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CHANGE OF THE EMISSION SPECTRUM OF SULFUR LAMP WHEN CHANGING THE PROPERTIES OF THE ELECTROMAGNETIC FIELD

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The paper is devoted to researching the behavior of the emission spectrum of an electrodeless sulfur lamp when the parameters of the microwave field pumping a system are being changed. Some cases of changes in the magnitude and spatial position of the microwave field antinode are studied. The obtained results make it possible to control the output radiation of the lamp when parameters of the microwave field are changing and monitor the pumping energy on the basis of the emitted spectrum of the sulfur lamp.

Keywords: sulfur lamp, microwave, LTE-model, color characteristics, emission spectrum.

INTRODUCTION

People perceive the color of visual environment in reflected sun light. Along with this natural effect for a long time humanity uses artificial light sources. Spectral composition of artificial light sources are usually quite different from the natural one, in practice it appears in change of objects colors by the transition between different light sources. Therefore, the creation of an artificial light source with a spectrum close to the spectrum of solar radiation is an important problem for modern physics of self-luminous objects, as well as for technical devices which implement these effects.

Such a light source is electrodeless lamp based on the emission of sulfur plasma maintained by a microwave. Establishment and improvement of these lamps require consideration and study of all the mechanisms that determine the steady-state and stability of the microwave discharge. These mechanisms include processes that provide alignment in the space of the maximum of the microwave field in a cavity with the location of the optical bulb with sulfur.

The main goal of the present work is the theoretical study of dependence between the behavior of the sulfur lamp emission spectrum and both the magnitude and the spatial position of the antinode of the microwave radiation relative to the center of the bulb.

In conditions of the local thermodynamic equilibrium (LTE) model changes of the microwave field parameters will have an impact on the temperature characteristics of the bulb. In turn, the emission spectrum of the lamp depends on its temperature conditions. Therefore, in this work relationship between the emission spectrum and the temperature profile given by microwave field in the cavity has been theoretically investigated.

1. ANALYSIS OF SULFUR LAMPS SPECTRAL CHARACTERISTICS

Sulfur Plasma lamps are between 25% and 100% more efficient than any other artificial source of high quality white light. The light is true full spectrum daylight and thus features all of the qualitative benefits of sunlight.

Unlike all other artificial light sources, the light output and colour (light output quality) does not degrade over time and it is fully dimmable down to 30%. The lamp consists of a hollow quartz sphere with sulfur and argon gas so, unlike all other forms of lighting, it is environmentally benign. It contains no lead, unlike most other lamps, no mercury, unlike all fluorescent lighting and no arsenic unlike most LEDs (Gallium Arsenide).

The sulfur plasma consists mainly of dimer molecules (S_2), which generate the light through molecular emission. From physical point of view the process occurs in the following way. Gas discharge is allowed by microwave radiation with a frequency of 2.45 GHz, which is widely used in industry, science and medicine. The microwave field causes the glow in a buffer gas, which has a low breakdown threshold when initial pressure is low. At the same time field heats – until evaporation – sulfur powder. In the formed high-pressure gas mixture microwave field takes atoms (as well as dimers, etc.) of sulfur in excited states. Under such conditions both direct channel of atomic and molecular absorption and collisional mechanism act. Finally, the re-emission from excited states forms the radiation spectrum of sulfur plasma.

The molecular emission of sulfur has complex character. At low sulfur vapor pressures of 50 Pa molecular emission is in the UV range (0.4–0.2 micron). With increasing of sulfur vapor pressure in the microwave discharge secondary processes begin to take significant impact on the molecules emission, among these processes reabsorption is dominated. Reabsorption of spectral lines in the discharge has a significant influence on the shape of the emission lines coming out from the discharge, on the distribution of radiation in the volume of the discharge and on the distribution of the outcoming radiation in space and even in some cases the flux of radiation. Reabsorption is particularly significant for UV resonance lines, since the concentration of normal (unexcited) molecules in the discharge that absorb this radiation is usually several orders of magnitude greater than the concentration of excited atoms. Ultraviolet radiation, resulting from transitions from the upper electronic states of the electrons in the molecule S_2, excites lower vibrational-rotational levels in the lower electronic states which in turn emit in the visible spectrum (0.7–0.4 microns) [1].

Because of this, instead of atomic emission, is the mechanism of light generation, the emission spectrum is continuous throughout the visible spectrum (Fig. 1).

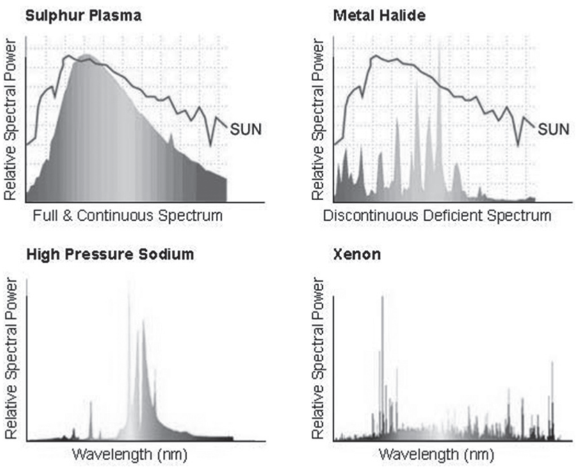

Fig. 1. Emission spectrum of light sources

The lamp's output is low in infrared energy, and less than 1% is ultraviolet light. As much as 75% of the emitted radiation is in the visible spectrum, far more than other types of lamps (Fig. 2).

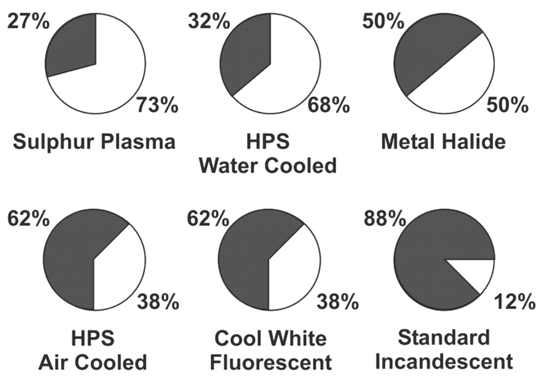

Fig. 2. Emission intensity diagrams of different light sources

The visible light output mimics sunlight better than any other artificial light source, and the lack of harmful ultraviolet radiation can be especially beneficial to more vunerable fixtures, equipment, young plants and humans.

The spectral output peaks at 520 nanometers and the correlated colour temperature (CCT) is approximately 6000 kelvin's with a colour rendering index (CRI) of 86. The lamp can be dimmed to 40% without affecting the light quality, and light output remains near constant over the life of the bulb.

Popular light sources currently used for solar simulation include the Hydrargyrum Quartz Iodide (HQI) lamp which is a type of high-intensity discharge (HID) light, produces its light by an electrical arc in a gas envelope using electrodes. Note that Hydrargyrum is the Latin name for the element mercury. Also Xenon lamps that use tungsten metal electrodes in a glass tube filled with xenon gas. For xenon flash tubes, a third "trigger" electrode usually surrounds the exterior of the arc tube. Xenon lamps often have a relatively short lifetime of 200 to 2000 hours. As with all electrode based light sources the colour quality and luminous efficiency of the light changes dramatically as the electrodes burn away during use. And the tungsten lamp, which is similar to the classic incandescent domestic version, but with an extra high-temperature filament so that it gives high illumination and high colour temperature for the price of a short lifetime.

Powerful xenon, halogen and other lamps are part of the solar simulators (SS).

The steadiness of the light flux in a simple simulator circuits is provided by the fitting and alignment of lamps in multiple-bulb illuminators, in more complex circuits – by the using of special reflectors (elliptical, elliptic-cylindrical, etc.), and by the application of special optical integrators for high-quality SS. In this way, in the worst case, the illumination nonuniformity of the light spot effective field should not exceed 10%.

In nearly all cases solar simulators using a combination of these old technologies can only represent part of the solar spectrum at the same time and many have extremely elaborate and vulnerable reflector and filter systems to simulate the Sun's radiation at all wavelengths.

2. THE THERMODYNAMIC MODEL OF THE SULFUR LAMP

In the present paper the case of stationary mode of the lamp after ignition was considered. That mode is characterized by steady-state mode of the microwave pumping device, as well as by formation of a homogeneous plasma, that emits in the whole visible spectral range the intensity of which is determined by Planck's formula (4), in the bulb of the lamp.

The following input parameters of the system were selected: the bulb of radius $r = 16$ mm, which the buffer gas and sulfur powder mass $m = 26$ g are placed in, is irradiated with microwave energy power of $P = 600$ W and oscillation frequency of $f = 2.45$ GHz. The pressure in the bulb is considered to be $p = 6 \cdot 10^5$ bar.

Sulfur plasma formed under the influence of microwave radiation in the bulb can be described by the model of local thermodynamic equilibrium (LTE) [2].

Under conditions of LTE, the composition of a gas mixture is governed by the local pressure and temperature. The mass action law establishes expressions for the ratios between the densities of the particles. For a mixture with N species X_s, a chemical reaction can be written as

$$\sum_{s=1}^{N} a_s X_s \Leftrightarrow \sum_{s=1}^{N} b_s X_s$$

and the mass action law can be stated as

$$\prod_{s=1}^{N} n_s^{(a_s - b_s)} = f(T)$$

where $c_s \equiv a_s - b_s$. The function f (T) depends on the nature of the reaction and can be expressed in terms of the species' partition functions. For excitation, ionization and association reactions, the equation reduces to the well-known Maxwellian (1) and Boltzmann (2) distributions, Saha (3) and Guldberg-Waage relations, respectively. And all of them for given volume contain the same local temperature value, which is also the same for all particle species.

Basic equations that describe the model of local thermodynamic equilibrium are as follows:

– distribution of particles of any type i by velocities v is expressed by the Maxwell function:

$$N_i(n) = 4pN_i\left(\frac{M_i}{2pkT}\right)^{\frac{3}{2}}\exp\left(-\frac{M_i n^2}{2kT}\right), \quad (1)$$

where $N_i(n)$ is the number of particles (concentration), with velocities ranging from n to $n + dn$; p – the pressure; M_i is the particle mass; N_i is the particle concentration; k – the Boltzmann constant.

– the number of atoms or ions in an arbitrary excited state s is determined by the Boltzmann formula:

$$N_s = N_0\frac{g_s}{g_0}\exp\left(\frac{-E_s}{kT}\right) = N\frac{g_s}{U}\exp\left(\frac{-E_s}{kT}\right). \quad (2)$$

Here N_0 is the population of the ground state; g_0 – the statistical weight of that state; g_s – the statistical weight of the excited state; E_s is the energy of the excited state, measured from the ground level.

– concentrations of atoms, ions and electrons are related to each other with Saha formula:

$$\frac{N_e N_{ion}}{N_a} = 2\frac{(2p\,m_e)^{\frac{3}{2}}}{h^3}(kT)^{\frac{3}{2}}\times \frac{U_{ion}(T)}{U_a(T)}\exp\left(\frac{-E_{ion}}{kT}\right), \quad (3)$$

where me is the electron mass, E_{ion} – the ionization energy, $U_{ion}(T)$ and $U_a(T)$ are partition functions of ions and atoms, respectively; $g = 2$– the statistical weight of the electrons.

– the spectral brightness of the plasma radiation I in the wavelength range from λ to $\lambda + d\lambda$ is determined by the Planck's formula:

$$Id\lambda = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda kT)-1}d\lambda. \quad (4)$$

Because of the assumptions of LTE-model the energy balance of the system, which describes the interaction between input energy and energy transfer associated with the electrical conductivity and the radiation flux is as follows:

$$\frac{1}{2}\sigma\cdot P^2\cdot e^{-\frac{1}{\delta(x)}} = \Lambda\cdot T + \int_0^\infty[4\pi j_\lambda - k_\lambda I]d\lambda, \quad (5)$$

where P is the input power of the system; $\delta(x)$ is the skin depth ($\delta(x) = \sqrt{2/\mu_0\sigma(x)\omega}$), T is the temperature; σ, Λ are electrical and thermal conductivity, respectively; j_λ and k_λ are emission and absorption coefficients.

The emission coefficient is calculated as follows:

$$j_v(r) = \eta_A\eta_B\left(\frac{h}{\sqrt{2\pi\mu k_B T}}\right)^{1/3}\times \exp\left(\frac{V_Q(r)}{k_B T}\right)\frac{hvA_{QP}(v(r))}{4\pi}\frac{4\pi r^2}{|dv(r)/dr|}. \quad (6)$$

The spectral absorption coefficient can be determined using Planck's formula:

$$k_v(r) = \eta_A\eta_B\frac{c^2A_{QP}(v(r))}{8\pi v^2(r)}\times \frac{4\pi r^2}{|dv(r)/dr|}\left[\exp\left(\frac{-V_P(r)}{k_B T}\right)\right], \quad (7)$$

where we neglected the stimulated emission

The transition probability for the electron is:

$$A = \frac{16S_2^2\pi^3v^3}{3\frac{h}{2\pi}c^3}r_0^2, \quad (8)$$

where r_0 is the internuclear distance of the dimer.

Since the LTE model was accepted all the possible reactions occurred in the bulb, except the excitation of molecules, can be expressed by the equation of dissociation balance.

On basis of this mathematical model a computer model was developed, by the instrumentality of which emission spectrum characteristics were analyzed.

The simulated emission spectrum of sulfur lamp is presented on Fig.3.

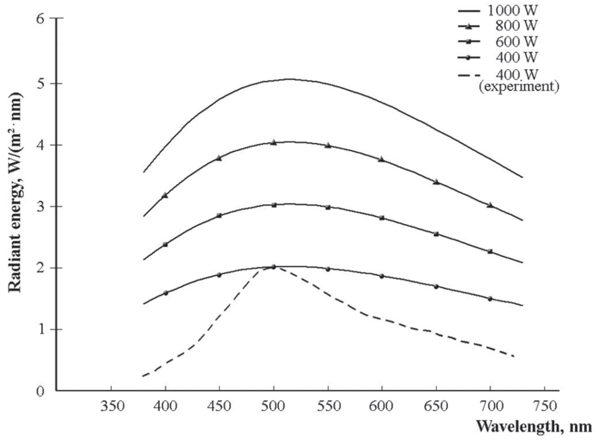

Fig. 3. Simulated emission spectrum of the sulfur microwave lamp for different values of input power

In our researches we considered the main mechanisms of energy exchange of a free electron with molecules and ions of sulfur in the field of electromagnetic radiation.

As it is generally known, the energy is transferred to the gas mixture through the collisions of electrons or other charged particles with neutral ones, which are the main component of natural gas:

$$S_2 + R \leftrightarrow 2S + R.$$

During inelastic interaction internal energy of an atom or molecule is changed. It may be the excitation of an atom or molecule to one of the higher energy level or its ionization:

$$S_2^- \leftrightarrow S_2 + e$$

$$S^- \leftrightarrow S + e.$$

If the electromagnetic field is large enough, some electrons acquire energy that exceeds the ionization energy without any inelastic collision. In this case secondary electron and positive ion may generated as a result of a collision (gas breakdown):

$$S + e \leftrightarrow S^{+} + e + e$$

$$S_2 + e \leftrightarrow S_2^{+} + e + e.$$

After performing calculations of equations of dissociation balance, we found that the dominant ion responsible for the emission of plasma is the ion S_2^{+}.

Using colorimetric formulas [3] for determining a color of self-luminous objects and selecting CIEL*a*b* color space (since a color description in this system in fact simulates process of color presentation by apparatus of human vision) for graphic representation of the color, we investigated the color spectrum of the sulfur lamp according to the method presented in [4, 5]. The color coverage of the real (A) and simulated (B) emission spectra of the sulfur lamp is shown in Fig. 4.

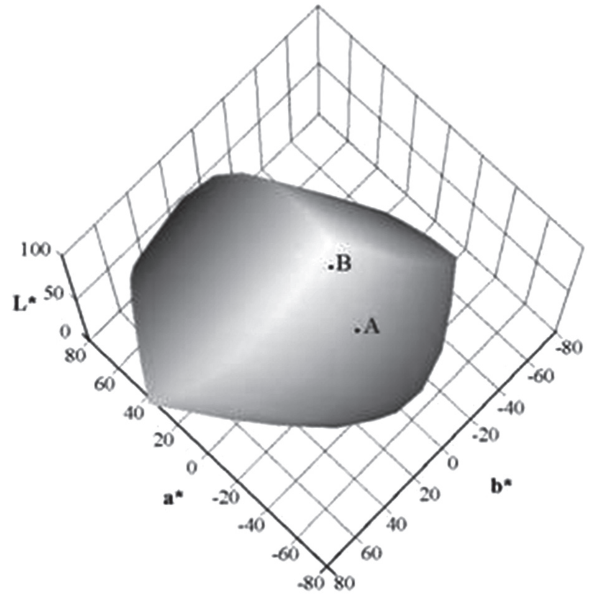

Fig. 4. Graph of color coverage of the real device radiation (A) and simulated spectrum (B)

As can be seen from Fig. 3 and 4, the spectrum of the simulated lamp has a higher intensity in the long-wave and short-wave regions, and it causes the color of the spectrum to shift closer to the white color area, while the real lamp radiation color has a greenish tint. This is probably due to the fact that the model takes into account only the emission of the dimer S_2^{+} and is not considered the effect of radiation from other modification of sulfur.

3. EFFECT OF PARAMETERS OF THE MICROWAVE FIELD ON THE EMISSION SPECTRUM OF SULFUR LAMP

Complex of numerical researches regarding the influence of the microwave field magnitude and the spatial position of the antinode on color and spectral characteristics of sulfur lamp was held. It was noticed that by using local thermal equilibrium model for description of sulfur plasma in nonelectrode lamps, microwave field parameters changes influence on a bulb temperature mode, therefore lamp spectrum behavior on different temperature profiles was studied: when whole bulb is irradiated (case 1), when the center of the bulb is irradiated (case 2), when irradiated maximum is displaced (case 3) (see Fig. 5).

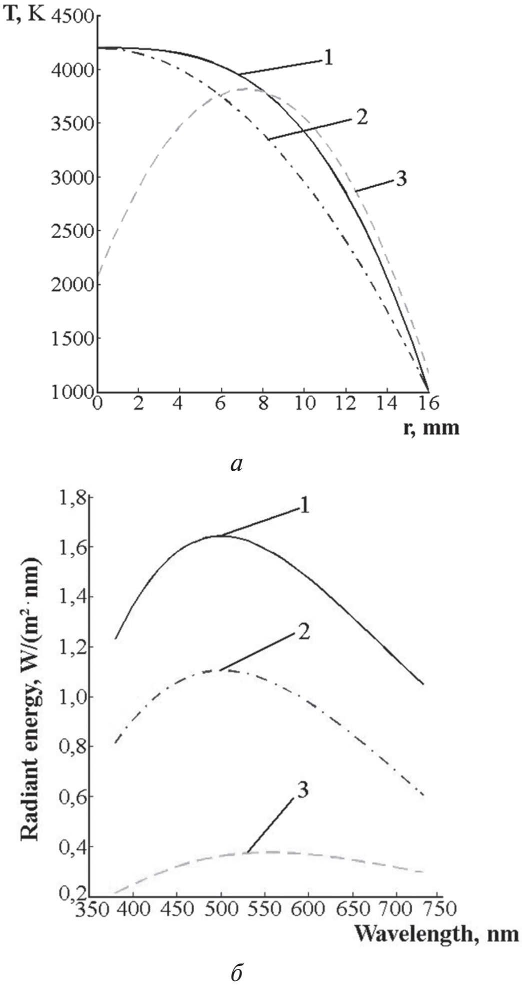

Fig. 5. Profiles of the plasma temperature in the bulb (*a*) and the corresponding emission spectrum of the sulfur lamp (*b*)

The research results show that maximum output radiation power is reached when microwave energy passes through whole bulb volume, in cases 2 and 3 the value of output energy decreases. When whole bulb volume or only its center is irradiated by microwave energy the lamp radiation color does not change while in case when microwave field antinode is displaced relative to the center of the bulb, the radiation color gets an orange hue. It happens because the sulfur plasma which is located in the center of the bulb doesn't get enough thermal energy as a result emission goes from lower energy levels.

Change of the color characteristics of the sulfur lamp emission for the cases 1–3 is shown on Fig. 6.

As can be seen on Fig. 6, when microwave energy irradiation of both whole volume of the bulb and only its center, the color of the emission spectrum does not change, while in the case of shift the antinode of the microwave field from the center of the lamp the color becomes light orange. It comes from the fact that sulfur plasma at the center of the bulb does not receive sufficient heat energy, as a result the emission occurs from lower energy levels.

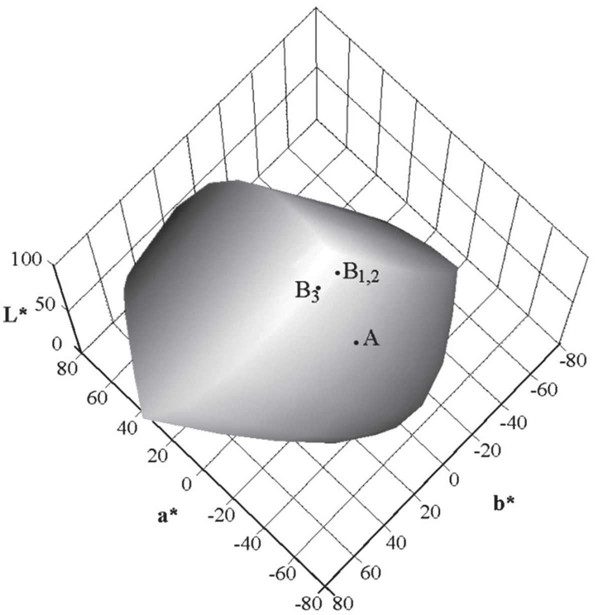

Fig. 6. Color space and areas that characterize emission colors of the simulated lamp (B) and the real one (A)

SUMMARY

Local thermodynamic equilibrium model that is used in this paper has wide application in modeling of the processes occurring in a high-pressure plasma [2, 6]. Within this model parameters that determine the state of the medium and effect of this medium on the emission characteristics of the object under study are selected, and it was done in this paper. From the results of researches made it follows that if in the process of sulfur lamp work there is a shift of the maximum of the microwave field from the center of the bulb, the radiated power will fall, and the emission spectrum will shift a little to shorter wavelengths and acquire an orange tint. When the diameter of the antinodes of the microwave field is less than the diameter of the bulb the color of light does not change, but the intensity of the output radiation decreases. The best result is given by the microwave energy exposure of the whole volume of the bulb.

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Изменение спектра излучения серной лампы при изменении свойств электромагнитного поля / Ю.П. Мачехин, Т.И. Фролова, Ю.А. Шунькова // Прикладная радиоэлектроника: научн.-техн. журнал. – 2011. Том 10. № 3. – С. 342-346.

Статья направлена на исследование поведения спектра излучения безэлектродной серной лампы в условиях изменения параметров СВЧ-поля, осуществляющего накачку системы. Рассмотрены случаи изменения величины и пространственного положения пучности СВЧ-поля. Полученные результаты дают возможность управлять выходным излучением лампы при изменении параметров СВЧ-поля, а также производить контроль энергии накачки исходя из излученного спектра серной лампы.

Клювевые слова: серная лампа, СВЧ, ЛТР-модель, цветовые характеристики, спектр излучения.

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Зміна спектра випромінювання сірчаної лампи при зміні властивостей електромагнітного поля /Ю.П. Мачехін, Т.І. Фролова, Ю.О. Шунькова // Прикладна радіоелектроніка: наук.-техн. журнал. – 2011. Том 10. № 3. – С. 342-346.

Стаття спрямована на дослідження поводження спектра випромінювання безелектродної сірчаної лампи в умовах зміни параметрів НВЧ-поля, що здійснює накачку системи. Розглянуто випадки зміни величини й просторового положення пучності НВЧ-поля. Отримані результати дають можливість управляти вихідним випромінюванням лампи при зміні параметрів НВЧ-поля, а також здійснювати контроль енергії накачування виходячи з випромененого спектру сірчаної лампи.

Ключові слова: сірчана лампа, НВЧ, ЛТР-модель, колірні характеристики, спектр випромінювання.

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