Effect of the prepulse plasma properties on the frequency and power characteristics of a Cu-vapor laser

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The nature of physical limitations of the frequency and power characteristics of Cu-vapor laser is considered. It is shown that the processes in the laser discharge circuit determine the power pumped into the gas-discharge through the active component of the discharge impedance, determining the kinetics of the processes during the pump pulse. The development of the processes in the discharge circuit can have aperiodic or oscillatory character. By tuning the laser discharge circuit, i.e., making higher the frequency of its free oscillations, a high pulse repetition frequency (PRF) can be achieved. However, as the frequency of free oscillations increases, the Q-factor of the laser discharge circuit grows while the efficiency of pumping the active medium falls. In the self-heating mode of the Cu-vapor laser operation, this yields a decrease of the mean power of output radiation with the increasing PRF. The maximum mean output power is achieved in maximizing the power deposition into the active medium per single pump pulse, i.e., when the process in the discharge circuit is aperiodic. Consequently, the same process also determines the optimum PRF, at which the power of output laser radiation is maximum, and the cause of its limitation is uniquely related to the prepulse electron concentration.

Introduction

It is a specific feature of the lasing transition in copper atom that the energy of the resonance level is close to the first ionization threshold. This energy position of the resonance level favors its de-excitation to the ionization state either directly or through intermediate high-excited states. As a result, the population of the resonance state saturates with the increase of the discharge current, what limits the energy of the output pulse.[1–5] The high rate of de-excitation of the resonance levels into the ionization state is a physical cause of limitation of the output energy of a copper-vapor laser (CVL) radiation and it determines the possible way of improving the output energy characteristics of the laser by increasing the pulse repetition frequency (PRF). Therefore, to evaluate the CVL power potential, it is very important to know the factors that determine the PRF.

The high rate of de-excitation of the resonance levels into the ionization states causes the occurrence of some critical prepulse population of the metastable states and when this population is achieved, no inverse population of the lasing levels in the CVL active medium is formed.[6,7] Consequently, the nature and mechanism of the PRF limitation in CVLs are the processes of population and relaxation of the metastable states (MSs) of copper atoms both during the pump pulse and in the period between the pump pulses. Three possible causes of the PRF limitation are now considered:

1) The conditions for occurrence of critical prepulse electron concentration, when it is impossible to heat the electron component of the plasma up to the electron temperature higher than 2 eV at excitation by the gas-discharge pump[8];

2) Population of the metastable states by the leading edge of the pump pulse[9];

3) High prepulse population of the metastable states (see, e.g., Ref. 10).

Consider whether the MS population could achieve the critical value under the above conditions.

1. Critical prepulse electron concentration

The conclusion that some critical prepulse electron concentration $\sim 10^{14}$ cm^{-3} may exist was drawn in Ref. 8 based on the following. As known, to produce the population inversion in CVL, the electron temperature should exceed some critical temperature $T_{\mathrm{e\,cr}} \sim 2$ eV. At $T_{\mathrm{e}} < T_{\mathrm{e\,cr}}$, the metastable states are excited by electrons more efficiently than the resonance levels, and therefore the population inversion is not formed. At the same time, the electron temperature reaches maximum value yet during the increase of the electric current. If the maximum temperature appears to be lower than the critical one $T_{\mathrm{e\,cr}}$, no lasing is possible. The possibility of producing high electron temperature, in its turn, is significantly limited by the initial electron density. The power pumped into the medium is proportional to the plasma resistance, i.e., inversely proportional to the electron density. At the same time, the power consumption for ionization is directly proportional to the electron density (see Eq. (1) below). Consequently, at a given current density and electron temperature, there exists such a critical electron density, starting from which the power pumped into the medium is lower than the power losses due to ionization. The kinetic model[8] of the copper vapor ionization by a heating pulse included equations for the density of copper ions N_{iCu} and of the inert gas N_{iNe}:

$$\mathrm{d}N_{\mathrm{iCu}}/\mathrm{d}t = K_{\mathrm{iCu}}N_{\mathrm{e}}(N_{\mathrm{Cu}} - N_{\mathrm{iCu}}), \qquad (1)$$

$$\mathrm{d}N_{\mathrm{iNe}}/\mathrm{d}t = K_{\mathrm{iNe}}N_{\mathrm{e}}(N_{\mathrm{Ne}} - N_{\mathrm{iNe}}). \qquad (2)$$

The ionization rate constants of copper K_{iCu} and neon K_{iNe} were believed to be equal to the rate of excitation of the resonance states. This is valid in the mode of the quasi-steady-state ionization, when every excitation event is accompanied by the event of ionization from the excited state.[11,12]

According to Refs. 11 and 12, the quasi-steady-state ionization occurs, when the ionization of atoms of the active medium is determined by the process of de-excitation of the atomic resonance states into the ionization states. However, the ionization process in Ref. 8 is described by Eqs. (1) and (2), corresponding to the direct ionization of atoms of the active medium. Such an “artificial” representation is quite valid, if we consider the processes in the quasi-steady-state ionization mode. Consequently, it can be concluded based on data from Ref. 8 that the electron temperature in the quasi-steady-state ionization mode cannot exceed 2 eV at the electron concentration exceeding $\sim 10^{14}$ cm^{-3}. This is confirmed by the experimental data. After the lasing pulse, when the electron concentration is $\sim 10^{14}$ cm^{-3} and higher, the electron temperature is below 2 eV (see Ref. 13). If, formally, following the Eqs. (1) and (2), the quasi-steady-state ionization starts at the moment the voltage is applied to the active medium. However, it is known quite well that the rate of the direct ionization of copper atoms is at least two orders of magnitude lower than the rate of population of the resonance states (see, e.g., Ref. 4), and the ionization of the active medium is determined by the processes of the direct and stepwise ionization. Consequently, equations of the stepwise ionization should be complemented to the Eqs. (1) and (2):

$$\mathrm{d}N_{\mathrm{iCu}}/\mathrm{d}t = 2K_{\mathrm{ri}}N_{\mathrm{r}}N_{\mathrm{e}}, \qquad (3)$$

where K_{ri} is the rate constant of the stepwise ionization of the copper atom; N_{r} is the population of the resonance state of the copper atoms. At the initial moment, the population of the resonance states is zero, and the ionization process is determined by the direct ionization, whose rate constant, as was mentioned above, is two orders of magnitude lower than the rate constant of population of the resonance states. Consequently, the actual energy losses due to ionization at the initial stage of the discharge development are two orders of magnitude lower than those mentioned in Ref. 8. This means that there is always some time Δt (between the moment the voltage is applied to the active medium and the moment in time when the quasi-steady-state ionization starts), during which the electron component can be heated above 2 eV. However, the equation for the critical electron density $N_{\mathrm{e\,cr}}$ was obtained in Ref. 8 by equalizing the power pumped into the medium at the peak current density $j_{\max}$ to the power losses due to ionization of copper atoms at the critical electron temperature. Consequently, to determine the critical electron concentration, it is necessary to take into account the time, during which the quasi-steady-state ionization mode is established, i.e., Δt should be shorter than the time of formation of the population inversion in the active medium.

Since the electron temperature follows the voltage applied to the active component of the gas-discharge tube (GDT) impedance, it is necessary to take into account the time Δt_{cr} of heating of the prepulse electrons to temperature $T_{\mathrm{e\,cr}}$. In this case, Δt_{cr} can be considered as the time, during which the MS population achieves the critical value $N_{\mathrm{m\,cr}}$ and no inverse population can be produced in the active medium. Consequently, it can be stated that under particular pumping conditions there exists a particular value of $N_{\mathrm{e\,cr}}$, which is determined by the time of heating the electron component of the plasma to the temperature $T_{\mathrm{e\,cr}}$.

2. Population of metastable states by the leading edge of the pump pulse

The electron temperature, determining the rate constants of population of the lasing levels, follows the variation of the field strength applied to the active component of the GDT impedance. The electric field strength applied to the active component is, in its turn, determined by the processes in the discharge circuit. The rate of the voltage growth is determined by the time constant $\tau \sim L/R_0$ (where L is the inductance of the discharge circuit, R_0 is the prepulse resistance of the plasma) for the aperiodic process in the discharge circuit and by the frequency of free oscillations in the case of the oscillatory process.[14] According to Ref. 14, we can always select such a storage capacitor that at the initial stage of the discharge development the process in the circuit is aperiodic, and the rate of the voltage growth is determined by the time constant $\tau \sim L/R_0$ or, since $R_0 \sim 1/n_{\mathrm{e0}}$ (where n_{e0} is the prepulse electron concentration), $\tau \sim Ln_{\mathrm{e0}}$. Actually, it is just this dependence that causes the governing role of the prepulse electron concentration in the limitation of the frequency and power characteristics of a CVL. Consequently, $\Delta t_{\mathrm{cr}} \sim Ln_{\mathrm{e0}}$.

For this time, the lower lasing level is additionally populated by ΔN_{m} and in this case $N_{\mathrm{m\,cr}}$ is determined as follows

$$N_{\mathrm{m\,cr}} = N_{\mathrm{m}0} + \Delta N_{\mathrm{m}}, \qquad (4)$$

where $N_{\mathrm{m}0}$ is the prepulse MS population. While the rate of population of the lower lasing level exceeds that of the upper one, the ionization contribution is negligibly small and

$$\Delta N_{\mathrm{m}} = N_{\mathrm{Cu}} n_{\mathrm{e}0} k_{0\mathrm{m}} \Delta t_{\mathrm{cr}}, \qquad (5)$$

where N_{Cu} is the density of copper atoms; $k_{0\mathrm{m}}$ is the rate constant of population of the lower lasing levels, that is,

$$\Delta N_{\mathrm{m}} \sim n_{\mathrm{e}0}^2. \qquad (6)$$

This clearly demonstrates that in an actual laser the prepulse electron density should be a significant factor limiting the laser PRF, and as PRF increases, the laser pulse energy changes in the inverse proportion to $\Delta N_{\mathrm{m}} \sim n_{\mathrm{e}0}^2$. At the same time, the particular value of $N_{\mathrm{e\,cr}}$ depends not only on the MS population at the leading edge of the pump pulse, but also on $N_{\mathrm{m}0}$. However, in an actual laser additional conditions can arise, leading to the sharpening of the voltage front at the active component of the GDT impedance.

Actually, GDT was considered as a load, consisting of the inductor L and the resistor R, connected in series. Only the gas-discharge channel of GDT, outside which the cylindrical electrodes are located in cold buffer zones, can be directly considered as such a load.[15] In addition, GDT has its own capacitance C_0.

Since in this case we consider the initial stage of the discharge development, it is necessary to take into account the time variation of the resistance of the near-cathode area and cold end zones, where no copper atoms are present. The analysis of these processes shows[16] that just the initial stage of the development of a pulsed discharge, used to pump CVL, plays an important role in excitation of the levels and production of the unsteady inversion of population. However, the processes on the CVL electrodes and in the cold near-electrode areas have studied very poorly. Therefore, within this analysis, we can note only the existence of a time delay between the pulses of electric current and voltage, observed experimentally under operating conditions typical for the CVL.[17] This time lag causes the possibility of charging the GDT's self-capacitance or a peaking capacitor, often used for this purpose, up to the voltage comparable with the voltage applied to the storage capacitor. If the further process on the electrodes and in the near-electrode zones develops as an avalanche, then, by analogy with Ref. 14, it can be considered as a "unit response." The rate of the voltage increase at the GDT discharge gap is determined by the frequency of free oscillations in the circuit, consisting of the elements L, R, and C_0, which can cause significant sharpening of the voltage front at the active component of the GDT impedance, while the energy pumped into the active medium is determined by the storage capacitance in the discharge circuit of the laser.

3. Mechanism of production of the prepulse population of the metastable states

The CVL active medium in the pulse-periodic operation mode is characterized by the high electron density ($\sim 10^{13}$ cm^{-3}) that should provide for high rate of the electron-impact de-excitation of metastable states between the pump pulses.[9] However, the measurements of time behavior of the MS population have shown (Fig. 1) that the actual process of the MS relaxation in the most cases has two components, namely, the high relaxation rate in the near afterglow (~1 μs) followed by the much slower relaxation after that. It is obvious that it is just the low relaxation rate that provides for high prepulse MS population thus being the factor limiting the frequency and power characteristics of CVL.

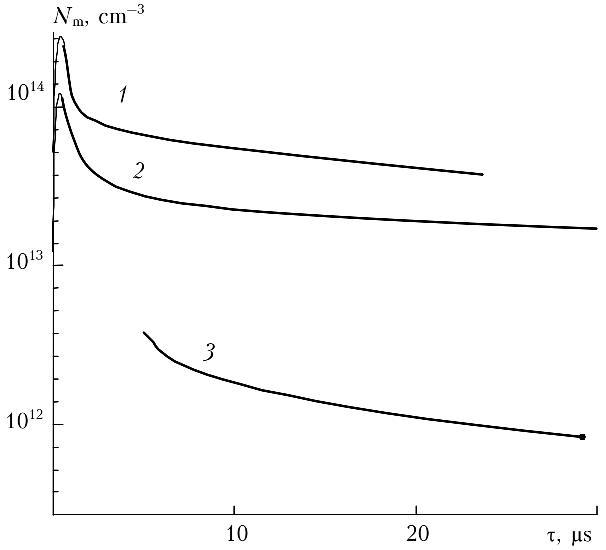

Fig. 1. Dependence of the population of the $\mathrm{Cu}(4s^2\,{}^2D)$ level on the afterglow time: results from Ref. 18 (curve *1*), Ref. 19 (*2*), and Ref. 20 (*3*).

The low rate of MS relaxation in the plasma, characterized by the high electron density (~ 10^{13} cm^{-3}), can be maintained only by the recombination flux and by the energy deposition into the active medium during the whole period between the pulses. The above-said is confirmed by the following experimental data.

The simplest method to change the MS density in the period between pulses is to apply a DC voltage to the active medium. The effect of the DC voltage on the CVL output power characteristics was studied (Fig. 2) with an LT30Cu GDT (discharge channel of 20-mm diameter and 80-cm length). A TGI1-1000/25 thyratron was used as a switch.

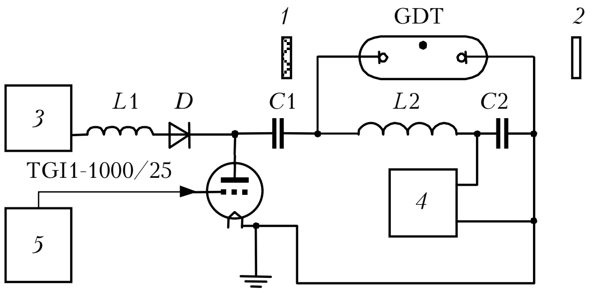

Fig. 2. Schematic diagram of the experimental setup: cavity mirrors *1*, *2*; rectifier of the pump voltage *3*; additional power supply *4*; master oscillator *5*; storage capacitor $C1$; capacitor $C2$ of the filter of the additional power supply *4*; charging supply choke $L1$ and diode D; shunt inductance coil $L2$.

An additional capacitor $C2 = 10^4$ μF was a capacitor of the filter of the additional power supply, whose voltage was applied to GDT. The shunt inductance coil $L2$ and the filter capacitor $C2$ ensured the isolation of the additional power supply from the pump pulses. The change of the voltage at the additional power supply from 0 to 60 V led to the change of the mean output power from the maximum value of ~10 W to zero at the following pump parameters: $C1 = 2200$ pF; PRF = 12 kHz; voltage at the high-voltage rectifier ~5.6 kV; current supplied from the high-voltage rectifier ~450 mA. As the voltage increases up to 60 V, the output energy decreases more sharply at $\lambda_1 = 510.6$ nm than at $\lambda_2 = 578.2$ nm. The radial profile of the output radiation also changes. The lasing is observed as a ring at $\lambda_1 = 510.6$ nm and then at $\lambda_2 = 578.2$ nm as the voltage increases up to 60 V. The experimentally observed result demonstrates clearly the effect of the energy deposition in the period between pulses into the relaxation process of the lower lasing levels.

Changing the MS population just before the pump pulse by injecting an additional pulse before every pump pulse, it is possible to estimate the actual energy losses due to the formation of high MS density and to assess the time of MS relaxation in the absence of the energy deposition. The experimental check was conducted using an UL-102 CVL GDT, whose discharge channel had the inner diameter of 2 cm and the length of 40 cm. The buffer gas was neon. The schematic diagram of the experimental setup is shown in Fig. 3.

TGI2-500/20 and TGI1-270/12 thyratrons were used as switches, generating the pump and additional pulses. The studies were carried out at the following parameters: storage capacitors $C1 = C2 = 2.2$ nF; $f = 10$ kHz; rectifier voltage and the mean current of 4.9 kV and 340 mA, respectively; rectifier voltage and the mean current of the additional source of 1 kV and 40 mA. The maximum mean output power of lasing in a plane-parallel cavity in the established thermal mode and the lag of 10 μs between the pulses was ~5 W.

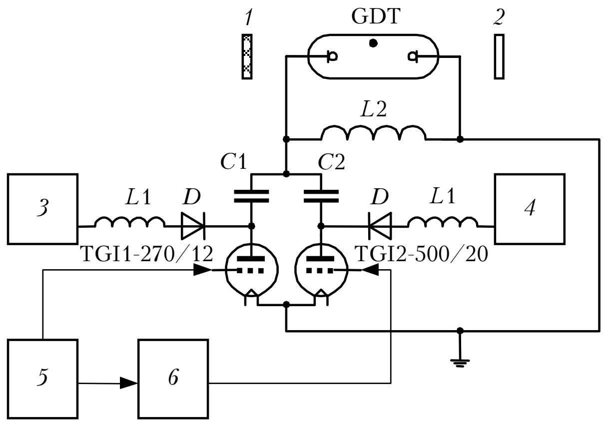

Fig. 3. Schematic diagram of the experimental setup: cavity mirrors *1*, *2*; rectifier of the additional power supply *3*; rectifier of the pump source *4*; master oscillator *5*; controllable delay line *6*; storage capacitors $C1$, $C2$; charging supply choke $L1$ and diode D; shunt inductance coil $L2$.

The studies have shown that the mean output power decreases from 5 W to 0 as the additional pulse approaches the pump pulse, as shown in Fig. 4.

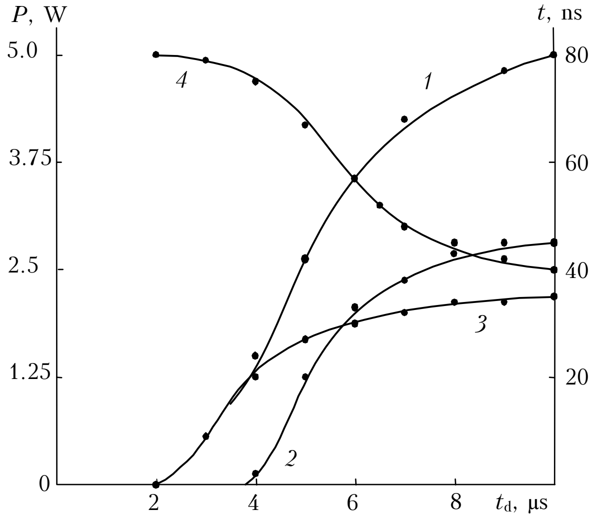

Fig. 4. Variation of the total mean output power (*1*), mean output power at $\lambda = 510.6$ (*2*) and 578.2 nm (*3*), as well as the lag of the lasing behind the beginning of the pump pulse (*4*) vs. the delay t_d between the pulses.

The decrease of the mean output power observed is sharper at the lasing line $\lambda = 510.6$ nm. The radial distribution of laser radiation density also changes. As the delay between pulses decreases, the transition to the ring lasing pattern at $\lambda = 510.6$ nm is first observed, then the lasing at this line disappears, and, as the pulses become closer, similar pattern is observed at $\lambda = 578.2$ nm. The lasing at both of these lines disappears completely at the delay between pulses of ~2 μs.

The results presented above demonstrate clearly the effect of the energy deposition into the active medium in the period between pulses on the process of MS relaxation. Now it is known that the energy deposition into the active medium in the period between pulses is provided by the following factors:

1) dissipation of the energy stored in the shunt inductance coil during the pump pulse[21];

2) charging current, flowing through the active medium[22];

3) dissipation of the energy stored in the reactive component of the GDT impedance.

It is obvious that the process of energy pump into the discharge plays the decisive role in the limitation of the MS relaxation as it can exist in between the pump pulses.

The energy stored in the shunt inductance coil during the pump pulse dissipates, according to Ref. 21, in the near afterglow and can affect the process of MS relaxation only at high PRF (~100 kHz). The current charging the storage capacitor that flows passing through the active medium affects significantly, according to Ref. 22, the power characteristics of the laser emission, since in Ref. 22 the investigations were carried out with the laser operating at PRF equal to the resonance frequency of charging the storage capacitor. Its influence can be eliminated easily by introducing a diode into the charging circuit of the laser power supply, and the time of charging of the storage capacitor is taken to be roughly 10 μs shorter than the period of pump pulses. Consequently, one of the causes of limitation of the MS relaxation process in the period between pulses may be the process of dissipation of the energy, stored in the reactive component of the impedance of both the discharge and, possibly, charging circuits, in the active medium.

It is obvious that only more detailed studies would allow finding technical solutions to this problem. One of the main causes for the possible high prepulse MS population is the density of the recombination flux to the MS levels. The recombination flux density, in its turn, is initially determined by the degree of the active medium ionization, which depends on the duration of the quasi-steady-state ionization. Since the population inversion in the active medium cannot be produced under conditions of the quasi-steady-state ionization, this mode is also parasitic for pumping and technical measures to its elimination should be sought for.

Conclusions

The analysis of processes causing the limitation of the CVL frequency and power characteristics has shown that the level of the power characteristics of the copper-vapor laser achieved by now is mostly determined by the electronic components available in designing the laser. At the same time, this analysis has allowed the formulation to be made of the general approaches to the optimization of the pump parameters in the experimental and theoretical investigations. Actually, the power pumped into the active component of the GDT impedance determines the kinetics of the processes in the laser pump pulse and is determined by the processes in the laser discharge circuit. The development of the processes in the laser discharge circuit can have aperiodic or oscillatory character. Tuning the laser discharge circuit, i.e., increasing the frequency of free oscillations, makes it possible to obtain high repetition frequency of the lasing pulses. However, as the frequency of free oscillations in the laser discharge circuit increases, the figure of merit of the circuit increases and the efficiency of pumping of the active medium decreases. For the self-heating mode of the CVL operation, this means the decrease of the mean output power with the increase of PRF.

The optimization of the laser pumping parameters is mostly aimed at obtaining maximum mean output power. This is achieved by realizing the maximum of power pumped into the active medium during the pump pulse, i.e., by aperiodic process in the discharge circuit. The optimal PRF, at which the mean output power is maximum, is also determined by this process. Consequently, the limitation of the optimal PRF is uniquely caused the prepulse electron concentration. Thus, the optimization of the parameters of pumping of the CVL active medium should be in selecting the conditions, under which the rate of the voltage increase applied to the active component of the GDT impedance within the framework of the aperiodic process in the laser discharge circuit is high.

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