresponding semiconductor crystal.

Ensuring optimal operating temperature of LEDs allows prolonging their service life and providing stable light and spectral parameters. High wattage [4] of modern LEDs and LED matrices makes the development of their cooling systems not so much a technical problem but a scientific one, requiring the use of modern analytical framework, complex software and the knowledge of thermophysics and materials science. Using these approaches in the development of cooling systems for high-power light-emitting structures allows optimizing their design [5], ensuring the maximum possible energy efficiency of the luminaire, and creating competitive lighting devices.

Powerful LED light sources are cooled by systems based on different operation principles: passive heat sinks [6, 7], thermoelectric coolers [8, 9], piezoelectric fans [10], and jet coolers [11]. There also are experimental cooling systems based on the electronic wind phenomenon [12-14].

Passive cooling systems based on heat sinks made of homogeneous materials with high thermal conductivity have the longest service life [6]. These heat sinks can be produced by various methods, the most common being extrusion, casting and stamping.

When the size of the device is limited or when the latter operates at high temperatures, active air cooling systems are widely used [8-14].The air flow directed at the heat sink is generated by a mechanical fan or piezo-mechanical facility. It allows reducing the size of the elements performing heat exchange with the air.

Despite the significant advantages over passive cooling systems (smaller size and weight), active systems have their drawbacks as well, the principal ones being limited applicability and service life. Another significant disadvantage of active air cooling systems is that they need additional power supply and control systems. The use of fans reduces the overall energy efficiency of the lighting fixture and increases its cost.

In order to enhance the efficiency of cooling systems, different system types are often combined in one. Each type of cooling system has both advantages and disadvantages, but there is an important requirement that cooling systems for LED light sources must meet – their service life needs to be close to that of the LEDs (50–100 thousand hours).

In recent years, the problem of efficient cooling of LEDs and high-power LED matrices was addressed by using two-phase heat transfer devices, *i.e.* thermosyphons [15], heat pipes [16-19] and vapor chambers [20-22]. There were also some developments of two-phase cooling systems for LEDs that involved immersing LEDs in a low-boiling liquid [23]. Of the listed types of cooling systems based on two-phase technology, heat pipes are the most commonly used.

Heat pipes allow reducing thermal resistance of the cooling system, thus lowering the temperature of the LEDs, which increases their service life and stabilizes their electro-optical parameters. The equivalent thermal conductivity of heat pipes can be above 10000 W/(m·°C) [24], which is much higher than that of homogeneous metals used to create heat-conductive elements for cooling systems (aluminum and its alloys –150...237 W/(m·°C) [25], copper – 393…419 W/(m·°C) [26]). The use of heat pipes can also significantly improve heat dissipation at high heat flux densities, which can exceed 105 W/m^2 on the casing of modern LEDs and LED matrices [4].

The high thermal conductivity of heat pipes makes it possible to significantly reduce the weight of the material required for the construction of the cooling system, while maintaining, and often reducing, the temperature of the LEDs. For example, in [27-32] heat pipes are used to cool powerful LEDs in combination with a heat sink cooled by free convection of ambient air, in [28] the pipes are combined with a melting substance, and in [30] – with a heat sink cooled by a fan. The most reliable and easy-to-manufacture are the cooling systems based on heat pipes and heat sinks with free air convection [29, 30]. They do not require electric power to move the working fluid and are best suited for use in LED luminaires for indoor lighting. Using heat pipes in the designs presented in [30-32] provides the lighting device with an attractive and aesthetic appearance.

The objective of this work was to performan experimental study of the electro-optical characteristics of the developed powerful lighting device with a LED matrix cooling system based on heat pipes and to analyze the areas where these devices can be used.

2. Design parameters of the compact LED luminaire prototype

The LED luminaire consists of a casing that carries a LED light source, a power supply unit, and a cooling system. The casing of the lamp presents a base made of aluminum alloy. A high-power LED light source (in this case – CXA3070-0000-000NTHAD50H LED matrix [33]) is installed on one side of the base. In order to increase the cooling efficiency of the LED matrix, the authors of this work propose a new compact cooling system with radial arrangement of heat pipes [34-36]. This arrangement brings the pipes to be as close as possible to the powerful LED matrix. In this design, the elements of the cooling system that perform heat exchange with ambient air are made in the form of concentric rings placed vertically, which is the most effective position in terms of heat exchange with ambient air.

The developed design of the cooling system for powerful LED light sources can be scaled according to the problems faced by the developers. Knowing the power of the LED matrix, the maximum value of its body temperature and ambient temperature, using the optimization technique described in [5], it is possible to determine the required number of heat pipes and cooling elements, as well as their optimal geometry in each specific case. For example, the calculations performed by the method from [5] have shown that, in order for the luminaire with a thermal load of its LED matrix of up to 100 W to be functional, four heat pipes will be enough. The diameter of this cooling system may be 300 mm. It is sufficient to use seven aluminum cooling rings with a height of 30 mm [36] as the elements performing heat exchange with ambient air. The exterior of the developed and manufactured LED luminaire prototype with the cooling system based on heat pipes and concentric cooling rings is shown in Fig. 1.

Fig. 1. LED lighting device: *1* – LED matrix, *2* – lens, *3* – heat pipes, *4* – elements of heat exchange with ambient air.

The earlier experimental studies of thermophysical characteristics of the cooling system of a manufactured LED luminaire [36] showed that the developed cooling system is capable to maintain the temperature of light-emitting structures at 79.6 °C when the thermal power of the LED light source reaches 91.5 W.

Though thermal characteristics are important for a LED lighting device, its electro-optical characteristics are no less essential, since they determine whether the device can serve its primary purpose, which creates the necessary lighting environment.

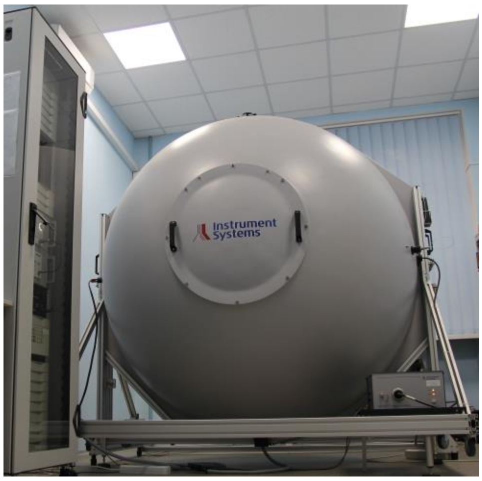
3. Determining electro-optical characteristics of the LED lighting device

Light and spectral parameters were determined using the following modern metrological equipment: a CAS-140 matrix spectroradiometer (Instrument Systems, Germany) and an integrating sphere 2 m in diameter, which allowed controlling light and spectral parameters of the lighting device in real time (Fig. 2).

The LED lighting fixture was powered, and its electrical parameters were determined by HAMEG HMP4040 power supply unit (Rohde & Schwarz, Germany). During the experiments, the authors measured the values of the electro-optical parameters of the luminaire in the interval between power-up and the moment of temperature stabilization as well as of reaching the stabilized values of power, light and spectral parameters.

Fig. 3 shows a normalized time dependence of electric power, while Fig. 4 demonstrates a normalized time dependence of luminous flux during temperature stabilization, *i.e*. from the moment of power-up until the stabilization mode is achieved, at three electrical current values of the LED matrix: 1, 2, and 3.5 A.

As shown in Figs 3 and 4, the increase in temperature of the semiconductor crystals of the matrix immediately after power-up causes a rapid decrease in electric power and luminous flux. Sometimes after power-up and the period of sharp decrease in power and luminous flux, a rapid thermal stabilization of semiconductor matrix crystals is observed. This indicates the beginning of efficient operation of the evaporation-condensation cycle in heat pipes and efficient heat dissipation from the LED light source.



a)

b)

Fig. 2. Integrating sphere with a spectroradiometer CAS-140 (a) LED luminaire inside an integrating sphere (b).

Table shows the measured values of the electro-optical parameters of the prototype LED lighting device for the maximum power values at which the chosen temperature conditions of light-emitting semiconductor crystals can be maintained (up to 85 °C).

4. Determining spatial distribution of luminous intensity of the LED lighting device

High concentrations of light power on the surface of LED light sources and constant luminous flux distribution indicatrices require from lighting designers to use diffusers or lenses to create the desired type of luminous flux distribution. Another important function of these light-forming elements is to protect the LED matrix from mechanical impact and contamination. The surface of the LED matrix is typically made of a soft polymer and can be easily damaged or contaminated, while the materials of light-scattering elements or lenses have much higher values of mechanical resistance.

Modern optical systems for LED lighting devices are mostly lenses and are usually designed specifically for certain sizes of LEDs and LED arrays.

Table. Electro-optical parameters of the LED light source.

Parameter	Parameter values		
Current intensity, A	1	2	3.5
Voltage, V	34.8	37.4	40.2
Electric power, W	34.8	74.8	140.7
Luminous flux, lm	5761	10015	15083
Correlated color temperature, K	4956	5124	5452
Color rendering index	82.4	83.2	85.1
Chromaticity coordinates (x; y)	0.3469, 0.3591	0.3419, 0.3520	0.3349, 0.3449
Light efficiency, lm/W	166	134	107

Using the lenses instead of reflectors to form the desired type of light distribution allows ensuring the LED luminaire efficiency and increasing the luminous flux efficiency. When the optical system is chosen correctly, no additional structures designed to form limiting angle can significantly affect the luminous efficiency of the lighting system.

The optical system for a powerful LED matrix is a lens made of borosilicate glass. The lens is attached to the LED unit to form the desired type of light distribution. The LED lighting device created in this work uses lenses manufactured by Reeth Glass Lens Co., Ltd, namely, the RH-HBL-71 lens [37], which allows forming the desired type of light distribution.

To assess how effectively a lighting device illuminates a particular object, the spatial distribution of luminous flux is measured. One of the common methods for determining the light flux distribution is to use a goniometer, for instance GO-2000, and a photo-detector λ-filter, which are placed inside a "black room". The goniophotometric complex makes it possible to automatically determine the spatial distribution of with a luminous intensity of the studied lighting device. The spatial light distribution is measured using the following technique.

The object of measurement is fixed on the moving part of the goniometer (Fig. 5). When its angular attitude relative to the photodetector is changed, the dependence of luminous intensity on the viewing direction is measured [38]. The measurement data are processed by PC software and stored as specialized files. The stored information about the light flux distribution of the light source later allows simulating the illuminance created by the lighting device with a high accuracy.

For the vast majority of lighting devices with cooling systems based on conductive heat transfer phenomena, the goniophotometric method of determining luminous flux makes it possible to perform high-precision measurements, and the integrated luminous flux values can be compared with the measurements using an integrating sphere and a spectroradiometer. The situation is different with two-phase heat dissipation devices, because when the position of such a cooling system relative to the horizon is changed, it affects its characteristics (maximum heat transfer intensity and effective thermal conductivity). Thus, thermal operating conditions of the LEDs change during measurements, and the luminous flux varies depending on system orientation in space [39-41]. This dependence affects the measurement results on luminous intensity at certain angles, making the measurements of spatial luminous flux distribution of the lighting system with two-phase heat transfer devices by using this type of goniophoto-meters inaccurate.

To increase the accuracy of determining the light flux distribution of the developed lighting device with heat pipes, it was proposed to perform measurements at such heat-transfer intensity values, at which the thermal conductivity of the heat pipes is not significantly affected by their orientation in space, *i.e.*, at up to 10% of the maximum heat-transfer intensity value.

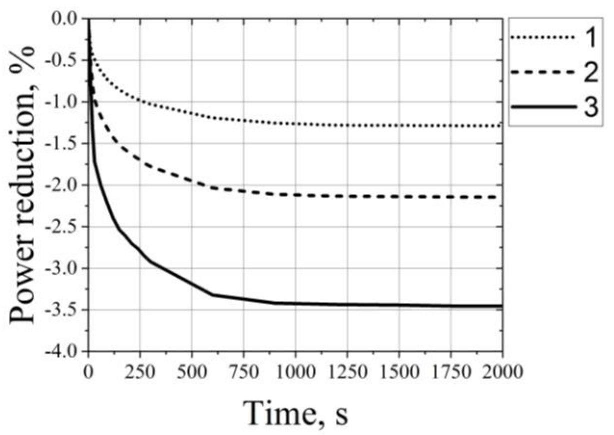


Fig. 3. Time dependence of electric power for different values of LED matrix power supply current: *1* – 1 A, *2* – 2 A, *3* – 3.5 A.

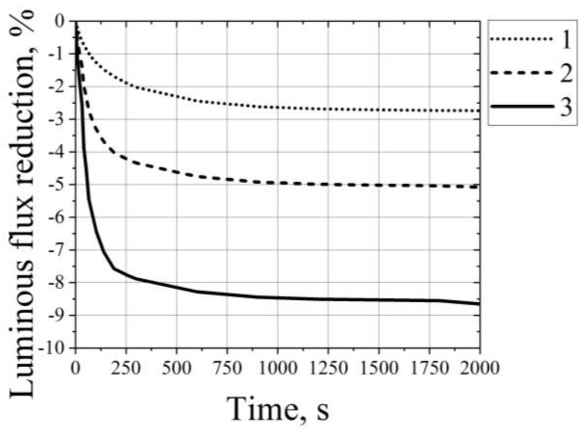


Fig. 4. Time dependence of luminous flux for different values of LED matrix power supply current: *1* – 1 A, *2* – 2 A, *3* – 3.5 A.

Fig. 5. Lighting device mounted on GO-2000 goniometer.

This value allows heat pipes with a powder capillary structure to function without significantly changing their characteristics. It was proposed to perform measurements when the LED matrix runs at an electric current of 1 A, which corresponds to a total power of 34.8 W and a thermal power of 16.9 W. When using 4 heat pipes, these parameters imply a heat load within 5 W per heat pipe (up to 10% of the maximum heat transfer intensity of heat pipes).

To obtain the light distribution of the LED matrix for the power of 140.7 W, the measured values for 34.8 W were multiplied by a factor of 2.62. This factor was obtained as the ratio of the values of integrated luminous fluxes measured at the power values of 140.7 W and 34.8 W, respectively, using the integrating sphere method.

The developed technique allows increasing the accuracy of determining luminous intensity by gonio-photometric measurements for luminaires with LED cooling systems based on two-phase heat transfer devices.

Given that the chosen lens type produces symmetrical light distribution, worth considering are only the luminous intensity distribution curves obtained in one plane. The values of luminous intensity for the half-brightness angle in the C0/180 plane are shown in Fig. 6a, while Fig. 6b presents a 3D visualization of the photometric body of the luminous intensity curve of the lighting device.

5. Recommendations for using the proposed high-power LED luminaire

In general, the high-power LED lighting fixtures are primarily designed for large rooms with high ceilings (such as warehouses, storage facilities for metal, spare parts, repair fund, finished products, spare parts awaiting repair, tools, *etc.*). Analyzing the results of determining the luminous flux spatial distribution of the studied lighting device using such modern software as Dialux,

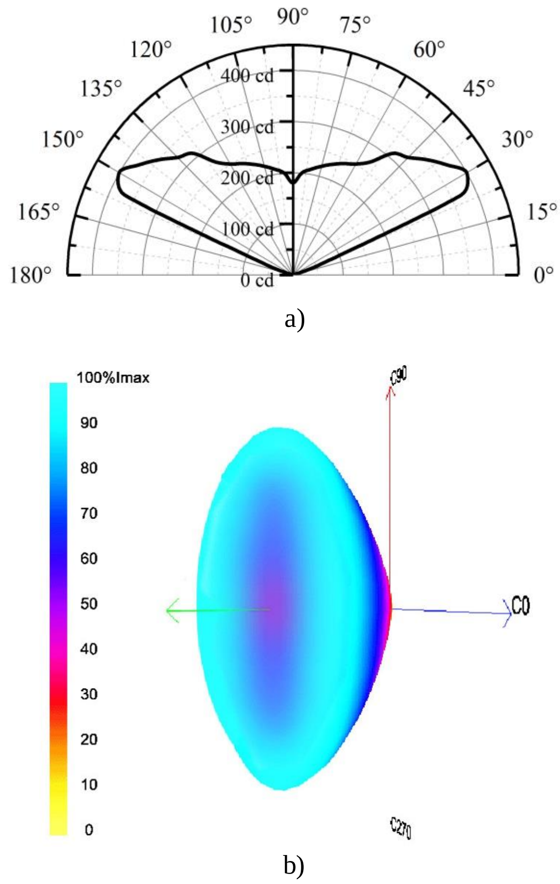


Fig. 6. Luminous intensity distribution curve for the C0/180 plane (a) and 3D photometric body visualization of the lighting device (b).

we can determine that this lighting device is capable of illuminating a 10×10 m room with a ceiling height of 5 m. It can provide a light flux distribution uniformity of over 0.5 (at a coefficient of reflection from the walls of over 40%) and an average illuminance of the floor of over 100 lx.

As mentioned in Section 2, the developed basic design of the LED lighting fixture can be scaled depending on the tasks developers are facing. The results of computer modeling of different versions of this lighting fixture with varying number of heat pipes and cooling rings [5, 35, 36] showed that it is possible to manufacture versions of this luminaire with much higher power values: from 300 up to 600 W. Estimated luminous flux values for modern LED arrays indicate that at this power it is possible to provide at least 30000 and 60000 lm of luminous flux, respectively. These lighting fixtures are able to create uniform lighting in rooms measuring 15×15 m and 20×20 m.

Another benefit of this LED luminaire is that when using the LED light sources with lower power values, the high-efficient cooling system of the luminaire can allow it to be used in environments with high ambient temperatures, for example hot shops.

There are no moving parts in the design of heat pipes, which significantly prolongs their service life, as long as there is no mechanical damage. When using more powerful advanced LED arrays with critically high local heat flux densities in the design of the luminaire, it is possible to use ceramic [20], metal [21] or silicon [22] vapor chambers as heat-transfer gaskets placed between the COB matrix and the supporting base. Being another two-phase heat transfer device based on the closed vaporization-condensation cycle of operation liquid, vapor chamber effectively disperses high local heat flux to a larger surface of the supporting base.

Since heat pipes and vapor chambers can operate both in stationary operating conditions and under mechanical loads, such as vibrations [42, 43], accelerations up to 10 g [44], shocks [45], tilts and oscillations [46], the developed LED luminaire can be used for lighting of vehicle interiors: cabins and trunks of automobile and tracked vehicles, passenger train carriages, urban transport, cabins, deckhouses and control posts on board ships and submarines, cabins and cockpit areas of airplanes and helicopters, *etc*.

However, to ensure high reliability of the luminaire under mechanical loads, it is recommended to modify its design by changing the position of the heat pipes from horizontal to the slightly tilted one (not less than 10°), so that the condensation zone is positioned above the evaporation zone. When being arranged in this manner, not only the heat pipes will remain unaffected by mechanical factors in a negative way, but the position will in fact help to move condensate back into the evaporation zone, thus improving the performance of the heat pipes and the cooling system in general.

Another way of solving the problem of heat delocalization for powerful LED light sources and distributing their heat flux over a larger heat-transfer surface by using two-phase technology is to apply non-traditional heat pipe designs, such as loop [47-50] and pulsating [51-54] heat pipes. In the loop heat pipes, liquid moves under the influence of a significant pressure difference caused by the peculiarities of heat transfer processes in the evaporator and condenser. The loop heat pipes have high thermal conductivity and are recommended to be used under vibration loads and for heat transfer over long distances (up to several meters), but their design and manufacturing technology are more complex than those of traditional heat pipes. Having a much simpler design and manufacturing technology, pulsating capillary heat pipes have been widely studied over recent years and offer prospects for use in LED lighting in the future, especially at high heat fluxes.

6. Conclusions

1. The authors propose to improve the environmental situation through a wider application of energy-saving LED lighting systems in combination with renewable energy sources (such as solar energy), by using a new LED luminaire design as one of the structural elements in these lighting systems. The new design has a cooling system based on heat pipes, which can be scaled to a light source power of 600 W.

2. Electro-optical characteristics of the prototype LED luminaire with heat pipes were studied, showing the cooling system based on heat pipes and concentric cooling rings to be able to stabilize the LED temperature and light flux in down to 300 s. The luminous flux and the electric power drop by 8.7% and 3.5%, respectively, from power-up to the moment when the temperature becomes stabilized.

3. To use the goniophotometric method for determining the spatial distribution of the LED light source with the cooling system based on two-phase heat transfer facilities, one should take into account the dependences of thermophysical characteristics of heat pipes, namely: effective thermal conductivity and maximum heat flux, on their position in space. This study proposes the method to minimize the influence of these factors on determining the light flux spatial distribution.

4. The studied prototype lighting device and the cooling system design implemented in it show the possibility to create lighting devices with the cooling systems based on heat pipes having an electric power of the LED light source of 140.7 W. These systems could be used to illuminate a room measuring 10×10 m with the ceiling height 5 m while ensuring high uniformity of light flux distribution.

5. The study considers possible areas of application of the studied LED lighting device and offers the ways for further improvement of the developed cooling system design based on two-phase technology (vapor chambers, loop heat pipes, and pulsating heat pipes).

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Authors and CV

Demid V. Pekur, PhD student at the V. Lashkaryov Institute of Semiconductor Physics. The area of his scientific interests includes design of perspective cooling systems for super-power LEDs and creation of LED technic on them.

Viktor M. Sorokin, Professor, Doctor of Sciences, Corresponding Member of NAS of Ukraine, Head of the Department of Optoelectronics at the V. Lashkaryov Institute of Semiconductor Physics, NASU. The author of more than 200 publications. His research interests include problems of liquid crystal materials science, lighting engineering and lighting materials. He organized massive implementation of LED lighting in Ukraine. He is the State Prize winner of Ukraine in the field of science and technology.

Valentyna V. Ponomarenko, Scientific Researcher at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. She is author of 5 scientific publications. The area of her scientific interests is properties of functional materials.

Volodymyr P. Kostylyov, Doctor of Physics and Mathematics Sciences, Head of the Laboratory of Physical and Technical Fundamentals of Semiconductor Photovoltaics at the V. Lashkaryov Institute of Semiconductor Physics. He is the author of more than 250 scientific publications. The area of his scientific interests includes development of equipment for silicon solar cells testing, research, analysis of silicon solar cells.

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. Field of scientific interests: heat removal from electronic components by using heat pipes.

Viacheslav S. Solntsev, PhD in Physics and Mathematics, the specialty 01.04.07 – solid state physics, Head of scientific and organizational department at the V.Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. He is author of 14 publications and 3 patents. His main research activity is in the field of nanotechnology, sensors, oxide semiconductors, functional nanomaterials.

Електрооптичні характеристики перспективного світлодіодного освітлювального приладу з охолодженням світлодіодної матриці за допомогою теплових труб

Д.В. Пекур, В.М. Сорокін, Ю.Є. Ніколаєнко, В.П. Костильов, В.С. Солнцев, В.В. Пономаренко

Анотація. Покращенню екологічної ситуації в світі сприятиме широке використання енергоощадних світлодіодних систем освітлення із залученням для їх електроживлення поновлюваних джерел енергії, зокрема сонячної. Одним із структурних елементів такої системи освітлення є світлодіодний освітлювальний прилад. У даній роботі вперше проведено експериментальне дослідження електрооптичних характеристик базового варіанта компактного потужного світлодіодного освітлювального приладу для внутрішнього освітлення приміщень. Особливістю освітлювального приладу є те, що система охолодження світлодіодного джерела світла реалізована на основі теплових труб та концентричних кілець охолодження, що дозволило забезпечити достатню ефективність охолодження світлодіодної матриці. Виявлена динаміка зміни оптичних та електричних параметрів під час температурної стабілізації свідчить про високу ефективність запропонованої системи охолодження забезпечувати нормальний тепловий режим світлодіодного джерела світла при електричній потужності до 140,7 Вт та світловим потоком 15083 лм. Результати визначення просторового розподілу світлового потоку освітлювального приладу вказують на можливість його використання для освітлення приміщень з великими площею та висотою стелі. Масштабування базового варіанта модульної конструкції системи охолодження дозволяє підвищити потужність світлодіодного джерела світла до 600 Вт.

Ключові слова: енергоощадне освітлення, LED, охолодження LED матриці, повітряне охолодження, теплова труба.