Numerical investigation of the effect of cesium on copper vapor laser performance

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The feasibility of using an easily ionized addition in a copper vapor laser to enhance the laser performance is studied numerically. For this study, a self-consistent computer model describing processes in an excitation electrical circuit and laser discharge tube was developed. It is shown that cesium addition improves formation of the population inversion and plasma relaxation in a copper vapor laser. These improvements are explained by reduction of the pre-pulse electron density and creation of conditions favorable for excitation of the laser upper levels.

Introduction

Since the advent of early metal vapor lasers,[1,2] investigators have passed a long way on studying the processes proceeding in both a discharge circuit and active medium of the lasers (see Refs. 3–5 and references therein). Works on modernization of existing systems are now carried out in many countries. These works are aimed, in particular, at the search of new additions, which, when introduced into an active medium, improve the power and frequency characteristics of the laser (see, for example, Refs. 6–8) and extend the service life of sealed-off samples. In most cases, the search is performed by experimental methods.

A copper vapor laser (CVL) is the most widely used representative of this class of lasers. It is known as a pulsed source of radiation at the wavelength of 510.6 and 578.2 nm. Having the high mean output power (more than 200 W, see Ref. 9), high pulse repetition frequency (up to 300 kHz, see Ref. 10), and high efficiency, these lasers are widely employed both in scientific research and in practice. The works on laser isotope separation by the ALVIS technology with the use of this class of lasers are now carried out most intensely.[11,12]

Relatively recent papers[13–15] presented the experimental results obtained in laser systems using copper vapor and copper compound lasers with an easily ionized addition added to the laser active medium. These papers reported that cesium additions increase the mean power, efficiency, and the pulse repetition frequency of the laser. It was assumed that cesium atoms de-excite copper atoms in the metastable state and thus improve the conditions for appearance of population inversion in the laser. However, this assumption was a subject of critical analysis at the qualitative level at AMPL-2001 conference.[16] It was noted that to reliably justify the mechanism through which cesium additions affect the CVL performance, the effect on the evolution of discharge and plasma parameters should be first studied numerically. This paper is devoted to consideration of this problem.

Description of kinetic models

The kinetics of metal vapor lasers consists of two stages. The first one is the stage of intense excitation of atoms and development of lasing; it is so-called pulse stage. The second one is the stage of predominant relaxation. This stage involves joint relaxation of the electron temperature and concentration of copper atoms in the metastable state and electrons. It should be noted that these stages are characterized by significantly different duration. If the excitation pulse lasts for hundreds nanoseconds, then the afterglow stage is tens microseconds long. According to this, to save computational resources, the computations were divided into two stages: excitation and afterglow with specialized computer models developed for each stage. To provide for model self-consistency, iteration computations were carried out, and, as a result, the final data of one model were used as initial data for another.

Excitation pulse

The model for computation of processes proceeding during the excitation pulse includes two mutually dependent systems of equations, one of which describes the processes in the electrical excitation circuit, while the another includes equations for temperature and electron concentration resulting from ionization of neon, copper, and an easily ionized addition (cesium). In computations, we considered a circuit of direct discharge of a reservoir capacitor, which is often used for pumping copper vapor lasers.[5,17] The parameters of the excitation circuit and gas discharge tube (GDT) are given below.

Parameters of excitation circuit and GDT

Capacity of reservoir capacitor, nF	1.045
Total inductance of discharge circuit, μH	3
Initial voltage across the capacitor, kV	10.3
Plasma column length, cm	50
Plasma column radius, cm	2
Repetition rate of excitation pulses, kHz	20

The Kirchhoff equations for the circuit have the following form:

$$\frac{dU_{Cs}}{dt} = -\frac{I_{DT}}{C_s}, \tag{1}$$

$$\frac{dI_{DT}}{dt} = \frac{U_{Cs} - R_d(N_e, T_e)I_{DT} - R_{th}(t)I_{DT}}{L_k}, \tag{2}$$

where U_{Cs} is the voltage across the reservoir capacitor; I_{DT} is the GDT current; L_k is the correcting inductance; C_s is the capacitance; R_{th} is the thyratron resistance, whose time dependence was specified as

$$R_{th}(t) = R_{th0}\left(\exp\left\{-\frac{t}{tth}\right\} + R_{thend}\right). \tag{3}$$

Here R_{th0} is the initial value of the thyratron resistance (≈ GΩ); R_{thend} is the end value of the thyratron resistance (≈ 1 Ω); tth is the switch parameter (≈ 1 ns).

The model for the excitation pulse can be expressed mathematically as follows:

$$\frac{dN_{Ne^+}}{dt} = k_{iNe}(T_e)N_{Ne}N_e - k_{iNe}(T_e)N_{Ne^+}N_e - \beta(T_e)N_{Ne^+}N_e^2, \tag{4}$$

$$\frac{dN_{Cu^+}}{dt} = k_{iCu}(T_e)N_{Cu}N_e - k_{iCu}(T_e)N_{Cu^+}N_e - \beta(T_e)N_{Cu^+}N_e^2, \tag{5}$$

$$\frac{dN_{Cs^+}}{dt} = k_{iCs}(T_e)N_{Cs}N_e - k_{iCs}(T_e)N_{Cs^+}N_e - \beta(T_e)N_{Cs^+}N_e^2, \tag{6}$$

$$\frac{d}{dt}\left[\frac{3}{2}N_eT_e\right] = Q_j - Q_i - Q_{\Delta T}, \tag{7}$$

$$Q_j = \rho(N_e, T_e)j^2(t) \tag{8}$$

is the power density going into Joule heating;

$$Q_i = (J_{iCu}k_{iCu}(T_e)N_e[N_{Cu} - N_{Cu^+}] - J_{iCu}\beta(T_e)N_{Cu}N_e^2) + (J_{iNe}k_{iNe}(T_e)N_e[N_{Ne} - N_{Ne^+}] - J_{iNe}\beta(T_e)N_{Ne}N_e^2) + (J_{iCs}k_{iCs}(T_e)N_e[N_{Cs} - N_{Cs^+}] - J_{iCs}\beta(T_e)N_{Cs}N_e^2) \tag{9}$$

is the power density going into ionization of neon, cesium, and copper atoms;

$$Q_{\Delta T} = 2\left\{\frac{m_e}{m_{Ne}}k_{Ne}N_{Ne} + \frac{m_e}{m_{Cu}}k_{ei}N_{Cu^+} + \frac{m_e}{m_{Cs}}k_{ei}N_{Cs^+}\right\} \times N_e\,[T_e - T_{gas}] \tag{10}$$

is the power density going into electron cooling due to elastic collisions with atoms of neon buffer gas, as well as cesium and copper ions; N_{Ne}, N_{Cu}, N_{Cs}, N_{Ne+}, N_{Cu+}, N_{Cs+} are the concentrations of atoms and ions of the neon buffer gas, copper, and cesium; $\rho(N_e, T_e)$ is the specific resistance of plasma,

$$\rho(N_e, T_e) = 0.043\,[a_1(T_e) + a_2(N_e, T_e)]\ (\Omega\cdot\text{cm}),$$

where

$$a_1(T_e) = 4/T_e^{3/2}, \tag{11}$$

$$a_2(N_e, T_e) = 7.4\cdot10^{-2}\frac{N_{Ne}}{N_e}T_e^{1/2} \tag{12}$$

are the contributions responsible, respectively, for electron-ion and electron-atom collisions; $N_e = N_{Cu} + N_{Cs^+} + N_{Ne^+}$ (cm^{-3}) is the electron concentration.

In this work, we mostly used the rate constants taken from Ref. 18:

$$\beta = 3.206\cdot10^{-27}\,T_e^{-9/2}\ \text{cm}^6/\text{s}$$

the rate of triple recombination of single ions;

$$k_{iNe} = 4.91\cdot10^{-11}\,T_e^{1/2}\exp(-16.6/T_e)\ \text{cm}^3/\text{s}$$

the ionization rate of neon atoms;

$$k_{iCu} = 5.13\cdot10^{-8}\,T_e^{1/2}\exp(-3.8/T_e)\ \text{cm}^3/\text{s}$$

the ionization rate of copper atoms;

$$k_{ei} = \frac{4\sqrt{\pi}}{3}\frac{e^4\Lambda}{T_e^2}\left[\frac{2T_e}{m_e}\right]^{1/2}\ \text{cm}^3/\text{s}$$

the rate of elastic collisions with ions, where

$$\Lambda = \frac{1}{2}\ln\left[1 + \frac{T_e^3}{2e^6N_e}\right]$$

is the Coulomb logarithm;

$$k_{Ne} = 8.9\cdot10^{-9}\,T_e^{1/2}\ \text{cm}^3/\text{s}$$

is the rate of elastic collisions of electrons with neon atoms.

The cross section of the process of elastic collision of an electron with a neon atom σ_{Ne} was thought to be equal to $1.5\cdot10^{-16}$ cm^2 (Ref. 18). The cross sections of ionization and excitation of the resonance levels of cesium atoms were borrowed from Refs. 19 and 20, respectively. The rates of the processes were obtained through averaging of the process cross section multiplied by the Maxwell speed distribution of electrons $k = \langle\sigma v\rangle$, $J_{iNe} = 21.6$ eV, $J_{iCu} = 7.73$ eV, $J_{iCs} = 3.89$ eV are the ionization energies of neon, copper, and cesium[19]; m_e, m_{Cs}, m_{Cu}, and m_{Ne} are the masses of electron and cesium, neon, and copper atoms; T_g is the gas temperature; $j(t)$ is the current density.

Afterglow stage

The kinetic model describing the behavior of plasma parameters at the stage of afterglow is rather simple. It includes the equation for the concentration of ions of the buffer gas, copper, and cesium, as well as the equation for the electron temperature:

$$\frac{\mathrm{d}N_{\mathrm{Ne}^+}}{\mathrm{d}t} = -\beta(T_\mathrm{e})N_{\mathrm{Ne}^+}N_\mathrm{e}^2 - D_\mathrm{a}^{\mathrm{Ne}}N_{\mathrm{Ne}^+}, \tag{13}$$

$$\frac{\mathrm{d}N_{\mathrm{Cu}^+}}{\mathrm{d}t} = -\beta(T_\mathrm{e})N_{\mathrm{Cu}^+}N_\mathrm{e}^2 - D_\mathrm{a}^{\mathrm{Cu}}N_{\mathrm{Cu}^+}, \tag{14}$$

$$\frac{\mathrm{d}N_{\mathrm{Cs}^+}}{\mathrm{d}t} = -\beta(T_\mathrm{e})N_{\mathrm{Cs}^+}N_\mathrm{e}^2 - D_\mathrm{a}^{\mathrm{Cs}}N_{\mathrm{Cs}^+}, \tag{15}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{3}{2}N_\mathrm{e}T_\mathrm{e}\right] = \beta(T_\mathrm{e})N_\mathrm{e}(J_{\mathrm{iCs}}N_{\mathrm{Cs}^+} + J_{\mathrm{iCu}}N_{\mathrm{Cu}^+} + J_{\mathrm{iNe}}N_{\mathrm{Ne}^+}) - Q_{\Delta T}, \tag{16}$$

where D_a are the coefficients of ambipolar diffusion for neon, copper, and cesium:

$$D_\mathrm{a}^{\mathrm{Cu}} = 30.201\left[\left(1+\frac{T_\mathrm{e}}{T_\mathrm{g}}\right)\frac{T_\mathrm{g}^2}{p_{\mathrm{Ne}}}\right]\frac{1}{r^2}, \tag{17}$$

$$D_\mathrm{a}^{\mathrm{Ne}} = 20.05\left[\left(1+\frac{T_\mathrm{e}}{T_\mathrm{g}}\right)\frac{T_\mathrm{g}^{1.65329}}{p_{\mathrm{Ne}}}\right]\frac{1}{r^2}, \tag{18}$$

$$D_\mathrm{a}^{\mathrm{Cs}} = 0.881\left[\left(1+\frac{T_\mathrm{e}}{T_\mathrm{g}}\right)\right]\frac{1}{r^2}, \tag{19}$$

where r is the GDT radius.

The initial values were obtained from iteration computations at the previous stage. (The input power was 2 kW/50 cm. The wall temperature was $T_\mathrm{w} = 1590°\mathrm{C} = 0.161$ eV, and the ratio of the temperature at the GDT axis to the temperature of the GDT walls in that case was 1.873. In computations, we used the following gas temperature: $T_\mathrm{g} = 1.5\ T_\mathrm{w}$).

Parameters of plasma at the buffer gas (neon) pressure of 300 Torr

Concentration of copper atoms, cm^{-3}	$1{\cdot}10^{15}$
Concentration of cesium atoms, cm^{-3}	$2{\cdot}10^{12}$
Gas temperature, K	2795
Initial concentration of copper ions, cm^{-3}	
for calculation of afterglow	$5.6{\cdot}10^{13}$
for calculation of excitation pulse	$1.34{\cdot}10^{13}$
Initial concentration of cesium ions, cm^{-3}	
for calculation of afterglow	$4.8{\cdot}10^{11}$
for calculation of excitation pulse	$1.998{\cdot}10^{11}$
Initial concentration of neon ions, cm^{-3}	
for calculation of afterglow	$2.888{\cdot}10^{9}$
for calculation of excitation pulse	$1.2{\cdot}10^{10}$
Initial electron temperature, eV	
for calculation of afterglow	0.8
for calculation of excitation pulse	0.31

Main results and discussion

Figure 1 depicts the data on the maximal electron temperature during the pump pulse as a function of different concentrations of atoms of the easily ionized admixture.

As can be seen from Fig. 1, there exists some critical concentration of cesium atoms, at which lasing terminates. This conclusion is based on the fact that to provide the population inversion in a copper vapor laser, the electron temperature must be higher than 1.7 eV. At lower electron temperature, the metastable levels of the copper atom are excited more efficiently (as compared to the resonance levels). This effect can be explained as follows: at the relatively low concentration (10^{12}–$10^{13}\ \mathrm{cm}^{-3}$), cesium atoms are ionized almost completely still in the initial interval of the excitation pulse, since the cross sections of direct ionization and ionization through the resonance level far exceed similar parameters for the copper atom, and the ionization threshold is as low as 3.89 eV (7.728 eV for copper).

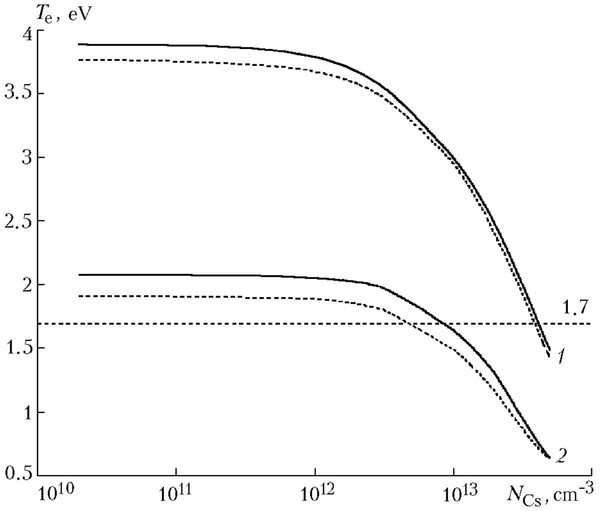

Fig. 1. Electron temperature vs. the concentration of cesium atoms at different buffer gas pressures: 300 Torr (solid curve) and 225 Torr (dashed curves) for $N_{\mathrm{Cu}^+} = 1.34{\cdot}10^{12}$ (*1*) and $1.34{\cdot}10^{13}\ \mathrm{cm}^{-3}$ (*2*).

It follows from Fig. 2 that at the initial stage the density of the power consumed for ionization of cesium atoms exceeds the density of the power going into ionization of copper atoms and, especially, into ionization of buffer gas atoms. Besides, according to Fig. 1, we can conclude that the critical concentration of cesium atoms depends on the buffer gas concentration and the pre-pulse concentration of electrons produced largely as a result of ionization of copper atoms.

Computations show that the maximal electron temperature decreases at lower concentration of buffer gas atoms and equal concentrations of an easily ionized admixture. However, the effect of the buffer gas is not so significant as compared with the effect of pre-pulse ionization of copper atoms. Since the copper concentration is far higher, even low (about few percent) ionization of copper atoms produces a considerable concentration of electrons, which prevent plasma heating.

Thus, it can be concluded that there exists a region of the optimal concentration of the easily ionized admixture, inside which we can expect an improved performance of metal vapor lasers. The upper boundary of this region is determined by the rate of increasing and maximal value of the electron temperature achievable during the excitation pulse.

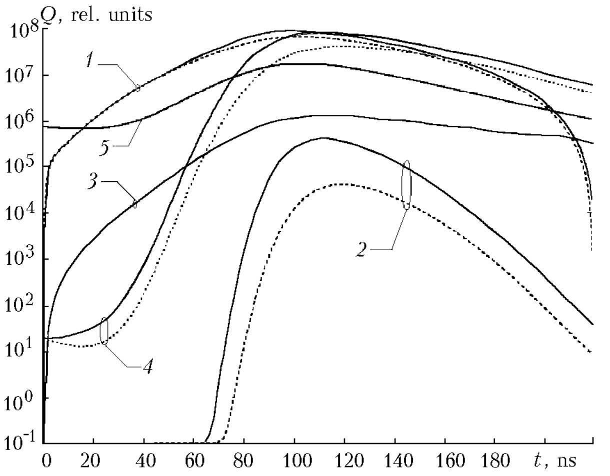

Fig. 2. Time dependence of power pumped into the GDT plasma (*1*), power going into ionization of neon (*2*), power consumed for gas heating in inelastic collisions (*3*), power going into ionization of copper (*4*), power going into ionization of cesium (*5*); $N_{\mathrm{Cs}} = 9 \cdot 10^{12}$ cm^{-3} (solid curves) and 0 (dashed curves).

Once cesium is added to the active medium, the power pumped into the GDT decreases, because lesser energy is needed to produce the same amount of electrons. This circumstance can increase the laser efficiency.

It follows from numerical experiments that introduction of cesium additions leads to the decrease in the power consumed for ionization of buffer gas atoms and to the decrease of the degree of neon ionization. The power consumed for ionization of copper atoms decreases as well (see Fig. 2), and the resulting ionization of copper decreases correspondingly. This effect is especially pronounced as the concentration of cesium atoms increases. It should be noted that the power consumed for electron cooling due to collisions with neon atoms and copper and cesium ions remains almost unchanged in this case.

In Ref. 16 it was noted that cesium affects insignificantly the population of the metastable level. Even at the cesium concentration of $2 \cdot 10^{14}$ cm^{-3}, the time for quenching copper atoms in the metastable state at collisions with cesium remains very long (few microseconds), while the duration of the excitation pulse is only hundreds of nanoseconds. At the stage of relaxation, collision with excited cesium atoms only speeds up the process of establishing the equilibrium between the metastable level population of the copper atom and the electron temperature. It should be noted that at this concentration of cesium atoms, the electron temperature does not achieve the level of 1.7 eV needed for development of lasing (see Fig. 1).

Before considering the effect of cesium additions to operation of the discharge circuit, let us note that the amplitude of the current responsible for Joule heating of electrons practically does not change as the amplitude of GDT voltage decreases and the maximum shifts toward longer times (Fig. 3).

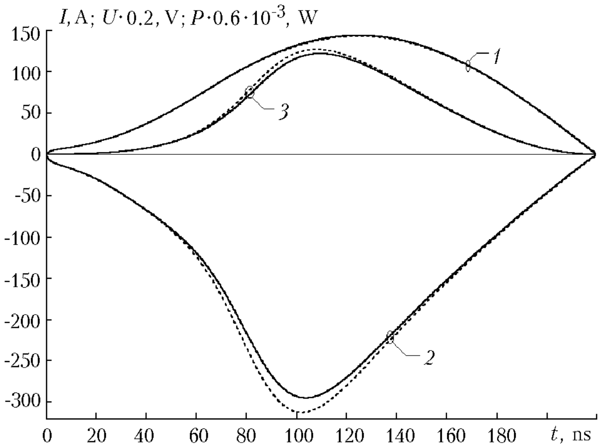

Fig. 3. Time dependence of current (*1*), voltage (*2*), and power (*3*); $N_{\mathrm{Cs}} = 2 \cdot 10^{12}$ cm^{-3} (solid curves) and 0 (dashed curves).

The contribution of electron-atom collisions to plasma resistance decreases, as the contribution of the Coulomb electron-ion collisions increases (Fig. 4). This is explained by the increase in the electron concentration, what is especially marked at the initial stage of the excitation pulse. However, for the considered cases of high buffer gas concentrations, the contribution of electron-atom collisions to resistance remains most significant except for the initial period.

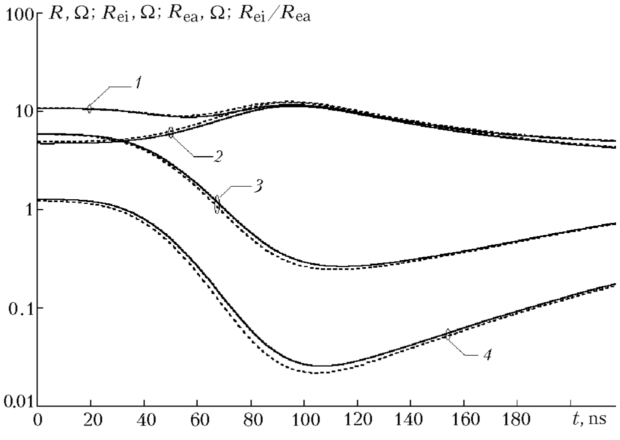

Fig. 4. Time dependence of the total GDT resistance R (*1*), the contribution of electron-atom collisions R_{ea} (*2*), the contribution of Coulomb electron-ion collisions R_{ei} (*3*), the ratio of the contribution of electron-ion collisions to the contribution of electron-atom collisions (*4*); $N_{\mathrm{Cs}} = 2 \cdot 10^{12}$ cm^{-3} (solid curves) and 0 (dashed curves).

The increase of the electron concentration in the initial period of the excitation pulse can also explain the fact that the increase of the electron temperature somewhat slows down with the simultaneous decrease of the maximum value.

Let us consider what is responsible for improvement of laser parameters in our experiments as compared with the experiments of Refs. 13–15. For this purpose, we analyze the processes proceeding during the excitation pulse and in the interpulse gap (relaxation phase).

Pump pulse

It follows from the experiments that the rate of increase of the electron temperature insignificantly slows down during the excitation pulse, and this must lead to some growth of the metastable level population of the copper atom and worsen the conditions of lasing. However, actually, at the beginning of the pump pulse, when the electron temperature still does not achieve the critical value, almost all energy pumped into the discharge goes into ionization and excitation of cesium atoms, while the energy going into excitation of copper atoms is insignificant. Only once cesium is almost completely ionized, the main part of the energy goes into excitation and ionization of copper atoms. It should be noted that by that time the electron temperature almost achieves the level of 1.7 eV, at which the rates of excitation of resonance and metastable levels of the copper atom become close. Thus, we obtain that the resonance excitation of mainly resonance levels takes place, and this favors formation of population inversion and enhances the laser output power.

At the beginning of the excitation pulse, cesium atoms are the main supplier of electrons to the discharge plasma. They are ionized quickly and almost completely at far lower energy consumption than at ionization of copper atoms. Some time later, electrons are largely produced due to ionization of copper atoms, but the resulting degree of ionization and the electron concentration turn out to be lower. After ionization of cesium atoms, the rate of increase of the electron concentration decreases.

As was noted above, with small cesium additions, the resulting degree of copper ionization and, as a consequence, the electron concentration decrease. The lower is the pre-pulse degree of ionization of copper atoms, the more pronounced is this effect. It should be noted here that in copper halide lasers the degree of copper ionization is lower, and thus the use of easily ionized admixtures in lasers of this type is more efficient as compared to CVL.

Afterglow stage

Consider now the processes proceeding at the afterglow stage. As it was noted above, the resulting ionization of copper atoms during the pump pulse in a laser with cesium addition decreases. Note that ionization of buffer gas atoms is insignificant. Let us follow how the total electron concentration relaxes at the afterglow stage. The total electron concentration is mostly determined by the contribution of electrons produced due to ionization of copper atoms and electrons produced due to ionization of cesium atoms. The rates of de-ionization and de-excitation of cesium atoms exceed those for copper atoms according to the detailed balance.[21]

As a result, the contribution of cesium atoms to the total electron concentration at the afterglow stage is negligibly small as compared with the contribution of copper atoms. Thus, because of the lower ionization of copper atoms, the total concentration of electrons decreases at the afterglow stage and, consequently, the pre-pulse electron concentration decreases as well. The relaxation rate of the electron concentration is almost completely determined by the relaxation rate of electrons produced due to ionization of copper atoms. The effect of additional electrons produced due to ionization of cesium atoms on the relaxation of the electron temperature is negligibly small as compared with the recombination flow from copper. It should be noted that the electron energy in this case is partly lost due to elastic collisions with cesium ions.

Conclusion

Thus, using the neon–copper mixture with cesium addition as an example and the method of numerical simulation, we have studied the effect of an easily ionized admixture on the discharge evolution and the behavior of plasma parameters. The results of computer experiments refute the interpretation[13–15] of improvement of laser energy and frequency characteristics through the process of de-excitation of copper metastable levels by cesium atoms. It is shown that cesium additions not only improve excitation conditions for resonance levels of the copper vapor laser, but also decrease the restrictions on the pre-pulse electron concentration, which is a significant factor determining both the frequency and energy parameters of the copper vapor laser.[22] Thus, we can expect the positive effect of small cesium additions on the performance characteristics of metal vapor and metal compound lasers.

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