EFFICIENCY OF THE COPPER VAPOR LASER

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The operating conditions of the repetitive pulsed copper vapor laser (CVL) are determined under which the effect of the inductance of the discharge circuit on the efficiency is small. It is shown that the efficient pumping of losing transitions in these lasers requires the formation of an excitation pulse with a steep voltage pulse across the active element, which ends at the moment of termination of losing pulse. The aperiodic discharge development during the action of the excitation pulse is needed as well. The formation of such an excitation pulse is possible only if the storage capacitor discharges partially in the discharge circuit of the laser. It is shown that under these conditions the efficiency by the energy delivered into the laser medium may reach 10%.

The paper presents a study of the dependence of the efficiency of a copper vapor laser on the duration and wave form of the excitation pulse. The excitation pulse duration was increased with increasing the capacitance of the storage capacitor in the discharge circuit of the laser. The investigations were performed with the active element of the CVL, whose operating channel was made of a BeO tube 400 mm in length and 10 mm in diameter. The buffer gas was chosen to be neon. The TGI1–1000/25 thyratron was used as a switch.

As can be seen from the oscillograms given in Fig. 1, the energy input into the active medium and the duration of the excitation pulse increase with increasing the storage capacitance. The current pulse risetime elongates. The onset of lasing is substantially delayed. If the storage capacitance is relatively high, the current pulse wave form indicates that the discharge has an aperiodic character at the initial stage of its development. A minor increase rather than the decrease of the pulse energy is observed when the energy delivered into the active medium decreases before the termination of the lasing pulse (Fig. 2). When the energy delivered into the active medium after the lasing pulse is "cut off", an efficiency of 4–6% may be obtained.

To understand the cause of increasing the efficiency of the CVL in the above-described case we will analyze the operation of the CVL discharge circuit shown in Fig. 3. The circuit includes the resistor R representing the active resistance of the discharge, the inductor L representing the industance of the discharge circuit, the ideal switch K, and a storage capacitor C. Let us assume that both the closing and opening time of the switch are much shorter than the duration of the excitation pulse τ_p which is equal to the time for the switch to be in the closed position. The interval τ_p comes to the end simultaneously with the moment of termination of the lasing pulse. The effect of the inductance L is small during the action of the excitation pulse. This assumption is valid if the discharge has an aperiodic character during the excitation pulse. In energy terms, the energy lost during discharging the storage capacitor only to a lesser extent is converted into the energy of the magnetic field of the inductor and to a greater extent is released at the active load. It can be seen from the experimental data that the discharge before lasinj had an aperiodic character in the case of large values of the storage capacitance. An aperiodic solution of a differential equation is known to exist if the roots of the characteristic equation are real, i.e., when $\frac{R^2}{4L^2} > \frac{1}{LC}$ or $R > 2\sqrt{L/C}$. Therefore, the storage capacitance will be considered to be large enough, so that during the excitation pulse the voltage across the storage capacitor remains practically unchanged. It is believed that during the action of the excitation pulse a rectangular voltage pulse is formed across the inductor L and across the resistor R, which has an amplitude U being equal to the value of the voltage across the storage capacitor. If the discharge develops aperiodically, the voltage across the inductor can be neglected and the voltage across the active resistor R can be considered to be equal to that across the storage capacitor.

Assuming that the plasma parameters are distributed uniformly over the cross section of the operating channel of the active element and that the ionization frequency ν_i in the discharge is independent of the average electron energy, we can. write down the set of equations and to estimate the electron concentration that allows the existence of an aperiodic discharge

$$U = IR\ ,\ R = \frac{1}{\sigma}\frac{l}{\pi r^2}\ ,\ \sigma = \frac{n_e e^2}{m\nu}\ ;$$

$$\frac{dn_e}{dt} = \nu_i n_e\ ,\ R > 2\sqrt{L/C}\ ,$$

$$\nu = \nu_{ei} + \nu'_{eCu} + \nu''_{e\,Cu} + \nu_{e\,Ne}\ ,$$

where l and r are the length and the radius of the active element, respectively, e and m are the electron charge and the mass, n_e is.las the electron concentration, v_{ei} is the frequency of collisions between electrons and ions, ν'_{eCu} and $\nu''_{e\,Cu}$ are the frequencies of elastic and inelastic collisions between electrons and copper atoms, respectively, and $\nu_{e\,Ne}$ is the frequency of collisions between electrons and neon atoms. It is assumed that the frequency ν and the inductance of the discharge circuit remain unchanged during the excitation pulse. Hence it follows that

$$n_e < \frac{m\,\nu}{2\,e^2\sqrt{L/C}}\,\frac{l}{\pi\,r^2}\ . \qquad (1)$$

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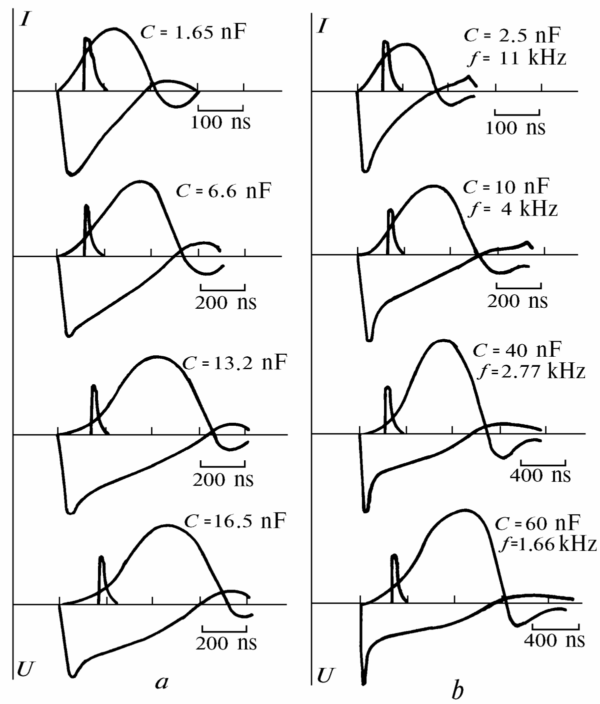

FIG. 1. Wave forms of current (1), voltage (2) and losing pulse (3) vs operating capacitance: a) for a constant pulse repetition frequency of 10 kHz and b) for a varying repetition frequency.

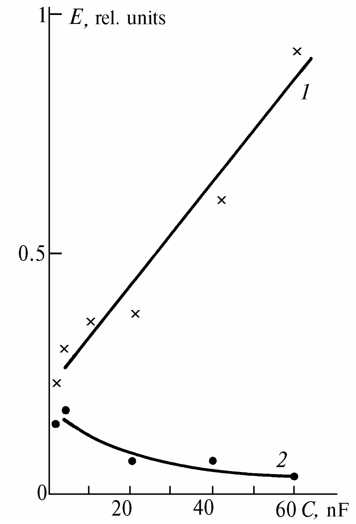

FIG. 2. Energy delivered into (he active medium of a CVL vs storage capacitance: 1) throughout the excitation pulse and 2) until the lasing terminates.

The typical values of the plasma resistance during the lasing pulse are roughly equal to 10 Ω, whereas the values of the inductance given in various papers are of the order of 10^{-6}–10^{-7} H. In this case the discharge will be aperiodic in character with a storage capacitance

$$C > 4\, L/R^2 = 4 \cdot 10^{-9} - 4 \cdot 10^{-8}\, F.$$

This agrees with the available experimental results. The above estimates demonstrate that for an actual CVL it is always possible to choose the circuit parameters obeying the condition of existence of an aperiodic discharge. Let us estimate the electron concentration during the lasing pulse (when the discharge develops aperiodically) for the circuit parameters $L = 2 \cdot 10^{-7}$ H, $C = 10^{-8}\,F$, $l = 0.4$ m, $r = 5$ mm assuming that ν_{ei}, $\nu'_{e\,Cu}$ and $\nu''_{e\,Cu}$, are small as compared with the frequency of collisions between electrons and neon atoms $\nu_{e\,Ne}$. The value of the frequency of elastic collisions between electrons and neon atoms $\nu_{e\,Ne}$ determined from the data of Ref. 1 is about $\sim 3 \cdot 10^9\ s^{-1}$. On the basis of the enumerated assumptions, the electron concentration during the lasing pulse should not exceed $n_e \sim 6 \cdot 10^{13}\ cm^{-3}$, which agrees with estimates and measurements of the electron concentration at which lasing in the CVL's is realized.[2,3]

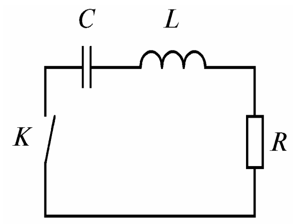

FIG. 3. Discharge circuit of the CVL.

To discuss the peculiarities of the processes occurring in the active medium, let us address to a theoretical model of the CVL. The above-mentioned discharge parameters together with the thermodynamic characteristics of the plasma, i.e., the pressure of the buffer gas P_{Ne}, the pressure of the copper vapor P_{Cu} , and the gas temperature T_g are used to estimate the role of the elementary processes occurring in the course of the excitation pulse. The prepulse values of the electron temperature; and concentration determined from the plasma conductivity and from the plots given in Ref. 4 are as follows: $N_e^{(0)} = 2{\cdot}10^{12}\ cm^{-3}$, $T_e = T_g = 0.25$ eV. The vapor concentrations of the buffer and working gases are $N_{\rm Ne} = 3 \cdot 10^{17}\ cm^{-3}$ и $N_{\rm Cu} = 2 \cdot 10^{15}\ cm^{-3}$, respectively.

The evaluation of the rates of the processes suggests that during the excitation pulse the velocity distribution of electrons is formed due to elastic electron – atom and electron – electron collisions. The calculation of the kinetics of population of the operating levels of the Cu atom is based on the following assumptions.

1. The velocity distribution of electrons is Maxwellian.
2. The energy distribution of the Cu atoms above the resonance level is determined by the Saha equation.
3. The fine structure of the operating levels can be neglected.
4. The balance equation for electron energies and particles takes into account

a) elastic and inelastic collisions between electrons and Cu atoms,

b) stepwise excitation and ionization of Cu atoms by electrons,

c) ambipolar diffusion and diffusion of the metastable states of Cu,

d) inelastic electron collisions with Cu ions and buffer Ne atoms, and

e) radiative processes during the resonance transition with due account of the self–absorption.

The set of kinetic equations has the form

$$\frac{dN_1}{dt} = N_e\,[(N_3\,\kappa_{31} + N_2\,\kappa_{21}) - N_1(\kappa_{12} + \kappa_{13} + \kappa_{1\infty})] -$$

$$- N_e\,N_1 \sum_{i=4}^{\infty'} \kappa_{1i} + N_e \sum_{i=4}^{\infty'} N_i\,\kappa_{i1} + N_e^3\,\kappa_{\infty 1} + N_3\,A_{31}\,F; \qquad (2)$$

$$\frac{dN_2}{dt} = N_e\,[(\,N_3\,\kappa_{32} + N_1\,\kappa_{12}) - N_2\,(\kappa_{23} + \kappa_{21} + \kappa_{2\infty})] -$$

$$- 5.76\,\frac{N_2 D_2}{R_2} + B_{32}\,\rho\,g(\nu_{32})\left(N_3 - \frac{g_3}{g_2}N_2\right) -$$

$$- N_e\,N_2 \sum_{i=4}^{\infty'} \kappa_{21} + N_e \sum_{i=4}^{\infty'} N_i\,\kappa_{i2} + N_e^3\,\kappa_{\infty 2}, \qquad (3)$$

$$\frac{dN_3}{dt} = N_e\,[(N_1\,\kappa_{13} + N_2\,\kappa_{23}\,) - N_3(\,\kappa_{32} + \kappa_{31} + \kappa_{3\infty})] -$$

$$- B_{32}\,\rho\,g(\nu_{32})\left(N_3 - \frac{g_3}{g_2}N_2\right) -$$

$$- N_e\,N_3 \sum_{i=4}^{\infty'} \kappa_{3i} + N_e \sum_{i=4}^{\infty'} \kappa_{i3}\,N_i + N_e^3\,\kappa_{\infty 3} - N_3\,A_{31}\,F; \qquad (4)$$

$$\frac{dN_e}{dt} = N_e\,(\,N_1\,\kappa_{1\infty} + N_{2\infty} + N_{3\infty}\,) + N_e \sum_{i=4}^{\infty'} N_i\,\kappa_{i\infty} - \frac{N_e\,D_a}{R^2} -$$

$$- N_e^3(\kappa_{\infty 1} + \kappa_{\infty 2} + \kappa_{\infty 3}) - N_e^3 \sum_{i=4}^{\infty'} \kappa_{\infty i}\ ; \qquad (5)$$

$$\frac{3}{2}\,\kappa\,\frac{dT_e}{dt} = \frac{jE}{N_e} - \frac{3}{2}\,\kappa\,T_e\,\frac{1}{N_e}\frac{dN_e}{dt} + N_2\,(\kappa_{21}\varepsilon_{21} - \kappa_{23}\varepsilon_{23} - \kappa_{2\infty}\,\varepsilon_{\infty 2}) +$$

$$+ N_3\,(\kappa_{31}\,\varepsilon_{31} + \kappa_{32}\,\varepsilon_{32} + \kappa_{3\infty}\varepsilon_{3\infty}) - N_1\,(\kappa_{12}\,\varepsilon_{21} + \kappa_{13}\,\varepsilon_{13} + \kappa_{1\infty}\varepsilon_{\infty 1}) -$$

$$- \frac{3}{2}\,\kappa(T_e - T_{\text{г}})\,\frac{2\,m}{M_{\text{г}}}\,\nu_{en} - N_1 \sum_{i=4}^{\infty'} \kappa_{1i}\,\varepsilon_{i1} -$$

$$- N_2 \sum_{i=4}^{\infty'} \kappa_{2i}\,\varepsilon_{i2} - N_3 \sum_{i=4}^{\infty'} \kappa_{3i}\,\varepsilon_{i3} +$$

$$+ \sum_{i=4}^{\infty'} N_i\,(\,\kappa_{i1}\,\varepsilon_{i1} + \kappa_{i2}\,\varepsilon_{i2} + \kappa_{i3}\,\varepsilon_{i3}) - \sum_{i=4}^{\infty'} N_i\,\kappa_{i\infty}\,\varepsilon_{\infty i} +$$

$$+ N_e^2\left[\kappa_{\infty 1}\left(\frac{3}{2}\kappa T_e + \varepsilon_{\infty 1}\right) + \kappa_{\infty 2}\left(\frac{3}{2}\kappa T_e + \varepsilon_{\infty 2}\right) + \kappa_{\infty 3}\left(\frac{3}{2}\kappa T_e + \varepsilon_{\infty 3}\right) + \right.$$

$$\left. + \sum_{i=4}^{\infty'} \kappa_{\infty i}\left(\frac{3}{2}\,\kappa T_e + \varepsilon_{\infty i}\right)\right] - \left(N_{\text{Ne}}\,\kappa^{\text{res}}_{\text{Ne}}\,\varepsilon^{\text{res}}_{\text{Ne}} + N_e\,\kappa^{\text{res}}_{\text{Cu}^+}\,\varepsilon^{\text{res}}_{\text{Cu}^+}\right), \qquad (6)$$

$$\frac{d\rho}{dt} = N_3 A_{32}\,h\nu_{32}\,\frac{\Omega}{4\pi} + \rho\left[B_{32} h\nu_{32} g(\nu_{32})\left(N_3 - \frac{g_3}{g_2}N_2\right) - \frac{1}{\tau_{\text{res}}}\right]. \qquad (7)$$

In the above equations N_1 N_2, and N_3 are the concentrations of the ground, metastable, and resonance levels of the copper respectively, K_{ij} are the rates of transitions during inelastic electron — atom collisions, D_2 and D_a are the coefficients of diffusion of metastable states and ambipolar diffusion, respectively, A_{32} and B_{32} are the Einstein coefficients for spontaneous and induced radiative transitions, j and F are the current density and the electric field strength determined from the parameters of the current pulse and the voltage across the plasma, $g(\nu_{32})$ is a factor taking into account the lasing line profile, $\varepsilon_{ij} = |E_i - E_j|$ is the difference in energy of the ith and jth levels, N_e and T_e are the electron concentration and temperature, ρ is the energy density of the electromagnetic field in the active medium, m and M_g are the electron and gas atom masses, ν_{en} is the frequency of elastic collisions between electrons and atoms, $\kappa^{\text{res}}_{\text{Ne}}$ and $\kappa^{\text{res}}_{\text{Cu}}$ are the rates of the resonance transitions in collisions of Ne and Cu atoms with electrons, respectively, $\varepsilon^{\text{res}}_{\text{Ne}}$ and $\varepsilon^{\text{res}}_{\text{Cu}}$ are the energies of these transitions, F is a factor taking into account the self-absorption of the resonance line, τ_{res} is the lifetime of a photon in the cavity, and Ω is the solid angle determined by the size of the gas-discharge tube.

The diffusion coefficients are calculated using the formulas given in Ref. 5. The excitation and ionization rates are determined according to the quasiclassical theory.[6] The set of equations (2)–(7) is solved numerically.

The calculations within the framework of the kinetic model are performed for the case of experimentally realized self-heating regime (1), and for the case of a modelled "cut off* of the excitation pulse before the termination of the lasing pulse (2). (It excitation pulse before the termination of the lasing pulse (2). (It is evident that in the second case the rates of the processes of excitation and destruction of the whole combination of levels change essentially, since the peak current decreases by a factor of 5–20.)

The electron concentration in the self-heating discharge is much greater than in the "model" discharge with a reduced input energy. The ionization degree at the 160-th nanosecond is 80 and 5%, respectively. In the second case the limitations on the lasing power connected with the stepwise ionization of the ground and resonance states are lifted, the possibility arises to increase the duration of the lasing pulse, and the efficiency increases greatly. Table I compares the power consumed in the self-sustaining and "model" regimes. The conversion coefficient reaches 10% in the second case.

TABLE 1. Values of input power P, average output power W, and efficiency n for self-heating and "model" discharges.

Parameter	Mode	
	Conventional discharge	Model discharge with reduced input energy
P, Wt	330	30
W, Wt	4	2.9
η, %	1.2	10

The foregoing allows one to make the following conclusions.

1. In order to efficiently pump the operating transitions in a CVL it is necessary to form an excitation pulse with a steep voltage pulse across the active element of the laser, which is terminated at the moment of termination of the lasing pulse provided that the discharge develops aperiodically during the excitation pulse.

2. The above-described excitation pulse can only be formed with a partially discharging storage capacitor.

Therefore, in order to efficiently pump the operating transitions of the CVL, it is preferable to use an electron tube or transistor switch as a commutator.

3. Increasing the efficiency of the CVL due to decreasing the energy delivered into the active medium in a pulse in combination with the diffusion mechanism of breaking down of the lower laser levels and charged particles will make it possible to increase the repetition frequency of lasing pulses, the energy extracted from a unit volume of the active medium, and the average lasing power.

REFERENCES

1. P. Bailie, J.–S. Change, A. Glaude, et al., J. Phys. **B**: At. Mol. Phys. **14**, 1485 (1981).

2. V.I. Batenin, V.A. Burmakin, P.A. Vokhmin, et al., Kvant. Elektron. **4**, 1572 (1977).

3. V.F. Elaev, V.S. Mel'chenko, V.V. Pozdeev, and A.N. Soldatov, in: *Efficient Gas Discharge Metal Vapor Lasers*, Institute of Atmospheric Optics, Siberian Branch of the USSR, Tomsk (1978), p. 179.

4. A.Kh. Mnatsakanyan, G.V. Naidis, and N.P. Shternov, Kvant. Electron. **5**, 597 (1978).

5. A.V. Eletskii, L.A. Palkina, and B.M. Smirnov, *Transport Phenomena in Plasma* (Atomizdat, Moscow, 1975), 220 pp.

6. L.A. Vainshtein, I.I. Sobel'man, and E.A. Yunov, *Electron Excitation Cross Sections of Atoms and Ions* (Nauka, Moscow, 1973), 213 pp.