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NUMERICAL MODEL OF LASER LEVEL POPULATION IN HELIUM-CADMIUM GAS DISCHARGE

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Abstract. A numerical model of eight energy levels describing the population of laser upper level Cd(II) $5s^2\,^2D_{5/2}$ for the line 441.6 nm in a cross section of He–Cd radio frequency gas discharge is presented. An optimization of the laser level population with respect to the applied electrode voltage at a constant electric power is carried out. It is established that under certain conditions the principle population mechanisms are the stepwise electron excitation and/or the Penning effect. Engineering solutions for effective control of the laser emission are proposed.

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1. Introduction

The enhancement of the output laser power for a large number of gas lasers, including metal vapor lasers, depends on the evaluation of many parameters, such as geometrical characteristics, types and quantities of the laser construction materials, electrical characteristics, conditions of the surroundings, etc. A complete investigation, which takes into account the degree of influence of any of these parameters on the laser emission quality and quantity, does not exist. Moreover, the specific role of the most of the parameters in RF discharge cannot be established experimentally, because of the great influence of the high frequency field. At these conditions, the numerical modeling gives an effective opportunity and is a question of present interest. The development of appropriate models would allow predicting the laser system behavior in order to improve its total efficiency.

In the present work we investigate numerically the laser population distribution of the Cd(II) $5s^2\,{}^2D_{5/2}$ level for the generation of the 441.6 nm line in a radio frequency excited He–Cd discharge. As a rule, the increase of the applied electric power leads to the rising of the laser emission. However, this process has its natural limits. At high electric power the laser medium overheats and thermoionization processes arise, which provokes laser emission deterioration and a decrease of the total laser generation. Therefore, an optimization of the laser level population at a constant electric power is of interest. That will provide a permanent temperature profile of neutral atoms and thermoionization stability of the gas discharge.

Another question of interest is the establishment of the principle excitation mechanisms, which create the population inversions in He–Cd$^+$ laser. During the last thirty years, many publications have been devoted to this problem (see for instance [1–3]). In paper [1] for the DC (direct current) discharge it has been calculated that the main population mechanism is the stepwise electron excitation: $\mathrm{Cd}^+ + e^- \longrightarrow \mathrm{Cd}^{+*} + e^-$. For the discharge in a hollow cathode it has been established a predominance of the Penning effect: $\mathrm{He}_m + \mathrm{Cd} \longrightarrow \mathrm{He} + \mathrm{Cd}^{+*}(5s^2\,{}^2D_{5/2}) + e^-$ over the stepwise excitation [2]. For RF discharge the Penning effect has been also indicated as a principle population mechanism [3].

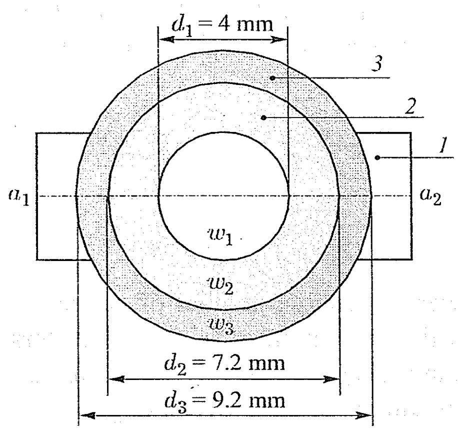

Fig. 1. Design of the He–Cd$^+$ laser tube 1) two outer longitudinal electrodes; 2) internal Al_2O_3 tube; 3) external quartz tube

In this study, we present a model describing the laser population of the $5s^{2\,2}D_{5/2}$ level of the cadmium-ion upper level of the important blue laser transition at 441.6 nm in a cross section of a radio frequency excited He–Cd discharge. The calculations are carried out for laser design constructed in the recent paper [4] at a constant applied electric power. The laser geometry is shown in Fig. 1. The relative influence of a number of parameters on the quality and quantity of the laser level population was estimated. Considerable attention was paid to the possible engineering solutions.

2. Preliminaries

The model is based on the preliminary determination of the following gas discharge macrocharacteristics: intensity of the electric field, gas temperature, EEDF of low-temperature bulk electrons. These macrocharacteristics were calculated by the methods, given in [5-7]. To clarify our further considerations here we present briefly some of the results, which have been obtained.

The electric field intensity E has been found as a solution of a quasi-stationary Poisson equation, subject to given boundary conditions at a specific distribution of the charged particles for the RF discharge. The problem has been solved in the cross section of the laser tube. Some distributions of the calculated intensities E on the line $a1-a2$ for different electrode voltages at a constant electric power P are shown in Fig. 2, where the influence of the electrode voltage U_a on the behavior of the intensity E can be seen. The maximum value of E in all the cases is near the "higher" electrode with the voltage U_a. On the left electrode the voltage is zero.

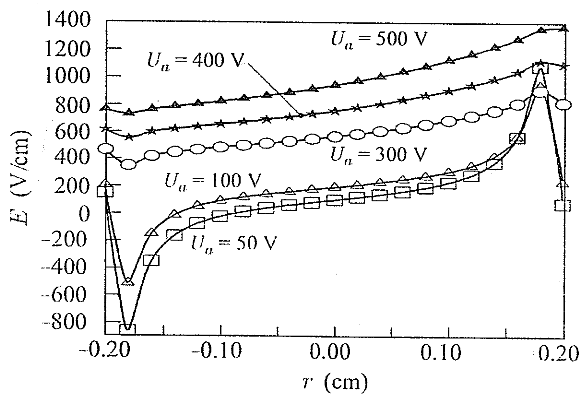

Fig. 2. Distribution of the electric field intensity E on the line a_1-a_2 for different values of the electrode voltages $U_a = 100$, 300, 400, and 500 V at a constant applied power $P = 360$ W

The temperature of the neutral gas T_g has been determined by solving a mixed boundary problem for two-dimensional conduction equation. The distribution of T_g on the line $a1-a2$ is illustrated in Fig. 3. It should be mentioned that the maximum value of T_g is slightly shifted to the direction of the "higher" electrode, where the electrode voltage U_a is applied. The highest temperature value on the outer surface of the laser tube has been achieved in the point $a2$.

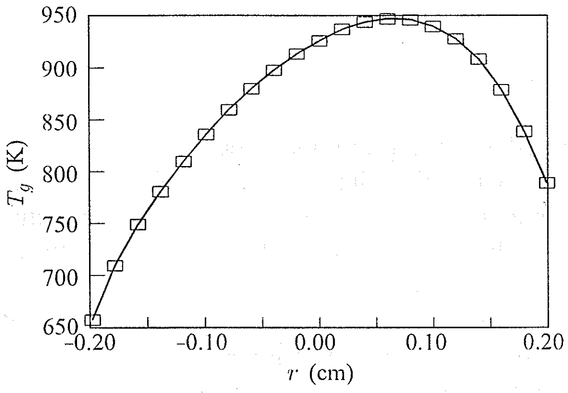

Fig. 3. Gas temperature distribution T_g in a cross section of the laser tube on the line a_1-a_2. Maximum value $T_{\max} = 947$ K

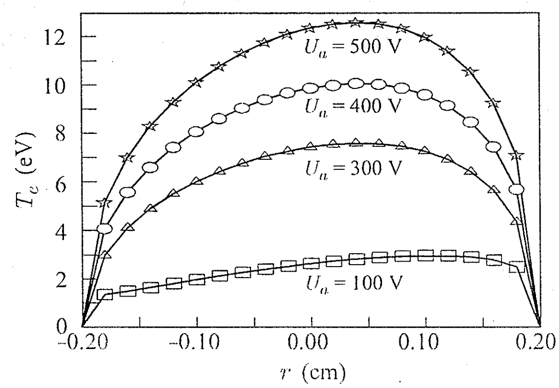

Fig. 4. Distribution of the electron temperature T_e on the line a_1-a_2 for different values of the electrode voltages $U_a = 100, 300, 400$, and 500 V at a constant applied power $P = 360$ W

The energy of the main group of the low-temperature electrons has been carried out by solving the electron conductivity equation. This approach is possible under the assumption of a Maxwellian distribution of these electrons. Figure 4 shows the distribution of T_e on the line a_1-a_2 for some electrode voltages U_a at $P = \text{const}$. The dependence between the intensity E and the electron temperature T_e can be seen.

3. Numerical Model

In order to investigate the properties and principal excitation mechanisms, which create the population inversions in He-Cd$^+$ laser, let us consider the following mathematical model of eight balance equations:

$$-D_1\beta_1^2\text{He}_m + n_e\text{He}S_1 - n_e\text{He}_m(S_2+S_3+S_4+S_5) - \text{He}_m^2\beta_2 - k_1\text{He}_m\text{Cd} = 0 \quad (1)$$

$$-D_2\beta_1^2\text{He}^+ + n_e\text{He}S_6 + n_e\text{He}_m(S_4+S_5) + \frac{1}{2}f_1\text{He}_m^2\beta_2 - \text{He}^+\text{He}^2\chi_1 - k_9\text{He}^+\text{Cd} = 0 \quad (2)$$

$$-D_3\beta_1^2\text{He}_2^+ + \frac{1}{2}(1-f_1)\text{He}_m^2\beta_2 + \text{He}^+\text{He}^2\chi_1 = 0 \quad (3)$$

$$\text{He} = \frac{p_{\text{He}}}{kT_g} \quad (4)$$

$$k_2n_e\text{Cd} + k_3n_e\text{Cd}^+ + k_4\text{He}_m\text{Cd} - (\chi_2+\beta_3n_e)\text{Cd}^{+*} = 0 \quad (5)$$

$$k_5n_e\text{Cd} + k_6n_e\text{Cd}_m + k_7\text{He}_m\text{Cd} - (\chi_3+k_3n_e)\text{Cd}^+ = 0 \quad (6)$$

$$k_8n_e\text{Cd} - (\chi_4+k_6n_e)\text{Cd}_m = 0 \quad (7)$$

$$\text{Cd} = \frac{p_{\text{Cd}}}{kT_g}. \quad (8)$$

These equations describe four levels for helium as follows: 1) He$_m$, the metastable atom; 2) He$^+$, the atomic positive ions; 3) He$_2^+$, the molecular positive ions; 4) He, the ground level neutral particles of the helium. For cadmium the four levels are respectively: 5) Cd^{+*}, the excited cadmium ion ($5s^2\,{}^2D_{5/2}$); 6) Cd$^+$, the cadmium ion; 7) Cd$_m$, the atomic metastable level; 8) Cd, the ground level of the cadmium density. In accordance with the experimental data from [8], the lower laser level $5p^2P_{3/2}$ is omitted, because of the more rapid decay of this level, having population density about 40 times smaller than that of the level $5s^2\,{}^2D_{5/2}$.

In order to derive the above eight levels we use the equations, given in [9] and [3]. In [9] the RF discharge in pure helium with turbulent flow has been described by means of five levels. In [3] for a He-Cd$^+$ laser operating in the conditions of DC discharge a system of six levels (two levels for helium and four levels for cadmium) has been considered. In our model, we select eight of the levels from [9], [3] and the appropriate terms, representing the processes, which could be responsible for populating the upper laser level $5s^2\,^2D_{5/2}$ in RF discharge. The levels and corresponding coefficients, included in (1)–(8), are illustrated in Fig. 5.

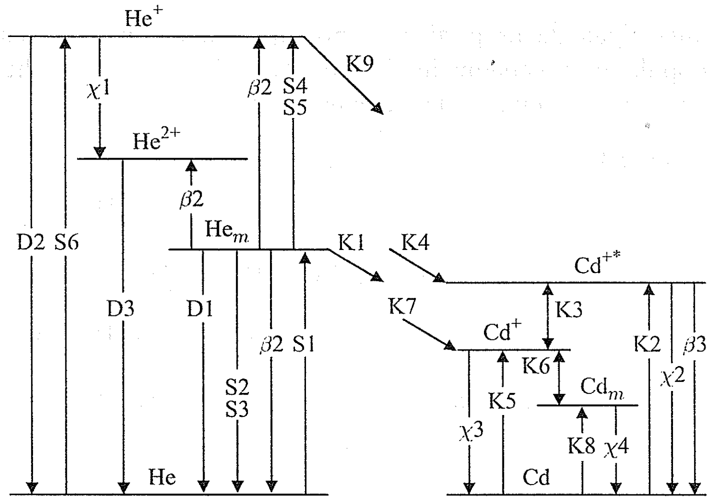

Fig. 5. General scheme of eight energy levels and coefficients interrelations, included in the numerical model (1–8)

The notations used in Eqs (1–8) are as follows: D_1 is the diffusion coefficient of atomic metastables of the He; D_2 is the ambipolar diffusion of atomic ions of the He; D_3 is the ambipolar diffusions of molecular ions of the He; S_1 is the rate coefficient for generation of atomic metastable by inelastic collisions of the tail electrons with the ground-level neutrals: $\mathrm{He} + e^- \rightarrow \mathrm{He}_m + e^-$; S_2 is the rate coefficient for superelastic collisions by bulk electrons with atomic metastables: $\mathrm{He}_m + e^- \rightarrow \mathrm{He} + e^-$; S_3 is the rate coefficient for superelastic collisions by tail electrons with atomic metastables: $\mathrm{He}_m + e^- \rightarrow \mathrm{He} + e^-$; S_4 is the rate coefficient for ionization of atomic metastables to form atomic ions by collisions with the bulk electrons: $\mathrm{He}_m + e^- \rightarrow \mathrm{He}^+ + e^- + e^-$; S_5 is the rate coefficient for ionization of atomic metastables to form atomic ions by collisions with the tail electrons: $\mathrm{He}_m + e^- \rightarrow \mathrm{He}^+ + e^- + e^-$; S_6 is the rate coefficient for ionization of ground-level neutrals by collisions with the tail electrons to form atomic ions: $\mathrm{He} + e^- \rightarrow \mathrm{He}^+ + e^- + e^-$; $\beta_1 = 3.03/d$ is the radial distribution of the electron number density n_e [9]; β_2 is the rate coefficient for [atomic metastable]-[atomic metastable ionizing] collisions: $\mathrm{He}_m + \mathrm{He}_m \rightarrow \mathrm{He} + \mathrm{He}^+ + e^-$ and $\mathrm{He}_m + \mathrm{He}_m \rightarrow \mathrm{He}_2^+ + e^-$; β_3 is the coefficient for the electron failure of the Cd^{*+} atom; f_1 is the fraction of [atomic metastable]-[atomic metastable ionizing] collisions forming atomic ions: $\mathrm{He}_m + \mathrm{He}_m \rightarrow \mathrm{He} + \mathrm{He}^+ + e^-$

and $He_m + He_m \rightarrow He_2^+ + e^-$; k_1 is the rate coefficient for common loss of the helium metastable atom in all metastable levels during the Penning effect: $He_m(2^3S_1, 2^1S_0, 2^3P, 2^1P) + Cd \rightarrow He + Cd^{*+}(5s^2\,{}^2D_{5/2}) + e^-$ [10]; k_2 is the rate coefficient for direct electron excitation in laser upper level of the Cd^{*+} atom: $Cd + e^- \rightarrow Cd^{*+} + e^- + e^-$; k_3 is the rate coefficient for stepwise electron excitation in laser upper level of the Cd^{*+} atom: $Cd^+ + e^- \rightarrow Cd^{*+} + e^-$; k_4 is the rate coefficient for electron excitation of the laser upper level of the Cd^{*+} atom, due to the Penning effect; k_5 is the rate coefficient for direct ionization of the Cd atom; k_6 is the rate coefficient for stepwise ionization of the Cd atom; k_7 is the rate coefficient for direct ionization of the Cd atom, due to the Penning effect; k_8 is the rate coefficient for direct ionization of the Cd_m metastable atom; k_9 is the rate coefficient for common loss of the helium ion in the charge-exchange phenomenon with Cd atoms; χ_1 is the rate coefficient for the three-body conversion of atomic ions to molecular ions; χ_2 is the rate coefficient for radiation decay of the Cd^{*+} atom; χ_3 is the ambipolar diffusion of the cadmium ion Cd^+; χ_4 is the rate coefficient for relaxation of the metastable Cd_m atom.

More details about the model and numerical values of the constants are given in [5].

4. Results and Engineering Solutions

The presented model (1)-(8) has been carried out for a variety of electrical parameters. The main idea was to optimize partially the population of the upper laser level $5s^2\,{}^2D_{5/2}$ in He-Cd RF gas discharge at a constant applied electric power P, in order to garantee a permanent temperature profile and thermoionization stability of the gas discharge.

The population for the $5s^2\,{}^2D_{5/2}$ level was calculated as a function of the electrode voltage (respectively of the electric field intensity) at $P = 360$ W. In Fig. 6 some numerical results in the center of the laser tube for several electrode voltages are shown. It can be observed the well expressed optimum for $U_a \approx 400$ V. These results represent the possibility to vary the quantity of the laser level population in large interval without a change of the electric power P. Figure 7 illustrates the population distribution on the line $a1$–$a2$. It can be seen that for some voltages ($U_a = 400$ V and $U_a = 500$ V) the populating of $5s^2\,{}^2D_{5/2}$ level in the central zone is smaller than that in the other parts of the line. This will result in a low quality of the laser beam. The improvement would be achieved by a suitable choice of the electrode voltage (in our case it is $U_a = 300$ V). One can conclude that the laser emission quality can be varied in large bounds by changing the electrode voltage at $P = \text{const}$.

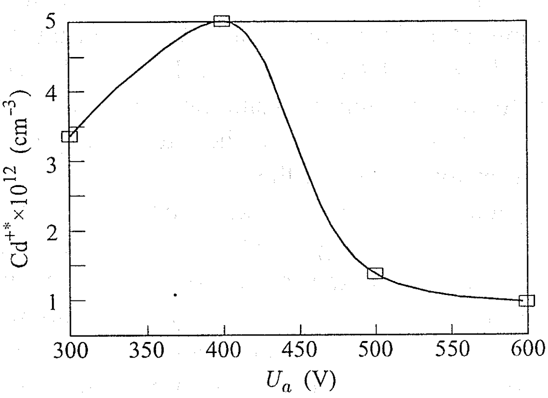

Fig. 6. Laser level population of $5s^2\,{}^2D_{5/2}$ level in the center of the discharge ($r = 0$ mm) as a function of the electrode voltage U_a

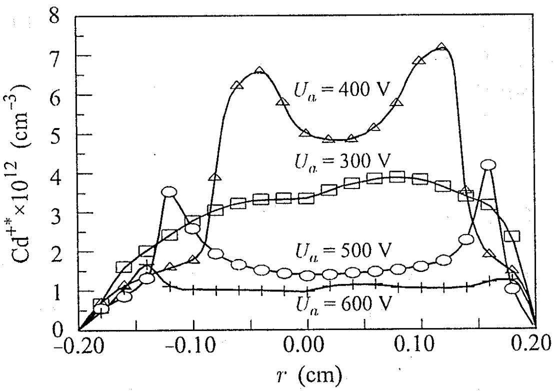

Fig. 7. Curves of population of the laser upper level of Cd^{+*} in the cross section of the laser tube for different electrode voltages U_a at a constant electric power $P = 360$ W

In fact, the results in Fig. 6 and Fig. 7 show that the electric field intensity has a substantial role in populating the $5s^2\,{}^2D_{5/2}$ level. The intensity values effect directly the low-temperature electrons energy and thus the laser level population of this level.

Another investigation was implemented to determine the principle excitation mechanisms, creating the population inversions in He-Cd^+ laser. Some results are given in Fig. 8, where the population of Cd^{+*} in the center of the laser tube ($r = 0$ mm) is calculated as a function of the electrode voltage U_a. The curve $S^+ = k_3 n_e \mathrm{Cd}^+$ gives the population due to the stepwise electron excitation: $\mathrm{Cd}^+ + e^- \to \mathrm{Cd}^{+*} + e^-$. The value $S_p = k_4 \mathrm{He}_m \mathrm{Cd}$ represents the laser level population obtained from the Penning effect: $He_m + Cd \rightarrow He + Cd^{+*}(5s^2\,{}^2D_{5/2}) + e^-$. These results show that at low electrode voltages (up to $U_a = 500$ V), the predominant excitation mechanism for populating the $5s^2\,{}^2D_{5/2}$ level is the stepwise electron excitation and for upper voltages, it is the Penning process.

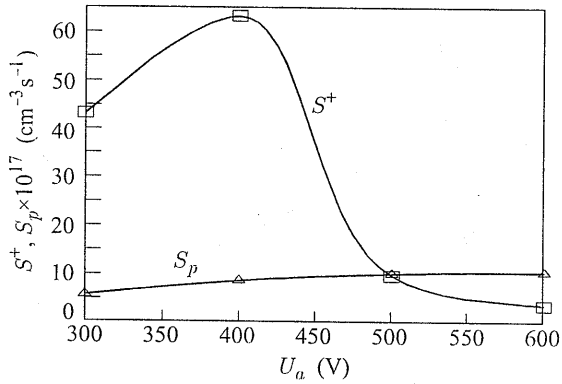

Fig. 8. Calculated mechanisms for populating the $5s^2\,{}^2D_{5/2}$ level of the Cd^{+*} atom in the center of the laser tube ($r = 0$ mm) as a function of the electrode voltage U_a
$S^+ = k_3 n_e Cd^+$ is the the stepwise electron excitation, $S_p = k_4 He_m Cd$, is the Penning process

In practice, for effective control on the laser population of this level at maintenance of a constant electric power, new technical requirements on the power supply can be imposed. The power unit must be constructed to provide a large variation of the current and electrode voltage at a given electric power $P =$ const. On the other hand, the high total consumed power (up to 2 KW) as well as the high operating frequency of 13.56 MHz additionally complicate the problem.

For actual power units some engineering solutions can be proposed. One of them consists in supplement of electronegative gases into the laser tube, such as Hydrogen or Nitrogen additives. This will result in electron loss in the gas discharge and medium resistance enhancement. At the same time the electric intensity and the energy of other electrons will rise. The current-voltage characteristic (CVC) of the discharge varies as it is shown in Fig. 9. The power unit operates in the conditions of the so-called (discharge, which is analogous to the abnormal glow discharge [11]. This type of discharge is characterized by its increasing CVC (curves *1* and *2* in Fig. 9). The electronegative gas additive will change the curve by making it more steepen (curves *1–3*, *1–4*, etc.). For every one of these curves the equal total consumed power $P = UI =$ const can be given (the points $a1$, $a2$, $a3$, ...). With the rise of the index i, the point ai will correspond to smaller current and higher voltage with respect to the initial point $a1$. Really, such regulation of the current and the voltage at $P = \text{const}$ can be realized up to some values. This method was successfully applied in other types of metal vapor lasers [12–13] to enhance the total laser efficiency.

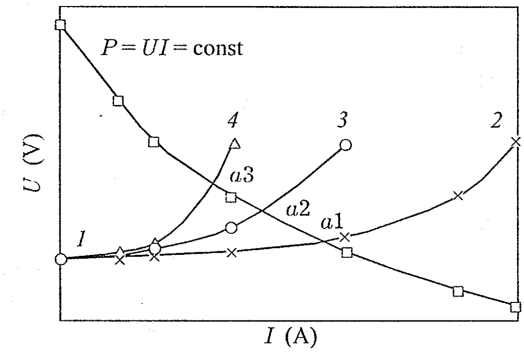

Fig. 9. Principal scheme of the influence of the electronegative gas additives on the CVC of the discharge

The use of the gas additives to the substantial gas (here helium) has its natural limits. More significant amount of the additive will have an adverse effect on laser levels population. A reasonable solution can be found by experimental investigations.

5. Conclusion

On the basis of the numerical model (1–8), the population of the upper laser level $5s^2\,{}^2D_{5/2}$ in RF excited He-Cd discharge was calculated. A partial optimization of the laser level population at permanent electric power was carried out. It was established the opportunity to control the laser output power quality and quantity by changing the electrode voltage in large limits. It has been numerically found, that at low voltages the principal excitation mechanism is the stepwise electron excitation and at more significant voltages is the Penning effect. In order to apply the obtained results in practice some engineering requirements for actual and new power sources were imposed.

Our results can be partially compared with some experimental data, obtained for the He(2^3S) metastable level in a hollow cathode discharge [2]. This type of discharge has almost the same characteristics as the RF discharge. The rate of the measured values for He(2^3S) in [2] is in good accordance with our results calculated from Eq. (1).

In the sense of the gene al regularities of the gas discharge and the principal of similarity, we can cor :lude that the proposed numerical approach can be applied for a large number of gas and metal vapor lasers.

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