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STUDY OF CHARACTERISTICS OF LEDS FOR PHYTOIRRADIATORS

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ABSTRACT

The present study comprises comprehensive research of red, green and blue light emitting diodes (LED), which are widely used in phytoirradiators for plant growing in protected ground in the environment of a photo-culture including their spectrum measurements within the wide range of current values at room temperature. Shifts of spectral peaks of radiation of red and green LEDs after increase of operating current were discovered. On the basis of the conducted study, recommendations for selection of current operating mode of light sources used in phytoirradiators for plant growing in the environment of photo-culture were worked out, and a model of a phytoirradiator was proposed and studied in this work with red, green and blue LEDs, which have their spectrum covering all regions of photosynthetic active radiation (PAR).

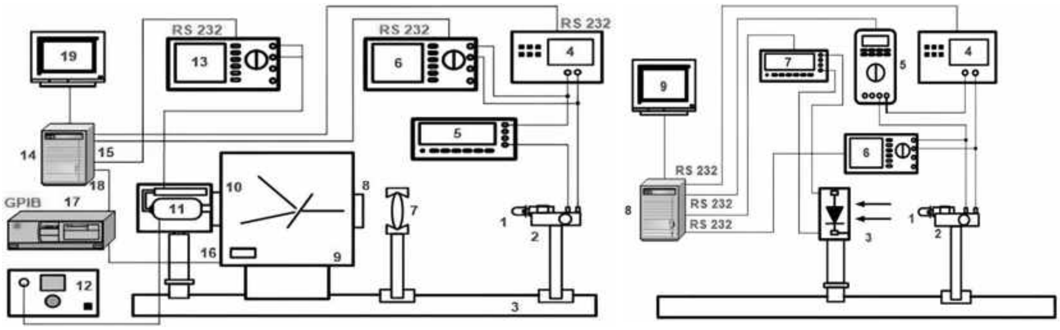
Keywords: light emitting diode, LED, phytoirradiator, protected ground facility, greenhouse, plant, photo-culture

1. INTRODUCTION

Optical radiation has been increasingly used today in processing in industry and agriculture, becoming an inherent part of chemical plants, and playing an important role in kettle and poultry breeding, and greenhouse cropping [1–3].

The effects of visible spectrum radiation on plants were studied by many authors (see, for instance, [3, 4]). In [4], the effect of illuminance and chromaticity of the radiation on efficiency of photosynthesis and productivity of plants with special pigments such as chlorophyll-*a,* chlorophyll-*b*, carotenoids, and etc. responsible for light absorption, was studied. Chlorophylls absorb blue and red radiation spectral range whereas carotenoids absorb blue and green light. The radiant energy absorbed by different pigments is used for development of the root system, ripening of seeds, blossoming, etc. The other parts of the spectrum, except for the amber one, are almost not used by plants [3, 5, 6].

Greenhouses farms do not represent cutting-edge technologies; however, in conditions of constantly growing population of the Earth and pursuance of stable, highly-efficient and standardised production of food, they will become a norm in the future establishing a new large sector of agricultural industry. Rapid development of LED technologies has become one of the most important achievements defining the future of protected ground facilities and practicability of their construction [3]. Contemporary light emitting diodes (LED) allow developing of illumination and irradiation devices that have required chromaticity of radiation and are extremely resistant to harsh conditions of environment, and relatively small-sized as compared to other types of illumination and irradiation devices. Moreover, they have rather large service life, are distinctive



a) *b)*

Fig. 1. The scheme of the experimental installation:
a) LED radiation spectra measurement installation
1 – LED; 2 – adjustable LED holder; 3 – optical bench; 4 – power supply unit; 5 – ammeter; 6 – voltage meter; 7 – collimator lens; 8 – entrance slit; 9 – *SPM-2* prismatic monochromator; 10 – exit slit; 11 – PMT; 12 – PMT power supply unit; 13 – voltage meter; 14 – control unit; 15 – management port; 16 – stepper motor; 17 – computer; 18 – stepper motor management port, 19 – screen;
b) The installation for measurement of dependence between LED radiant intensity and current
1 – LED; 2 – adjustable LED holder; 3 – photoelectric detector; 4 – power supply unit; 5 – ammeter; 6 – voltage meter; 7 – control unit; 8 – computer; 9 – screen

with low operating voltage, and relatively low heat losses [7].

The purpose of this work is formation of the basis for selection of LEDs for application in phytoirradiators for growing plants in protected ground facilities in environment of photo-culture. In order to reach this goal, the task of studying spectral characteristics of red, green and blue light LEDs, explaining their spectral characteristics behaviour as well as modelling a phytoirradiator operating within the whole region of photosynthetic active radiation (PAR) and, not least importantly, with an adjustable radiation spectrum, was set.

These studies represent one of the directions currently taken which is based on application of coloured (monochromatic) LEDs for use in phytoirradiators. Selection of samples of three wavelength regions, blue, red and green, is based on it.

2. EXPERIMENT METHODOLOGY

The characteristics of red, blue and green LEDs were studied using an automatic experimental set based on a *SPM-2* spectrometer. This set, with its scheme shown in Fig. 1, allows us to measure LED radiation spectra within a wide range of current values as well as dependences between LED radiant flux and current. Red, green and blue LEDs with their crystals grown using the gaseous epitaxial method on the basis of organ metallic compounds were the study subjects. Approximate crystal dimensions in the studied LEDs are (0.350×0.350) mm. The crystals were mounted in a metal-base reflector with approximate area of 1.0 cm^2. Such base reduces heat-transfer resistance of LED and allows increasing of operating current. The structure of the base comprises metal pins for mounting and electrical connection of LED. The area of the reflector is filled with a polymer-based optical gel, which increases the radiation coupling-out ratio of a crystal. On top, the body of LED is closed by a polycarbonate lens which allows formation of a light distribution curve with angle of approximately 30°. Around the crystal, the optical gel creates an environment which does not cause large mechanical load on it and allows small deflections due to heat expansion. This is increasing the threshold value of current through the small-size crystal up to values exceeding 150 mA. The structure and production technology of the studied LEDs is rather typical for this type, which allows us to use the obtained results as a basis for approximation for other types of LED.

3. EXPERIMENTAL RESULTS

In the course of the work, the radiation intensity spectra of the studied LEDs at different values of current within the range of 5 mA up to 120 mA were measured in arbitrary units; typical examples of the spectra are given in Figs. 2–4.

In the case of red LED (Fig. 2), shift of the peak of relative spectral distribution of radiant flux to the long-wave region by approximately 20 nm can be observed after increasing current from the re-

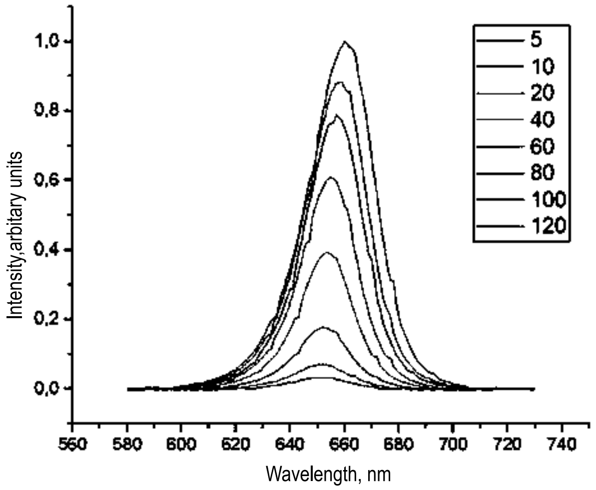


Fig. 2. Typical spectra of red LEDs at different values of current (the digits in the figure stand for values of current in mA)

gion approximately corresponding to wavelength of 650 nm to the region corresponding to wavelength of 670 nm. Such shift is typical for structures based on gallium phosphide and its solid solutions emitting red and yellow light [8].

In the case of green LED (Fig. 3), the shift of the peak can also be observed after increase of current. In this case, the peak shifts to the short-wave region approximately by 10nm from the wavelength region approximately corresponding to wavelength of 530 nm to the region corresponding to wavelength of 520 nm. Such a shift of the peak of radiation spectrum is rather typical for hetero-structures based on gallium nitride and its solid solutions emitting green light [9–12].

In the case of blue LED spectrum (Fig. 4), the shift of the peak with increase of current almost cannot be observed at all considered values of current, the peak wavelength of intensity spectral distribution is located in the region approximately corresponding to wavelength of 470 nm. Non-availability of the shift of peak wavelength of intensity spectral distribution after increase of current is also rather typical for crystals based on gallium nitride and its solid solutions emitting blue light [9–12].

Non-availability of the shift of peak wavelength of intensity spectral distribution in blue LEDs after current increase may be associated with more homogeneous structure of active region of blue LED crystals due to less indium content and, therefore, less dependence between recombination energy of media and temperature.

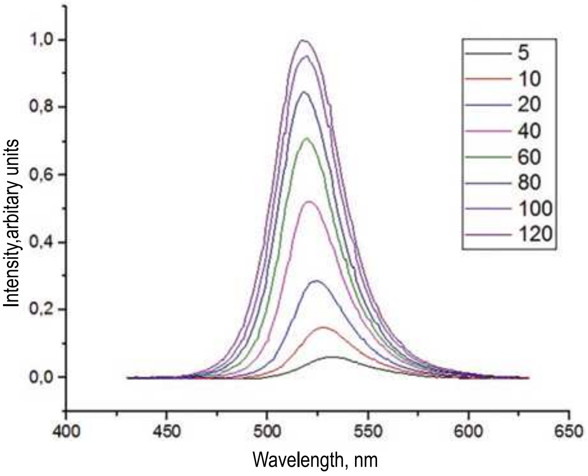


Fig. 3. Typical spectra of green LEDs at different values of current (the digits in the figure stand for values of current in mA)

The graphs of dependence between LED intensity and current (Figs. 5–7) show that red LEDs intensity at values of current are less than (35–40) mA increases in linear fashion with increase of current. With further increase of current approximately up to 60 mA, intensity continues to increase; however, the speed of its increase is reducing. At currents less than (70–80) mA, the increase of radiant intensity with increase of current gradually ceases, and the dependences between intensity and current level are saturated at current of about 120 mA or higher.

The similar nature of the dependence between intensity and current is observed for green (Fig. 6) and blue (Fig. 7) LEDs. At values of current of less

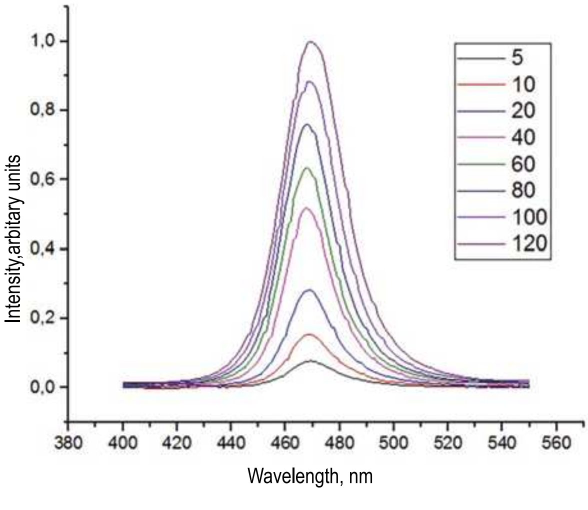


Fig. 4. Typical spectra of blue LEDs at different values of current (the digits in the figure stand for values of current in mA)

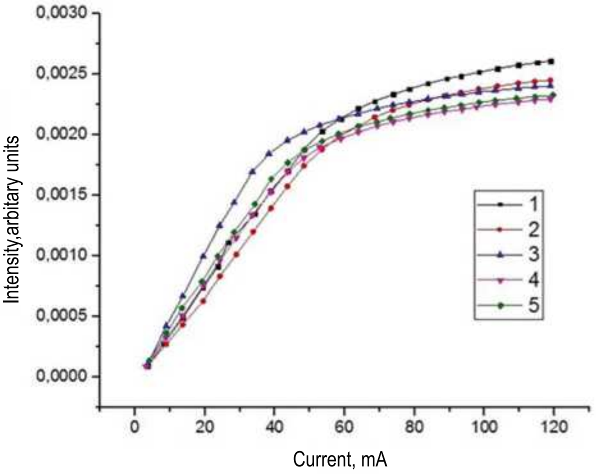


Fig. 5. Dependence between radiant intensity and current in red LEDs (the digits in the figure stand for sample numbers)

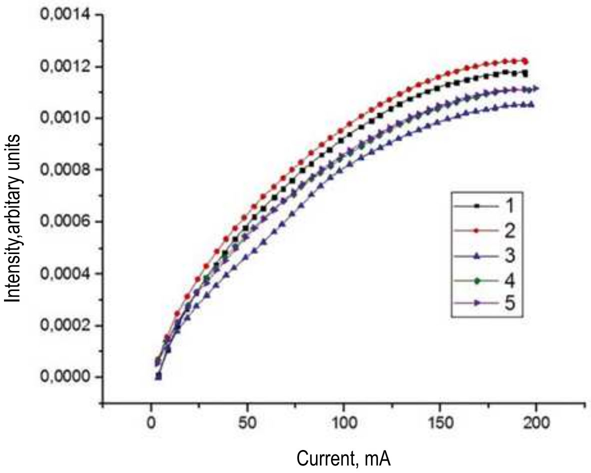


Fig. 6. Dependence between radiant intensity and current in green LEDs (the digits in the figure stand for sample numbers)

than approximately 35mA, the dependences between radiant intensity and current of green LEDs can also be roughly approximated by a linear function. The intensity increase is beginning to slow down with further increase of current. In the case of green LEDs, intensity levelling off is observed at higher values of current than those for red LEDs, at about (125–150) mA.

In the case of blue LEDs (Fig. 7), linear intensity and current dependence is observed at the current less than approximately (75–80) mA, whereas the increase of radiation intensity gradually starts slowing down with further increase of current, like in the case of green LEDs, and its levelling off for blue LEDs is observed at values of current equal to about (130–150) mA.

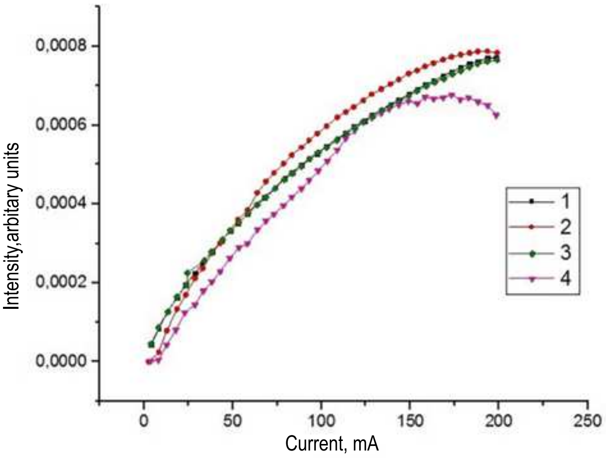


Fig. 7. Dependence between radiant intensity and current in blue LEDs (the digits in the figure stand for sample numbers)

4. DISCUSSION OF THE EXPERIMENTAL RESULTS

1. The above mentioned changes of slope in dependence of intensity from current in the region of current density about 130 A/cm^2 for red LEDs and exceeding 140 A/cm^2 for green and blue LEDs, may be explained by heating of active regions of LED crystals, which leads to changes of current passage mechanisms and mechanisms of media recombination in the active region.

2. For description of major peaks of radiation spectra, you can use the radiation spectrum approximation proposed in [14] which can be represented in the following form:

$$I(\hbar\omega) = A_0 \cdot \frac{1+exp\left(-\frac{\hbar\omega_{max}-E_g}{E_0}\right)}{1+exp\left(-\frac{\hbar\omega-E_g}{E_0}\right)} \times$$
$$\times \frac{1+exp\left(\frac{\hbar\omega_{max}-\left(E_g+\Delta F\right)}{E_1}\right)}{1+exp\left(\frac{\hbar\omega-\left(E_g+\Delta F\right)}{E_1}\right)}, \qquad (1)$$

where $\hbar\omega_{max}$ is the spectrum peak energy, E_g is the energy gap of the crystal active region, ΔF are the shifts of energy bands (valence band and conduction band) in the crystal active region, E_0 and E_1 are the spectra approximation parameters in the long-wave and short-wave regions respectively.

Table 1. The Results of Approximation of Radiation Spectra of Red LEDs

J, A/cm^2	$\hbar\omega_{max}$, eV	E_g^*, eV	E_0, eV	E_1, eV
5.56	1.906	1.885	0.015	0.021
11.11	1.902	1.893	0.017	0.026
22.22	1.901	1.894	0.015	0.028
44.44	1.898	1.892	0.017	0.027
66.67	1.895	1.888	0.017	0.027
88.89	1.890	1.876	0.018	0.027
111.11	1.885	1.875	0.016	0.030
133.33	1.872	1.858	0.016	0.033

Table 2. The Results of Approximation of Radiation Spectra of Green LEDs

J, A/cm^2	$\hbar\omega_{max}$, eV	E_g^*, eV	E_0, eV	E_1, eV
5.56	2.332	2.282	0.048	0.029
11.11	2.350	2.341	0.055	0.030
22.22	2.365	2.361	0.056	0.030
44.44	2.379	2.391	0.058	0.033
66.67	2.387	2.408	0.058	0.035
88.89	2.391	2.401	0.057	0.039
111.11	2.390	2.386	0.057	0.041
133.33	2.390	2.377	0.056	0.046

Table 3. The Results of Approximation of Radiation Spectra of Blue LEDs

J, A/cm^2	$\hbar\omega_{max}$, eV	E_g^*, eV	E_0, eV	E_1, eV
5.56	2.644	2.634	0.045	0.027
11.11	2.644	2.634	0.043	0.028
22.22	2.644	2.634	0.038	0.029
44.44	2.649	2.640	0.040	0.030
66.67	2.649	2.640	0.041	0.033
88.89	2.649	2.649	0.044	0.034
111.11	2.644	2.649	0.045	0.039
133.33	2.640	2.640	0.048	0.041

The results of approximation for red, green and blue LEDs are shown in Tables 1, 2 and 3 respectively. The values of the parameters are given for several values of current density, which makes it possible to use them for comparison of LEDs with crystals of different area.

Table 1 shows that peak radiation $\hbar\omega_{max}$ of red LEDs shifts towards lower energies with increase of current density, which corresponds with the spectrum shift to the long-wave region observed during the experiment.

The results presented in Table 2 show that peak radiation of green LEDs shifts towards higher energies, which also corresponds with the experimentally observed shift of green LEDs spectra to the short-wave region of radiation with increase of density of current passing through the crystal. It also may be noted that the shift of peak diminishes with increase of current density and it is practically not observed with current density exceeding 100A/cm^2.

The results shown in Table 3 show that the shift of peak radiation is not observed in blue LEDs with increase of density of current passing through the crystal unlike red and green LEDs. Like in the cases of red and green LEDs, the presented cal-

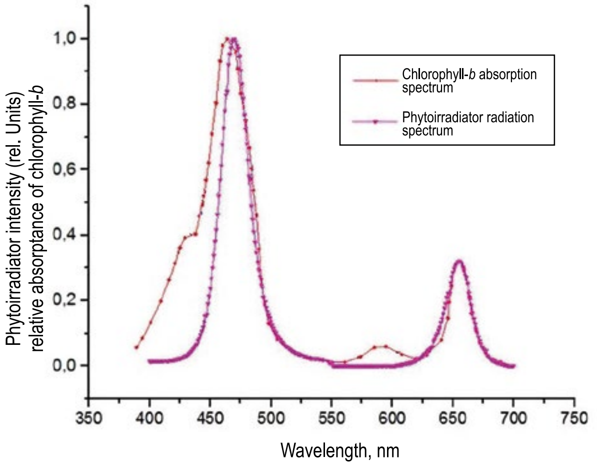


Fig. 8. Absorption spectrum of chlorophyll-*b* and modelled radiation spectrum of phytoirradiator

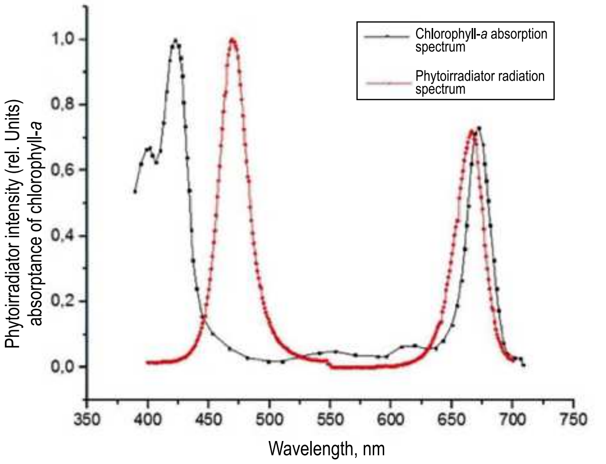


Fig. 9. Absorption spectrum of chlorophyll-*a* and modelled radiation spectrum of phytoirradiator

culation results correspond with the experimental data obtained for blue LEDs.

3. Heating of the structure may be assessed based on the approximation parameter E_1. It should be noted that for all studied LED it is possible to assume $E_1 \approx kT$ which is equal to about 26 meV at room temperature. Therefore, based on the results of approximation of radiation spectra at different values of current, it is possible to evaluate heating of the crystal active region at different values of current density.

The increase of peak width at half height visible in Figs. 2–4 with its average value of about 10 nm to 25 nm can also be explained by heating.

Such shift is especially visible in red LEDs the crystals of which are based on complex four-component solutions of aluminium, gallium, indium and phosphorus and in green LEDs with high indium content in the active region of their crystals. The indium content in the active region of blue LED crystals is lower and the shift is, therefore, not so visible.

4. For red, green and blue LEDs, the approximation parameter E_0 varies within the ranges of (15–20) eV, (45–60) eV and (50–62) eV respectively. It is seen that the values of this parameter in red LEDs are lower than *kT*, however, the difference is not very significant, whereas for green and blue LEDs, the value of the parameter E_0 is much higher than *kT*. This difference is especially significant in nitrides due to larger potential fluctuations.

5. Based on the obtained results, it is possible to formulate recommendations for development and manufacture of light sources and lighting devices based on red, green and blue LEDs. Since the shift of peak position is observed in the spectra of red and green LEDs with increase of current, the said shift shall be taken into account when selecting the operating mode of a lighting device by selecting both operating current range and heat mode. Correct selection of the operating current and the heat mode is also important due to the fact that increase of current density in the active region of a LED crystal leads to its overheating which may be critical for degrading of parameters of LEDs and light sources, and, so, phytoirradiators based on them. For selection of the heat mode, it is necessary to use efficient heat dissipation means, which include even forced cooling of a LED device in cases when it is critical.

5. PHYTOIRRADIATOR MODELLING

On the basis of the conducted studying of LED characteristics, a source of radiation with adjustable spectrum for use in phytoirradiators was modelled. The control parameters included current for changes of spectral peak positions in regions of active absorption of pigments and the number of operating single emitters for adjustment of the radiant flux ratio or photons in different ranges of PAR region [2, 3].

Such phytoirradiator would be capable to provide required radiation spectrum for different vegetation periods. In other words, it would be able to provide the required spectrum during the whole period of plant growing with minimum energy consumption. By changing the control parameters, it is possible to achieve high efficiency at each stage of plant growth. Another advantage of such phytoirradiator is that it uses a rather wide spectral range

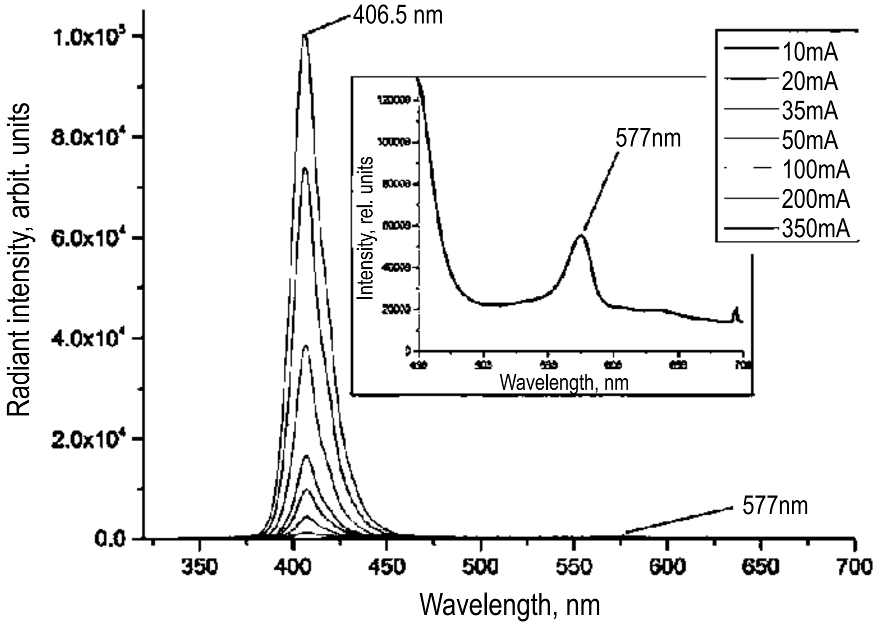


Fig. 10. Radiation spectrum of a violet LED at different values of current [13]

which includes all (red, green and blue) PAR regions. After modelling the radiation source with adjustable spectrum and conducting studies using it, it is possible to determine the optimal number of LEDs requiring for a specific plant and thus to develop an optimised phytoirradiator for each type of plants, which may be economically viable.

On the basis of the obtained results, phytoirradiator spectra were modelled. The modelling was conducted so that the radiation spectrum of the irradiator would be correlating well with the absorption spectrum of a given pigment of a plant. For instance, Fig. 8 shows the absorption spectrum of chlorophyll-*b* as well as the spectrum of the modelled phytoirradiator (the values of operating current of red, green and blue LEDs are equal to 60 mA, 0 mA and 80 mA respectively). Fig. 8 shows that the radiation spectrum of the modelled phytoirradiator correlates rather well with the absorption spectrum of chlorophyll-*b*, therefore, such emitter may provide relatively high energy efficiency.

It is worth noting that the studied LEDs do not cover a part of the chlorophyll-*b* absorption spectrum shown in Fig. 8 (the region of (600–620) nm). To use this spectrum region, it is necessary to use amber LEDs which had not been studied in this work.

Fig. 9 shows the absorption spectrum of chlorophyll-*a* as well as the spectrum of the relevant modelled phytoirradiator (the values of operating current of red, green, and blue LEDs are equal to 120 mA, 0 mA, and 100 mA respectively). This figure shows that using the studied LEDs it is possible to form a spectrum which relatively well correlates with the absorption spectrum of the pigment only at longer wavelengths.

For shorter wavelengths of the absorption spectrum of chlorophyll-*a* and other pigments it is necessary to use violet LEDs [13, 14]. Fig. 10 presents radiation spectra of such LEDs at different values of current [13, 14]. The figure shows that the radiation peak of such LEDs corresponds with the peak of absorption of chlorophyll-*a* in the violet region of the spectrum (Fig. 9), which indicates that with such LEDs a phytoirradiator may also efficiently operate with pigments at shorter wavelengths of the spectrum.

6. CONCLUSION

As a result of the conducted study of red, blue and green LEDs, the dependences of their spectra and radiation intensity (in arbitrary units) from current were obtained. By means of approximations, the mechanisms of current passage and recombination in the studied LEDs were explained and the correlation between the results of spectral measurements and measurements of the dependence of intensity from current was discovered for red, green and blue LEDs. On the basis of the obtained experimental results, the model of a phytoirradiator with adjustable radiation spectrum was proposed, formulated with consideration of experimentally discovered spectral features, e.g. the shift of peak of the radiation spectrum after increase of current towards long waves in red LEDs and towards short waves in green LEDs whereas no shift of the peak was observed in blue LEDs. The conducted modelling showed that these phytoirradiators allow us to adjust the radiation spectrum depending on the needs: different vegetation periods of plants require different radiation spectra since at different stages of a plant development the pigments with different absorption spectra are responsible for its growing.

A similar model of a multi-colour radiation source with adjustable spectrum was described in [15] with the authors proposing a multi--colour LED based light source with functionality of spectrum control by measuring the current passing through LEDs for use as a universal calibration source. The difference is that the authors of [15] also used white LEDs in their source apart from colour LEDs of different visible-light spectrum ranges. Given the results obtained in [15], fair to assume that white LEDs may be used in phytoluminaires, and research and modelling of their characteristics may be a subject for continuation of the study described above.

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