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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

INVESTIGATION OF THE OPTICAL PARAMETERS OF WHITE LEDS OBTAINED BY THE "CHIP ON BOARD" TECHNOLOGY

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INTRODUCTION

Relevance and degree of development of the topic. The relevance of this work is based on the large research capacity in the development of more efficient sources of light energy for various fields of application at the moment, such as use in general lighting, in data display devices, and also for signal transmission. Most of these devices have a principle of operation based on luminescence in electron-hole transitions, as well as various luminescent materials. The issue of economical use of electricity is of a global origin; interest in the creation of highly efficient artificial light sources from an energy point of view is growing. In short, since the demand for lighting is growing rapidly, the transition to LED lighting can save ~130 million manats per year. Therefore, an important task nowadays is to increase the conversion efficiency of electrical energy into optical energy by solid-state devices via improving the technology and materials used for the production of such devices. Enormous efforts have been made for creation of efficient LEDs, including complex doping schemes or combinations of materials, to increase the recombination efficiency in the active region of the crystal and reduce losses and leaks in the near-contact regions. However, there are still unresolved problems in the field of light conversion efficiency on the part of phosphors and even the LEDs themselves (for example, low efficiency of green LEDs), which is an obstacle to their final penetration into the commercial lighting markets. Today, there is another task of optimization of LEDs to solve issues such as internal scattering and absorption of photons within the LED package, which have a significant impact on the final efficiency. For this reason, along with research in the field of increasing the quantum efficiency of semiconductor LED structures, the development of methods for increasing the extraction of photons is of particular relevance.

The topic of the dissertation, being extensive, was studied by the authors of many works, a sufficient number of scientific publications have also been published on it. However, there is still great potential for research in this area.

The purpose and objectives of the research.

The aim of the study is to increase the luminous efficiency of white LEDs by increasing the extraction of photons through optimization of parameters and operating mode of LEDs and minimization of such effects as scattering and reflection inside the LED package.

To achieve this purpose following tasks were performed:

- Performance of a theoretical calculation of the maximum conversion efficiency of electrical power into output optical power, taking into account the conversion coefficients of all components of the LED package.
- Creation of LEDs based on blue light-emitting InGaN chips by chip-on-board technology with the use of phosphors.
- Study of LED parameters such as correlated color temperature, color rendering index, luminous efficacy and extraction efficiency.
- Investigation of the experimental change patterns in the optical characteristics of LEDs depending on various parameters and the mode of operation of LEDs.
- Improvement of the quality of color parameters of LEDs by using various phosphors.
- Calculation of the quantum efficiency of phosphors used in the manufacture of LEDs by measuring the reflected, absorbed and transmitted emitting light.
- Development of methods for the manufacture and packaging of LEDs for increasing their efficiency.
- Development of three-dimensional software models of LEDs with further simulation of optical parameters by ray tracing using optical design programs.

Research methods included: measurement of photometric characteristics and analysis of emission spectra of white and blue LEDs; measurement of photoluminescence spectra, measurement of reflection, absorption and transmission in phosphors; study of the electrical parameters of LEDs; simulation study of LEDs using ray tracing.

Research objects.

In this thesis, the objects of research are light-emitting diodes consisting of InGaN chips, substrates that serve as the basis for chips, and phosphors. The processes occurring in the systems substrate-chip-phosphor-reflector-lens are investigated, since photons interact between these components, which are reflected, absorbed and transfer energy.

Scientific novelty of the research.

The scientific novelty of the thesis consists of performing comprehensive studies of the characteristics and optical parameters of LEDs and development of methods for increasing the efficiency of LEDs. To be precise, the following works were carried out for the first time:

- A LED phosphor layer with an improved pyramid shape was developed, in which an increase in the extraction efficiency was observed due to the reabsorption of photons.
- A three-dimensional computer model similar to the produced physical LEDs was developed, on the basis of which a simulation was performed using the ray tracing method, and the values of the luminous flux, the distribution and intensity of the rays propagating in the LED were calculated using this software method, which were later compared with experimental data.
- A LED capsule packaging method promoting the increase of the light extraction has been developed, with the phosphor located under a layer of a spherical transparent epoxy, in which multiple internal reflections occur.
- The "phosphor on chip" method has been developed, where a phosphor layer with a thickness of 30 microns is applied to the emitter part of the chip by spin coating method, and which gives an increase in efficiency and improves the angle characteristics of the light emitting diode.
- The dependence of the wall-plug efficiency of the LED on the emitter area of the chip, as well as the effect of the chip area on the light conversion of phosphor deposited by the "phosphor on chip" method has been investigated.

- The spherical shape of the transparent epoxy encapsulation has been proven to increase the extraction efficiency of the LED.
- Electrical circuit for powering the LED has been developed and implemented in practice, which uses an analog voltage multiplier in the feedback circuit to maintain a constant power at the output of the converter.

Basic scientific theses put forward to defend:

1. The ideal concentration of phosphor particles for an LED in terms of efficacy is 2×10^7 per cm^3 at a thickness of 50 μm.
2. Changing the current of a white YAG:Ce phosphor based LED does not affect its chromaticity coordinates in a wide range.
3. The extraction efficiency of the LED increases from 94.5% to 98% when using a spherical encapsulation form compared to a flat one, where a larger encapsulation radius, as well as the refractive index of the encapsulation material, lead to a higher extraction efficiency.
4. An InGaN chip with a wavelength of 440 nm most closely matches the excitation spectrum of the YAG:Ce phosphor.
5. Phosphor-on-chip LED packaging technology promotes more intense emission absorption, which increases efficiency by 6%, and also improves the LED's angular distribution of color temperature.
6. The wall plug efficiency of the LED increases with a reduction in the emitter area of the chip, both without a phosphor and with a phosphor on the chip.
7. The use of $Y_3Al_5O_{12}:Ce^{3+}$ and $Gd_3Al_5O_{12}:Ce^{3+}$ phosphors as a converters mixed in a ratio of 80:20% increases the emitted luminous flux by 8.3%, improves the correlated color temperature and color rendering index of the LED.
8. Integrated measurement of the optical characteristics of the YAG:Ce phosphor shows that 55% of the initial radiation is transmitted, 34% is reflected by phosphor particles, and 11% is lost due to absorption.
9. The method of packaging LEDs, in which the phosphor is located under a spherical layer of transparent encapsulating material,

gives an increase in the LED radiant flux of 13% due to an increase in the emission angle of outgoing radiation photons.

10. The pyramid shape of the phosphor converter promotes re-absorption of photons scattered by the phosphor, increasing the light output by 14%.
11. Electrical converters based on an analog multiplier are able to stabilize the output power with a shift in power value of only 0.008 mW with the LED temperature change by 1°C.

The practical significance of the research.

The practical significance of this work lies in the results obtained in the process of studying the optical characteristics of white LEDs and their application to optimize a number of important parameters of the performance of LED packaging features in order to improve the output characteristics. Research carried out in the process of manufacturing white LEDs based on InGaN emitting chips and YAG:Ce phosphor and packaging them into a complete device allows obtaining pure white light with a wide spectrum of emission and a high color rendering index. The developed methods of LED packaging, such as LED with a spherical capsule phosphor and pyramid-shaped packaging of the LED, make it possible to increase the efficiency of LEDs by 10-20%. Experience from the application of manufactured white LEDs for lighting and research carried out in the testing process of such aspects as temperature control in the housing and the long-term operation of the modules, allows optimizing the packages of the LEDs for release to the consumer market in the country. Also, electrical voltage converters for powering LEDs have been improved and equipped with additional electrical elements to maintain the operating mode of the LEDs, which prolongs their service life.

Approbation of the results.

Results obtained in the thesis have been discussed at the following conferences: "1st International Conference of Young Researchers, dedicated to the 94th anniversary of national leader Heydar Aliyev" (Baku Engineering University, 2017); "Actual problems of applied physics and energetics– 2018, dedicated to the 100th anniversary of the Azerbaijan Democratic Republic" (Sumgait

State University, 2018); "Multidisciplinary approaches in solving modern problems of fundamental and applied sciences, Dedicated to the 75th anniversary of Azerbaijan National Academy of Sciences" (Azerbaijan National Academy of Sciences, 2020); "Actual Problems of Applied Physics and Energetics, II International Scientific Conference" (Sumgait State University, Kazan State Power Engineering University, 2020); «2nd International, Conference on Light and Light-Based Technologies'» (Gazi University, 2021).

11 scientific papers were published on the topic of the dissertation (5 theses at international conferences; 2 articles in foreign journals with an impact factor of 0.5; 4 articles in republican journals).

The name of the organization in which the dissertation was carried out: Institute of Physics, National Academy of Sciences of Azerbaijan, Baku, Azerbaijan.

The structure and scope of the thesis. The dissertation consists of an introduction, 4 chapters, main conclusions and a list of 101 literature sources. The total volume of work is 150 pages, including 45 figures and 8 tables.

THE CONTENT OF THE WORK

The introduction substantiates the relevance of the topic, the purpose of the study and the work done to achieve the set goal, objects of research, scientific novelty, basic scientific theses put forward to defend, practical significance, approbation, the structure of the dissertation. General information is given, which introduces the state of matter on the LEDs and the history of their creation.

The first chapter, "An overview of physical processes and LED technology" briefly describes the physical processes occurring in semiconductor diodes, LED technology. The characteristics of LEDs are described, such as: luminous flux, radiant flux, color temperature, radiation pattern, radiation spectrum, color rendering index, color space, electrical characteristics (current, voltage). Methods for obtaining white light using LEDs are described, the most common of which is the use of a blue LED and a phosphor with a broadband emission spectrum, such as $Y_3Al_5O_{12}$:Ce^{2+}.

The efficiency of LEDs is considered, including the internal quantum efficiency of the LED chip, the quantum efficiency of the phosphor, the extraction efficiency, as well as the losses arising in the components of LEDs that limit the efficiency.

The maximum luminous efficiency of white LEDs converted by the phosphor is considered, based on the photometric theory, in order to have its relative importance for comparison with the experimental results obtained below. It is shown that the maximum theoretical luminous efficiency increases linearly from 215 to 300 lm/W with an increase in α from 0.6 to 0.9 based on the equation:

$$\eta_{\mathrm{lm}} = 683\left[\frac{\mathrm{lm}}{\mathrm{W}}\right] \times \eta_{\mathrm{f}} \frac{(1-\alpha) \int \mathrm{V}(\lambda)\, [\mathrm{P_b}(\lambda) + \mathrm{P_y}\, (\lambda)]\mathrm{d}\lambda}{\int \mathrm{P_{by}}(\lambda)\mathrm{d}\lambda} \tag{1}$$

Here, α is the ratio of the power absorbed by the phosphor to the power emitted by the chip; $V(\lambda)$ - function of eye sensitivity; $V(\lambda)$ is a dimensionless quantity normalized to 1 at 555 nm; $P_b(\lambda)$ and $P_y(\lambda)$ are the spectral power density of blue and yellow light, respectively, which can be obtained by measuring the spectrum of a white LED.

It follows that, since the yellow light emitted by the phosphor overlaps much better with the eye sensitivity function than blue light, an increase in the spectral intensity of yellow light over blue light is a contributing factor in increasing the luminous efficacy of a white LED. Therefore, with an increase in the absorption of the blue radiation of the chip by the phosphor, an increase in the luminous efficiency can be expected.

The second chapter "Manufacturing and Investigating the Optical Characteristics of White LEDs" addresses the assembly technology of LEDs used in experiments. The process of mounting chips on a substrate for performing experiments for this dissertation was carried out on an A1 machine from FK Delvotec. To install electrical contacts on the chips, ultrasonic welding equipment G5 from FK Delvotec was used. For coating the phosphor layer of the LEDs, dispensers were used which pour the phosphor onto the substrate with chips. For the production of experimental samples, programmable dispensers from Fisnar, model F 4200 N were used.

The chapter also looks into the methods of measuring the characteristics of LEDs, in the course of which the excitation spectra and emission LEDs were investigated. They were measured using a spectrometer that includes an Horiba Yvon Joben 1250M monochromator and an Andor Newton ^{TM} detector . The diffraction grating installed in the monochromator consists of 1800 diffraction slits with an operating range from 200 to 1000 nm. As a detector, an Andor Newton detector with a charge-coupled sensor with a resolution of 1024×255 and a pixel size of 26×26 µm was used. To measure the optical and electrical parameters of LEDs, we used integrating spheres with a diameter of 150 cm and 30 cm from Everfine.

In order to determine the degree of influence of encapsulation and LEDs on their productivity, two types of encapsulation have been tested – flat and spherical, the luminous flux from the blue light emitting array, depending on the shape and size of its encapsulation was calculated. Extraction efficiency η_{ext} was calculated by measuring the initial luminous flux and the luminous flux output after encapsulation. This study was completed by ray tracing simulation, which also investigates the effect of encapsulation radius and refractive index on light extraction efficiency. The results show that spherical encapsulation has an advantage over flat encapsulation, increasing efficacy from 94.5% to 98% in experimental data and from 96% to 98% in simulation data. An increase in the encapsulation radius and refractive index of the encapsulation material also leads to an increase in the extraction efficiency. It can be seen how the extraction efficiency η_{ext} decreases significantly when the radius of the encapsulating lens becomes commensurate with the dimensions of the chip.

Futher, the characteristics of the phosphor were investigated using an integrating sphere with a diameter of 30 cm. The sample was placed on the wall of the sphere, so that one of its sides faces outside. To register photons scattered by the sample and backward emitted by the phosphor, the source excited the sample from inside the sphere, the emission from which was measured with a spectrophotocalorimeter. To register the photons transmitted through the sample and converted by it, the sample was excited from outside of the sphere, while the source was located outside the integrating sphere.

To determine the absolute values of the amount of reflected and transmitted radiation for YAG: Ce based phosphors, firstly, the power of the initial blue radiation was measured in a sphere. The spectrophotocalorimeter measures the spectral flux distribution (W/nm), which shows how much of the measured power corresponds to a certain wavelength, which allows one to directly calculate the optical powers for individual wavelengths corresponding to the emissions of both the chip and the phosphor. As a sample of the phosphor, we used YAG:Ce mixed with an epoxy at a concentration of 0.5 g/cm ^{3} with a wavelength of 550 nm, as well as the same phosphor pressed without a polymer. The phosphor concentration in the silicone was 10% because the density of the phosphor particles in the 10% sample (~ 9 × 10 ^{4} particles/mm ^{3}) is of the same order of magnitude as the density in the phosphor layers commonly used in LEDs. It is important to calculate the weight of the phosphor to maintain a uniform concentration per unit volume throughout the sample for those with and without epoxy.

After receiving all the necessary experimental values quantum efficiency of the phosphor was calculated from the equation:

$$\eta_{lm} = \frac{N_{\text{rad}}}{N_c} = \frac{N_{\text{rad}}}{N_c^{\text{total}} - (N_c^{scat} + N_c^{tr})}, \qquad (2)$$

Here N_{rad}- the number of photons emitted by the phosphor, N_c- the number of photons emitted by the chip, $N_c^{scat} + N_c^{tr}$- reflected and transmited blue photons, respectively.

The measurement results showed that 34% of the initial light energy is lost while being scattered by particles in the case of a free phosphor. Another 11% of the optical power is lost during the nonradiative absorption of blue photons by the phosphor. These losses are due to the Stokes shift and the quantum efficiency of the phosphor. Transmitted blue and yellow photons emitted by the chip and phosphor, respectively, account for only 55% of the initial radiation power at the output. As a result, the measured efficiency was 89% for the free phosphor and 87% for the encapsulated phosphor.

It was concluded, that the traditional LED packaging method is not ideal for efficient extraction of photons in the phosphor layer. Even if the quantum efficiency of the phosphor had been 100%, not all of the photons emitted by the phosphor upon excitation will have been extracted from the optical system of the LED.

Also in the second chapter, the influence of the concentration and thickness of the phosphor on the conversion of the LED spectrum is studied. The concentration of phosphor particles was varied between $1.0 \cdot 10^{7}$ to $8.0 \cdot 10^{7}$ particles per cm^3, which was registered by calculation from the values of the average particle size and density of the phosphor. The thickness of the phosphor layer was also varied from 50 to 500 μm. It was investigated how the emission of LED packaging as a whole depends on the concentration, location and distribution of the phosphor. From the experiments carried out, it is concluded that with a layer thickness of 0.5 mm, the optimal balance between the converted yellow light and the original blue light (color temperature closest to the 6500K point) belonged to the samples with a concentration of ~ 2.0 E7 cm^{-3}; more concentrated samples inhibit blue light transmission, while less concentrated samples give less converted emission. It was found that with an increase in the phosphor concentration to a certain level, the yellow component of the converted light increased, which lead to the shift of the CIE 1931 chromaticity coordinates towards the white light point (0.33, 0.33). In particular, a change in the phosphor concentration from 1.0 E7 to 2.5 E7 per cm^{-3} shifts the X-Y chromaticity coordinates from (0.28; 0.34) to (0.32; 0.38). It was concluded that the optimized phosphor concentration and thickness are 2.5 E7 per cm^{-3} and 50 μm, respectively.

We also investigated the dependence of the light intensity on the density of the current flowing through the LED in the integrating sphere, where the excitation current varied in the range of 10 - 70 A/cm^2. It is seen that the intensity increases with an increase in the excitation current. However, when the flowing current changes, the chromaticity coordinates of white light do not change, and the luminous flux of emitted white light becomes three times the flux of exciting blue light at a phosphor concentration of 2.5 E7 cm^{-3}, a layer thickness of 50 µm, and a current density of 30 A/cm ^{2}.

By adding the $Gd_3Al_5O_{12}:Ce^{3+}$ phosphor, which has a significant intensity in the red region, the potential for improving such light parameters as correlated color temperature, color rendering index and the luminous flux of the LED was studied. For this experiment, we used blue GaN chips manufactured by Fullsun, 1x1 mm in size with a dominant wavelength of 450 nm and a power of 1 W. The phosphors used were $Y_3Al_5O_{12}:Ce^{3+}$ and $Gd_3Al_5O_{12}:Ce^{3+}$ with peak wavelengths of ~ 550 nm and ~ 580 nm and full widths at the half-amplitude level of 91 nm and 100 nm, respectively. LEDs were fabricated as follows: 1) chips were attached to substrates with a conductive glue; 2) then they were heated up to 150°C in a furnace; 3) a mixture of transparent epoxy and phosphors was produced in the ratio of 1 gram of phosphor to 10 grams of silicone; 4) the $Y_3Al_5O_{12}:Ce^{3+}$ phosphor was mixed with $Gd_3Al_5O_{12}:Ce^{3+}$ in two concentrations - 10% and 20% (the total amount of powder and encapsulant remains unchanged), and one of the samples was left without the addition of $Gd_3Al_5O_{12}:Ce^{3+}$ for comparison; 5) the phosphor composites were dispensed and completely cured. For pure $Y_3Al_5O_{12}:Ce^{3+}$ phosphor, the peak value is at 530 nm, and the full width at half amplitude is 91 nm; with the addition of 10% $Gd_3Al_5O_{12}:Ce^{3+,}$ the peak value shifts to 562 nm, and the full half-amplitude width is 100 nm; and with the addition of 20% $Gd_3Al_5O_{12}:Ce^{3+,}$ these values are 570 nm and - 83 nm, respectively.

As a result, the luminous flux shows the highest value with the concentration of red-orange phosphor $Gd_3Al_5O_{12}:Ce^{3+}$ being 20%. The color temperature, on the other hand, decreases with increasing concentration of $Gd_3Al_5O_{12}:Ce^{3+}$, since a red component is added to the emission spectrum. The color rendering index is maximum at a concentration of $Gd_3Al_5O_{12}:Ce^{3+}$ being equal to 10%, and this ratio is optimal for obtaining white light, since a further increase in the percentage of $Gd_3Al_5O_{12}:Ce^{3+}$ results in the coordinates of emission strongly shifting into the red region.

According to the experiment, the addition of a red-enhanced phosphor improves the color characteristics of the phosphor-converted LED, bringing the coordinates closer to pure white light. It is concluded that the use of several phosphors with different chemical composition is a good alternative to LEDs with two and three chips of different wavelengths, allowing to obtain white light.

The effect of the wavelength of the pumping chip on the conversion efficiency of the phosphor was also studied. To test the effect of the wavelength on the exciting light on the intensity in general, an experiment was carried out with three different chips with different wavelengths being used: 440 nm, 450 nm and 456 nm. All chips had the same dimensions with an emitting area of 1 mm^2 . All three chips were used to pump the phosphor compound with $Y_3Al_5O_{12}:Ce^{3+}$ in the same package, the amount of phosphor in the deposited layer was kept the same for all three chips to exclude its influence on the emitted flux. In order to determine the effect of just the wavelength of the chip, the current through the chips was set so that the radiation flux Φ_e of the blue chips was equal for all three LEDs.

The experimental results were evaluated based on three main factors: the wall-plug efficiency of the LED η_{wall}, the quantum efficiency of the phosphor η_{phos}, and the luminous flux Φ_v . It was found that the wall-plug efficiency becomes higher as the wavelength of the phosphor exciting chip decreases from 456 nm to 440 nm. For the LED with a chip with a wavelength of 440 nm, the phosphor efficiency η_{phos} was 88.1%, for the LED with 450 nm - 71.3%, and for a 456 nm LED - 65.4%. The luminous flux also showed a tendency to increase with decreasing chip wavelength. In the original LED in these three cases, the luminous flux emitted by the blue chip was 5.4 lm, but after phosphor conversion it increased to 50 lm, and the luminous flux difference between LEDs with 440 and 456 nm chips was 14.4 lm.

In the course of the experiment, it was determined that a shift in the wavelength of the pumping chip by 10 nm to the short-wave or long-wave region affects the conversion efficiency and it was determined that the excitation spectrum of the widely used $Y_3 Al_5O_{12}:Ce^{3+}$ best corresponds to the wavelength of 440 nm.

The third chapter "Development of the methods for increasing the efficiency of LEDs" reports on the development of a method for applying phosphor, in which it is concentrated on the emitter area of the chip, in a weight ratio of 1:1 and a concentration of 5 g/cm^3, and the phosphor is distributed only above the emitter area of the chip surface. To apply the phosphor, a spin-coating method was used, which makes the layer very thin and uniform. The phosphor powder was mixed with epoxy encapsulant until a good dispersion was achieved in a weight ratio of 1:1, with the concentration being 5 g/cm^3 . The viscosity and specific weight of the polymer were 3.8 Pa·s and 1.23 g/cm^{3,} respectively. This concentration is considered high, which makes it possible to obtain layers 8-10 times thinner while maintaining the phosphor concentration per unit layer thickness. To analyze the LED performance, color temperature, CRI and flux of the phosphor-on-chip LED were measured in an integrating sphere at a forward current of 350 mA. A luxmeter was also used to measure the distribution of color temperature and luminous flux. The distance between the luxmeter and the LED was 2 m. The color temperature of the LED was recorded every 5°, whilst the angle between the LED and the detector was changed from –90° to + 90°.

With a constant directional angle of the LED relative to the detector, the illumination pattern from such an LED with a phosphor on the chip is more uniform, as well as the color temperature in the illuminated area. Method "phosphor-on-chip" provides a high concentration of phosphor particles within the area of the emitter chip, which prevents scattering of blue photons away from the chip, eliminating the "yellow ring" effect. The half-brightness angle, at which the luminous flux is half that of the center emission, is 50°, compared to 60° for an LED with conventional phosphor dispensed on a substrate. The radiation flux of this phosphor coating method is about 0.206 W, while for the conventional phosphor coating it is 0.191 W. The deviation of the color temperature with an angle of 90° is 450 K compared to the deviation of the color temperature of 1700K in case of the dispensed phosphor.

The influence of the phosphor covered chip area on the efficiency of the entire LED package is also investigated. In order to investigate the practical significance of the chip size reduction for increase of the radiation efficiency, we used two chips with different sizes: 1×1 mm and 1×0.45 mm. Both chips are based on an InGaN heterostructure with an emission wavelength λ=450 nm. These chips were coated with a yellow YAG:Ce phosphor. Thus, it was established that the size of the emitter area affects not only the efficiency of extraction of blue photons from a semiconductor, but also the extraction of photons from a chip and a phosphor as a single light system. It was found that LED chips produce higher radiation power with the same consumed current as their area decreases. It has been shown that a blue chip of both sizes without a phosphor will have a higher light output than with a deposited phosphor. As a result, at 100 mA, the small chip showed 2% higher conversion efficiency than the large chip. The phosphor chips also showed a 2% increase in wall-plug efficiency.

The developed method of capsule LED production is also considered, in which the phosphor is located under the layer of the silicone encapsulating material. The capsule is located on the chip and has the shape of a hemisphere, which to some degree serves as a convex-concave lens. The capsule thickness is ~200 μm with an outer diameter of 3 mm. During the manufacturing process, the phosphor was diffused onto the inner part of the epoxy layer, attaching on it by the adhesive properties of the epoxy. As a result, the phosphor layer with a thickness of the order of several diameters of the phosphor particles is obtained. This method provides an increase in light output compared to the traditional method. This method also promotes internal reflection of photons in the encapsulating layer of a transparent polymer, while they do not interact with phosphor particles, which contributes to their better extraction at the output of the LED package. An increase in the optical power with this method is observed in comparison with the traditional method, as the current through the LED increases, the difference in optical power also increases, and reaches 13%.

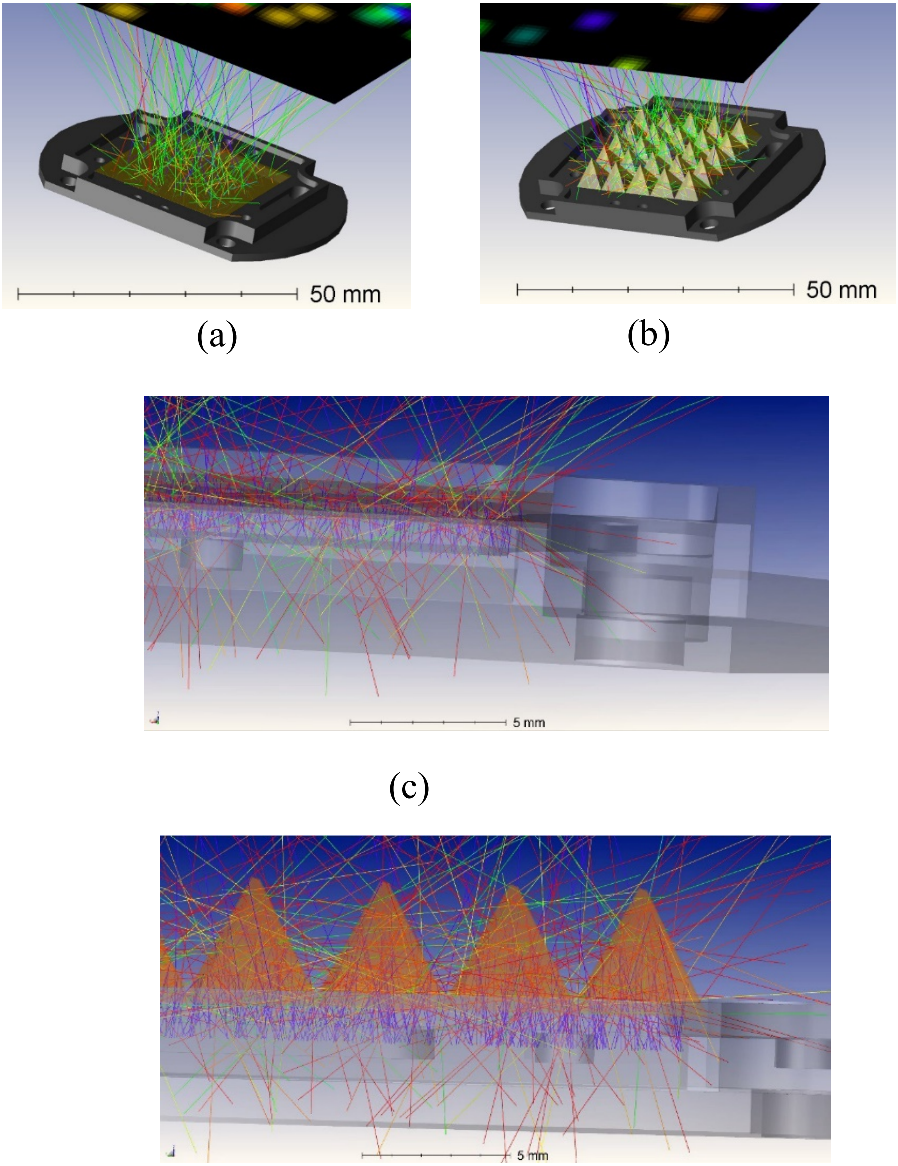
The chapter also reports on the developed pyramid-shaped phosphor, where the structure of hollow pyramids gives the LED the geometry of optical propagation of photons, which determines the path of light rays for their maximum extraction from the optical system. For the manufacture of a pyramid-shaped conversion phosphor layer, YAG:Ce was used. To create pyramidal cones, two silicone plates were formed into pyramid-like structures as molds, and then cast into epoxy to give them a hard consistency, into which the composite was later dispensed. YAG:Ce was mixed with epoxy silicone in proportions of 1:10 (the phosphor concentration was optimal - 0.5 g/cm^3), with which these molds were filled, and then they were pressed to form a thin phosphor layer. Conversion layer composed of 25 pyramids (5 rows 5 columns) of 4 mm in height and width of 4 mm at the base. To measure the photoluminescence of the manufactured phosphor coatings, an LED array was assembled, consisting of 100 serial and 100 parallel chips.

The dependence of the luminous flux and luminous efficiency on the direct current through the LED shows an increase from 93 to 107 lm/W for a pyramid-shaped phosphor and from 65 to 68 lm/W for a flat-type converter in the range of direct LED current of 100-3000 mA. An increase of 8% was observed at 100 mA and 14% at 3000 mA compared to the flat type phosphor converter. The increase in luminous flux approached 8% at lower currents and reached almost 10% at the maximal values of the LED current. The correlated color temperatures of the two LEDs were 4324 K for the pyramid and 4644 K for the conventional LED.

A ray tracing method was applied to study the distribution of rays in the pyramid structure of the LED packaging, for which the OpticStudio software from Zemax was used. For this, a substrate has been modeled, which has an identical geometric shape to the physical "chip on board" substrate was used. The tracing results confirmed that blue photons back scattered by the flat-type phosphor propagate in the opposite direction from it, and in the pyramid-shaped phosphor these rays are directed at different angles inside the pyramid, also contributing to their re-direction to the output (fig. 1). The ZEMAX OpticStudio software presents the optical parameters from the virtual detector in two values: detector illumination and total luminous flux. The illumination in the case of a pyramid-shaped phosphor was 9.525E+2 Lm/cm^2 in the simulation results, and in the case of a flat type phosphor - 7.909E+2 Lm/cm^2, and the total luminous flux registered by the detector was 1.01E+5 Lm for a model with a pyramid-shaped phosphor and 8.123E+4 lm for the flat type phosphor model. Thus, a pyramid phosphor LED shows a 15% increase in peak illumination and a 19% increase in total luminous flux compared to the conventional flat dispense type phosphor method, while experimental data show a 10% increase in luminous flux.

The color temperature of the pyramid and capsule LEDs was compared with the color temperature of a conventional LED, measured as a function of the viewing angle. If we consider the change in the angular dependence of the color temperature from 0 ° to 90 °, its deviation over 90° for the flat-type of phosphor is 680K, for the pyramid-type - 525K, and for the capsule-type - 86K. The question of the 2D spatial illumination distribution of white LEDs is investigated. 60° is the theoretical scattering angle, calculated from the geometry of the substrate, beyond which light does not propagate directly from the LED itself, without reflecting off the edges of the substrate. The pyramid method does not show a significant broadening of the beam angle from the center, despite its protruding structure. The capsule packaging method has a different distribution due to its spherical shape. The capsule method deflects light at a wider angle than the rest of the measured LED samples.

The fourth chapter “Factors affecting the parameters of the obtained LEDs and their optimization” studies the radiation diagram of an LED chip, which describes the relative intensity of light in any direction from the light source. To determine the direction and pattern of emission of blue InGaN chips using a goniometer, the diagram of their radiation intensity distribution was measured. A metal layer was deposited on the back side of the substrate on which the chip was grown, so that the reflected radiation was redirected towards the chip. To measure the radiation diagram of the LED chip, the goniometer was equipped with a photometer. The alignment of the



(a) (b)

(c)

(d)

Figure 1. Images of ray tracing simulation for the: a) flat type b) pyramid type c) side view for flat type d) side view for pyramid type LEDs

LED with respect to the center of rotation of the reference frame was performed using a step-by-step process in which the LED is alternately aligned between two orthogonal views using a laser. The alignment ended when no shift of the LED was observed when the azimuth angle was changed. From the results on the intensity distribution, it can be seen that the main radiation of the chip surface is directed forward from the frontal surface of the chip, and significant radiation also occurs from the side sections of the chip.

Further, the influence of phosphor particles inhomogeneity in the layer on the optical characteristics of the light-emitting diode radiation is considered. For this, a layer of epoxy and phosphor was made, having a square geometric shape and a thickness of ~ 400 μm with a uniform phosphor concentration of 10 vol.%. To simulate a non-uniform distribution, the volume V_0 of the reference layer was divided into volumes V_1 and V_2 having the same width but half the thickness of the reference phosphor layer. These layers were placed alternately above the LED, perpendicular to the direction of light. The phosphor concentration in the lower layer was set either below or above the phosphor concentration in the reference layer. The phosphor concentrations k_1 and k_2 in the volumes V_1 and V_2 are interdependent and follow the expression:

$$V_0 k_0 = V_1 k_1 + V_2 k_2 = const \qquad (3)$$

The investigated ratios between k_1 and k_2 vary up to $k_1{:}k_2 = 1{:}24$, which means that the concentration in layer 1 is 24 times higher than in layer 2, with the following ratios also investigated: 1:12, 1: 6, 1: 3, 1: 2, 1: 1, 2: 1, 3: 1, 6: 1, 12: 1, 24: 1. The experimental results show that in the case of the concentration of the phosphor in layer 1 being lower than the concentration in the layer with a uniform distribution of the phosphor, the light emission becomes more intense. The results suggest that layers with a lower phosphor concentration near the LED chip make it possible to produce white LEDs with an identical overall average chromaticity coordinate X, but with a higher energy flux Φ_e than in LEDs with a uniform phosphor distribution in the layer.

Moreover, the negative influence exerted by defects in the phosphor layer, such as air bubbles around the phosphor particles, as well as the effect of its inhomogeneity on the optical characteristics of the LED, is investigated. To eliminate this problem, a study was carried out in which a method of manufacturing a phosphor layer using vacuum pump was applied. The luminous flux of the LEDs was measured with a luxmeter at different distances in order to determine its dependence on the distance to the LED, and compare it with the same distances for the LED without bubbles. The integrated intensity of the bubble free LED was measured, and found to have a higher luminous efficacy of 102 lm/W compared to 97 lm/W for an LED obtained without a vacuum. With distance, a bubbled LED has a more intense luminous flux decay than a non-bubbled LED.

The electrical power supply circuit of the LED power supply has been developed and tested. With the electrical load change, the current in this supply unit remains constant. To convert mains 220V voltage circuit was built in which the inverter inlet is formed by a diode bridge and a filter on the capacitance C. A PWM controller LD7552BPS is used to generate high-frequency pulses. To maintain constant electrical and optical power of the LED, an AD633JNZ series analog multiplier approach is adopted. To stabilize the output power of the constant voltage source, the analog multiplier is used as an active amplifier in the feedback circuit, the input X of which is supplied with a voltage proportional to the LED current, which settles as voltage drop across the current-sensitive resistor R , and the voltage drop from the LED itself. As a result, the analog multiplier outputs a signal value equal to the product of the LED current and voltage values. The output voltage from the multiplier is then fed to the inverting input of the operational amplifier, which is subtracted from the reference voltage at the non-inverting input. Thus, the current through the transistor is kept constant and the output impedance of the source is high.

To test the assembled converters, their output electrical characteristics were measured over a period of time. The output optical power and other optical parameters were measured in the integrating sphere. Within 10 minutes, the substrate temperature was measured using a thermocouple, and it changed from 20° C to 80° C. The change in the LED output power was 0.008 mW/°C. For comparison, the average power change of a conventional LED current source is 0.04 mW /°C over a temperature range of 1 to 80 ° C.

Testing of the results obtained in the dissertation was carried out by the introduction of manufactured white LEDs in street lighting. The characteristics of three different types of street luminaire designs with integrated LED modules were tested. The illumination pattern of the roads lightened with manufactured luminaires was investigated and compared with a typical distribution in the form of a diagram. The susceptibility of street LED modules to degradation was also investigated, as they were subjected to continuous operation at a current of 3.0 A, and the luminous flux was measured with a luxmeter every 48 hours. After 500 hours, the brightness of the LEDs decreased exponentially, and after 10 thousand hours, the luminous flux decreased by 13%. It was also found that with increasing ambient temperature, the optical power of the output radiation decreases.

RESULTS

1. When pumping the $Y_3Al_5O_{12}:Ce^{3+}$ phosphor, used in LEDs with blue light, the number of reflected photons was 34%, the number of photons transmitted through the phosphor was 55%, leading to a quantum efficiency of 89%.
2. The use of a combination of $Y_3Al_5O_{12}:Ce^{3+}$ and $Gd_3Al_5O_{12}:Ce^{3+}$ phosphors in LEDs in a percentage ratio of 80: 20%, instead of a single $Y_3Al_5O_{12}:Ce^{3+}$, increases in luminous flux by 8.3%, color rendering index from 70 to 75, and lowers the color temperature from 7134 K to 6433 K, bringing the coordinates on the CIE 1931 diagram closer to ideal white light.
3. Spherical LED encapsulation increases the extraction efficiency compared to flat encapsulation from 94.5% to 98.0%, respectively, due to the recirculation of refracted rays; ray tracing results show an enhancement in efficiency with increasing radius and refractive index of encapsulation.
4. The emission flux of a developed “phosphor-on-chip” LED is 7.8% higher than that of a standard LED, and the angular distribution of

color temperature is improved by an average of 13 Kelvin/degree due to the smaller photon scattering angle with this method.

5. A decrease in the area of the phosphor layer, when applied to an LED chip with a 55% smaller emitter area, has an increased quantum efficiency in photoluminescence from 19% to 21%, which is due to more efficient absorption of photons in the phosphor and improved current injection in the LED chip.
6. The use of the developed LED model, where the phosphor is located inside a spherical encapsulating film in the form of a capsule, leads to an increase in the radiation flux by 13%, due to an increase in the extraction of photons as a result of internal reflection in the film and an increase in the photon output angle.
7. The use of the developed pyramid-shaped structure of the phosphor coating leads to an increase in the luminous efficiency of the LED by 14% due to an increase in the angle of reflection of photons, as a result of which reabsorption and excitation of the phosphor occurs.
8. The Monte Carlo ray tracing method, carried out using the ZEMAX OpticStudio software, showed a 19% increase in luminous flux and a 15% increase in illumination in the simulation of the parameters of the manufactured pyramid LEDs.

THE LIST OF THE WORKS PUBLISHED ON THE TOPIC OF THE DISSERTATION

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