Optimal operating modes of copper vapor laser under efficient pumping conditions

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The dependence of observed energy parameters of a copper vapor laser (CVL) on excitation conditions determining the reliability of the efficient pumping criterion is analyzed experimentally. CVL energy parameters are shown to correspond to the efficient pumping criterion in the case that the process of direct ionization of copper atoms prevails during formation of population inversion. The main factor limiting the CVL frequency-energy characteristics is the dependence of the rate of voltage increase at the active component of impedance of the gas-discharge tube on the concentration of electrons in the active medium. It is concluded that conditions of efficient pumping of the CVL active medium can be realized in two modes.

Introduction

The current level of insight into the physics of self-terminating metal atomic lasers, as well as the state of the art in experimental and theoretical studies are considered in most detail in Ref. 1. At the same time, in spite of numerous papers devoted to the study of this class of lasers, some experimentally observed regularities still did not receive proper explanation even at the qualitative level. This is true of, first, the experimentally observed dependence of laser energy characteristics on the excitation conditions determining the reliability of the efficient pumping criterion. Below we consider this dependence in more detail. In such a situation, it is difficult to evaluate promises of further development of this class of lasers. In this paper, we will try to explain the observed dependence at the qualitative level and evaluate the possible ways of improving the energy characteristics of the copper vapor laser (CVL).

1. Criterion of efficient pumping of active medium

The criterion, according to which for efficient pumping of the CVL active medium the excitation pulse must have a steep excitation front and the duration comparable with the population inversion lifetime, was formulated by G.G. Petrash in 1971 (see Ref. 2). It was assumed that the voltage increase front in CVL is determined by a switch. Consequently, for a particular switch, for example, a thyratron, the energy characteristics of a laser can be improved only by increasing the current growth rate in the laser discharge circuit. Actually, as the voltage across a reservoir capacitor increases and the capacity decreases in circuits with complete discharge of a reservoir capacitor, the current growth rate in the laser discharge circuit and the laser pulse energy increase, thus supporting the validity of the formulated criterion. The increase of the pulse repetition frequency (PRF) for excitation pulses also increases the current growth rate in the discharge circuit, but decreases the laser pulse energy, and the increasing capacity of the reservoir capacitor causes the decrease in the current growth rate before the beginning of the laser pulse, but the increase in the laser pulse energy (see, for example, Ref. 1).

The above dependences introduce some uncertainty into the assessment of the validity of the formulated criterion. The partly positive conclusion about the validity of this criterion is given in Ref. 3, where it is shown that the front of voltage increase at the active component of impedance of a gas discharge tube (GDT) is determined not only by a switch, but also by the parameters of the discharge circuit. Actually, the time of voltage increase at the active component of GDT impedance is determined by the following equation[3]:

$$\tau = \sqrt{\tau_{sw}^2 + \tau_c^2}\ , \qquad (1)$$

where τ_{sw} is the switch-on time; τ_c is the time of the voltage increase determined by the circuit parameters. As the PRF of excitation pulses increases, the concentration of electrons (n_e) in the active medium increases, what leads to the increase of τ_c, the voltage increase front elongates, and the energy of a laser pulse decreases.

According to Refs. 3 and 4, as the capacity of the reservoir capacitor increases, the process of discharging

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the reservoir capacitor in the laser discharge circuit transits from oscillatory to aperiodic. This leads to the increase of the amplitude and the rate of voltage increase at the active component of GDT impedance and to the growth of the laser pulse energy. As the capacity of the reservoir capacitor decreases and the voltage for maintenance of GDT thermal conditions, under which the discharge process in the circuit has an oscillatory character, decreases, the frequency of free oscillations in the circuit increases, as well as the voltage growth rate and the laser pulse energy.

It follows from Ref. 3 and from the above-said that the CVL energy characteristics are in direct dependence on the amplitude and rate of voltage growth at the active component of GDT impedance. This agrees with the conclusion of Ref. 1 that the electron temperature, which determines the population rate of upper and lower lasing levels in CVL, follows variations of the field strength at the active medium. However, it is unclear why no direct dependence of the current and voltage growth rate is observed in CVL.

This discrepancy is most pronounced at the increasing capacity of the reservoir capacitor in the CVL discharge circuit.[4] A CVL operating in the repetitively pulsed mode with the PRF of excitation pulses ~ 10 kHz has the high pre-pulse electron concentration $n_e \sim 10^{13}$ cm^{-3}. Under these conditions, the pre-breakdown stage of the discharge evolution is absent, and the current through the laser active medium is determined by ionization processes.

Two characteristic stages are observed experimentally in the discharge development in CVL. The first stage is characterized by the low rate of the current growth in the laser discharge circuit, and the second has a higher rate. As the capacity of the reservoir capacitor increases, the time for development of the first stage of the discharge increases, the duration of the excitation pulse becomes longer, and the lasing begins as the discharge transits from the first stage to the second one. According to Ref. 4, the transition from the first to the second stage corresponds to the transition of the discharging process from aperiodic to oscillatory. Figure 1 depicts the CVL current, voltage, and lasing pulses for the reservoir capacitor of 1.6 and 16.5 nF.

The measurements were conducted at the PRF of excitation pulses equal to 10 kHz and the same values of the capacity of the reservoir capacitor and the temperature of the wall of the GDT discharge channel. Figure 2 shows the variation of the CVL plasma conductivity corresponding to the oscillograms depicted in Fig. 1. The maximal difference in the conductivity change rate before the beginning of the lasing pulse in the excitation pulse with the reservoir capacitor of 1.6 nF was almost two orders of magnitude as compared with the 16.5-nF capacitor.

It is known that ionization in the active medium can be caused by the processes of direct or stepwise ionization, whose rates may differ by two orders of magnitude. We can assume that the direct ionization prevails at the first stage of discharge development.

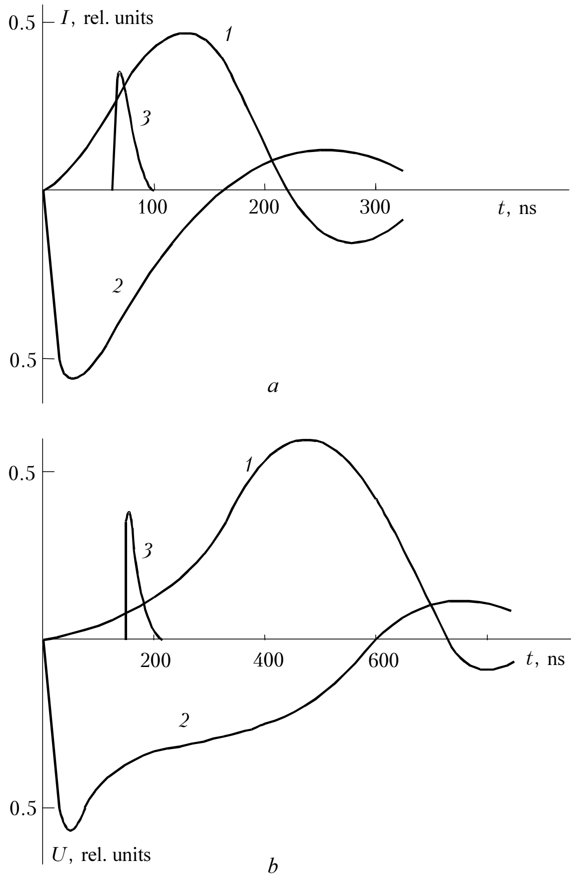

Fig. 1. Current (*1*), voltage (*2*), and lasing (*3*) pulses with a reservoir capacitor of 1.6 (*a*) and 16.5 nF (*b*) in laser discharge circuit.

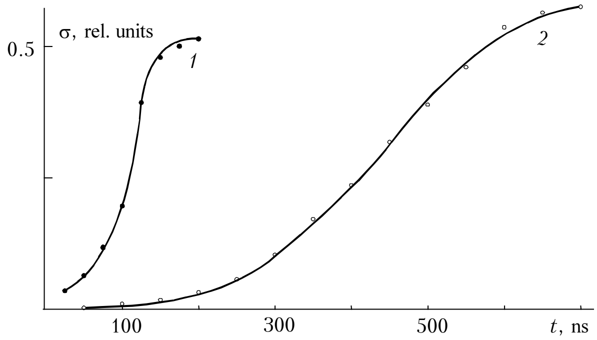

Fig. 2. Variation of plasma conductivity during the excitation pulse with a reservoir capacitor of 1.6 (*1*) and 16.5 nF (*2*) in the laser discharge circuit.

During the second stage, the prevalent process is the stepwise ionization with the characteristic rate ~ 10^{-7}–10^{-6} cm^3/s mostly from resonance levels of the copper atom.[5] It follows from the above-said that the CVL energy characteristics increase in the case that the front of current increase is determined by the increase in the rate of direct ionization of copper atoms. Otherwise, if the stepwise ionization is the prevalent process, the decrease is observed in the CVL energy characteristics. This is confirmed not only by the above dependence of the CVL energy characteristics on the excitation conditions, but also by the corresponding change in a glow of copper ionic lines. As is well-known, an ion can be excited directly, that is, due to collision of an electron with an atom in the ground state; in this case, the atom is ionized and excited simultaneously. Besides, stepwise ion excitation is also possible: first the ion in the ground state is generated, and then it is excited. In the presence of both the direct and stepwise processes, the intensity of the ionic line is described by the following equation:

$$I \approx N_0\, n_e\, q_1\, \Phi_1(\tau_{e1}) + N_i\, n_e\, q_2\, \Phi_2(\tau_{e2}), \qquad (2)$$

where N_0 and N_i are the concentrations of atoms and ions in the ground state; q_1 and q_2 are the effective cross sections at maximum for collisions leading to direct excitation of the ion being in the ground state; $\Phi_1(\tau_{e1})$ and $\Phi_2(\tau_{e2})$ are the excitation functions. Depending on the relationship between q_1 and q_2 and on the discharge conditions, the role of the first and second terms in Eq. (2) is different. In the low-pressure discharge, when the electron temperature T_e is high, the main role is played by the direct excitation, and in accord with Eq. (2) the dependence of I on n_e is close to linear. At higher pressure, when T_e is lower, the second term in Eq. (2) becomes significant; in this case, the dependence of I on n_e acquires the parabolic character. Kagan and Zaharova[6] studied the excitation of ionic lines in discharge in mercury vapor under different conditions and observed the above dependence. This dependence of glow of copper ionic lines was observed at CVL operation in the mode of "cut-off" of the energy pumped into the active medium[7] (Fig. 3). The analysis of experimental dependences of the CVL energy characteristics on the excitation conditions supports the validity of the efficient pumping criterion for self-terminating lasers in the case that direct ionization of atoms of the active medium is predominant during formation of population inversion. This also makes clear the mechanisms of restriction of CVL frequency-energy characteristics (FEC) that are connected with the pre-pulse electron concentration and relaxation of lower laser levels.[8,9]

2. Restriction of CVL frequency-energy characteristics

Restriction of CVL FEC is connected with the electron concentration in the active medium, when $\tau_c > \tau_{sw}$, because the rate of voltage growth at the active component of GDT impedance decreases with the increase of n_e. Otherwise, the decisive process may be relaxation of lower laser levels. Actually, in the case that the voltage growth front is determined by the switch-on time, the rate of population of laser levels must not change. As the PRF increases, n_e increases, and the populations of laser levels increase proportionally to the latter as well, but this is not true for the population inversion. This was demonstrated in the experiments with "cut-off" of the energy pumped into the active medium[7] (Fig. 3).

This mode was studied experimentally with small-size GDT having a low inductance $L < 0.5$ μH and impedance $\rho \sim 10\ \Omega$. Consequently, in a wide range of variability of the pre-pulse electron concentration, aperiodic discharge is realized before the beginning of lasing. The time constant of the discharge circuit is ~ 5–20 ns in all laser operating modes, what is less than the switch-on time. In this case, as can be seen from the oscillograms, no changes were observed in the time and energy of a lasing pulse at significant change in the energy pumped into the active medium and n_e.

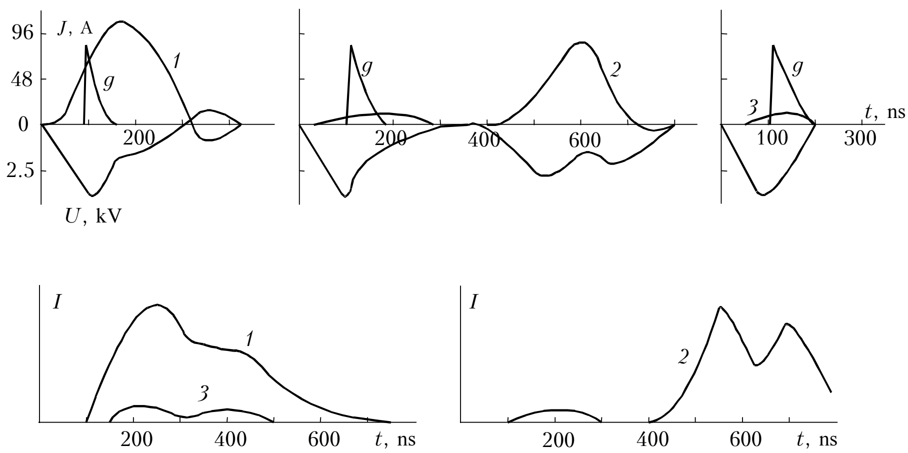

Fig. 3. Current $J(t)$, voltage $U(t)$, and lasing g pulses, as well as pulse of spontaneous emission I of 490.7 nm CuII ionic line in three laser operating modes[7]: self-heating mode (*1*), mode with "splitting" of the pumped energy (*2*), mode with "cut-off" of the pumped energy (*3*).

The above differentiation is rather conditional. Within the efficient pumping criterion, when direct ionization predominates during the population inversion formation, n_e cannot be the direct factor restricting CVL FEC. Actually, the increase of n_e or decrease of the voltage growth rate at the active component of GDT impedance lead to the increased population of the lower laser levels and to the increased threshold conditions for appearance of the population inversion. To achieve these threshold conditions, the energy pumped into the active medium must be increased, what contradicts with the principle of self-heating CVL operation. In other words, the laser efficiency decreases in the above case, and this follows directly from the criterion of efficient pumping.

The increase of n_e or decrease of the rate of voltage growth at the active component of GDT impedance at the limited energy pumped into the active medium by one excitation pulse lead not only to the increased population of lower laser levels, but also to the situation that stepwise ionization begins to play a significant role in formation of population inversion. The presence of stepwise ionization in the formation of population inversion restricts the populations of the upper laser levels[5,10] and thus causes the mechanism of restriction of CVL FEC.[8]

In the case $\tau_c < \tau_{sw}$, the increase of n_e also leads to extra population of the lower laser levels at the voltage increase front and to the increased threshold conditions, what requires extra energy and decreases the CVL efficiency (see Fig. 3). The effect of n_e can be compensated only due to the increase of the rate of voltage growth at the active component of GDT impedance. As the rate increases, the CVL efficiency increases, and the laser pulse energy increases with the increase of the field strength, because just the electric field strength determines the rates of population of the upper and lower laser levels. The rate of voltage growth at the active component of GDT impedance can be principally increased due to the increase of the GDT voltage amplitude or due to the decrease of the time of voltage growth τ. As the amplitude of GDT voltage increases, the energy pumped into the active medium increases, and to maintain the thermal conditions of laser operation, PRF of excitation pulses must be decreased. The time of voltage growth can be decreased at the expense of τ_c and τ_{sw}.

In the case $\tau_c < \tau_{sw}$, the increase of the switch speed leads to the decrease of threshold requirements for CVL lasing, and, correspondingly, requires lower energy consumption. The decrease of the energy pumped into the active medium decreases the degree of its ionization and, consequently, τ_c. This opens a possibility to realize high energy characteristics through the increase of PRF of excitation pulses.

Conclusion

For efficient pumping of the CVL active medium, it is necessary that direct ionization of copper atoms to be the prevalent process during formation of population inversion. Toward this end, the excitation pulse must have a steep front of voltage at the active component of GDT impedance with duration about the population inversion lifetime.

The prevalent process restricting CVL FEC is pre-pulse electron concentration, when $\tau_c > \tau_{sw}$, since in this case the rate of voltage increase at the active component of GDT impedance decreases with the increase of n_e. Otherwise, when $\tau_c < \tau_{sw}$, the relaxation of the lower laser levels may be the decisive process.

The conditions of the efficient pumping can take place in two modes of CVL operation. The first one is the mode of reduced pumped energy. In this mode, it is worth using a controlled switch like an electronic valve. The reservoir capacitor is selected based on the condition that the voltage across the reservoir capacitor keeps almost unchanged during the excitation pulse, that is, the following condition must fulfill:

$$CU^2/2 \gg E,$$

where C is the capacity of the reservoir capacitor; U is the voltage across the reservoir capacitor; E is the excitation pulse energy. The value of U is taken minimal, at which direct ionization of copper atoms is the decisive process during the excitation pulse. Duration of the excitation pulse is determined by the time needed to achieve the threshold lasing conditions and lasing duration; according to Ref. 5, it can be equal to hundreds of nanoseconds. Taking into account that the energy pumped for one pulse does not exceed 10% of typical values under these excitation conditions, the self-heating operating conditions and high practical efficiency can be realized only at high repetition rates of excitation pulses ~ 100 kHz. Since in this mode of CVL operation the electron concentration is $\sim 10^{13}$ cm^{-3} by the end of the excitation pulse, the CVL PRF is determined by the rate of depopulation of the lower laser levels. Consequently, the optimal PRF for lasing pulses ~ 100 kHz for this CVL operating mode is quite achievable, and the practical efficiency is about 7–8%, as indicated by the results of Refs. 7 and 11–13.

By analogy with the first mode, the second mode can be called the mode of increased pumped energy. Imagine that the voltage across the reservoir capacitor in the first mode is increased. This results in the increase of the rate of direct ionization, the rate of growth of the electron concentration, and the rate of excitation of the upper laser levels. As this takes place, the time needed to achieve the threshold lasing conditions decreases, as well as the duration of the excitation pulse. However, the optimal PRF of lasing pulses must decrease with the increasing electron concentration and pumped energy.

One of the most important parameters in self-terminating metal atomic lasers is the repetition frequency of laser pulses, since it largely determines the mean laser power and the practical efficiency. Therefore, for assessment of the energy potential of self-terminating lasers, it is very important to know the causes and mechanisms of PRF restriction.

P.A. Bokhan in his papers stated and justified that lasing PRF in CVL is restricted by the low rate of energy pumping into plasma because of the presence of inductance in the discharge circuit, what leads to the insufficient rate of heating of residual electrons of the previous pulse at the gas-discharge method of excitation. The last, in its turn, causes the increase of parasitic population of metastable levels and decreases the rate of excitation of resonance states of the copper atom.[8,14]

To the contrary, G.G. Petrash in his papers stated and justified that the main factor restricting the lasing PRF in this class of lasers is high pre-pulse population of metastable levels.[9] As a proof, he presented direct measurements of the excitation kinetics of CVL working levels in the dipulse mode.[15] The absence of agreement in the key problem for self-terminating lasers was and still is the subject of wide discussions. Actually, if we consider Bokhan's papers based on the above-said, then we can see that they initially postulate that the increase of voltage at the active component of GDT impedance is determined by "parameters of discharge circuit." At such formulation, the mode of reduced pumped energy is excluded from consideration. In Petrash's papers, to the contrary, it is initially postulated that the voltage growth rate is determined by a switch.[9,16] In this case, the "logic" chain must give the corresponding conclusion. The more basic character of restriction of laser FEC is obviously connected with the effect of pre-pulse electron concentration, since the laser efficiency decreases with its increase. However, the rate of its decrease is different depending on the laser operating mode, and in the mode of reduced pumped energy we may have the case that the lasing PRF is restricted by the pre-pulse population of the lower laser level. Obviously, it is necessary to study the mode of reduced pumped energy, since just in this mode we may obtain the high practical efficiency of CVL at gas-discharge excitation of the active medium.

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