ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2009. No. 8(96)
ELEKTRONIKA IR ELEKTROTECHNIKA

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ELEKTRONIKA

Solid-State Lamp for the Improvement of Nutritional Quality of Leafy Vegetables

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Introduction

Solid-state lighting technology, which is based on narrow-bandwidth light-emitting diodes (LEDs), offers vast possibilities in horticultural lighting [1, 2]. In particular, control of morphogenenesis and productivity of plants can be implemented through tailoring the emission spectrum of semiconductor junctions to the absorption spectrum of phytopigments [3–5]. However, economical constraints (high capital cost of LEDs) result in that solid-state lighting is not widely used for full-cycle plant cultivation so far. Fortunately, the advantages offered by LEDs can be already exploited within a short part of the growth cycle. An example of such an application is short-term pre-harvest treatment of leafy vegetables, such as lettuce, grown under common artificial sources of light (e.g. high-pressure sodium lamps) by intense red light generated by a solid-state illuminator [6]. Such treatment was shown to substantially reduce nitrate concentration in the vegetables and to increase the concentration of nutritionally valuable carbohydrates [7].

In comparison with conventional lamps, LEDs has numerous inherent advantages, such as high efficiency, mechanical robustness, compactness, longevity, fast switching, simple control of the generated flux, low operating voltage, compatibility with computer electronics, narrow-band emission without undesired spectral components, freedom from mercury, etc. However, constructing of a solid-state lamp involves several important issues such as the selection of type of LEDs, as well as the design of power supply, means of heat management, and luminaire. Besides, a particular application, such as greenhouse lighting, poses additional requirements on solid-state lamps, such as high resistivity to humid environment, low thermal radiation directed towards plants, and improved power management through automatic dimming in the presence of sunlight.

Here we present a descripion of a solid-state lamp developed for short-term treatment of plants in order to reduce nitrate concentration within a phytotron or greenhouse by a high-density photosynthetic photon flux.

Design of the lamp

The selection of type of LEDs was based on considerations as follows. First, the LEDs must generate photosynthetic red light, which has the highest capacity in stimulating nitrate reductive activity [7]. The highest efficiency of photosynthesis is attained for wavelengths around 660 nm that match the absorption spectrum of chlorophyll *a*. Such light can be generated by AlGaAs LEDs, which lack radiant efficiency and exhibit reduced operating time under high-temperature and high-humidity conditions, however. Second, single-chip high-power LEDs are preferred for the simplicity of assembling to high-density flux fixtures and improved heat management. Again, such LEDs are not available within AlGaAs technology. Therefore, we made use of red AlGaInP LEDs, which are widely used in traffic lights and other signage. Although the peak wavelength of such LEDs is somewhat shorter than that of the absorption peak of chlorophyll *a*, high photosynthetic rates in plants are still preserved [4]. Also, AlGaInP technology is used for the manufacturing of high-power chips with the operating time in excess of 50,000 hours. Therefore, we made our selection in favour of on this type of LEDs. In particular, we used PHILIPS LUMILEDS LIGHTING Luxeon-III series LXHL-LD3C type red LEDs with the highest available rated flux and driving power of 3 W. These LEDs have the peak wavelength $\lambda \approx 638$ nm at the junction temperature of 25 °C with the temperature coefficient of about 0.13 nm/K. The LEDs are supplied already mounted on individual aluminium-core PCBs that are handy to assemble on a heat sink.

The block diagram of the lamp circuitry is presented in Fig. 1. The lamp features a luminaire and a driver that cosistes of a standard switch-mode AC/DC voltage converter (SIEMENS Sitop power flexi model 6EP1353-2BA00) with the built-in voltage regulation circuit and two feedback loops. One feedback loop is used for photoelectric regulation in order to maintain a constant photosynthetic photon flux density.

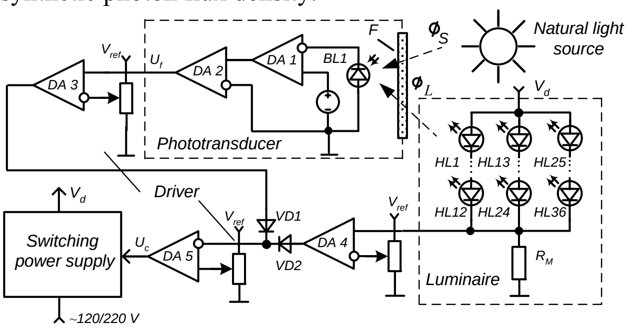

Fig. 1. Block diagram of the solid-state lamp. The voltages indicated are the photo-transducer output voltage (U_f), power source control voltage (U_c), reference voltage (V_{ref}), and LED power source output voltage (V_d)

Another feedback loop is used for the protection of the LEDs from excess current. The two feedback loops are switched by a diode-based commutator.

The photoelectric feedback loop consists of a phototransducer and a control unit. The phototransducer contains a light-to-voltage converter Burr-Brown model OPT 101 (photodiode BL1 with operational amplifier DA1) and operational amplifier DA2. The photodiode is equipped with an optical filter F with the optical transmittance spectrum tailored to the spectral sensitivity of the photodiode in such a way that the output voltage of the phototransducer is almost proportional to the density of the net photosynthetic photon flux density Φ_A. The latter is the sum of the flux density generated by the lamp Φ_L and that due to sunlight Φ_S. The control unit consists of an operational amplifier DA3 that is biased using a potentiometer connected to a source of reference voltage V_{ref}. The bias voltage is preset to equal the voltage at the output of the phototransducer to that corresponding to a required magnitude of the photosynthetic photon flux density.

Fig. 2 depicts a typical spectrum of the photo-syntetic quantum action of plants (1), spectral power of solar irradiance at the sea level (2), spectral power of the LEDs used (3), and spectral sensititivity of the photo-transducer with the optical filter taken into account (4).

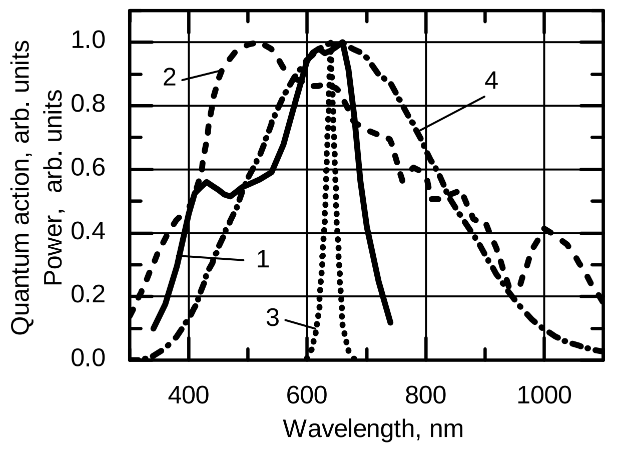

Fig. 2. Typical spectrum of photosyntetic quantum action of plants (1); spectral power of solar irradiance at the sea level (2); spectral power of the LXHL-LD3C LED output (3); phototranducer sensitivity spectral distribution (4).

The protective feedback loop contains a measuring resistor R_M and an operational amplifier DA4. The measuring resistor is connected in series with the LED strings and the voltage drop across the resistor is proportional to the current flowing through the strings. The amplifier is biased by a voltage equal to the voltage drop across the measuring resistor when the current flowing through the LED strings is of highest permissible magnitude.

The feedback loop commutator, which consists of silicon diodes VD1 and VD2 and a follower operational amplifier DA5, switches between the two loops depending of which of those has a higher output voltage. The driving circuit persists in maintaining a constant net photosynthetic photon flux density by the first feedback loop until the output current attains the highest permissible magnitude. Simultaneously, the drift of the lamp output due to the variation of LED junction temperature and aging is compensated. Once the highest permissible current is attained, the control is passed to the second loop and the driver starts operating in the current regulator mode.

The luminaire contains 36 LEDs HL1–HL36 that are connected into three parallell strings, each having 12 LEDs.

An example of the lamp is shown in Fig. 3a. It consists of the heat sink with the LEDs mounted on it and the driving unit attached to the tail of the heatsink. A plastic waveguide probe is used for directing a part of the net irradiance to the photo transducer.

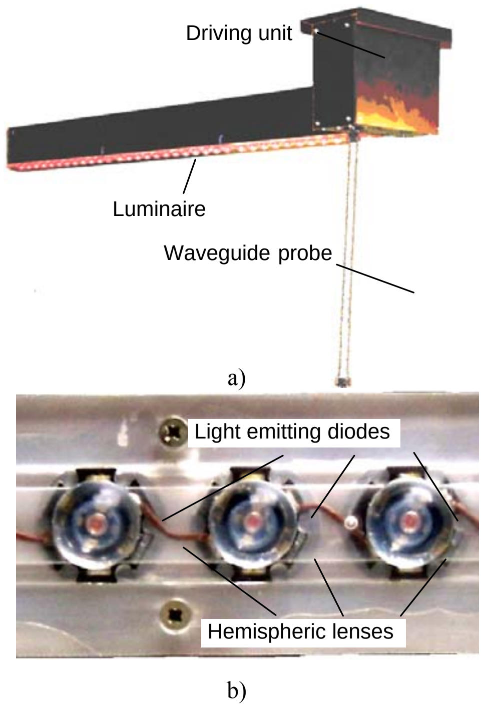

Fig. 3. Overall view of the lamp (a); part of the bottom view (b)

The LEDs are mounted on an aluminum rail type heatsink with vertical ribs directed upward. The surface of the ribs is processed to have a high value of thermal radiation factor and the ribs are perforated to ensure convection. The bottom face of the heatsink the LEDs are mounted on is polished to have a low value of thermal radiation factor. Such a design of the heatsink allows for minimizing thermal radiation directed towards plants.

The LEDs are protected against humid environment by a translucent polycarbonate lid with hemispherical lenses. The gap between the lenses and LED domes is filled with translucent silicon rubber in order to maximize optical coupling. Such a design makes cleaning from dust and insect contamination easy.

Fig. 3b shows a fragment of the bottom face of the luminaire with the polished surface, mounted LEDs, wiring, translucent plastic lid, and hemispherical lenses exposed.

An industrial prototype of a greenhouse illuminator is shown in Fig. 4. The illuminator, which contains ten solid-state luminaires described above and a common photo-transducer for the control of the net flux density, is installed in a greenhouse of the Lithuanian Institute of Horticulture (Babtai, Kaunas district).

Fig. 4. Solid-state illuminator installed in the greenhouse

Typically after attaining technical maturity under daylight with supplementary lighting provided by standard high-pressure sodium lamps, leafy vegetables, such as lettuce, spinach, celery, marjoram, and green onions, are moved to a harvesting terminal, where they are treated under the solid-state illuminator for three days with a photoperiod of 18–24 hours. Such a treatment results in the reduction of nitrate concentration by 2–3 times and in an increased concentration of nutritionally valuable carbohydrates [6, 7].

Main characteristics of the lamp

The main characteristics of the developed lamp are as follows:

Operating wavelength, nm 640

Maximal photosynthetic photon flux density generated at a distance of 30 cm, μmol m^{-2} s^{-1} 300

Size of the radiation pattern at a distance of 30 cm for 80% level, cm^2 .... 80×70

Accuracy of the net photosynthetic photon flux density regulation, % 5

Power consumption of a single lamp, W 120

Lamp bottom surface area, cm^2 ....4.5×100

Lamp length, cm 100

Number of lamps in the illuminator 10

Fig. 5 shows the results of an experiment for testing the photosynthetic photon flux regulation. When the ambient flux density is increased from about 2 to 35 μmol m^{-2} s^{-1} (1), the generated flux is seen to drop from about 44 to 9 μmol m^{-2} s^{-1} (2) in such a way that the variation of the net flux density does not exceed 5% (3). This is confirmed by an almost stable output voltage of the photo transducer (4).

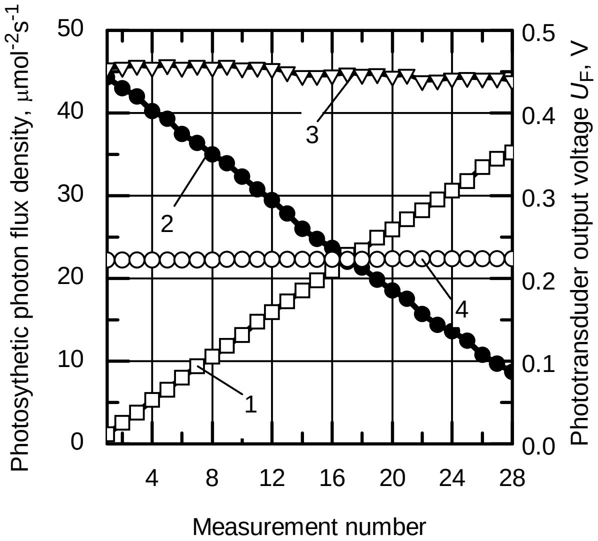

Fig. 5. Dependence of the net and generated photosynthetic photon flux density on the ambient flux density: ambient flux density (1); generated flux density (2); net flux density (3); phototrasducer output voltage (4)

Fig. 6 shows the distribution of the photosynthetic photon flux density in the plane at a distance of 30 cm from the lamp (typical distance from the lamp to the treated plants).

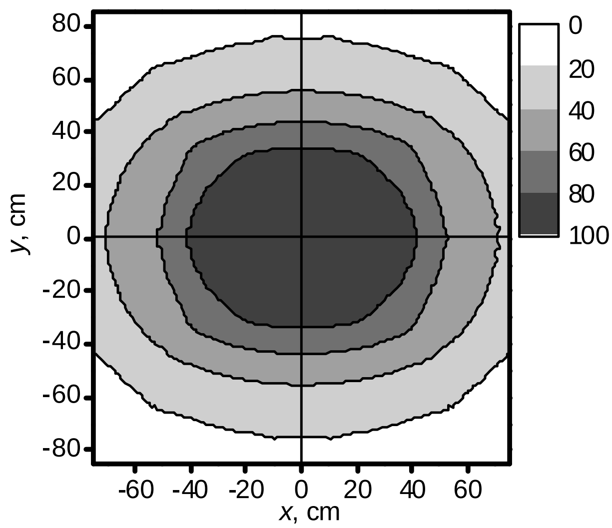

Fig. 6. Radiation pattern of the photosynthetic photon flux density at a distance of 30 cm distance from the lamp

The radiation pattern is seen to have an elliptical shape with the dimensions of about 80 cm in the longitudinal direction and 70 cm in the tranverse direction for the irradiance level constituting 80% of the peak one (300 μmol m^{-2} s^{-1}). This data can be used for the estimation of the spacing between lamps when assembling large-area illuminators, such as that shown in Fig. 4.

Summary

A solid-state lamp for treatment of plants by a high-density photosynthetic photon flux was developed. The lamp features high-power red AlGaInP LEDs, a switch-mode power supply with photoelectric regulation, a heat sink with the minimized thermal radiation directed toward plants, and a protective lid, which allows for the operation in humid environments. Such lamps can be assembled into large-area illuminators for using in cost-efficient improvement of nutritional quality of leafy vegetables through reduction of nitrate concentration by short-term pre-harvest treatment.

Acknowledgment

The work was supported by the Lithuanian State Science and Studies Foundation.

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Received 2009 05 29

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A solid–state lamp for the reduction of nitrate concentration by shotr–term pre–harvest treatment of leafy vegetables is described. The lamp contains 36 3–W light–emitting diodes (LEDs) operating at a wavelength of 640 nm that generate a photosynthetic photon flux density of up to 300 μmol m^{-2} s^{-1}. The lamp is driven by a switch–mode power supply with a dual feedback, which allows for dimming in the presence of sunlight, compensating the output drifts, and protecting the LEDs from excess current. The luminaire of the lamp was designed to withstand humid environment and to avoid exposing the plants to thermal radiation. A greenhouse lighting facility containing 10 lamps with a common photoregulator was demonstrated. Ill. 6, bibl. 7 (in English; abstracts in English, Russian and Lithuanian).

З. Близникас, К. Брейве, А. Новичковас, П. Витта, А. Жукаускас, П. Духовскис. Твердотельная лампа для повышения пищевого качества листовых овощей // Электроника и электротехника. – Каунас: Технология, 2009. – № 8(96). – С. 47–50.

Описана полупроводниковая лампа для уменьшения концентрации нитратов в листовых овощах. Это осуществляется кратковременной обработкой зрелых овощей фотосинтезным потоком высокой плотности. Лампа содержит 36 светодиодов (мощность каждого 3 Вт), которые создают поток фотонов плотностью до 300 мкмол/$м^2$с и с длиной волны 640 нм. Лампа питается от импульсного источника напряжения, который управляется двухконтурной обратной связью. Первый контур обеспечивает фотоэлектрическую стабилизацию потока с учетом внешней освещённости и изменения потока из-за нагрева диодов и их старения, а второй контур обеспечивает защиту диодов от токовой перегрузки. Лампа приспособлена для эксплуатации в условиях влажной среды теплиц, а ее осветитель изготовлен так, что тепловое излучение светодиодов направлено в сторону от растений. Изготовлена осветительная система с 10-ю лампами, фотоэлектрическая стабилизация потока которых осуществляется от общего фотоэлектрического преобразователя. Ил. 6, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

Z. Bliznikas, K. Breivė, A. Novičkovas, P. Vitta, A. Žukauskas, P. Duchovskis. Kietakūnė lempa lapinių daržovių maistinei kokybei gerinti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 8(96). – P. 47–50.

Aprašyta kietakūnė lempa, skirta nitratų koncentracijai lapinėse daržovėse mažinti prieš nuėmimą trumpai apdorojant jas didelio tankio fotosinteziniu srautu. Lempą sudaro 3 W elektrinės galios šviesos diodai (36 vnt.), kurie sukuria iki 300 μmol m^{-2} s^{-1} tankio 640 nm bangos ilgio fotonų srautą. Lempa maitinama iš impulsinio įtampos šaltinio, kuris valdomas dviejų kontūrų grįžtamuoju ryšiu. Pirmasis kontūras skirtas fotoelektrinei srauto stabilizacijai, atsižvelgiant į aplinkos apšvietą ir šviesos diodų srauto pokyčius dėl senėjimo ar kaitimo, o antrasis kontūras skirtas jų apsaugai nuo srovės perviršio. Lempos šviestuvas pritaikytas darbui drėgnoje šiltnamių aplinkoje ir pagamintas taip, kad nekaitintų augalų. Yra sukurta apšvietimo sistema su 10 tokių lempų, kurioje fotoelektrinė srauto stabilizacija atliekama naudojant vieną bendrą fotoelektrinį keitiklį. Il. 6, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).