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OPTICAL CHARACTERISTICS AND PLASMA PARAMETERS OF THE GAS-DISCHARGE RADIATOR BASED ON A MIXTURE OF CADMIUM DIIODIDE VAPOR AND HELIUM

The optical characteristics and plasma parameters have been found for the gas-discharge radiator emitting in the red spectral interval and operating on a mixture of cadmium diiodide vapor and helium. The reduced electric field strength at which the specific discharge power spent for the excitation of exciplex cadmium monoiodide molecules is maximal is determined as well. Additional processes of population of the upper $B^2\Sigma^+_{1/2}$-state of exciplex cadmium monoiodide molecules giving rise to the radiation power growth have been revealed. The research results can be used to create a more efficient gas-discharge radiator emitting in the red spectral interval.

Keywords: barrier discharge, gas-discharge plasma, radiation emission by exciplex molecules, plasma parameters, cadmium diiodide, helium.

1. Introduction

Gas-discharge plasma ignited in a mixture of cadmium diiodide vapor with an inert gas is the source of a selective radiation in a spectral interval of 610–720 nm, which coincides with one of the radiation intervals for the active photosynthesis by plants, namely, 610–720 and 400–510 nm [1,2]. Sources emitting radiation in those spectral intervals are mainly used for artificial lighting. Here, the most widely used are high-pressure sodium lamps. One-third of the absorbed radiation power is converted and emitted by them in the spectral interval of active plant photosynthesis [3].

For the light control over photosynthesis together with the growth and development of plants and algae to be more efficient, the creation of a new generation of radiation sources with selective characteristics in the spectral ranges of 610–720 and 400–510 nm is required. LED lamps found the substantial practical application in those spectral intervals. They have the highest luminous efficiency among other light sources (100 lm/W). At the same time, it was found that the application of powerful (>100 W) LED lamps is limited by a necessity to cool them. Otherwise, they would lose their operational capability [4].

There is no such restriction on gas-discharge radiation sources (excilamps) in the visible spectral range. Furthermore, those sources possess a capability to scale the radiating surface without changing the specific energy characteristics [5–7]. In the 610–720-nm spectral interval, an exciplex gas-discharge radiator on the basis of mixtures of cadmium diiodide vapor and inert gases can play such a role [8–10]. The present work is devoted to the study of the optical characteristics and parameters of a plasma-discharge radiator based on the mixture of cadmium diiodide vapor and helium. The aim of the work is to reveal regularities both in the spectral, integral, and temporal characteristics of radiation emitted by excilamps

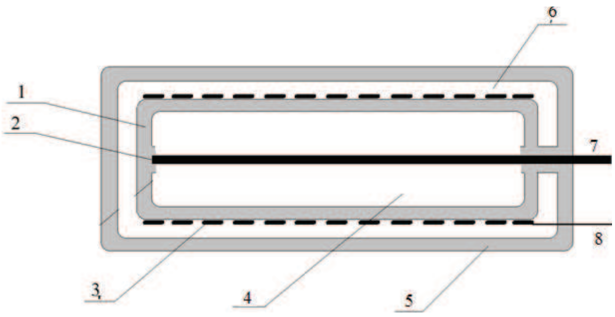

Fig. 1. Schematic diagram of exciplex radiator: quartz tube (*1*), electrode (*2*), perforated electrode (*3*), discharge region (*4*), quartz tube (*5*), vacuum (*6*), electrical inputs (*7, 8*)

and in their plasma parameters, which can be used to find physico-chemical capabilities to increase their energetic efficiency.

2. Experimental Equipment and Technique

Figure 1 schematically illustrates the main components of an exciplex gas-discharge radiator, in which a single-barrier discharge was used to create plasma in a working mixture of cadmium diiodide vapor and helium. The radiator had a cylindrical design. The lateral surface of the radiator served as the working area for radiation emission.

Exciplex gas-discharge radiator (*1*) was fabricated from a quartz tube 16 mm in diameter and 220 mm in length. Tungsten electrode (*2*) with a circular cross-section 4 mm in diameter was arranged along the tube axis. The second, stainless steel electrode (*3*) was perforated (with a radiation transmittance of 50%) and arranged on the outer surface of the tube. The diameter of discharge region (*4*) and the burning distance of the coaxial bulk discharge were 12 and 216 mm, respectively. The exciplex source was located in an end-welded quartz tube (*5*) 230 mm in length and 26 mm in diameter. The atmospheric air in volume (*6*) between the exciplex lamp and the quartz tube (*5*) was pumped out. The both electrodes (*2*) and (*3*) were supplied with a pulse-periodic voltage from a voltage pump source through metal-quartz input contacts (*7*) and (*8*).

The presence of volume (*6*), from which the atmospheric air was pumped out, in the design of the exciplex gas-discharge source was dictated by a necessity to provide high partial pressures of cadmium diiodide vapor in discharge region (*4*) by elevating the temperature of the working mixture. In turn, this enabled us to enhance the energy characteristics of the radiation source by 40% as compared to the radiator design without such a volume.

The radiation was emitted from quartz tube (*1*) normally to tube (*5*). A discharge was excited in a mixture of cadmium diiodide vapor and helium in the 31-cm^3 discharge region (*4*) with the help of a pulse-periodic generator of nanosecond high-voltage pulses. The generator provided the amplitudes of the voltage and current pulses at the radiator electrodes at levels of 10–20 kV and 300 A, respectively. The repetition rate of voltage and current pulses was 18–20 kHz.

The working mixtures were prepared immediately in the device volume. A 100-mg piece of cadmium diiodide (CdI_2) powder was evenly poured into quartz tube (*1*). After the salt was loaded, the radiator was dehydrated by heating it at 50 °C and pumping out for two hours; then, helium was introduced. The partial pressure of the saturated vapor of cadmium diiodide was created by heating the working gas-vapor mixture owing to the discharge energy dissipation. The partial pressure values were determined according to the temperature of the coldest radiator point by interpolating the reference data of work [11]. The partial pressure of helium was measured using a standard membrane pressure gauge. The spectral, integral, and temporal characteristics of the exciplex source were studied with the help of a registration system described in work [12].

3. Experimental Results

Figure 2 demonstrates a surveillance spectrum of radiation emitted by an exciplex source operating on the mixture of cadmium diiodide vapor and helium. The radiation spectrum of this mixture was characterized by the presence of a system of spectral bands associated with the $B^2\Sigma^+_{1/2} \rightarrow X^2\Sigma^+_{1/2}$ electron-vibrational transition in exciplex molecules of cadmium monoiodide (CdI^*) with a radiation maximum at the wavelength λ = 650 nm, $\nu' = 0$–$2 \rightarrow \nu'' = 61.62$ [13], a steep intensity growth of those spectral bands on their long-wavelength side, and their slow recession on their short-wavelength side. The heads of spectral bands overlapped a wavelength interval of 470–700 nm. Besides those spectral bands, radiation was also observed at the wavelengths $\lambda = 479.991$ and 508.582 nm (the $5p^3P^0$-$6s^3S$ ($J = 1$–

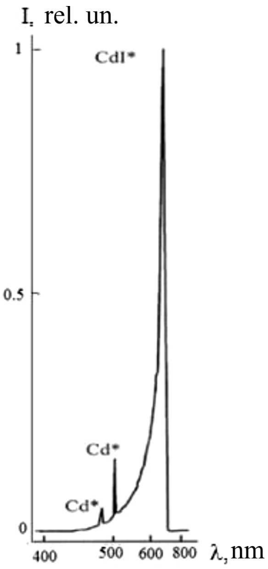

Fig. 2. Surveillance spectrum of radiation emitted by an exciplex source on a mixture of cadmium dioxide vapor with helium. The pump pulse repetition frequency f = 18 kHz, the voltage and current amplitudes U = 10 kV and I = 300 A, respectively. The total pressure of the mixture p = 250.024 kPa

1) and $5p^3P^0$-$6s^3S$ (J = 2–1) transitions in Cd atoms [14]). As the pump pulse repetition rate was changed from 18 to 20 kHz, the radiation intensity in the spectral bands and lines increased by 10%. The radiation intensity of CdI* molecules in its maximum located at the wavelength λ = 650 nm exceeded the radiation intensity of cadmium atoms at the wavelengths λ = 479.991 and 508.582 nm by 3.4 and 1.8 times, respectively.

The dependence of the average emitted power P on the partial helium pressure p_{He} is exhibited in Fig. 3. With the growth of p_{He} from 120 to 260 kPa, the power P first increased when p_{He} grew within an interval of 120–250 kPa, then reached a maximum value at p_{He} = 250 kPa, and finally decreased, as the helium pressure grew further. The partial pressure of cadmium diiodide vapor was p_{CdI_2} = 24 Pa.

When the partial pressure of cadmium diiodide vapor p_{CdI_2} was increased to 1000 Pa, the average radiation power first increased, when p_{CdI_2} grew within an interval of 1–100 Pa, then reached a maximum of 55 W at p_{CdI_2} = 100÷110 Pa, and finally decreased, as the pressure p_{CdI_2} increased further (Fig. 4). When measuring the dependence of the average radiation power P on the partial pressure of cadmium diiodide

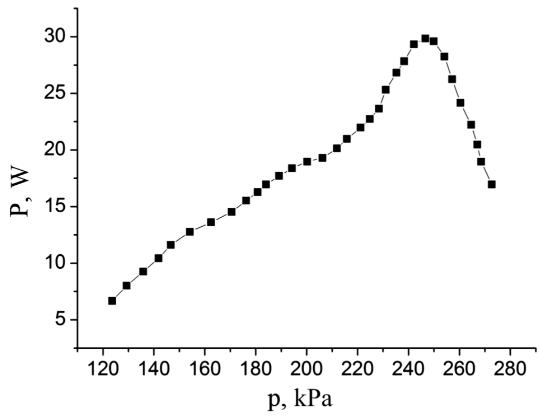

Fig. 3. Dependence of the average radiation power P on the partial pressure of helium p_{He}. The voltage and current amplitude U = 10 kV and I = 300 A, respectively. The pump pulse repetition frequency f = 20 kHz

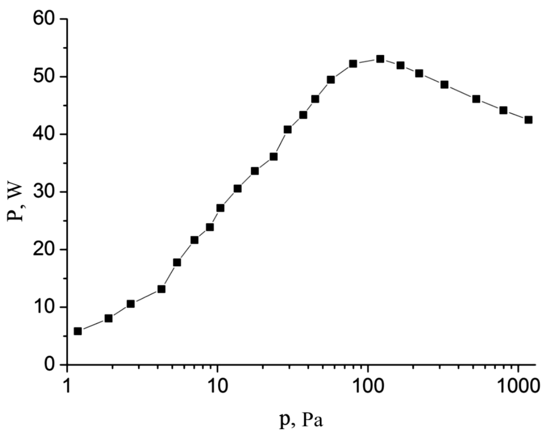

Fig. 4. Dependence of the average radiation power P on the partial pressure of cadmium diiodide vapor $p\mathrm{CdI}_2$ at a partial pressure of helium p_{He} = 250 kPa. The voltage and current amplitude U = 10 kV and I = 300 A, respectively. The pump pulse repetition frequency f = 20 kHz

vapor p_{CdI_2}, the latter was varied by heating the radiation source with the help of an external electric heater switched on after the partial pressure of the cadmium diiodide vapor had reached a value of 24 Pa.

In Fig. 5, the dependence of the radiation power on the number of pump pulses or the discharge burning time (i.e. the time of the visual observation of the discharge since the moment of its ignition by pump pulses). This dependence is characterized by a linear increase of the radiation power until the number of pulses reaches a value of 3.5×10^7. If the number of pump pulses increases further, the radiation power decreases by 11%.

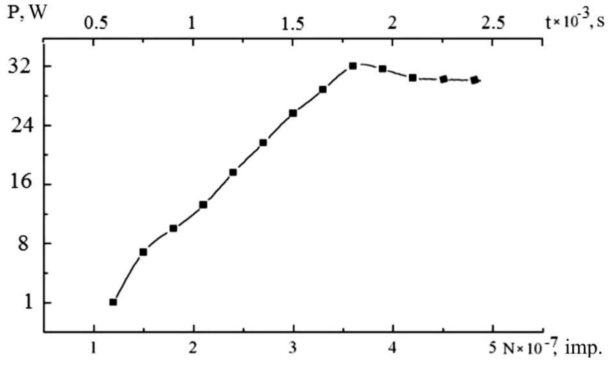

Fig. 5. Dependences of the average radiation power P on the number of pulses (bottom axis) and the discharge burning time (upper axis). The amplitude of voltage pulses $U = 10$ kV. The helium partial pressure $p_{\mathrm{He}} = 250$ kPa. The pulse repetition frequency $f = 20$ kHz

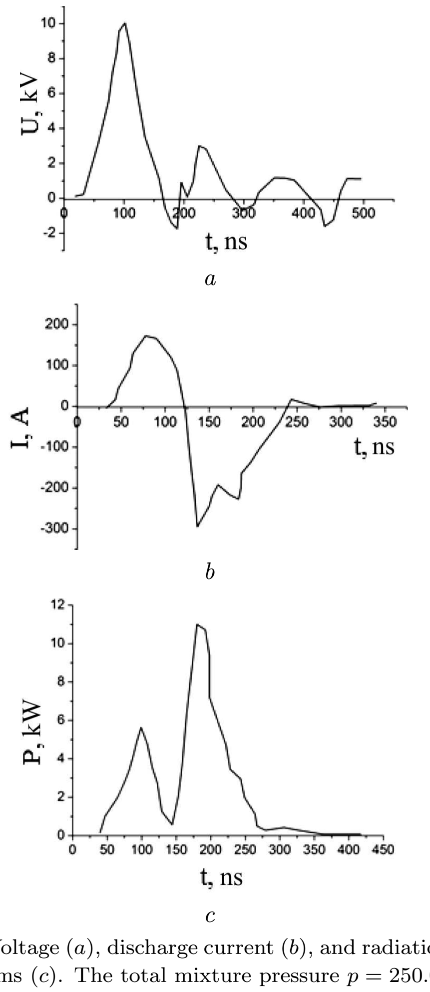

Fig. 6. Voltage (a), discharge current (b), and radiation power oscillograms (c). The total mixture pressure $p = 250.024$ kPa, the pulse repetition rate $f = 20$ kHz

The efficiency factor of the radiation source was 4.3% at an average radiation power of 32 W.

Figure 6 demonstrates characteristic voltage, discharge current, and radiation power oscillograms. The error and reproducibility of the results of oscilloscopic measurements were 10% and 90%, respectively. The current pulses had different polarities, with a maximum amplitude of 300 A and a duration of 150 ns.

The time dependence of the radiation power (Fig. 6, c) has two peaks, whose maxima coincide in time with the maxima of current pulses (Fig. 6, b). The amplitudes of the second current and radiation power pulses are larger than the amplitudes of the corresponding first pulses. The second radiation power pulse is characterized by a longer duration in whole and a longer trailing edge in comparison with their counterparts for the first pulse.

4. Numerical Simulation

In the experiment, we used an atmospheric-pressure pulse-periodic barrier discharge generated at a pump voltage pulse duration of 150 ns. Under the experimental conditions, the discharge was uniform. The optimal plasma parameters for obtaining the maximum radiation power from the electric barrier discharge in the CdI_2–He (0.000095 : 0.999905) mixture at a total pressure of 250.024 kPa were determined numerically. They were calculated as the complete integrals of the electron-energy distribution function (EEDF). The latter was found by solving the Boltzmann kinetic equation for the quasistationary electron distribution function [15]. Its application is valid, if the plasma environment changes in an electric field that varies more slowly than the electron distribution function relaxes to the equilibrium [15].

The time required for a quasistationary electron distribution to relax is known to be approximately equal to the relaxation time of the average electron energy [16],

$$\tau = \frac{m\nu_e\varepsilon}{e^2E^2},$$

where m is the electron mass, e the electron charge, ε the average electron energy, E the electric field strength, and ν_e is the frequency of elastic electron collisions with He atoms and CdI_2 molecules in the gaseous mixture. The estimate of the relaxation time

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τ for our experimental conditions gave a value of 1×10^{-13} s, which is much shorter than the pulse duration (150 ns). This circumstance means that the plasma environment changed in an electric field that varied more slowly than the relaxation time of the EEDF.

The EEDF was calculated making use of the well-known Bolsig+ software program [17]. The results of calculations were applied to determine a number of plasma parameters and their dependences on the magnitude of the reduced electric field (the ratio E/N between the electric field strength E and the total concentration N of helium atoms and a small admixture of cadmium diiodide molecules). The variation interval for the parameter E/N was 1–100 Td (1×10^{-17}–1×10^{-15} V cm^2), and it included the interval of E/N values that were realized in our experiment. All calculations were performed for the discharge at partial pressures of 24 Pa for cadmium diiodide and 250 kPa for helium, at which the maximum radiation power was reached in the experiment (Fig. 3).

In the integral of electron collisions with atoms and molecules, the following processes were taken into account: elastic electron scattering at helium atoms; excitation of energy levels in helium atoms (a threshold energy of 19.8 eV); ionization of helium atoms (a threshold energy of 24.58 eV); dissociative excitation of the $B^2\Sigma^+_{1/2}$ state of cadmium monoiodide molecules (a threshold energy of 4.986 eV) and cadmium atoms (at λ = 479.991 and 508.582 nm, a threshold energy of 6.386 eV); and dissociative ionization of cadmium diiodide molecules with the formation of cadmium diiodide (a threshold energy of 10 eV), cadmium monoiodide (a threshold energy of 11 eV), cadmium (a threshold energy of 13 eV), and iodine (a threshold energy of 14 eV) ions. The data for the effective cross-sections of those processes, as well as their dependences on the electron energy, were taken from database [17] and works [18, 19]. The electric field strength E and the reduced electric field strength E/N in plasma at which the observed radiation power in the spectral band of the cadmium monoiodide molecule (with $\lambda_{\max} = 650$ nm) was maximum were found to equal 2.0×10^6 V/m and 55.9 Td, respectively. They were determined using the method described in our work [12].

The numerical simulation of the electron transport characteristics in the mixture of cadmium diiodide vapor and helium at their partial pressure ratio $p_{\mathrm{CdI_2}} : p_{\mathrm{He}} = 24$ Pa : 250 kPa (see Fig. 7 and Table 1) showed that if the reduced field strength E/N in the plasma increases, the average energy ε of electrons, their temperature T, and drift velocity V_{dr} also increase, whereas their concentration N decreases. The constants of excitation and ionization rates of cadmium diiodide molecules and helium atoms by electrons (see Fig. 8 and Table 2) also increase with the E/N parameter. The maximum values are observed for the dissociative excitation constant of cadmium monoiodide molecules.

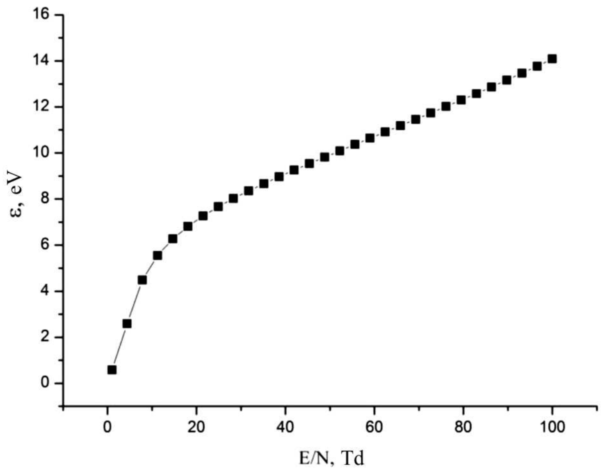

Fig. 7. The dependence of the average electron energy on the reduced electric field strength E/N in plasma in the mixture CdI_2–He (0.000095 : 0.999905) at the total pressure p = = 250.024 kPa

Specific power losses of the discharge in the mixture of cadmium diiodide vapor with helium owing to elastic and non-elastic electron collision processes with the mixture components were maximum for helium atoms (Fig. 9, curves *8*, *9* and *10*). For the elastic scattering of electrons by helium atoms, those losses reached 98% at a reduced electric field strength

Table 1. **Transport characteristics of electrons in plasma in the mixture of cadmium diiodide vapor and helium at the partial pressure ratio of components $p_{\mathrm{CdI_2}} : p_{\mathrm{He}} = 24$ Pa : 250 kPa**

E/N, Td	ε, eV	T^0, K	V_{dr}, m/s	N, m^3/s
7.83	4.490	52 084	1.6×10^5	4.2×10^{18}
55.9	10.37	120 292	1.7×10^5	4.0×10^{18}
100	14.09	163 444	1.9×10^5	3.6×10^{18}

Table 2. **Rate constants for excitation of the $B^2\Sigma^+_{1/2}$ state of CdI* exciplex molecules (k_{CdI^*}), excitation of cadmium atomic levels (k_{Cd^*}), ionization of CdI_2 molecules ($k_{CdI_2^+}$), electron elastic scattering (k_e), excitation of helium atomic levels (k_{He^*}), and ionization of helium atoms (k_{He^+}) in the mixture of cadmium diiodide vapor and helium at the partial pressure ratio of components $p_{CdI_2} : p_{He}$ = 24 Pa : 250 kPa**

E/N, Td	$k_{CdI^*} \times 10^{+15}$, m^3/s λ = 650 nm	$k_{Cd^*} \times 10^{+15}$, m^3/s λ = 479 nm	$k_{Cd^*} \times 10^{+15}$, m^3/s λ = 509 nm	$k^+_{CdI_2} \times 10^{+14}$, m^3/s	$k_r \times 10^{+14}$, m^3/s	$k_{He^*} \times 10^{+16}$, m^3/s	$k^+_{He} \times 10^{+17}$, m^3/s
	CdI_2				He		
7.83	3.002	0.1203	0.1804	0.2265	6.930	0.017	0.002
55.6	7.481	1.205	1.827	2.113	7.757	2.448	9.359
100	9.101	2.188	3.325	3.530	7.545	6.789	51.58

of 4.41 Td (Fig. 9, curve *9*). At the same time, for cadmium diiodide molecules, they did not exceed 1% for the dissociative excitation of the $B^2\Sigma^+_{1/2}$ state of CdI* exciplex molecules at E/N = 7.8 Td (Fig. 9, curve *4*)), being at a level of 0.05% for a reduced field strength of 55.9 Td at which the experimentally observed radiation emission power in the spectral band of cadmium monoiodide molecules with λ_{max} = 650 nm was maximum. With the increase of the E/N parameter value to 100 Td, the specific losses of the discharge power in the mixture became maximum (51%) for the excitation (a threshold energy of 19.80 eV) and ionization of helium atoms (Fig. 9, curves *10* and *8*, respectively). For the ionization of cadmium diiodide molecules with the formation of CdI_2^+ ions, the specific discharge power losses were 1.5% at E/N = 11.2 Td. For a reduced field strength of 55.9 Td, the specific losses of the discharge power spent for the ionization of helium atoms and cadmium diiodide molecules were 31% and 2.5%, respectively. For the excitation of a metastable helium energy level with a threshold energy of 19.80 eV, the specific power losses were maximum and equal to 90%.

Because of high losses of the discharge power spent on the excitation of the metastable energy level of helium atoms (a threshold energy of 19.80 eV), we may expect that the process of energy transfer from metastable helium atoms to cadmium diiodide molecules should affect the amplitude and shape of the radiation pulse (Fig. 6, *c*). This assumption is confirmed by a modification in the shape of the second radiation pulse as compared to that of the current pulse (Fig. 6, *b*). One may also expect a substantial increase of the radiation power in the spectral band of cadmium monoiodide molecules with λ_{max} = 650 nm when applying a field with a reduced strength of 7.8 Td, at which the discharge power losses for the dissociative excitation of the $B^2\Sigma^+_{1/2}$ state of CdI* exciplex molecules are maximum.

5. Discussion of the Results

The spectral bands with the maximum at the wavelength λ = 650 nm correspond to the electron-vibrational transition $B^2\Sigma^+_{1/2} \rightarrow X^2\Sigma^+_{1/2}$ of the CdI* molecule in gas-discharge plasma in the mixtures of cadmium diiodide vapor with helium. They are a result of processes leading to the formation and destruction of the $B^2\Sigma^+_{1/2}$ state of a cadmium monoiodide molecule. The major of them are as follows [4, 20]:

$$\mathrm{CdI_2} + e^- \rightarrow \mathrm{CdI_2}(^{3,1}\Sigma^+_u) \rightarrow \mathrm{CdI}(B^2\Sigma^+_{1/2}) + \mathrm{I} + e^-, \quad (1)$$

$$\text{or} \rightarrow \mathrm{CdI}(B^2\Sigma^+_{1/2}) + \mathrm{I}^-, \quad (2)$$

$$\mathrm{CdI}(B^2\Sigma^+_{1/2}) \rightarrow \mathrm{CdI}(X^2\Sigma^+_{1/2}) + h\nu \quad (3)$$

$(\lambda_{max} = 650\ \text{nm})$,

and

$$\mathrm{CdI}(B^2\Sigma^+_{1/2}) + M \rightarrow \mathrm{CdI}(X^2\Sigma^+_{1/2}) + M + \Delta E, \quad (4)$$

where M stands for the CdI_2 molecules and He atoms, and ΔE is the reaction energy difference. As follows from the time dependences of the current and radiation power amplitudes (see Figs. 6, *b* and *c*) [1], reactions (1) and (2) are the main sources

[1] The time difference between the beginning and the maximum of the pulse was the same for the current and radiation power pulses to within an oscilloscope measurement error of 10%.

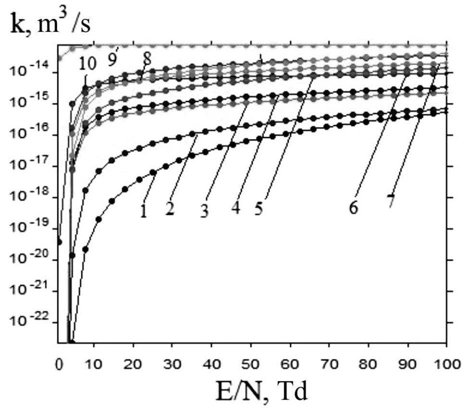

Fig. 8. Dependences of the rate constants of electron collisions with cadmium diiodide molecules and helium atoms in the mixture of cadmium diiodide vapor and helium CdI_2–He (0.000095 : 0.999905) on the parameter E/N at the total pressure in the mixture p = 250.024 kPa: ionization of a helium atom (*1*), excitation of the helium atomic level (the threshold energy E_{th} = 19.8 eV) (*2*), dissociative excitation of a cadmium atom (E_{th} = 9.85 eV, λ = 479.991 nm) (*3*), dissociative excitation of a cadmium atom (E_{th} = 9.85 eV, λ = 508.582 nm) (*4*), dissociative ionization of a cadmium monoiodide molecule (E_{th} = 11 eV) (*5*), dissociative ionization of a cadmium atom (E_{th} = 13 eV) (*6*), ionization of a cadmium diiodide molecule (E_{th} = 10 eV) (*7*), dissociative ionization of an iodine atom (E_{th} = 14 eV) (*8*), elastic electron scattering by a helium atom (*9*), dissociative excitation of the $B^2\Sigma_1/2^+$ state of a cadmium monoiodide molecule (E_{th} = 5 eV) (*10*)

of the generation of CdI* exciplex molecules. The electron-vibrational transitions $B^2\Sigma^+_{1/2} \rightarrow X^2\Sigma^+_{1/2}$ of CdI* molecules give rise to the emission of spectral bands with the maximum intensity at the wavelength λ_{max} = 650 nm [reaction (3)]. The quenching reaction (4) describes the electron-vibrational transition of a cadmium monoiodide molecule into the ground state without radiation emission.

The emission of cadmium spectral lines takes place owing to the reactions [21]

$$CdI_2 + e^- \rightarrow Cd(5p^3P^0) + I + I^-, \quad (5)$$

$$Cd(5p^3P^0) \rightarrow Cd(6s^3S^0, \quad J = 1\text{–}1) + h\nu \quad (6)$$

(λ = 479.991 nm),

and

$$Cd(5p^3P^0) \rightarrow Cd(6s^3S^0, \quad J = 2\text{–}1) + h\nu \quad (7)$$

(λ = 508.582 nm).

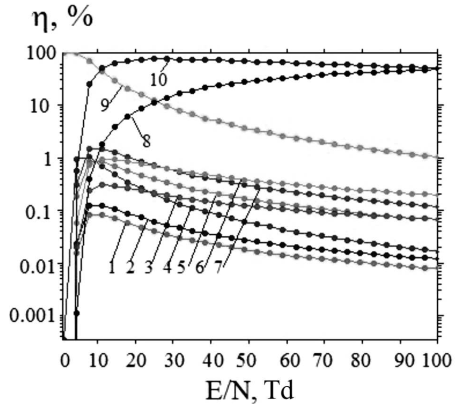

Fig. 9. Dependences of specific discharge power losses spent on electron collisions with cadmium diode molecules and helium atoms in the mixture of cadmium diiodide vapor and helium CdI_2–He (0.000095 : 0.999905) on the parameter E/N at the total pressure in the mixture p = 250.024 kPa: dissociative excitation of a cadmium atoms (E_{th} = 9.85 eV, λ = 479.991 nm) (*1*), dissociative excitation of a cadmium atom (E_{th} = 9.85 eV, λ = 508.582 nm) (*2*), dissociative ionization of a cadmium atoms (E_{th} = 13 eV) (*3*), dissociative excitation of the $B^2\Sigma_1/2^+$ state of cadmium monoiodide molecules (E_{th} = 5 eV) (*4*), dissociative ionization of a cadmium monoiodide molecule (E_{th} = 11 eV) (*5*), dissociative ionization of iodine atoms (E_{th} = 14 eV) (*6*), ionization of cadmium diiodide molecules (E_{th} = 10 eV) (*7*), ionization of helium atoms (*8*), elastic electron scattering by helium atoms (*9*), excitation of the helium atomic level (the threshold energy E_{th} = 19.8 eV) (*10*)

The excitation rate constant equals 7.481×10^{-15} m^3/s for the $B^2\Sigma^+_{1/2}$ state of a cadmium monoiodide exciplex molecule, and 1.203×10^{-15} and 1.804×10^{-15} m^3/s for cadmium atoms at the reduced electric field strength E/N = 55.9 Td, which took place for the mixture of cadmium diiodide vapor and helium under our experimental conditions (see Table 2). A contribution of the discharge power to the excitation of the $B^2\Sigma^+_{1/2}$ state of CdI* exciplex molecules [reactions (1)–(3)] was about 0.05% at a reduced field strength of 55.9 Td (Fig. 9, curve *4*), which could not provide an experimental efficiency value of 4.3%. In this connection, additional processes for the population of the $B^2\Sigma^+_{1/2}$ state of CdI* exciplex molecules should be considered:

$$CdI_2 + e^- \rightarrow CdI_2(D) \rightarrow$$
$$\rightarrow CdI(C^2\Pi_{1/2}, D^2\Pi_{3/2}) + I + e^- \quad (8)$$

and

$$\mathrm{CdI}(C^2\Pi_{1/2}, D^2\Pi_{3/2}) + \mathrm{CdI_2(He)} \rightarrow$$
$$\rightarrow \mathrm{CdI}(B^2\Sigma^+_{1/2}) + \mathrm{CdI_2(He)} + \Delta E_{1,2}. \quad (9)$$

Formula (8) describes the excitation of CdI_2 molecules into the state D by electrons [22, 23]. This state is the sum of all states of a cadmium diiodide molecule located between the threshold (5 eV) and ionization (11 eV) energies [22]. One may expect that the effective excitation cross-section of this state in a cadmium diiodide molecule by electrons is close to the corresponding parameter for the D state of a mercury dibromide molecule (about 10^{-15} cm^2 [23]). No emission is observed from the D state of a CdI_2 molecule, because this state predissociates with the formation of a cadmium monoiodide molecule in the C and D states. The emission from the latter states was also not observed under our experimental conditions owing to a high efficiency of the quenching process (9) [23]. The population of this state is transferred to the $B^2\Sigma^+_{1/2}$ state of CdI_2 molecules or into other non-optical channels [23, 24].

A drastic increase of the radiation intensity on the large-wavelength side of the spectrum and its slow decrease at short wavelengths (Fig. 2) are explained by the behavior of potential curves (the excited $B^2\Sigma^+_{1/2}$ state is shifted toward longer internuclear distances with respect to the $X^2\Sigma^+_{1/2}$ state), as well as the processes of population relaxation on upper vibrational levels of the excited electron state, which are more rapid than the electron-vibrational transition into the ground $X^2\Sigma^+_{1/2}$ state [25].

The fact that the partial pressure of the helium buffer gas has an optimum value (Fig. 3) is connected with the discharge energy fraction spent for the heating of a working mixture [26]. As the total pressure in the mixture increases, the E/N parameter decreases. As a result, the specific losses of the discharge power on the elastic scattering of electrons at atoms and molecules increase (Fig. 9, curve *9*), the mixture is heated, and, consequently, the partial pressure of cadmium diiodide vapor and the radiation power emitted by CdI* molecules grow. If the helium pressure increases further, the presence of the maximum in the dependence of the radiation power P of CdI* molecules on the helium pressure p_{He} (Fig. 3) is a result of two factors: (i) a reduction in the average energy of electrons (see Fig. 6 and Table 1), which, in turn, leads to a lower rate constant for the dissociative excitation of the $B^2\Sigma^+_{1/2}$ state of a CdI* molecule by electrons in the gas-discharge plasma [see Fig. 7, curve 4 and reaction (1)]; and (ii) the quenching process of the $B^2\Sigma^+_{1/2}$ state of cadmium monoiodide molecules by helium,

$$\mathrm{CdI}(B^2\Sigma^+_{1/2}) + \mathrm{He} \rightarrow \mathrm{CdI}(X^2\Sigma^+_{1/2}) + \mathrm{He} + \Delta E, \quad (10)$$

where ΔE is the reaction energy difference released in the form of heat.

The dependence of the average radiation power P on the partial pressure of cadmium diiodide vapor $p_{\mathrm{CdI_2}}$ (Fig. 4) is explained by the growth in the concentration of molecules in the $B^2\Sigma^+_{1/2}$ state, as their partial pressure increases, and by the process of their quenching. The optimum partial pressures for cadmium diiodide vapor are determined by an establishment of a dynamic equilibrium between those processes. Above a certain value of the partial cadmium diiodide vapor pressure, the quenching process

$$\mathrm{CdI}(B^2\Sigma^+_{1/2}) + \mathrm{CdI_2} \rightarrow \mathrm{CdI}(X^2\Sigma^+_{1/2}) + \mathrm{CdI_2} + \Delta E, \quad (11)$$

where ΔE is also the reaction energy difference released in the form of heat, begins to play a substantial role. Therefore, the radiation power decreases. The corresponding rate constant equals $(9.2 \pm 1.1) \times 10^{-10}$ cm^3/s [27].

The increase in the radiation power P with the growth of the number of pump pulses N (Fig. 5) is governed by the process of discharge energy dissipation. Namely, at a larger number of pump pulses, the mixture becomes more heated, and, accordingly, the partial pressure of cadmium diode vapor and the power of radiation emission by means of processes (1)–(3) increase. The saturation in the dependence of the radiation power on the number of pump pulses, its further decrease by 11%, and stabilization at a level of 32 W are induced by the quenching process (9) and the stabilization of the working mixture temperature.

The oscillatory character of the voltage pulse amplitude (Fig. 6, *a*) is a result of the mismatch between the output impedance of a voltage generator and the input impedance of a radiation source. The structure of the current pulse (Fig. 6, *b*) is associated with the charging and discharging of the insulator capacitance during a voltage pulse, the amplitude of which is sufficient to break down the discharge gap [28]. The difference between the front- and back-edge shapes of current pulses appears due to the opposite directions of the current flow through the gas gap. Accordingly, there arise different conditions of charge absorption at the internal insulator surface in the case of a single-barrier discharge, which was realized in our experiment. The temporal broadening of both the second power radiation pulse and its back edge in comparison with the first pulse is caused by the accumulation of cadmium monoiodide in the ground energy state within the time interval between the pulses, because not all cadmium monoiodide molecules have enough time to recover via the process [27]

$$\mathrm{CdI}(X^2\Sigma^+_{1/2}) + \mathrm{I} + \mathrm{He} \to \mathrm{CdI_2} + \mathrm{He}.$$

This ultimately modifies the amplitude and the temporal behavior of the second pulse by increasing the population of the $B^2\Sigma^+_{1/2}$ state of cadmium monoiodide through the electron excitation of the $X^2\Sigma^+_{1/2}$ state,

$$\mathrm{CdI}(X^2\Sigma^+_{1/2}) + e^- \to \mathrm{CdI}(B^2\Sigma^+_{1/2}) + e^-.$$

6. Conclusions

To summarize, in this work, we have studied the optical characteristics (in the red spectral interval) and some other parameters of the plasma created in a mixture of cadmium diiodide vapor with helium by a pulse-periodic barrier discharge excited in an exciplex gas-discharge radiator. It is found that the radiation spectrum of the given source is mainly composed of the bands emitted by cadmium monoiodide molecules. Those bands are located within an interval of 470–700 nm, with the maximum intensity at the wavelength $\lambda = 650$ nm. More than 90% of the radiation power is concentrated in the red spectral interval. The application of a heat-insulating screen in the radiator construction allowed the radiation power to be increased by 40%. We have determined the partial pressures of cadmium diiodide vapor and helium at which the maximum values of the average and peak radiation power are obtained. Additional processes giving rise to the population growth in the $B^2\Sigma^+_{1/2}$ state of cadmium monoiodide exciplex molecules due to the quenching process of transitions from the $C^2\Pi_{1/2}$ and $D^2\Pi_{3/2}$ states at electron collisions with cadmium diiodide molecules and helium atoms are revealed. The magnitude of the reduced electric field strength at which the specific contribution of the electric discharge power to the excitation of the $B^2\Sigma^+_{1/2}$ state of cadmium monoiodide molecules is maximum was determined. The obtained value equals 7.8 Td, which makes it possible to enhance the energy parameters of a gas-discharge radiator operating on the mixture of cadmium diiodide vapor and helium and emitting in the red spectral interval. Gas-discharge radiators of this kind can be used to more effectively control the photosynthesis process, as well as the growth and development of plants and algae.

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ОПТИЧНІ ХАРАКТЕРИСТИКИ І ПАРАМЕТРИ ПЛАЗМИ ГАЗОРОЗРЯДНОГО ВИПРОМІНЮВАЧА НА СУМІШІ ПАРІВ ДИЙОДИДУ КАДМІЮ ТА ГЕЛІЮ

Встановлено оптичні характеристики та параметри плазми газорозрядного випромінювача червоного спектрального діапазону на суміші парів дийодиду кадмію та гелію, величину приведеної напруженості електричного поля, при якій питома потужність розряду, що вноситься в збудження ексиплексних молекул монойодиду кадмію, максимальна. Встановлено додаткові процеси заселення верхнього $B^2\Sigma^+_{1/2}$-стану ексиплексної молекули монойодиду кадмію, які збільшують потужність випромінювання. Результати досліджень можуть бути використані для створення більш ефективного газорозрядного випромінювача, що працює в червоному спектральному діапазоні.

Ключові слова: бар'єрний розряд, газорозрядна плазма, випромінювання ексиплексних молекул, параметри плазми, дийодид кадмію, гелій.