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WIRELESS NETWORKS OF ENERGY EFFICIENT DYNAMICALLY CONTROLLED LED SOURCES

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The paper presents the results of development and practical implementation of wireless networks of controlled spectrally tunable light emitting diode (LED) light sources using RF transceivers operating in the unlicensed frequency bands of 868 and 2400 MHz. Such sources allow synthesizing either a white light with various color temperatures or a colored light with different tints; they are of significant interest in connection with general lighting and with some special applications. The problems of practical realization of light sources and their optimization with respect to luminous efficiency, dynamic range and the distance of wireless control have been investigated.

Key words: LED; dynamic control; ISM and ZigBee technologies; PCB antenna

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БЕСПРОВОДНЫЕ СЕТИ ЭНЕРГОЭФФЕКТИВНЫХ, ДИНАМИЧЕСКИ УПРАВЛЯЕМЫХ СВЕТОДИОДНЫХ ИСТОЧНИКОВ

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Приведены результаты разработки и практической реализации беспроводных сетей управляемых, спектрально перестраиваемых светодиодных источников освещения, приемопередатчики которых действуют в нелицензирумых диапазонах 868 и 2400 МГц. Подобные источники, позволяющие синтезировать либо белый свет в широком диапазоне световых температур, либо окрашенное излучение различных цветовых оттенков, представляют большой интерес как для общего освещения, так и для ряда специальных применений. Рассматриваются вопросы практической реализации источников света и их оптимизации по световой отдаче и динамическому диапазону по дальности радиоканала управления.

Ключевые слова: светодиод; динамическое управление; технология ISM; технология ZigBee; радиочастотный приемопередатчик; антенна

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Introduction

Light emitting diodes (LEDs) due to their technical and economic advantages (low power consumption, a long service life and low service costs, a small size, the absence of hazardous IR and UV radiation, ease of disposal) are the leading contenders for future light sources. Currently, when the world-leading manufacturers such as Nichia, Cree, Philips, Lumileds and Osram have all achieved a very high level of luminous efficiency of 150 – 200 lm/W in their mass-produced LEDs, the quality of generated light becomes increasingly important [1, 2]. Lighting systems have to be capable of generating light with a wide range of color temperatures (2700 – 6500 K) and with a high color-rendering index. To satisfy the modern requirements to high-quality lighting, the average color-rendering index R_a must be more than 95, and special color-rendering indexes $R_8 - R_{14}$ must be no less than 85 [3, 4].

Another important property of lighting is its controllability, i.e., the possibility to change its spectral and color parameters. The ability to control the spectrum and color expands functionalities of light sources. It also changes the approaches to solving many lighting problems, from general lighting, including street lighting, comfortably mixed and room lighting, to special tasks like medicine, especially surgery, agricultural technology, exterior architectural and museum lighting [5 – 7]. The control range may be variable, from small variation of color temperature with time to production of a large gamut of natural colors including millions of colors.

This paper presents the results of practical implementation of wireless networks of energy efficient, dynamically controlled LED light sources for illumination of living, communal and industrial quarters with the capability to regulate color, spectral and brightness lighting characteristics with time and creation of an optimal lighting environment, including:

Imitation of natural light (inside windowless rooms) with a gradual change in the color temperature during the day thus matching the biological cycles, especially in winter when there is a lack of natural light;

Creation of special lighting conditions to increase the efficiency, attention and concentration of personnel working under pressure and to provide relaxation and relief of the nervous pressure;

Museum lighting to provide art exhibitions with better conditions of color perception of paintings and to create comfortable lighting conditions for appreciation of works of art;

Lighting systems for child care and medical establishments.

The LED light sources described above produce white light with the required spectral, color and brightness characteristics using the principle of RGBW color-mixing: controlled polychromatic LED light source (CPLLS) and energy-efficient dynamically controlled LED light sources (EDCLLS) [8]. Most European wireless equipment operates at 2.4 GHz, however, 868 MHz is used for some narrow-band and wide-band application, such as street light control, social alarm, generic alarm and non-specific SRDs.

Practical implementation of CPLLS and EDCLLS networks

The wireless CPLLS and EDCLLS networks contain the following components: terminal devices (lamps) with LED light sources playing their role; a remote control station (RCS) which coordinates the network and controls its operation in all modes; a PC that also serves as a network coordinator when setting up the network and for some modes of its operation.

The CPLLS and EDCLLS devices themselves incorporate the following components: a main power supply; a power supply for the standby mode; a microcontroller with a control board including a wireless link; LED drivers for power management; LED bars with series-connected LEDs.

Main characteristics of CPLLS

The problem of optimal color mixing in order to provide white light with the required color temperature and concurrently to achieve a good compromise between the luminous efficiency and color-rendering index was investigated in Ref. [9, 10]. One of the main results of this work can be briefly formulated as follows: given the typical half-width of the color spectra of semiconductor light sources $\Delta\lambda_{0.5} \approx 15 - 40$ nm creation of white light with the high color rendering index $R_a > 95$ require extra radiation of 4 – 5 semiconductor light sources with various peak light wavelengths λ_{peak}, relatively uniformly spread over the whole visible region. Even denser filling of the black-body radiation spectrum by adding auxiliary LEDs does not improve the CRI but leads to a decrease in luminous efficacy and an increase in complexity. At the same time, even a small deviation of the peak light wavelength of any of the LEDs from the optimal value can result in a sharp decrease in some of the color rendering indexes, especially $R_8 - R_{14}$, related to highly saturated colors. The problem can be solved by using luminophore-based LEDs which exhibit a wider spectrum of $\Delta\lambda_{0.5} \approx 70 - 100$ nm.

The key element of a light source is a polychromatic LED module [11] consisting of six light-emitting diodes with the wavelengths of 460±5, 490±5, 510±10, 530±10, 560±10 and 630±10 nm. Four such modules are connected in series. The spectra of the selected LEDs are shown in Fig. 1.

It is important to note that each color temperature T_c requires adding only four bands. Six-band LED module was selected to achieve universality by covering a wider band of T_c and accentuating some colors for special lighting conditions (for microscopy, surgery, museums).

CPLLS provides the color temperature range 2700 – 6500 K, the light intensity from 1700 to 2400 lm and high values of the color-rendering indexes not less than 80 – 90. The power used by the source is less than 20 W (18.4 W), the luminous efficacy from 85 to

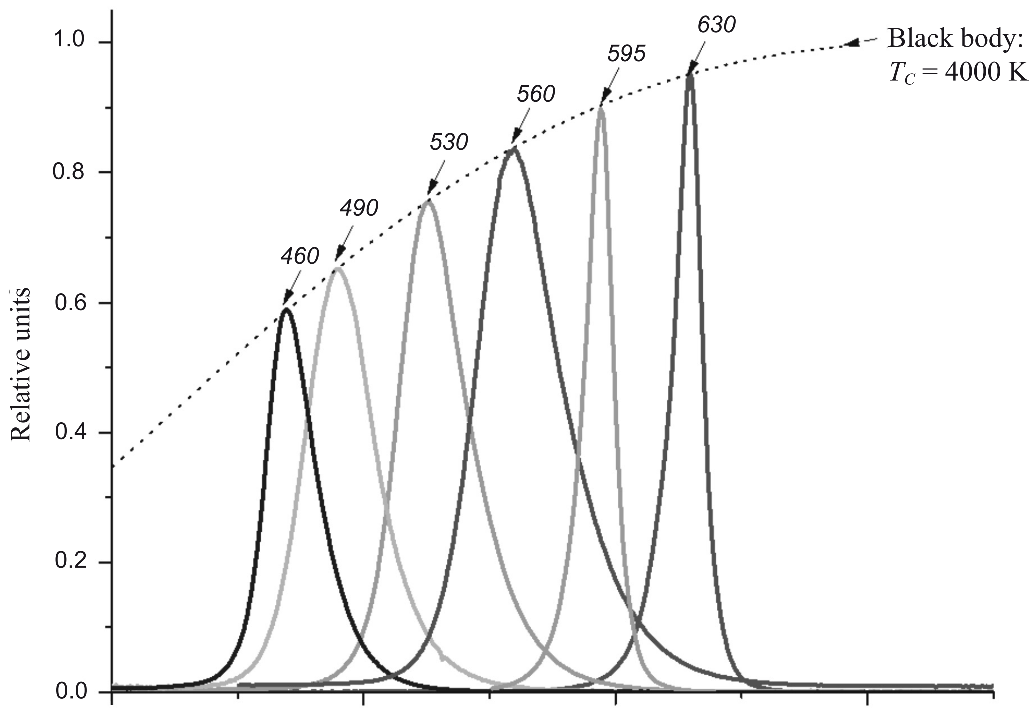

Fig. 1. Spectral distributions of 6 LEDs used in color mixing; the envelope is the black-body spectrum at T_c = 4000 K (shown by a dotted line)

120 lm/W. Six drivers transform the constant current from a power supply to the LED's feed current with pulse width modulation (PWM). The total supply current is no more than 1 A. The PWM frequency was set by a microcontroller within a range of 1.25 – 10 kHz and the duty cycle of PWM varied from 100 to 1 (from 1 to 100 % PWM). The brightness was varied by increasing the PWM period relative to the brightness at the optimal PWM frequency (F_{opt} = 2.5 kHz) corresponding to 100 % light intensity of the LED unit. At 10 % light intensity the PWM period corresponds to 250 kHz frequency. This improves the speed of CPLLS and is higher than the 100 Hz threshold sensitivity of the human eye to the modulation of brightness.

RCS operating in the 868.7 – 869.2 MHz band that can be used with narrow- or wideband (NB or WB) frequency modulation, has the transmitter effective radiated power (ERP) of 25 mW (+14 dBm) and the duty cycle less than 0.1 %. The receiver category is defined by ETSI EN 300-220-1.

A microcontroller receives commands from an RF transceiver using the SPI interface, controls the current drivers for LEDs and turns the light source on and off. The same transceiver chip CC1110FX is used in the microcontroller board and in the RCS. The chip is a low-power SoC (System-on-Chip) ISM/SRD with MCU, Memory, USB controller and high sensitivity (–110 dBm at 1.2 kBaud and –87 dBm at 250 kBaud). The receiver has high selectivity and a good blocking performance, the programmable data rate up to 500 kBaud and the output power up to 10 dBm, the low current consumption (RX: 16.2 mA @ 1.2 kBaud, TX: 15.2 mA @ –6 dBm). There are two power saving modes: Power Mode 1 (0.8 μA) and Power Mode 2 (0.6 μA). The CC1110FX uses the GFSK (Gaussian Frequency-Shift Keying) modulation.

The CC1110 chip is compatible with many PCB mounted antennas including a DN024 antenna used in the RCS and a microcontroller unit as a transmitting and receiving antenna, respectively. An RCS controls the CPLLS according to the program entered by the operator manually after pressing the 'on' button and setting the color temperature using the light intensity control button. In standby mode the CPLLS power consumption is less than 0.5 W.

The CPLLS network has a star topology. The RCS serves as the network coordinator and the light sources are terminal devices.

Each RCS has a unique address that is set during manufacturing. If any button on the RCS is pressed, then a light control command is sent. This command contains the RCS address. Each light source is programmed to work with only one RCS. The number of light sources can be quite large.

Main characteristics of EDCLLS

For the EDCLLS network realized the most promising technology using the LR-WPAN (Low-Rate Wireless Personal Area Network) devices is based on the IEEE 802.15.4 standard and on the accompanying higher layer ZigBee standard [12, 13]. The IEEE 802.15.4 standard describes only two lowest networking layers: a physical one (PHY) and a medium access sublayer (MAC), while ZigBee has all seven layers supporting the creation of monitoring and control networks. IEEE 802.15.4 standard has proved to be successful and now many manufacturers produce devices supporting it.

The standard architecture of IEEE 802.15.4 has several layers; each of them is responsible for the realization of one part of the standard and provides its services to the higher layer. LR-WPAN device provides PHY including radiofrequency (RF) transceiver with a low-level control mechanism and MAC provides access to PHY for all types of transmission.

PHY provides information for PHY and the control services, maintaining control functions and supporting a database of controlled objects connected with the defined physical layer. The PHY information service performs transmission and reception of the protocol data units (PDU) via the radio channel.

ZigBee and IEEE 802.15.4 standards require wireless device to implement a duty cycle of no more than 1% of the total operating time that helps to increase the autonomy of devices up to several months or years. The devices supporting IEEE 802.15.4 standard use a low transmitted power because increasing the power up to more than 10 dBm in a low-cost system-on-chip is economically ineffective. According to the European regulation (ETS EN 800328), transmission with the power higher than 10 dBm may be problematic without additional frequency filtering of out-of-band emissions. Most IEEE 802.15.4 compliant devices exhibit the transmitted power level in the range of −3 – 0 dBm to reduce interference. The transceivers use a frequency band of 2400.0 – 2483.5 MHz that is allowed in the Russian Federation. The Offset Quadrature Phase-Shift Keying (O-QPSK) modulation and Direct Sequence Spread Spectrum (DSSS – a method of transforming a binary sequence into a pseudo-random sequence modulating the carrier frequency) are used. This allows tolerating low values of the signal-to-noise ratio (SNR) and the signal-to-interference one. A typical low-cost receiver achieves a packet error rate (PER) of 1 % and so it requires SNR values from 5 to 6 dB.

The ZigBee devices have one of the lowest power transmitters in combination with the most sensitive receivers of all the competing devices. This combination makes a positive impact of low microwave radiation exposure on people from the ZigBee networks. This is especially important for EDCLLS. In this case manufacturers take into account that devices must provide optimal lighting in the areas of constant human presence. In this regard, the ZigBee technology is particularly attractive for providing ecological safety as compared to all other wireless standards.

The MAC layer maintains the continuity of the MAC information service and the MAC control service. They provide the network control interface and support a database of objects controlled at MAC layer. The MAC information service provides the transmission and the reception of MAC layer protocol units (MPDU) using the PHY information service.

A data transfer model is defined by the network topology. The EDCLLS network uses a star topology with two data transfer modes: a transfer to a network coordinator (a personal computer (PC) or a remote control station (RCS)) and that from a coordinator to a network device.

The EDCLLS is a PAN network without any support for beacons, where the information unit is sent to a coordinator using a domainless scheme CSMA-CA.

An analysis of all color-rendering indexes shows that quite satisfactory results are produced by the four-color color-mixing schemes RGBA and RGBW. A combination of five spectral bands of LED sources is optimal for producing high-quality white light with a wide range of color temperatures: T_c = 2500 – 10,000 K.

A five-color LED module was selected to increase and equalize the color-rendering indexes for each color temperature T_c and to emphasize some colors for special cases of lighting.

The electronic design and the technical specification of the RF channels of the RCS and the control microcontroller of the EDCLLS are identical because the same module, ZigBit 2.4 GHz Single chip Wireless Module ATZB-S1-256-3-0-C [14] supporting the IEEE 802.15.4 standard, is used. The module has high sensitivity (−97 dB at packet error rate 1 %) and the optimal transmitter output power of +3 dBm result in the unique power budget (up to 100.6 dB) of the link. The range of the radio link is 170 – 570 m in the free space if the transceivers are located at a height of 0.5 m above ground. This result is achieved at various combinations of the transceiver's orientations (polarizations) and in the absence of interference from other transmitters. In actual practice, multi-path propagation, interference and other factors can significantly reduce the range of the radio link.

The power consumption of the RCS in the programming mode is less than 5 W and 0.5 W in the control mode.

Since the control of the EDCLLS network by the RCS is continuous, the problem of reducing the standby power is important. The problem was solved by developing a power supply unit for both RCS and EDCLLS transceivers, the latter having a power consumption of 60 – 80 mW during reception and 1 – 5 W in standby mode. Low power levels are due to the low supply current of the ATZB-S1-256-3-0-C microcontroller: they are 9.6 mA, 16.4 mA and 0.6 μA during reception, transmission and standby modes, respectively. The AC/DC converter of the RCS is the same as in an EDCLLS. It uses a UPLNK574 chip and provides ultra-low power consumption during continuous operation.

The power supply of the EDCLLS consists of two modules of 20 W each (40 W total). The modular design is determined by the shape of the EDCLLS's case and allows reducing the power supply's volume and increasing its reliability and electromagnetic compatibility.

The EDCLLS network has three shortened addresses: individual, broadcast and group.

Let us describe the messages sent in the EDCLLS network.

Search for network devices. The network coordinator (PC) sends a request with a broadcast address (with an identification number PAN = 0×FFFF and a device address 0×FFFF). The source (PC) address can be of any number. All EDCLLS devices in return send a packet of data to the network coordinator address. The packet contains the network identification number and the individual EDCLLS device number. The transmission is performed using the domainless CSMA-CA method. The result of the search is a table of all devices within radio link reach.

Control data transmission to an individually selected device. The network coordinator (PC) sends control data to any address within the table. No acknowledgement is required.

Connect a device to a group. Any device after receiving a command to connect to a group containing its address memorizes a network identification number (PC PAN).

Control data transmission to a group address. This message is sent to the 0×FFFE address with no acknowledgement required. The number of individually controlled EDCLLS groups is 65534 (the addresses 0×0000 and 0×FFFF are excluded).

The EDCLLS network software has the following operating modes:

The control of the EDCLLS network (possibly, from the RCS) via a radio link in continuous-operation energy-saving mode;

Programming of individual addresses for each RCS and EDCLLS device during manufacture;

Testing of the EDCLLS devices and setting up a network using a PC with a USB-adapter Atmel ATZB-X -233-USB instead of an RCS;

Programming the RCS from a PC using a USB adapter Atmel ATZB-X 233-USB.

Conclusion

Creating spectrally tunable semiconductor light sources and their application is a complex multidisciplinary task linking several areas of science and technology. New lighting technologies radically improve the ability to control the quality of light, including a time variation of the spectral content, the color, the intensity, the modulation frequency (individual tuning and smart lighting). This work presents two variants of building wireless networks of dynamically controlled polychromatic light sources using the technologies of ISM/SRD and ZigBee (IEEE 802.15.4 standard).

The CPLLS light source has a luminous efficacy in the range of 85 – 120 lm/W, T_c = 2700 – 6500 K, the color rendering index $R_a > 90$. For the RGBW version of this source, a powerful 6-chip module has been developed using AlInGaN and AlGaInP heterostructures. In the EDCLLS the spectral and the color parameters of a 4-color RGBW optical module vary from 2700 K with the color-rendering index CR_1 = 97.17 to 10,000 K with CR_1 = 85.83.

In both light sources the RGB-source parameters are stabilized with respect to intensity, temperature and time using the PWM of the supply current and negative feedback systems based on color sensors. There is a possibility to select two types of color influence: relaxing (T_c = 1700 K) and activating (T_c = 10,000 K). Using these sources, it is possible to create controlled light sources capable of purposefully correcting the psycho-physiological state of the human organism.

A nearly continuous spectrum very close to the natural spectrum of light, exhibiting high values of color-rendering indexes, has been achieved. A combination of hardware and software tools was developed to provide testing, tuning and control of the network in various operating modes.

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