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LED MUSEUM LIGHTING: BACK TO NATURAL LIGHT

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ABSTRACT

Article overviews prospects of application of adjustable polychrome LED luminaires based on *RGB* mixture principle for museum lighting. Such light sources allow creating of high-quality lighting systems with capability to adjust luminous flux and chromaticity characteristics with a wide range of correlated colour temperatures between 2800 K and 6500 K and high values of all colour rendering indexes: R_1-R_{14}. Application of adjustable LED light sources makes it possible to do artificial museum lighting similar to natural environment at the moment of creating of a piece of art by an artist, hence, to make its perception more precise. Possibility to adjust the correlated colour temperature allows creating individual lighting of paintings in compliance with the genre and subject of a work (a portrait, a landscape, time period, etc.). The article also briefly describes major theoretical, circuit design and software aspects of creation of a dynamically adjustable LED system of museum lighting and gives first examples of its application.

Keywords: light emitting diode (LED), light source, adjustable LED lighting system, *RGB* mixture, luminous efficacy, colour rendering indexes, correlated colour temperature, remote control

1. INTRODUCTION

The rapidly developing LED lighting systems have been being applied in museums more widely. This process itself, with participation of such great museums as Louvre, Prado, Amsterdam Rijksmuseum and exhibition of such masterpieces as Mona Lisa (Gioconda), Night Watch, etc. with LED lighting, witnesses high quality of existing LEDs and the light created by them [1, 2]. In point of fact, recognition of LED lighting by many museums is related to significant increase of major light engineering indicators of LED as well as to "approaching the consumer" by widening of the product range and increase of convenience of LED luminaires application. As is known, the advantages of LED, which brought them to the lighting market for the first time in the early 2000s, consisted in the absence of IR and UV radiation components, luminous efficacy (LE) comparable with fluorescent lamps, and long service life. But the quality of light was far from perfect. Nowadays, advances in increase of efficiency of LEDs based on *AlInGaN* hetero-structures have surpassed the wildest expectations. The record values of efficiency for blue semiconductor emitting crystals (used as a basis for phosphor white LEDs) are equal to ~85 % [3]. For white phosphor LEDs based on efficient blue LEDs, *Cree Inc.* demonstrated the level of LE reaching to 303 lm/W, which is close to the theoretical level [4]. The LE value of commercial devices is (150–200) lm/W which exceeds all known types of lamps [5].

But the quantitative indicators, illuminance and LE, are not so important for museum lighting as qualitative indicators, primarily the correlated colour temperature (T_{cc}) and colour rendering indexes (CRI). According to contemporary requirements for high-quality lighting, general CRI R_a should be equal to at least 95 whereas special

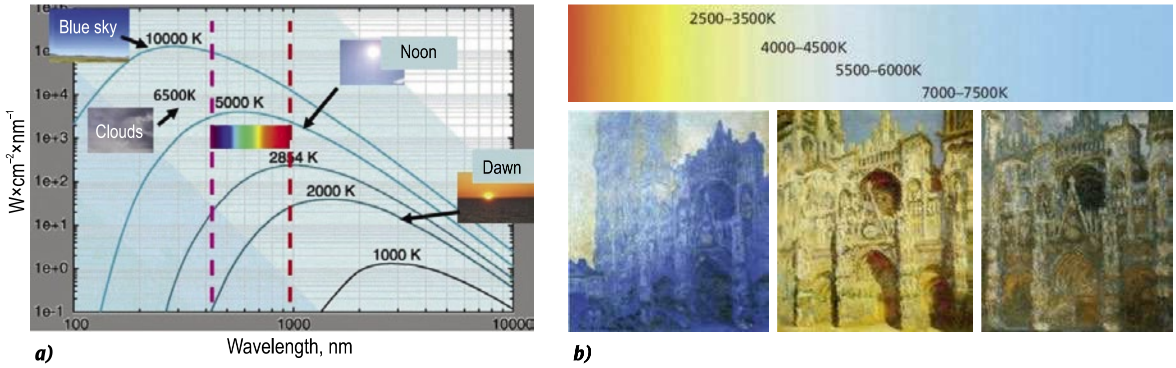


Fig. 1. Spectral distribution of natural lighting in different time periods and with different weather conditions (a); C. Monet, the Rouen Cathedral series in morning, day, evening (b)

CRIs for saturated colours R_8–R_{14} should be equal to at least 85 [6]. It must be admitted that, thanks to development of phosphor technology and, partially, the semi-conductor radiators as well (which can be not only monochrome but also double-sideband [7]), colour rendering of phosphor LEDs has increased dramatically becoming acceptable for illumination of paintings. But, after becoming more efficient and qualitative than most of fluorescent lamps, in one respect phosphor LEDs are still heirs of fluorescent lamps. That is their radiation is static, the spectrum of radiation is specified during manufacturing and cannot be varied in the course of operation.

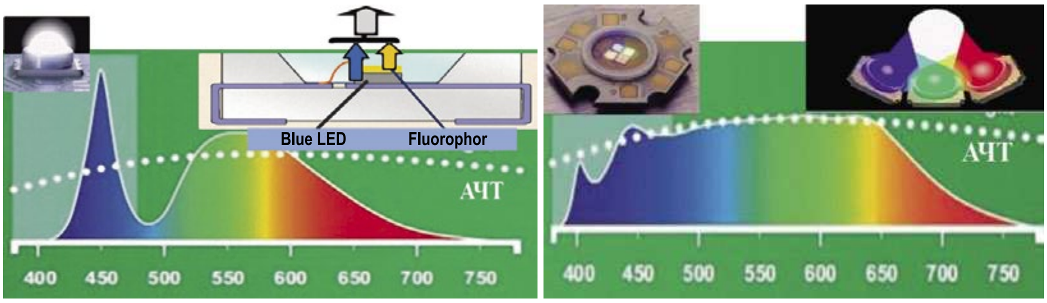
Herewith, for a number of applications including museum lighting, capability of dynamic control of spectral and colour characteristics seems to be attractive. Controllability of spectrum (colour) first determined by E.F. Schubert as *smart light* [8] radically widens functionality of light sources (LS), in particular, changing approaches to museum lighting. The degree of controllability may be different, for example, from varying over time within a specific range of T_{cc} to reproduction of a wide range of natural colours, which includes millions of shades [9]. It is possible to imitate natural light with all its transitions from warm to cold hues or, in other words, to turn artificial light into natural one.

Paintings of the Old masters, like most of paintings by contemporary artists, were painted with natural lighting. From the physical point of view, natural light is characterised by wide continuous spectrum close to that of a Planck's radiator (Fig. 1a) providing ideal colour rendering of illuminated objects (all CRIs of the Planck's radiator are equal to 100). The maximum point of the natural light radiation spectrum differs throughout the day from warm hues (at dawn) to cold ones (at noon) and then to warm colours again (in the evening) as well as in compliance with weather conditions (sunny, cloudy, overcast). In terms of colorimetry, it is reflected as variation of T_{cc} between warm hues (T_{cc} ~ (2,000–2,500) K) and cold hues (T_{cc} ~ (6,000–10,000) K). Such variation of lighting to the large extent determines perception of an imaged object by an artist, as exemplified by the Rouen Cathedral series by Claude Monet shown in Fig. 1b.

However, in museums, artificial light is used always or most of the time, until recently it was made by tungsten halogen lamps, mercury fluorescent lamps or metal halide lamps. This light is far from natural one. Although the spectral distribution of incandescent lamps is similar to that of a Planck's radiator, due to low temperature of the filament their spectrum almost does not include the blue range of wavelengths, which, for instance, causes adverse impact on landscapes with sea or sky. The fluorescent lamps are characterised by a selective spectrum of radiation, which make them not acceptable for lighting of paintings due to low CRIs. The listed features of the lamps a priori confirm that their light differs from that at the moment of creation of a painting and perception of paintings by a spectator may not comply with what an artist saw and wanted to express.

Is it possible to create artificial LSs returning natural light? Yes, there is such possibility these days. Its implementation is linked with development of polychrome mono-crystal LED matrixes applying the *RGB* mixture principle. The white light is created as a sum of radiation bands of multi-colour LEDs contained in the matrix, hue (T_{cc}) control is performed by changing the share of any component of the total spectrum.

The theoretical aspects of colour mixture for creation of high-quality white colour as well as the



a) b)

Fig. 2. Typical spectra of radiation of the phosphor white LED (a) and a polychrome multi-crystal LED (b) compared with a spectrum of a Planck's radiator (dashed line)

structure of a controllable LED LS based on this principle and functional diagram of the whole lighting system including remote control and software are briefly described below.

2. SIMULATION OF COLOUR MIXTURE, SELECTION OF COMPONENTS OF THE CONTROLLABLE LS

As mentioned above, nowadays LSs on the basis of white phosphor's LEDs with original blue radiation of a semi-conductor crystal partially re-radiated to the yellow-green area by a phosphor are the most commonly used and their total double-band spectrum is equal to white light (Fig. 2a). Despite the high values of luminous efficacy and colour rendering (LE~200 lm/W; R_a>80) of phosphor LED, their disadvantage is their typical "two-peak" spectrum, due to which some special CRIs R_i are lowered, but the main disadvantage is incapability to change spectrum and colour characteristics in the course of operation of LS.

Controllability (fine adjustment, regulating, and programming) is possible with another scheme of a LED LS, which is based on mixture of radiation in multi-crystal polychrome LED matrixes [10]. The main question here is how many and which semi-conductor radiators spectrum distribution should be mixed to obtain white light with specified characteristics. Let's examine this important question a bit more careful. The contemporary LEDs with specific efficiency fill in almost the whole visible spectrum (except for a little gap close to wavelength ≈550 nm called *the green gap*), and, by selecting of 8–10 monochrome LEDs with relevant power, it is possible to obtain an envelope of the total spectrum similar to that of a Planck's radiator with any T_{cc} (Fig. 2b) [11, 12]. However, for both technical and economical reasons, this approach is suitable only for development of unique (reference) LSs [13] and is not feasible for common practice. Over the last 20 years, a large number of studies had been devoted to simulation and calculation of minimal but sufficient amount of LEDs for creation of white light with specified parameters [14–16]. This question does not have the unique solution and faces the main contradiction between quantitative and qualitative characteristics of white light, LE and R_a (increase of one of these parameters always leads to reduction of the other one). The brief conclusion of the results obtained in these studies is as follows. With typical half-breadth of monochromatic semi-conductor radiators of $\Delta\lambda_{0.5}$ ~ (15–40) nm, obtainment of white light with high value of general CRI of R_a~90 requires mixture of radiations of 4 or 5 semi-conductor radiators with optimal selected peak values at wavelength λ_{peak} relatively uniformly distributed throughout the visible spectrum. Further increase of the number of LEDs adds little to the value of R_a but causes significant decrease of LE. It is significant that even low deviations of peak values of wavelength λ_{peak} of particular LEDs from optimal values may cause sharp decrease of the values of special CRIs R_i.

To solve the task of LED spectra mixture, we used a computational model and software developed by OOO SOFT-IMPACT allowing to find the optimal value using a special objective function while varying lots of parameters [17]. As a result of calculation, the total radiation spectrum is defined and analysed in part of chromaticity coordinates x, y, correlated colour temperature T_{cc}, general and special CRIs, and LE calculations. The model allows to form a multi-parameter objective function and to optimise white light with specified T_{cc} provided that the values of R_a (as well as specific R_i) and LE will not be less than the specified ones.

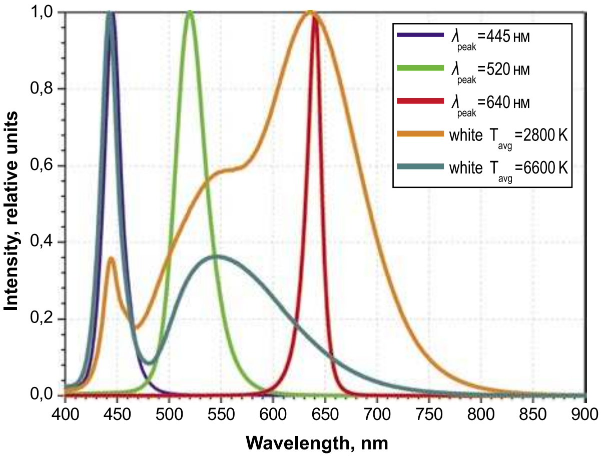


Fig. 3. Spectral distributions of LEDs (3 monochrome and 2 phosphor) used as a basis for colour mixture

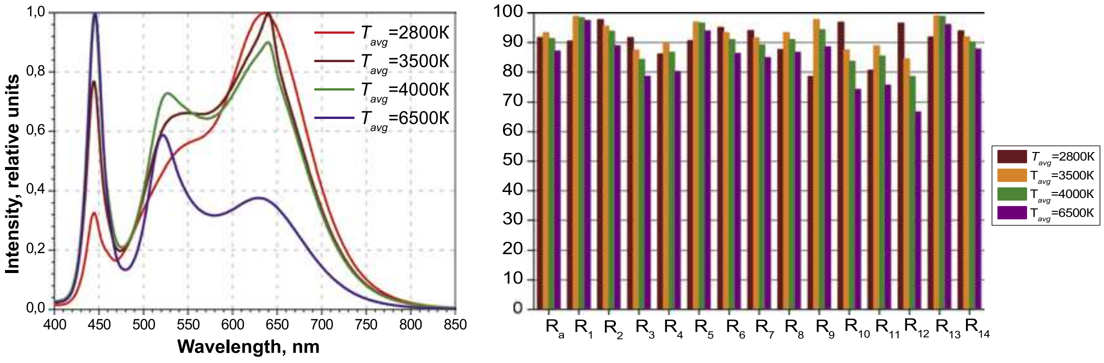
After analysing a number of combinations of polychrome *RGB*, *RGBA*, $RGBW_c$, $RGBW_w$ type matrices (*R, G, B, A* are monochrome LEDs with red, green, blue and amber colour respectively and W_c and W_w are phosphor white LEDs with cold and warm hues), the variant of a radiator with 5 components was chosen as an optimal one for museum lighting according to the results of computer simulation. There are three monochrome LEDs (two *AlInGaN*-based with λ_{peak} = 460 nm, $\Delta\lambda_{0.5}$ = 22 nm and λ_{peak} = 520 nm, $\Delta\lambda_{0.5}$ = 34 nm) and one *AlGaInP*-based with λ_{peak} = 630 nm, $\Delta\lambda_{0.5}$ = 15 nm, and two phosphor LEDs of warm (W_w) and cold (W_c) hues with T_{cc} equal to 2800 K and 6600 K respectively. The spectra of radiation of the selected original LEDs are shown in Fig. 3.

In the course of white light creation experiments with specified values of T_{cc}, at first the values of output optical power obtained during simulation (optimisation with maximum R_a) were set and then, with direct visual control of colorimetric characteristics, using the *OL 770-LED High-speed LED Test and Measurement System* the values of power of radiators were adjusted individually until better compliance with a point of the Planck's radiator envelope at relevant colour temperature was obtained.

The experimental studies and simulation showed that the selected combination of 5 basic LEDs allows us to create a LS providing high-quality white light with a wide range of T_{cc} = (2800–6500) K, i.e. almost the whole range practically important for lighting. In Fig. 4, the relevant spectral distributions, the values of general and special CRIs at 4 T_{cc} values (2,800; 3,500; 40,000 and 6,500 K) are presented. It is worth noting that at all T_{cc} the major contribution in the total luminous flux is made by phosphor LEDs providing also high values of LE. The blue, green and red monochrome LEDs correct the special CRIs and increase them. As shown in Fig. 4b, in the area of warm and neutral white light, (2,800–4,000) K, there is a situation when $R_a \geq 90$ and all values of special CRIs $R_i \geq 80$. The values of some special CRIs (R_1, R_5, R_{13}) are proximate to 100. The high values of R_9, R_{13}, reaching 95–98, are especially important. These indexes are not taken into account for calculation of R_a but they play an important role in reproduction of bright-red colours and shades of human skin colour.

3. LED SYSTEM OF CONTROLLABLE LIGHTING: THE STRUCTURE, THE KEY ELEMENTS, THE FUNCTIONING PRINCIPLES, AND SOFTWARE

The LED system of controllable museum lighting may include both one LS and a group of LSs depending on the task to be solved, lighting of one painting, a group of paintings, or common illumina-



a) ***b)***

Fig. 4. Spectral distributions (a) and values of CRI R_a, R_i (b) for a controllable source of white light with T_{cc} equal to 2,800 K; 3,500 K; 4,000 K; 6,500 K

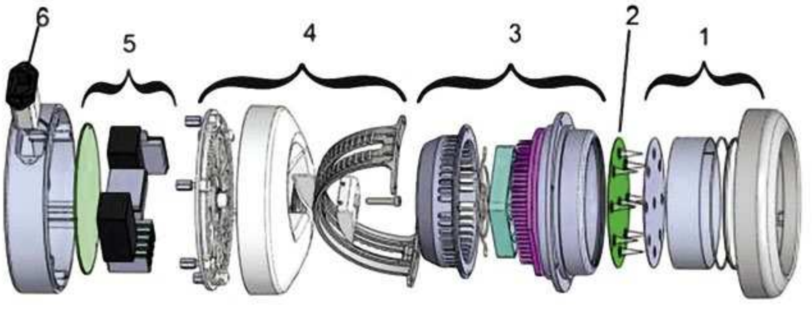
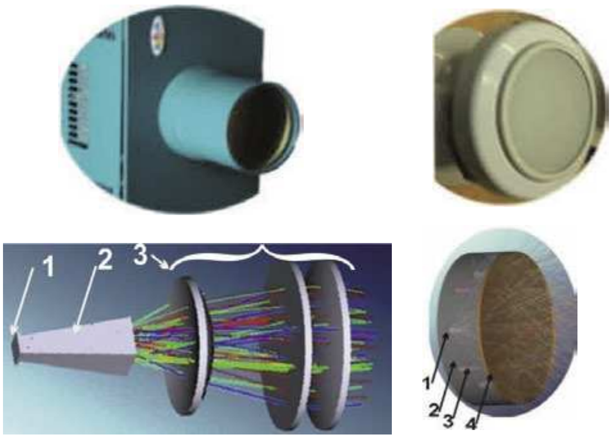


Fig. 5. Diagram of the major units of the controllable LS: **1** – optical system, **2** – LED module, **3** – radiator with a fan, **4** – bottom of the body with a rotary device, **5** – electronic power supply and control unit, **6** – power supply filter

tion of a hall. A separate LS itself is a device containing electronic and optical units.

The structure of LS is shown in Fig. 5. The key element of LS is the multi-crystal polychrome module, which is a board ***2*** with a set of multi-colour LEDs and secondary optics for mixture of radiations. The spectral characteristics of LEDs forming the module were defined in the previous section and, based on the complex of qualities, primarily LE, we selected 4-crystal LEDs *LE RTDUW S2W (R-G-B-*W_c) and *LE CWUW S2W* (W_c-W_w) [18] manufactured by *Osram Opto Semiconductors*. The LEDs are mounted on an aluminium radiator equipped with a fan ***3***. The study of thermal parameters showed that in the heaviest operation modes, the temperature of the active area of LED does not exceed 95 °C (thermal resistance of individual LEDs ~ (4–5) K/W) and none uniformity of heating of the board does not exceed 10 %. To stabilise the thermal conditions (which is required for continuity of spectral and performance characteristics of LED), the board of radiators is equipped with a temperature sensor turning the fan ***3*** on.



a) ***b)***

Fig. 6. Photo and optical diagrams of two types of LS
a) – projection-type LS for lighting of an individual painting (part of a painting):**1** – LED matrix, **2** radiation mixer, **3** – three-element lens;
b) – diffusing-type LS for lighting of spaces: **1** – LED matrix, **2** radiation mixer, **3** – diffuser, **4** – side reflector

The optical system of LS1 should provide high ratio of radiation transmission between LED and the exit aperture, the specified value of spatial distribution of radiation as well as colour uniformity in the far-field and near-field, i.e. good mixture of radiation from several LEDs. The calculations and optimisation of the optical scheme were performed in accordance with the optimal optical systems architecture. Taking the most important art objects lighting conditions into account, the two types of luminaires had been designed:

– The first one with projection lenses creating a bright limited illuminated field used for local lighting of one painting (or a particular area of a painting);

– The second one with diffusing optics providing uniform lighting of the whole room.

The photos of the luminaires and both variants of the optical scheme are shown in Fig. 6. It is worth noting that an important optical element of both systems is the mixer of radiation from separate radiating crystals, which provides uniformity of the colour field at all angles of radiation (over the surface of the illuminated object).

The radiating module itself is located on a rotary device mounted to the bottom of the body ***4*** with the electronic unit ***5*** located inside. It's functional diagram (Fig. 7) includes power supply, transceiver modules for data exchange with the remote control unit (RCU) or the computer via wireless channel, the microcontroller and control units (CU) setting the LED operation modes and, subsequently, their output radiation characteristics. The LEDs form five colour groups (lines, sequential radiators): R, G, B, W_c and W_w connected with five CU units controlling radiant power of each colour group of LEDs according to the level set by the microcontroller.

The LS radiation parameters may be controlled using signals transferred to input of the microcon-

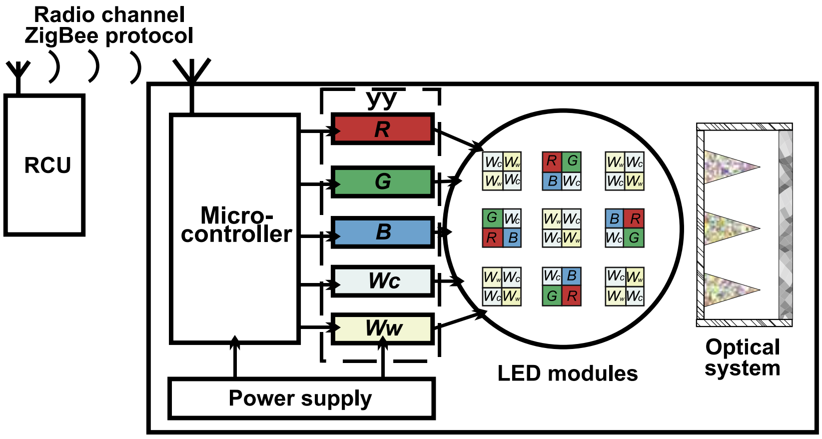


Fig. 7. Functional electric scheme of LS

troller via wireless network (radio channel) from a personal computer or RCU. The microcontroller receives control signals, sets light characteristics of LED groups with different chromaticity and monitors temperature of the LED board. The main task of the wireless network is to transfer relatively small data volumes to short distances, and the network should have minimal consumption implementing various schemes of monitoring and control in the course of solving light engineering tasks [19].

The network in our lighting system is based on *IEEE802.15.4* standard and its *ZigBee* specification [20, 21]. Low signal-to-noise ratio allows the signals to co-exist successfully with alternative sources of radiation at the same frequency (*Wi-Fi*, *Bluetooth*). The standard also specifies channels with frequency different from that of competitors, which allows us to arrange a network even in close proximity to powerful sources of radiation.

The RCU has the form of a unit plugged in the power supply socket with a coloured *TFT* indicator (diagonal size of 3.5 inches) and a six-button keyboard. The RCU sets the specified T_{cc} and brightness of lighting as well as the mode or time of their change. RCU controls LS at a distance of up to 35 m.

The network software includes a set of programmes and allows us to control a branched network via a radio channel using a RCU or a PC throughout the day and in energy-saving mode.

4. EXPERIMENTS OF ILLUMINATION OF PAINTINGS BY CONTROLLED LED LIGHT SOURCES

The developed controllable LSs were tested for lighting of paintings with different colour palette in exhibitions [22] and museums [23]. The experiments showed that the optimal selection of lighting reached as a result of varying T_{cc} of LSs allows obtainment of the best reproduction of colours of a painting close to that in daylight. T_{cc} of the controllable LS selection is determined by the subject of a painting and by what is painted in it, and, of course is partly subjective, basing on opinion of the expert group evaluating varying lighting conditions. For example, Fig. 8 shows the painting by B. Karafyolov with cold blue hues prevailing at two lighting variants. In Fig. 8a, the painting is lighted with light from a controllable LS after selection of T_{cc} = 5,000 K as optimal, whereas Fig. 8b shows the same painting lighted with an incandescent lamp with T_{cc} = 2,800 K. Comparison of the figures clearly shows distortion of colour rendering caused by standard lamp lighting since the blue part of spectrum is reproduced insufficiently.

It is worth noting that in some cases adjustment of the controllable LS may differ from the standard requirement of high CRI. Deviation from good white light may be used for the so-called accent lighting. For example, lighting without green and yellow component (low values of R_3, R_{10}, R_{11}) may be applied for increasing of image contrast. It means to increase brightness of blue and red objects against the background of the others. The same approach, i.e. selection of particular spectrum components of lighting, may be used for art conservation allowing particular layers of paint to distinguish from others.

5. CONCLUSION

The article reviews the operational principle, design and major characteristics of controllable LED based lighting systems with application of multicrystal polychrome matrices. It shows the capability of adjustment of spectral and colour characteristics

Fig. 8. Comparison of a painting with optimal lighting by means of a controllable LS with T_{cc} = 5000 K (a) and of an incandescent lamp with T_c = 2800 K (b)

including creation of high-quality white light with T_{cc} in range (2800–6500) K, with general and special CRIs ~ 90, in other words, the capability to return artificial light to natural light with its variations depending on the time period and weather conditions. At the same time, it is possible to set special accent lighting for contrast reproduction of particular colours.

In our opinion, application of such controllable LED LSs opens new interesting prospects for museum lighting. It can be transformed from general to individual, complying with the subject of a painting. Roughly speaking, it means that if a painting shows a marine landscape at noon, the controllable LS should illuminate it at T_{cc} ~ 6,000 K so that the spectator sees it with the same lighting that the artist saw while creating the painting.

Although the production volumes and product lines of controllable polychrome LED LSs are less than those of phosphor white LEDs, they are already ready to be applied in the following fields:

– General lighting of single objects,

– Special lighting for treatment of psychological and physical state of human,

– Lighting of operating rooms for contrast visualisation of tissues, etc.

In this row, the controllable museum lighting seems to be an important and interesting field, development of which requires cooperation of developers and museum workers.

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REFERENCES

1. Whitaker, T. LED lights illuminate paintings in London’s National Gallery // LEDs magazine, 2011, June, p. 9. URL: http://ledsmagazine.com/news/8/4/13.

2. Philips Sheds New Light on Night Watchat the Rijksmuseum // LED professional, 2011, # 28, p.5.

3. Hurni, Ch.A., David, A., Krames, M.R. et al. Bulk GaN flip-chip violet light-emitting diodes with optimized efficiency for high-power operation //Appl. Phys. Lett. 2015, Vol. 106, # 3, p. 031101.

4. Cree: First to Break 300 Lumens-Per-Watt Barrier. URL http://cree.com/News-and-Events/Cree-News/Press-Releases/2014/March/300LPW-LED-barrier.

5. Cree’s MK-R LED Offers up to 200 Lumen-Per-Watt // LED professional Review. 2013, V. 35, p. 6.

6. Specifications for the Chromaticity of Solid State Lighting Products. ANSI/NEMA C78.377–2008.

7. Mirhosseini1, R., Schubert, M.F., Chhajed, S., Cho, J., Kim, J.K., Schubert, E.F. Improved color rendering and luminous efficacy in phosphor-converted white light-emitting diodes by use of dual-blue emitting active regions // OPTICS EXPRESS, 2009, Vol. 17, # 13, p. 10806.

8. Schubert, E.F., Kim, J.R. Solid-State Light Sources Getting Smart // Science, 2005, Vol. 308, # 5726, pp. 1274–1278.

9. Zakgeim Alexander L. Light-emitting Diode Illumination Systems: Energy Efficiency, Visual Perception, and Safety for Health (Review)// Light & Engineering Journal, 2013, Vol.21, #2, pp.25–40.

10. Shur M.S. Zukauskas A. Solid-State Lighting: Toward Superior Illumination // Proc. of the IEEE, 2005, Vol. 93, # 10, pp. 1691–1703.

11. Eduard M. Gootzait, Alexander L. Zakgeim, Lev M. Kogan, Vladimir E. Maslov, and Soschin Naum P. Concerning Simulation of Standard Light Sources Using Light-emitting Diode Modules// Light & Engineerig Journal, 2013, Vol.21, #4, pp.75–80.

12. URL http://seoulsemicon.com/en/technology/SunLike/.

13. Nina Carli, Armin Sperling, and Grega Bizjak “Optimization Methods for Spectral Synthesizing of a Tuneable Colour Light Source”// Light & Engineering Journal, 2018, Vol. 26, #3, pp.99–108.

14. Zukauskas, A., Vaicekauskas, R., Ivanauskas, F., Gaska, R., Shur, M.S. Optimization of white polychro-

matic semiconductor lamps // Appl. Phys. Letters, 2002, Vol. 80, # 2, pp. 234–236.

15. Zukauskas, A. et al. Quadrichromatic white solid-state lamp with digital feedback // Proc. of SPIE2004, Vol. 5187, pp. 185–198.

16. Ohno, Y. Spectral design considerations for white LED colour rendering // Optical Engineering, 2005, Vol. 44, # 11, pp. 11302–1 – 11302–9.

17. Bulashevich K.A., Kulik A.V., Karpov S. Yu., Chernyakov A.E., Aladov A.V., Talnishnikh N.A., Sackheim A.L. Optimisation of Colour Mixture for Adjustable Solid Light Sources // Abstracts of the Reports of the 10th All-Russian Conference “Nitrides of Gallium, Indium and Aluminium – Structures and Devices”, Saint Petersburg, 2015, pp. 12.

17. Bulashevich K.A., Kulik A.V., Karpov S. Yu., Chernyakov A.E., Aladov A.V., Talnishnikh N.A., Zakgeym A.L. Optimizatciia semshcheniia tsvetov dlia perestraivaiemykh tverdotel’nykh istochnikov sveta //Tezisy dokladov desiatoi Vserossiyskoi konferencii “Nitridy gallia, indiia i alumiia – struktury i pribory. S-Pb, 2015, pp. 12.

18. URL http://www.osram-os.com/osram_os/en/company/index.jsp.

19. Aladov A.V., Valyukhov V.P., Zakgeim A.L., Chernyakov A.E., Tsatsulnikov A.F. Dynamically Controlled LED Lights Sources for New Lighting Techologies // Scientific and Technical Bulletin of SPbPU. Physics and Mathematics. 2014, Issue 4 (204), pp. 38–47.

19. Aladov A.V., Valyukhov V.P., Zakgeim A.L., Chernyakov A.E., Tsatsulnikov A.F. Dinamicheski upravliaemyie svetodiodnyie istochniki sveta dlia novykh tekhnologiy osveshcheniia // Nauchno-tekhnicheskiie vedomosti SPbPU. Fiziko-matematicheskiie nauki. 2014, Issue 4 (204), pp. 38–47.

20. ZigBee and IEEE802.15.4. Wireless Networks. Yu. Semenov (ITEP-MIPT): http://book.itep.ru/4/41/zigbee.htm.

20. ZigBee i IEEE802.15.4. Bespovodnyie seti. Yu. Semenov (ITEP-MIPT).: http://book.itep.ru/4/41/zigbee.htm.

21. Aladov A.V., Valyukhov V.P., Dyomin S.V., Zakgeim A.L., Chernyakov A.E., Tsatsulnikov A.F. Wireless Networks of Controllable Energy-Efficient LED Light Sources // Scientific and Technical Bulletin of SPbPU. Physics and Mathematics, 2015, Issue 1 (213), pp. 50–60.

21. Aladov A.V., Valyukhov V.P., Dyomin S.V., Sackheim A.L., Chernyakov A.E., Tsatsulnikov A.F. Besprovodnyie seti upravliaemykh energoeffektivnykh svetodiodnykh istochnikov osveshcheniia // Nauchno-tekhnicheskiie vedomosti SPbPU. Fiziko-matematicheskiie nauki. 2015, Issue 1 (213), pp. 50–60.

22. URL http://artholtn.ru/exhibitions/2016/dina-rubina-okna.

23. Aladov A.V., Sackheim A.L., Mizerov M.N. On Capabilities of Application of Smart LED Light Sources for Museum Lighting // Architecture and Construction. 2012, Issue 2–3 (13–14), pp. 2–6.

23. Aladov A.V., Zakgeim A.L., Mizerov M.N. O vozmozhnosti primeneniia intellektual’nylh svetodiodnykh istochnikov sveta dlia nuseinogo osveshcheniia // Arkhitektura i stroitel’nyie nauki. 2012 Issue 2–3 (13–14), pp. 2–6.

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