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ELECTRODELESS SULFUR LAMP ON THE BASIS OF MICROWAVE EXCITATION: ESTIMATION OF SPECTRAL EFFECTIVENESS OF RADIATION FOR BIO-OBJECTS

T. FROLOVA

The paper considers a lighting system based on an electrodeless sulfur lamp with microwave excitation for bio-objects. As a result of the intensive development of new technologies in the field of lighting equipment (LED, HID lamps, and others) it is necessary to replace outdated lighting for a more energy-efficient one, by using new modern lamps of artificial radiation for biological objects (human, animals and plants). The parameters of optical radiation sources for different biological objects are different (for humans and some animals they are based on the sensitivity of the eye (photonic response curve), for plants – it is the photon flux density of photosynthetically active radiation (PAR) from 400 to 700 nm). High-pressure sodium lamps (HPSL) and metal halide lamps (MHL) are the most common among the artificial light sources used in greenhouses. However, at present, the most effective and promising are lighting systems based on LED lamps and the electrodeless sulfur lamp with microwave excitation. The latter is environmentally friendly (it does not contain mercury), with a high efficiency of PAR (72%) and durable (above 60,000 hrs.) Analysis of the spectral efficiency of radiation showed that the electrodeless sulfur lamp with microwave excitation has a high photosynthetic photon flux density (PPFD) (1440 $\mu mol \cdot s^{-1} \cdot m^{-2}$) in an optical range of 400-700 nm.

Keywords: electrodeless sulfur lamp with microwave excitation, bio-object, sunlight, spectral irradiance, photosynthetically active radiation, photosynthetic photon flux density.

INTRODUCTION

At present the problem of finding and implementing energy-efficient solutions in various areas of human economic activity is a priority, the role of an artificial lighting is particularly important. Artificial radiation sources have different effects on living organisms (human, animals, plants, etc.), therefore, depending on the effect on bio-objects, the ones of photophysical, photochemical and photobiological action are distinguished [1]. Sources of photobiological action are used in agro-industrial complexes (example, for growing plants in the protected ground) [2-4]. The percentage of the sectoral electricity consumption in the technological processes of the greenhouse farm with the use of optical radiation is 10-15%, and the losses in them reach 40%. Plants grown in greenhouses, using the radiant energy of artificial light sources, transform this energy into the chemical energy of plants. At the same time, the higher the absorption coefficient of artificial radiation sources, the less electrical energy is spent on growing a unit of plant products. The spectrum of light affects both the consumption of electrical energy by plants and the efficiency of photosynthesis. Visible radiation is the main source of energy for photosynthesis, therefore, with increasing illumination, the intensity of photosynthesis will also increase.

The purpose of this paper is to evaluate the spectral efficiency of the electrodeless sulfur lamp based on microwave excitation for use in illuminate of the plants in agro-industrial complexes.

Photometric methods [5], mathematical modeling and quantitative analysis were used during the research.

1. FORMULATION OF THE PROBLEM

The best artificial light sources are sources that have a spectrum close to sunlight (Fig. 1) [6].

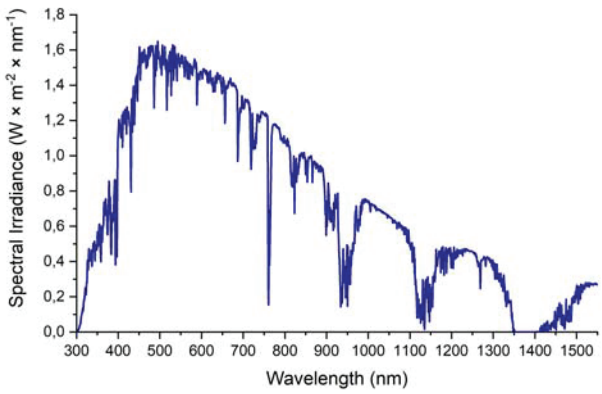


Fig. 1. The spectrum of solar radiation AM 1.5G on the surface of the Earth

When choosing the artificial radiation source for plants, one cannot be based on the parameters of lamps for humans, where the luminous flux is measured in lumens (lm). Since the spectral sensitivity curves of the standard human eye, birds, and photosynthesis of plants are different. Every living organism has its own spectrum of absorption of optical radiation. In fig. 2 are presented:

- averaged spectral sensitivity curve of the standard human eye, established by an international agreement in 1924 [5];
- averaged curve of the spectral sensitivity of the eye of a domestic bird [7];
- the curve of the relative quantum efficiency as determined by the average plant response for photosynthesis (from K. J. McCree [8]).

The curves of the spectral sensitivity of the human and animal eye (bird) have the peak about 550 nm. Humans and many animals use what is called photopic vision in well-lit conditions to perceive color and light, so

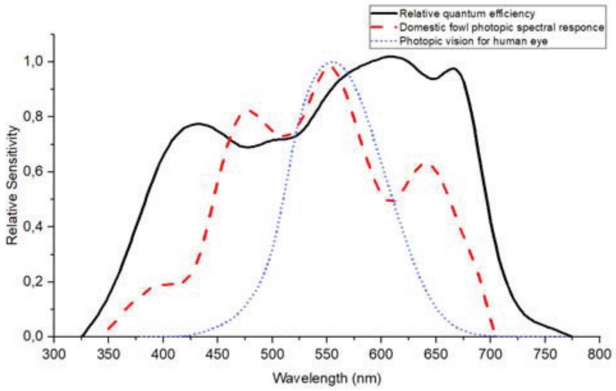


Fig. 2. Spectral sensitivity curves for human, birds, and plants

this graph is also called the photopic response curve. The peaks of the photosynthetic efficiency response of plants are in the red (600–675 nm) and blue (425–450 nm) regions and it is called Relative Quantum Efficiency (RQE). Therefore, plants react differently to light than humans and animals.

Such a difference in the spectra is due to the influence of optical radiation on the efficiency of photochemical processes in the plant (photosynthesis, photomorphogenesis, chlorophyll synthesis, etc.). This is due to the fact that a particular organ of photosynthetically activity in plants is the leaf where the specialized cell structures are located – chloroplasts containing pigments and other components necessary for the processes of absorption and conversion of light energy into chemical potential. The photosystem contains about 250 molecules of pigments capable of absorbing light. The source of energy is electromagnetic radiation of the visible region of the spectrum with an energy of 1–3 eV [9]. Each pigment has its own individual absorption spectrum and, accordingly, its own spectral characteristic of the light activity of the exciting radiation. Green pigments are the main pigments of plants that provide for the absorption of radiant energy and its use for building biomass.

There are several ways to accelerate growth and increase the period of plant growth by using artificial radiation sources. Artificial radiation sources are used:

- as an addition to natural daylight; to increase the level of assimilation lighting in order to increase the intensity of photosynthesis and thereby accelerate growth and improve the quality of plants in greenhouses (additional assimilation lighting);
- to control the light period by lengthening the natural daylight through the use of artificial lighting (photoperiodic lighting);
- as full daylight replacement with artificial lighting, it allows achieving maximum climate control (cultivation without daylight).

2. PHOTOBIOLOGICAL PROCESSES OCCURRING IN PLANTS

Photobiological processes in plants are photosynthesis (synthesis of organic molecules under the influence of the energy of sunlight), phototropism (rotation of leaves or plant stems to light or from light) and photoperiodism (regulation of diurnal and annual cycles of life through cyclic influences of day/night) [10]. The main and energy-intensive process is photosynthesis, which occurs when the optical radiation energy is absorbed by plants.

The leaves of plants absorb visible and part of ultraviolet radiation and synthesize organic substances from mineral (photosynthesis). The scientists found out that each part of the spectrum of solar radiation near the Earth's surface (Figure 2) affects plants differently. Some scientists distinguish the red spectrum, as the main illumination for photosynthesis. However in the papers of Voskresenskaya N. P. and Tikhomirov A. A. was shown that the most effective can be both red and blue light, depending on the kind of the plants [11, 12]. Other scientists believe that plants need the entire solar spectrum for normal development and life activity because the effect of optical radiation on the plant is diverse and cannot be reduced to photosynthesis alone [9].

However, it should be noted that the excess of the certain spectrum in the source of artificial radiation can be bad for plants:

- the high content of blue color causes inhibition of growth of the stem and leaf surface, thus leaves are formed with a high specific gravity;
- the high content of red color promotes an intensive growth of leaf area and elongation of axial organs;
- with the predominance of green color, thin leaves with small count cells and chloroplasts are formed.

Table 1 presents the results of researches of a better percentage content of the blue, green, and red spectrum of radiation in the source of optical radiation for plants [13].

Table 1

Requirements for the distribution of optical radiation

Plant species	Blue (400 – 500 nm), %	Green (500 – 600 nm), %	Red (600 – 700 nm), %
Tomato	15	17	68
Cucumber	17	40	43
Lettuce	45	20	35
Radish	34	33	33
Wheat	25	1	74
Other	30	20	50

3. PHOTOSYNTHETICALLY ACTIVE RADIATION

The effectiveness of light exposure is determined by the whole complex of reactions associated with the conversion of radiation energy into biological radiation. The speed of these reactions and the effectiveness of the photosynthetic effect depends on many factors: the irradiation density, the stage of plant growth, the spectral composition of the radiation, and other.

The sources of optical radiation for human are chosen based on the value of illuminance is measured in lux (lx), whereas for plants the determining value is the photon flux incident on the surface of the leaf. However, at the moment there is no single approach to measuring the photon flux. This is due to the lack of an official unit for measuring the photon flux in the international SI system.

For the sources of optical radiation of the greenhouse complex, the values of photosynthetically active radiation (PAR-photosynthetically active radiation) and photosynthetic photon flux density (PPFD) are used.

Part of the optical range to which the plant is most susceptible, i. e., a necessary and sufficient range for life support and biomass formation in the process of photosynthesis that it promotes the development of the plant, is the PAR region [8]. The PAR range is determined from 400 nm to 700 nm [8, 14], or from 380 nm to 710 (720) nm [9]. However, this difference does not significantly affect the measurement of the PAR of the artificial radiation source.

The value for evaluating the PAR of artificial optical sources is defined as the photosynthetic photon flux density PPFD, which shows the number of photons in the 400–700 nm waveband incident of the leaf per unit time on a unit surface. It is now customary to measure PPFD in μmol·s^{-1}·m^{-2}. However, there is no single approach to determining PPFD, so the universal formula was chosen [8]:

$$PPFD = \frac{\int_{400}^{700} \left(E(\lambda)\cdot\lambda\right)d\lambda}{h\cdot N_A\cdot c}\ , \quad (1)$$

where $E(\lambda)$ is the irradiance, which characterizes the absolute value of the PAR radiation at the wavelength, W/m^2; λ – wavelength, nm; h – Planck's constant, J·s; N_A - Avogadro's number, 1/mol; c – speed of light, m/s.

Irradiation is a physical quantity, one of the radiometric quantities, which characterizes the surface power density of a radiation incident on the unit surface. The value of the efficiency of PAR shows, as a percentage, how much the spectrum of the artificial radiation source coincides with the RQE of the plant (see Fig. 2).

4. EVALUATION THE SPECTRAL EFFICIENCY OF AN ELECTRODELESS SULFUR LAMP BASED ON MICROWAVE EXCITATION FOR GREENHOUSES

The use of specialized artificial radiation sources in crop production is diverse today, but not all sources are effective and safe. New and prospective sources of artificial lighting in protected ground conditions are LED and plasma (in particular, the electrodeless sulfur lamp with microwave excitation) lamps [9, 15].

The efficiency of application of the electrodeless sulfur lamp with microwave excitation for the agro-industrial complex is considered [16]. For comparison, a the LED lamp is also selected. The characteristics of the lamps are given in Table. 2.

Table 2

Parameters of lamps

Parameter	Electrodeless sulfur lamp with microwave excitation	LED lamp
Rated current, A	4,7	3,5
Input voltage, V	220	32 – 36
Power consumption, W	1850	120
Angle of divergence, °C	80	90
Start-up Time, sec	12	1 – 3
Efficacy, lm/W	101	174
Temperature, ºC	50 – 80 (on the searchlight glass)	60 – 90 (on a chip)
Rated life, hours.	60000 – 100000	50000 – 70000

In fig. 3 shows the spectral characteristics of the lamps, as well as the average photosynthetic response of plants to light energy (McCree curve).

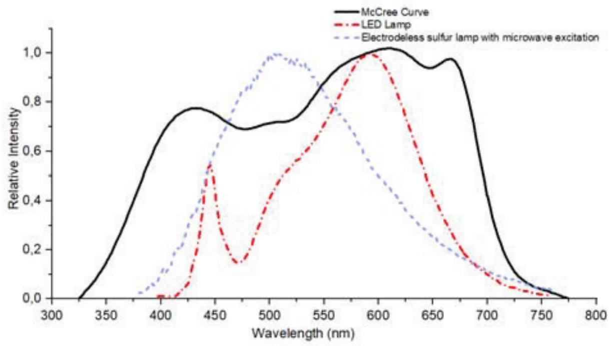


Fig. 3. Spectral characteristics of the electrodeless sulfur lamp with microwave excitation, LED lamp and average photosynthetic response of plants to light energy according to McCree

The spectral characteristics of the lamps are in the PAR waveband (400-700 nm) and are close to the spectral absorption of the plant leaf. The LED lamp has peaked in blue (400-500 nm) and in the red (600-700 nm) spectral range. The sulfur lamp with microwave excitation has a peak at 510 nm, which is closer to the spectrum of solar radiation AM 1.5G and the spectral sensitivity curve of the human eye (550 nm).

As noted earlier, illumination is not a determining parameter for the artificial radiation source for plants in the agro-industrial complex. For greenhouses, it is important to know the parameter of PPFD lamps. For its definition, it is necessary to convert from radiometric (irradiance ($E(\lambda)$, W/m^2)) to photometric units of PPFD (μmol·s^{-1}·m^{-2}). This recalculation is carried out using the formula 1. That is, to calculate the parameter PPFD it is necessary to define the absolute value of irradiance in the PAR range. This value can be measured with a spectrometer (ASEQ LR1).

This instrument measures the amount of the energy contained within the light of the optical radiation source, which is the irradiance in the PAR waveband. Measurements of the irradiance dependence in PAR range perform for the electrodeless sulfur lamp with microwave excitation was carried out at a distance of 2 m and 3.5 m from the end of fiber optic cable for direct light into the spectrometer, and for the LED lamp – it is of 20 cm and 40 cm. The results of the experiment are shown in Fig. 4 and Fig. 5, as well as the color space of the investigated lamps in Fig. 6.

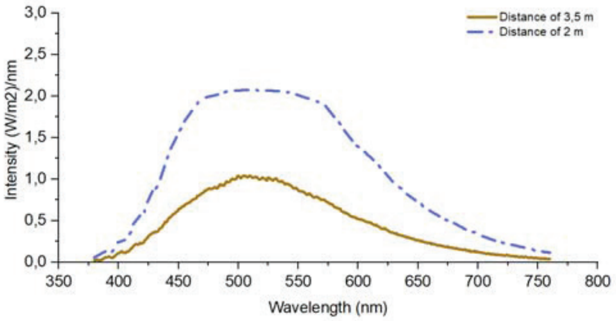


Fig. 4. The spectral characteristic of the electrodeless sulfur lamp with microwave excitation at a distance of 2 m and 3.5 m

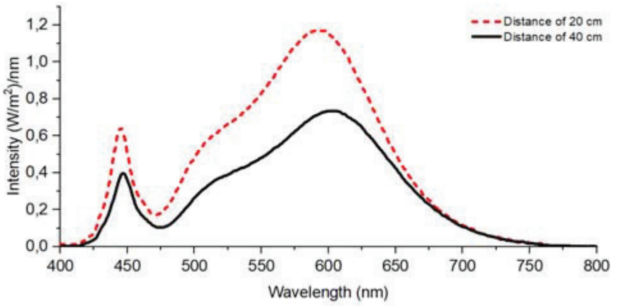
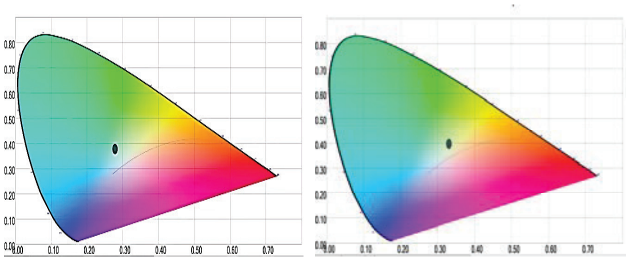


Fig. 5. The spectral characteristic of the LED lamp at a distance of 20 cm and 40 cm



(a) (b)

Fig. 6. Color space of electrodeless sulfur lamp with microwave excitation (a) and LED lamp (b)

As mentioned above, the best source of optical radiation for plants is the Sun. Therefore, the parameters of lamps that are used in conditions of protected ground, should be approximated to the characteristics of the Sun at the surface of the Earth - AM 1.5G. AM (Air Mass).

Fig. 7 shows the spectral characteristics of the electrodeless sulfur lamp with microwave excitation and the LED lamp for different distances from the end of fiber optic cable of the spectrometer, as well as solar spectrum AM 1.5G, and the average photosynthetic response of plant leaves.

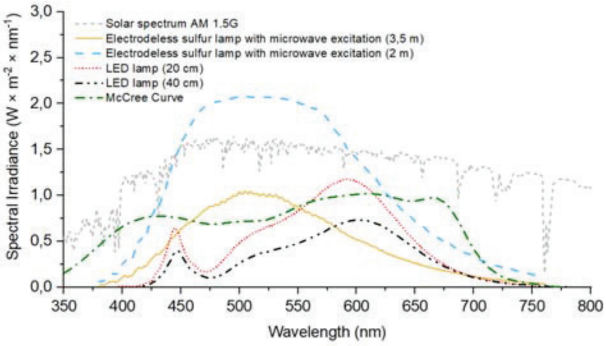


Fig. 7. Spectral characteristics of the artificial radiation sources, standard solar spectrum AM 1.5G, and McCree curve

As can be seen, from Fig. 7, the spectral characteristics of the electrodeless sulfur lamp with microwave excitation at a distance of 3.5 m with an illumination area of ~ 30 m^2 have the best match to the spectral characteristics of the Sun (AM 1.5G). At a distance of 2 m, this lamp has a very large value of irradiance, which exceeds the value of the irradiance of the Sun. Therefore, the electrodeless sulfur lamp with microwave excitation should be placed at a distance of 3.5 m from plants in large industrial greenhouses, so as not to damage them. The spectrum of the LED lamp at a distance of 20 cm has an illumination area of ~ 0.15 m^2 and therefore this lamp can be used for small greenhouses. For the use of LED lamps in large greenhouses possible with combining, for example, 6 lamps together, thereby increasing the value of the radiation intensity in the PAR range. 6 lamps at a distance of 1 m create the same irradiance as at a distance of 20 cm, but with an illumination area of ~ 12 m^2.

Table 3 shows the percentage of the spectrum of lamps in the PAR range, which was calculated by the formula

$$k_i = \frac{\int\limits_{\lambda_{min}}^{\lambda_{max}} (E(\lambda))d\lambda}{\int\limits_{400}^{700} (E(\lambda))d\lambda} \cdot 100\% ,$$

where $E(\lambda)$ is the absolute value of the PAR irradiance for blue (λ_{min} = 400 nm and λ_{max} = 500 nm), green (λ_{min} = 500 nm and λ_{max} = 600 nm) and red (λ_{min} = 600 nm and λ_{max} = 700 nm) spectra; $i = 1,2,3$.

Table 3

The percentage of the spectrum of lamps in the PAR range

Source	Blue (400–500 nm), %	Green (500–600 nm), %	Red (600–700 nm), %
Sun AM 1,5	34	38	35
Electrodeless sulfur lamp with microwave excitation	37	43	20
LED lamp	14	47	45

For artificial radiation sources used in greenhouses, it is recommended to provide such ratios of the spectral ranges of the PAR irradiance:

- blue (400-500 nm) - 20 - 25%;
- green (500-600 nm) - 20 - 25%;
- red (600-700 nm) - 60 - 50%.

As can be seen from Table. 3 the electrodeless sulfur lamp with microwave excitation does not have enough radiation intensity in the red region (600-700 nm), which should be the largest percentage in the spectrum [46-48].

The value of the PPFD parameter for normal plant growth is:

- light-loving plants – from 700 to 800 $\mu mol \cdot s^{-1} \cdot m^{-2}$;
- plants that are less demanding of light – from 300 to 500 $\mu mol \cdot s^{-1} \cdot m^{-2}$;
- shadow-tolerant plants – from 200 to 300 $\mu mol \cdot s^{-1} \cdot m^{-2}$.

The values of the PPFD parameter for the investigated lamps are presented in Table. 4.

Table 4

The value of PPFD for the different sources

Source	PPFD, $\mu mol \cdot s^{-1} \cdot m^{-2}$
Sun AM 1,5G	1700
Electrodeless sulfur lamp with microwave excitation; 2 m	3620
Electrodeless sulfur lamp with microwave excitation; 3,5 m	1440
LED lamp; 20 cm	904
LED lamp; 40 cm	514
6 LED lamp; 1 m	914

As can be seen from Table. 4 LED lamp has insufficient PPFD value in comparison with the Sun, but it is sufficient for normal plant growth. The electrodeless sulfur lamp with microwave excitation has more than twice the value of PPFD at a distance of 2 m (3620 $\mu mol \cdot s^{-1} \cdot m^{-2}$). Therefore, at this distance, in no case should you place the lamp. This will negatively affect the vital activity of plants. However, at a distance of 3.5 m from the lamp, the radiation intensity is very close to the intensity of the solar spectrum. The location of the lamp at this distance allows us to cover a large area of the plant surface, so it is effective for industrial greenhouse complexes.

CONCLUSION

In this paper, an evaluation of the efficiency of the application of the electrodeless sulfur lamp with microwave excitation for the illumination of plants in agro-industrial complexes was carried out. Studies have shown that they have a spectral characteristic close to the spectrum of the Sun AM 1.5G on the Earth's surface in the waveband of 400-700 nm (PAR), to which the plant is most sensitive.

The electrodeless sulfur lamp with microwave excitation has a high index of PPFD (at the distance of 2 m is 3620 $\mu mol \cdot s^{-1} \cdot m^{-2}$ and 3.5 m is 1440 $\mu mol \cdot s^{-1} \cdot m^{-2}$). It follows that the electrodeless sulfur lamp with microwave excitation is better used for industrial greenhouses (the illumination area of one lamp is ~ 30 m^2), whereas LED lamps cannot compete with it even in case of combining them into 6 pieces together the value of PPFD at a distance of 1 m, in this case, is 914 $\mu mol \cdot s^{-1} \cdot m^{-2}$ and an illumination area of ~ 12 m^2. Therefore, LED lamps can be used in small greenhouses.

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Tetyana Frolova, M.Sc. (1997), Ph.D. (2005), Associate Professor (2011), Leading Researcher at the Dept. of Physical Fundamentals of Electronic Engineering, Kharkiv National University of Radio Electronics. Research interests – develop 2D and 3D mathematical and computer models for the study of physical processes in vacuum devices and plasma, the design of new high-performance devices based on microwave devices, such as microwave discharge lamps.

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Фролова Т. И. **Безэлектродная серная лампа на основе СВЧ возбуждения: оценка спектральной эффективности излучения для биообъектов** / Т. И. Фролова // Прикладная радиоэлектроника: науч. – техн. журнал. – 2018. – Том 17, №. 1, 2. – С. 72–77.

В работе рассматривается осветительная система на основе безэлектродной серной лампы с СВЧ возбуждением для биообъектов. В связи с интенсивным развитием новых технологий в области осветительной техники (светодиодных, газоразрядных ламп и др.) необходима замена устаревшего освещения на более энергоэффективное, за счет применения новых современных источников искусственного излучения для биологических объектов (человека, животных и растений). Для различных биологических объектов параметры источника оптического излучения отличаются (для человека и некоторых животных основываются на чувствительности глаза (кривая фотопического отклика), для растений – это плотность потока фотонов в диапазоне фотосинтетически активной радиации (ФАР) (англ. photosynthetically active radiation, PAR) от 400 до 700 нм). Натриевые лампы высокого давления (НЛВД) и металлогалогенные лампы (МГЛ) являются наиболее распространенными среди искусственных источников света, используемых в теплицах. Однако наиболее эффективными и перспективными на сегодняшний день являются осветительные системы на основе светодиодов и безэлектродной серной лампы с СВЧ возбуждением. Последняя является экологичной (не содержит ртуть), с высоким КПД ФАР (72%) и долговечной (свыше 60 тыс. ч.). Анализ спектральной эффективности излучения показал, что безэлектродная серная лампа с СВЧ возбуждением имеет высокий показатель плотности фотосинтетического фотонного потока (англ. photosynthetic photon flux density, PPFD) (1440 μмоль·с$^{-1}$·м$^{-2}$) в оптическом диапазоне 400–700 нм.

Ключевые слова: безэлектродная серная лампа с СВЧ возбуждением, биообъект, солнечный свет, облученность, фотосинтетически активная радиация (ФАР), плотность фотосинтетического фотонного потока.

Табл. 04. Ил. 07. Библиогр.: 16 назв.

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Фролова Т. І. **Безелектродна сірчана лампа на основі НВЧ збудження: оцінка спектральної ефективності випромінювання для біооб'єктів** / Т. І. Фролова // Прикладна радіоелектроніка: наук. – техн. журнал. – 2018. – Том 17, №. 1, 2. – С. 72–77.

В роботі розглядається освітлювальна система на основі безелектродної сірчаної лампи з НВЧ збудженням для біооб'єктів. У зв'язку з інтенсивним розвитком нових технологій в області освітлювальної техніки (світлодіодних, газорозрядних ламп та ін.) Необхідна заміна застарілого освітлення на більш енергоефективне, за рахунок застосування нових сучасних джерел штучного випромінювання для біологічних об'єктів (людини, тварин і рослин). Для різних біологічних об'єктів параметри джерела оптичного випромінювання відрізняються (для людини і деяких тварин ґрунтуються на чутливості ока (крива фотопічного відгуку), для рослин – це щільність потоку фотонів у діапазоні фотосинтетично активної радіації (ФАР) (англ. Photosynthetically active radiation, PAR) від 400 до 700 нм). Натрієві лампи високого тиску (НЛВД) і металогалогенні лампи (МГЛ) є найбільш поширеними серед штучних джерел світла, що використовуються в теплицях. Однак найбільш ефективними і перспективними на сьогоднішній день є освітлювальні системи на основі світлодіодів і безелектродної сірчаної лампи з НВЧ збудженням. Остання є екологічною (не містить ртуть), з високим ККД ФАР (72%) і довговічною (більш ніж 60 тис. год.). Аналіз спектральної ефективності випромінювання показав, що безелектродна сірчана лампа з НВЧ збудженням має високий показник щільності фотосинтетичного фотонного потоку (англ. Photosynthetic photon flux density, PPFD) (1440 μмоль·с$^{-1}$·м$^{-2}$) в оптичному діапазоні 400–700 нм.

Ключові слова: безелектродна сірчана лампа з НВЧ збудженням, біооб'єкт, сонячне світло, опромінення, фотосинтетично активна радіація (ФАР), щільність фотосинтетичного фотонного потоку.

Табл. 04. Іл. 07. Бібліогр.: 16 найм.