Abstract. **The relation between the lasing efficiency of a copper vapour laser and relaxation of the metastable states is studied at high average pump powers. The prepulse concentration N_{ms0} of metastable states in tubes of diameter 2 cm in lasers with a high efficiency (above 1 %) is shown to be negligible up to linear output powers of ~ 50 W m^{-1} and has no effect on the output power. At a lower lasing efficiency caused by the mismatch between a power supply and the laser tube, the population of metastable states strongly increases during afterglow and can become a main factor restricting the output power in a repetitively pulsed regime. As the neon pressure is increased or hydrogen is added, the matching is facilitated and the effect of N_{ms0} on the lasing parameters of a high-power copper laser decreases.**

Keywords: *copper vapour laser, frequency – energy parameters, prepulse electron density, relaxation of metastable states.*

1. Introduction

The limitation of the frequency – energy parameters of self-terminated lasers, in particular, a copper vapour laser is commonly attributed to an insufficient relaxation of metastable-state populations [1] and to a slow recombination of a plasma during afterglow [2]. In the first case, the prepulse population N_{ms0} of the metastable state can be so high that it begins to affect the laser-pulse energy with increasing its repetition rate F, reducing finally the average output power. For a certain threshold population N_{ms}^{th} of the metastable state, the prepulse population can become so high that the difference $N_r - g_r/g_{ms}N_{ms} < 0$ during the pump pulse, and lasing does not occur (here, N_{ms} and N_r are the populations of the metastable and resonance states, respectively, and g_r and g_{ms}

2. Effect of N_{ms0} on the lasing properties of optimised sealed copper vapour lasers

The conclusion about a negligible effect of N_{ms0} on the restriction of $P_{r\,las}$ in copper lasers was formulated for the first time in Ref. [2]. The results [2] were obtained for optimised lasers [20] at moderate pump ($P_{rp} \sim 450$ W m^{-1}) and output ($P_{r\,las} \sim 7$ W m^{-1}) powers. Modern lasers, in particular, sealed lasers operate at much higher powers $P_{rp} \sim 4$ kW m^{-1} [15, 19] and $P_{r\,las} \sim 40$ W m^{-1} [15]. It follows from Ref. [19] that $P_{r\,las}$ in these lasers is mainly limited by a high concentration N_{ms0}. These data contradict to results [12] obtained for a copper laser and [21] for a Cu – Br laser, where the output powers were predominantly restricted by a high concentration N_{e0}.

To elucidate the reasons for this discrepancy, we studied the effect of N_{ms0} on the lasing parameters of high-power copper lasers using a laser setup described in Ref. [22]. Radiation from a master oscillator with a GL-201 copper-vapour laser tube with an unstable resonator was directed to two sequentially located Kristall LT-40Cu tubes of diameter 2 cm [15]. The switching time of the power supply of the second tube could be shifted with respect to synchronously operating power supply of the first tube and the master oscillator from zero to ± 90 μs (the interval between pulses).

A typical value of $P_{r\,las}$ of a Kristall LT-40Cu tube operating in the oscillator – amplifier regime exceeds 50 W m^{-1} for an overall power of 70 W, while the lasing efficiency (with respect to the rectifier power) was 1.3 % – 1.8 %, which is close to the efficiency at low pump powers [2, 20]. Typical pump parameters at which the maximum lasing power was obtained were $F = 11$ kHz, the amplitude voltage $U_a \approx 25$ kV, the duration of the pulse leading edge ~ 25 ns, the current pulse FWHM ~ 45 ns, and the average consumed power was up to 4.5 kW. The pump pulse from the power supply, which was based on a scheme of a partial discharge of a capacitance through a GMI-29A vacuum tube, was fed to the tube through a 10-m long cable with the wave impedance 75 Ω. The use of such a driver does not provide the quality of matching of the oscillator with a load as in Ref. [20]. For this reason, the amplitude of the first positive current pulse for the maximum output power, which was observed after a double passage of the pulse through the cable, was ~ 50 % in our experiments compared to ~ 5 % in Ref. [20].

We measured the populations of metastable states and of their influence on the lasing parameters by the method of spaced absorption and lasing regions developed in Ref. [21]. The advantage of this method is that it allows one to separate accurately the influence of N_{ms0} on the lasing parameters of self-terminated lasers and distinguish it from the effect of N_{e0}.

We used the following experimental procedure. By adjusting the pump power, we obtained the conditions under which the output power after the first tube was ~ 0.5 of the output power after the second tube in the case of a perfect synchronisation of pump pulses, i.e., the identical lasing properties of the laser tubes were achieved. Then, the pumping of the first tube was delayed, and the power of radiation of the first tube propagated through the second tube was measured. To eliminate the influence of superradiance from the second tube, we performed measurements in the far-field zone.

Curves (*1 – 3*) in Fig. 1 show the time dependences of the radiation power from the first tube propagated through the second tube for output powers equal to 55, 35, and 27 W. Curves (*1′ – 3′*) are the decay curves of the total population of the Cu(^2D) state during the afterglow corresponding to cases 1 – 3. One can see that, for the pulse repetition rate used in our experiments and lasing conditions close to optimal ones (the output power is $P_{las} = 55$ W and the lasing efficiency is $\eta = 1.31$ %), the prepulse population of metastable states has no effect on the lasing parameters of the copper laser.

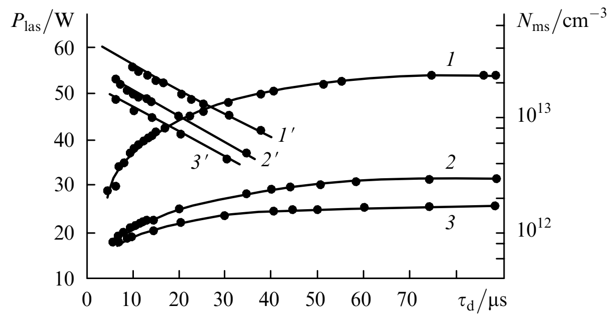

Figure 1. Time dependences of the transmitted radiation power (*1*, *2*, *3*) and decay curves of the population of the Cu(^2D) state in the afterglow (*1′*, *2′*, *3′*) for the output powers equal to 55 W, 35 W, and 27 W, respectively.

3. Effect of the pump pulse profile and the degree of matching of a power supply with a laser tube on the lasing efficiency and relaxation of the metastable-state populations

The result obtained above does not contradict to the data [11, 16], according to which the metastable-state depopulation time in Cu atoms is $\tau = 1/k_e N_e < 0.5$ μs under typical pumping conditions (here, k_e is the rate constant of deexcitation caused by electrons and N_e is the electron concentration). The relaxation times observed in experiments were substantially longer than 0.5 μs. Therefore, the metastable-state relaxation time, as in [16], is determined by the rate of electron cooling in a given time interval. Let us show that the matching of a laser cell with a power supply substantially affects the relaxation mechanism both at the initial and, strangely enough, final stages of the afterglow.

In the case of the unsatisfactory matching typical for laser cells heated by a discharge, the current oscillations can proceed at least for several hundreds nanoseconds [23, 24] and even for several microseconds [25]. As a result, the high electron temperature T_e is maintained during afterglow, resulting in the increase of N_{ms} and N_e. This leads to a slower decay of metastable states, which have some effect on the output power, and also to some individual features in the power limitation mechanism in each specific case.

One of the forced reasons resulting in a strong mismatch is the deviation from an optimal scheme of the laser pumping. It was shown in Ref. [20] for a copper vapour laser that, in the case of the maximum efficiency, the optimal storage capacitance was

$$C_{opt} \sim 15d^2/l, \tag{1}$$

Table 1. Parameters of lasers at optimal working temperatures.

References	$w_p/$ μJ cm^{-3}	$w_{las}/$ μJ cm^{-3}	η (%)	C_{opt}/nF	C/nF	C/C_{opt}	d/cm	l/cm	P_p/kW	P_{las}/W	F/kHz	δ
[19]	1.6	4.0	0.25	–	*	–	2.0	40	2.0	5	10	~ 1
[26]	1.0	3.34	0.33	0.54	6.0	11.1	1.8	90	1.8	6	7.85	0.72
[27]	0.35	2.7	0.76	6.4	12	1.9	8.0	150	13.2	100	5.0	< 0.12
[9]	0.23	2.5	1.07	4.6	10	2.2	8.0	210	12.1	130	5.0	< 0.09
[2]	0.2	3.2	1.6	4.4	4	0.9	2.7	25	0.11	1.8	4.0	0.02
This paper	1	13.1	1.31	–	*	–	2	120	4.2	55	11.1	< 0.02

Note: w_p and ${}_{las}$ are the specific pump and output powers; η is the lasing efficiency; C is the working capacitance; P_p and P_{las} are the average pump and output powers; F is the pulse repetition rate; * is the partial discharge of the capacitance through a lamp switch.

where d and l are the diameter and length of a laser tube in centimetres, respectively; and C is measured in nanofarads. This provided the 3 % efficiency of the copper laser in a single-pulse regime and the 2.6 % efficiency in the repetitively pulsed regime. The deviation from the optimal capacitance and the specific pump energy related to it reduces the lasing efficiency and strongly affects the behaviour of metastable-state populations during afterglow.

Consider six cases, including this paper, which encompass a variety of pumping conditions of laser tubes of different sizes. In five cases, the specific radiation energy was approximately identical (Table 1). Fig. 2 shows the decay curves for the Cu$(^2D_{5/2})$ metastable state. The decay data for this state under the conditions of Ref. [2] are presented in Ref. [28].

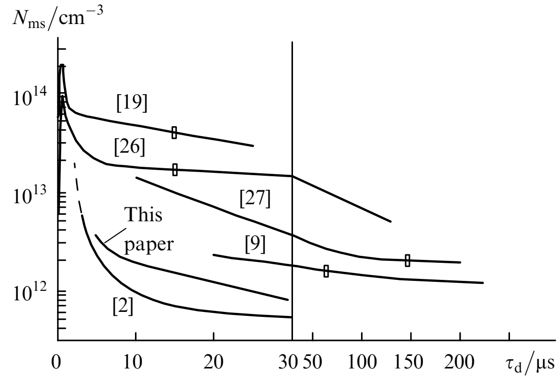

Figure 2. Dependences of the population of the Cu$(4s^2\,^2D)$ level on the afterglow time. The curves are denoted in accordance with references in Table 1 ($\square$ is the delay time of lasing). The vertical straight lines separate the regions with different time scales; the dashed part of curve [2] corresponds to extrapolation.

One can see from Table 1 and Fig. 2 that, irrespective of the tube diameter, the lasing efficiency is the highest and the metastable-state population is the lowest when the storage capacitance is close to its optical value C_{opt}. A comparison of data from papers [19, 26] and [2, 28] showed that, for virtually the same energy output, the difference in the metastable-state population amounted to two orders of magnitude.

4. Mechanism of a delay of the metastable-state decay in non-optimised lasers

It is necessary to understand why comparatively small changes in the specific pump energy (see papers [2, 19], Table 1 and Fig. 2) result in a drastic (almost by two orders of magnitude) increase in N_{ms} in the range from 10 to 15 μs after the pump pulse end. Consider for this purpose the electron energy balance during the pump pulse and afterglow.

During the active phase of the pump pulse, which is conditionally limited by the instant of lasing termination, resonance states are strongly populated. During this period, step processes are efficient [8, 29], which result in a strong population of higher states [30, 31] and in the ionisation of copper atoms. The metastable states have no time to be populated significantly. Thus, the lasing terminates, according to theoretical [4, 32] and experimental [25, 33] data, when $N_e \sim (2-5)\times 10^{13}$ cm^{-3} by the time $\tau_f \sim 100$ ns after the beginning of a current pulse. Therefore, the maximum density of atoms populating a metastable state through a direct excitation channel Cu$(4s\,^2S) + e \to$ Cu$(4s^2\,^2D) + e - \Delta E$ is

$$N_{ms}^{f}(^2D) = \int_0^{\tau_f} \langle\sigma v\rangle N_a N_e \mathrm{d}t \leqslant 10^{13}\ \mathrm{cm}^{-3}, \qquad (2)$$

where $\langle\sigma v\rangle$ is the rate constant of excitation of metastable states [32, 34] and N_a is the concentration of copper atoms. Approximately the same number of atoms populate metastable states through the lasing channel at the energy output $w_{las} \sim 4$ μJ cm^{-3} (Table 1), which is confirmed by calculations [34]. It is quite obvious that $N_r \sim (g_r/g_{ms})N_{ms}$ by the lasing termination.

If after the lasing termination, electrons are not heated by subsequent current waves (as in optimised lasers matched with a power supply), then T_e rapidly decreases due to step processes of the type Cu$(4p\,^2P) + e \to$ Cu$(ns\,^2S) + e - \Delta E$. According to data [32, 35], the rate k_e^* of step processes for $T_e > 1$ eV exceeds 10^{-7} cm^3 s^{-1}. The overall population of resonance and other highly excited states is $\sum N_k \sim 10^{14}$ cm^{-3}. This results in the characteristic time of the electron cooling $\sim 10^{-7}$ s. Simultaneously with decreasing T_e, the populations of all the levels, including metastable levels, decrease with certain rate constants [11, 16] down to the values at which step processes become inefficient. The last of these processes, which causes electron cooling, is the process Cu$(4p\,^2P) + e \to$ Cu$(5s\,^2S) + e - \Delta E$ (transition from the resonance state to a nearest higher-lying state, which is dipole-coupled with the resonance state).

This occurs at $T_e \sim 0.4$ eV, when the rate of step reactions becomes equal to the rate of the metastable-state deexcitation accompanied by electron heating. If the values of N_r and N_{ph} (N_{ph} is the specific number of emitted photons) are comparable with N_{ms}^{f} [see (2)], then such a mechanism of electron cooling, together with the relaxation of the metastable state to the ground state Cu$(4s^2\,^2D)+$

$e + \mathrm{Cu}\,(4s\,^2S) + e + \Delta E$, reduces N_{ms} below 10^{13} cm^{-3} already at the first stage of the afterglow (the stage of a rapid decrease in N_{ms}, when the population can decay lower than T_{e}). This is followed by a slow decay of N_{ms}, when the metastable-state population is determined by the relaxation of the temperature T_{e}.

If electrons are heated by subsequent current waves, then, according to [32] (conditions of [26]), the temperature $T_{\mathrm{e}} > 1$ eV till the afterglow time $\tau_{\mathrm{d}} \sim 500$ ns and it remains high (above 0.5 eV) for several microseconds [7, 36, 37]. By this moment, the metastable states are already populated up to $N_{\mathrm{ms}} \sim 10^{14}$ cm^{-3} [34] and above [19, 26], while all the highly excited states, including resonance states, are depopulated down to the level when $\sum_k N_k \ll N_{\mathrm{ms}}$. For this reason, the only remaining channels of electron cooling are ambipolar diffusion (in small-diameter tubes at a low pressure of a buffer gas) and elastic collisions with heavy particles [38] (electron cooling due to relaxation of the metastable states of copper in collisions with heavy particles is inefficient [16]).

The cooling time of electrons in collisions with neon under optimal conditions (at the neon pressure $p_{\mathrm{Ne}} \sim 20-30$ Torr) is ~ 20 μs, and this value is typical for the second stage of the metastable-state decay both in optimised and non-optimised lasers. However, this stage begins at substantially different values of N_{ms}, which exerts, as one can see from Fig. 2, a strong effect on the metastable-state relaxation and the recovering of lasing during a subsequent pulse.

5. Discussion of results

An exponential decrease in N_{e} during the afterglow [39] is observed at substantially different energy inputs and different initial values of N_{e}. For this reason, the values of N_{e0} are restored in optimised and non-optimised lasers approximately at the same delays. However, in optimised lasers, a rapid decrease of T_{e} is completed at $N_{\mathrm{ms}} < 10^{13}$ cm^{-3}, and already by this moment a medium is again capable of lasing according to the N_{ms0} criterion, i.e., after several microseconds, irrespective of the active medium of a laser, the pumping method, and the method for measuring N_{ms} [21, 40, 41]. In this case, the dominating action of N_{e0} on the lasing recovery can be readily detected. In non-optimised lasers, the value of N_{ms} decreases below 10^{13} cm^{-3} substantially later for the reasons considered above, and it may happen that N_{ms0} will not only affect the output energy but will determine it completely [19].

Let us estimate the effect of the concentration N_{ms0} for the cases presented in Table 1. At present, there is no convenient methods for estimating the influence of N_{ms0} on the lasing parameters of self-sustained lasers. The qualitative methods, which were developed, for example, in papers [42, 43], are not satisfactory because they contradict to the quantitative data of the authors of these papers themselves.

The discrepancy is that the limitations begin at substantially different metastable-state populations [19, 43]. Thus, in paper [19], lasing disappears at $N_{\mathrm{ms0}} \approx 4 \times 10^{13}$ cm^{-3}, whereas in paper [43], at $N_{\mathrm{ms0}} \approx 1.5 \times 10^{12}$ cm^{-3}, the energy outputs at operating pulse repetition rates being close. The quantitative methods based on computer calculations of the laser kinetics (see, for example, [4, 12, 32]) are also vulnerable because of an inaccurate determination of the rate of many important processes. Therefore, we will estimate the influence of metastable states on lasing parameters by using semiquantitative calculations based on the initially measured parameters such as the specific energy output, the absorption coefficient before the pump pulse, etc.

This method is based on the model of lasing in the presence of absorbing particles in the laser resonator. The presence of these particles before the pump pulse results in the reduction of lasing. If the particles in the ground state do not relax during the laser pulse, as in self-terminated lasers, they reduce the output energy compared to that for free-running lasing by $\Delta w_{\mathrm{las}} = h\nu N_{\mathrm{ab}}/2$ [44], where N_{ab} is the concentration of absorbing atoms. The geometrical position of absorbing particles in the resonator and the type of population of the working levels during the pump pulse are not important. Based on this model, the relative reduction in the output of a self-terminated laser caused by the prepulse metastable-state population can be written in the form

$$\frac{\Delta W}{W} = \frac{g_{\mathrm{r}}}{g_{\mathrm{r}} + g_{\mathrm{ms}}} \frac{N_{\mathrm{ms0}}}{N_{\mathrm{ph0}}}, \tag{3}$$

where N_{ph0} is the specific number of photons emitted at $N_{\mathrm{ms0}} = 0$. In the repetitively pulsed regime, N_{ph0} is the specific number of photons in the regime when N_{ph} is independent of F. Under threshold conditions, when $\Delta W/W = 1$, we have

$$N_{\mathrm{ms}}^{\mathrm{th}} = \frac{g_{\mathrm{r}} + g_{\mathrm{ms}}}{g_{\mathrm{r}}} N_{\mathrm{ph0}}. \tag{4}$$

The value of N_{ms} is often calculated in experiments from the absorption coefficient k_0^- at the working transition. One can show that

$$\frac{\Delta W}{W} = \frac{k_0^-}{k_{\mathrm{max}}^+}, \tag{5}$$

where k_{max}^+ is the gain at the inversion maximum. The value of k_{max}^+ for a copper laser can be calculated quite accurately by measuring the energy output w_{las}. Because

$$w_{\mathrm{las}} = N_{\mathrm{ph}} h\nu = \frac{N_{\mathrm{r}}^{\mathrm{m}} - (g_{\mathrm{r}}/g_{\mathrm{ms}}) N_{\mathrm{ms}}^{\mathrm{m}}}{1 + g_{\mathrm{r}}/g_{\mathrm{ms}}} h\nu, \tag{6}$$

and the absorption (amplification) cross section for both laser lines weakly depends on temperature in a broad range of conditions [17], we have

$$\frac{\Delta W}{W} = \frac{k_0^-}{7.6 \times 10^{-2} w_{\mathrm{las}}} \quad \text{for the green line} \tag{7}$$

and

$$\frac{\Delta W}{W} = \frac{k_0^-}{5.6 \times 10^{-2} w_{\mathrm{las}}} \quad \text{for the yellow line,} \tag{8}$$

where $h\nu$ is the photon energy and w_{las} is the specific radiation energy in μJ cm^{-3}.

If the reduction and disappearance of lasing with increasing pump pulse repetition rate are obeyed to expressions (3)–(8), it is obvious that the reduction is related to the prepulse concentration of metastable states. If these expressions are not valid, but lasing is reduced nevertheless, i.e., $\Delta W/W > k_0^-/k_{\mathrm{max}}^+$, it is obvious that the lasing reduction is caused by some other processes that are not related to N_{ms0}. In this case, the ratio

$$\frac{k_0^-}{k_{max}^+}\left(\frac{\Delta W}{W}\right)_{real}^{-1} = \left(\frac{g_r}{g_r+g_{ms}}\frac{N_{ms0}}{N_{ph0}}\right)\left(\frac{\Delta W}{W}\right)_{real}^{-1} = \delta \quad (9)$$

determines the contribution of N_{ms0} to the real reduction $(\Delta W/W)_{real}$ of lasing.

The fraction β of involved processes, which are not related to N_{ms0}, can be estimated from the expression

$$\beta = 1 - \frac{k_0^-/k_{max}^+}{(\Delta W/W)_{real}}; \quad (10)$$

under the threshold conditions, $\beta = 1 - k_0^-/k_{max}^+$. The value of β obtained in this way determines the lower limit of the fraction of processes reducing (apart from N_{ms0}) the output energy. This is due to the fact that an increase in the specific output energy for a real self-terminated laser is not always proportional to k_{max}^+ but can be higher, because N_r^m and k_{max}^+ decrease due to superradiance, in particular, in nonaxial beams [45].

In the lasing regime or in the master oscillator–power amplifier (MOPA) regime, the adverse influence of superradiance decreases or even can be reduced to zero, which results in a greater increase in W compared to k_{max}^+. In other words, the estimate based on expressions (5), (7), and (8) gives the upper bound of the degree of influence of the prepulse metastable-state concentration on lasing parameters. Expression (3) is exact, however, the concentration N_{ms} is not related to the number of laser parameters being initially measured. To calculate N_{ms}, a priori information is required (for example, on the transition probability, the absorption line shape, etc.).

Let us estimate, using expressions (3) and (9), the role of N_{ms0} in the disappearance of lasing under the conditions of Table 1. The dependence of the average output power P_{las} or the pulse energy on the pulse repetition period T (Fig. 3 and data [7, 10, 11]) shows that $N_{ph0} \sim 1.7N_{ph}^m$, where N_{ph}^m is the number of photons emitted under conditions when P_{las} is maximal. The relative contributions δ of N_{ms0} in the lasing disappearance calculated taking this into account are presented in Table 1. One can see that only in papers [19] and [26] the threshold conditions are mainly determined by the value of N_{ms}. However, it is in these papers that the authors used the experimental conditions that were strongly different from optimal conditions. In all other cases in Table 1, as in [7] (Fig. 3), lasing is reduced and disappears much earlier than predicted by expressions (5)–(9). In these cases, $\delta < 0.15$, and therefore the optimal pulse repetition rate and the maximum output power are predominantly limited by an increase in N_{e0} with increasing F, as in [2, 16]. This increase results, in particular, in the relative increase in the rate of metastable-state excitation at the leading edge of a current pulse. As an example, we present in Table 2 the experimental rates [28] of excitation of resonance and metastable states at the beginning of the laser pulse for $F = 2.8$ and 12.5 kHz and for conditions of paper [2].

The calculation of the effect of N_{e0} based on models [3, 4], taking into account the rates of excitation of the working levels [32], deexcitation of metastable states [16], and recombination of a plasma in the Cu–Ne mixture at elevated pressures of Ne [14], yields the dependence of the relative output energy W/W_0 on the interval between pulses

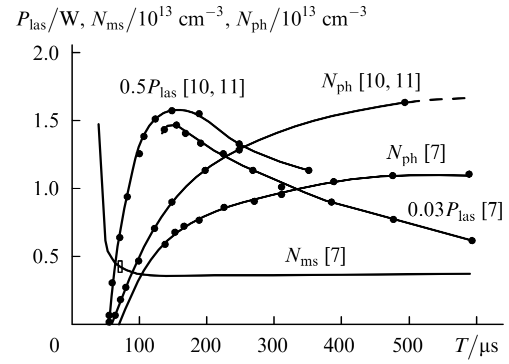

Figure 3. Dependences [7, 10, 11] of the average lasing power, the specific number of emitted photons, and the population of the $Cu(4s^2\,{}^2D_{5/2})$ level on the pulse repetition rate (▯ is the time delay of lasing).

Table 2. Redistribution of the excitation rates of the upper $(dN/dt)_r$ and lower $(dN/dt)_{ms}$ working levels upon changing the pulse repetition rate F [28].

F/kHz	$(dN/dt)\Delta t$/ 10^{12} cm^{-3}	Δt_r/ ns	$(dN/dt)_r$/ 10^{20} cm^{-3} s^{-1}	Δt_{ms}/ ns	$(dN/dt)_{ms}$/ 10^{20} cm^{-3} s^{-1}
2.8	4.0	3.4	11.8	7.2	5.6
12.5	4.0	4.5	8.9	6.5	6.2

Note: Δt is the time during which N_r and N_{ms} change by 4×10^{12} cm^{-3}.

(curve 1 in Fig. 4). Curve (2) shows the dependence of P_{las} on $1/T$, taking into account the influence of N_{e0}; curve (3) shows this dependence, taking into account the influence of only N_{ms0}, in accordance with curve (1) in Fig. 1; and curve (4) takes into account both N_{e0} and N_{ms0}. Dependence (5) shows a linear increase in P_{las} with increasing $1/T$. The results of a detailed study of the effect of N_{e0} on the lasing parameters of a Kristall LT-40Cu tube will be reported elsewhere.

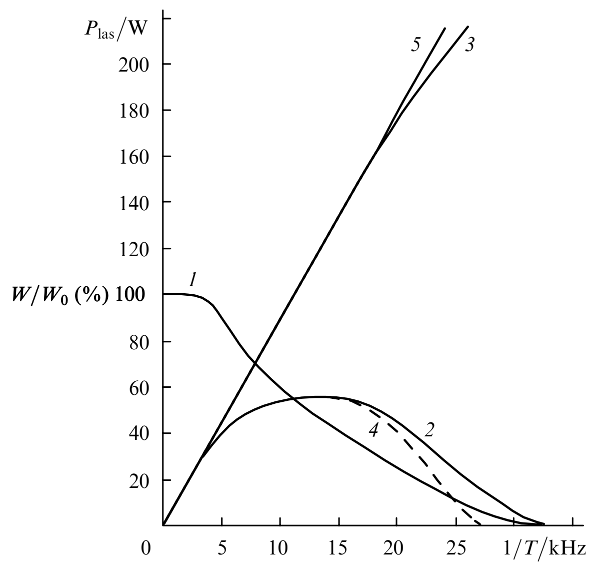

Figure 4. Dependences of the output energy (1) and power (2) on the interval between pulses calculated taking into account only N_{e0}, taking into account only N_{ms0} (3) and both N_{e0} and N_{ms0} (4); (5) a linear increase in P_{las} with the pulse repetition rate.

An increase in the neon pressure [14], an addition of hydrogen [2] or electronegative impurities [13] reduce the value of N_{e0} and enhance the resistance of a gas-discharge tube, which improves its matching with a power supply. This facilitates the electron heating at the leading edge of a current pulse, thereby eliminating the restrictions related to N_{e0}. Because the current oscillations after the pump pulse are reduced in this case, the effect of N_{ms0} is also reduced.

Let us compare the decay of N_{ms} in high-pressure lasers measured in this paper (Fig. 1) with that for a low pressure of neon (Table 1 and Fig. 2). One can see that for the lasing efficiency close to that obtained in Ref. [2] (Table 1), the specific energy input is much higher, which results in a more than fourfold increase in the energy output. Comparison of optimal working temperatures in Ref. [2] and in Kristall LT-40Cu laser tubes [15] shows that the working concentration of copper atoms increases approximately in the same degree. Taking this into account, we present in Fig. 2 the decay of the population of the Cu ($^2D_{5/2}$) state in a Kristall LT-40Cu tube normalised to the energy output $w_{las} = 3.2$ μJ cm^{-3} measured in this paper. One can see that the metastable-state population is lower than that measured in Ref. [9] ($\eta = 1.07$ %) but higher than that measured in Ref. [2] ($\eta = 1.6$ %). This confirms the above conclusion about the increase in N_{ms} in the afterglow with decreasing the lasing efficiency. Nevertheless, one can see from Fig. 1 that, for the pulse repetition rate used in experiments and the lasing conditions close to optimal ($P_{las} = 55$ W), the pre-pulse metastable-state population has no noticeable effect on the lasing parameters of the copper laser.

The identity of the decay of N_{ms} shown by curves (*1′*–*3′*) in Fig. 1 and the identity of current pulses suggest that the population N_{ms} in the afterglow is determined by the value of T_e at which the population becomes constant. The latter depends in turn on the degree of matching of a power supply with a laser tube. One can see from Fig. 1 that, although the matching is not perfect, nevertheless N_{ms0} does not determine the lasing parameters of Kristall LT-40Cu tubes. This was also demonstrated by oscillograms.

Thus, one can hope that a further optimisation of the excitation conditions neutralising the effect of N_{e0}, namely, increasing neon pressure accompanied by the corresponding increase in the working voltage and decreasing the duration of the leading edge of voltage and current pulses will result in a substantial increase in both the average output power of Kristall LT-40Cu laser tubes and their efficiency.

The results obtained above are quite reliable in our opinion because they were obtained based on fundamental principles of lasers and initially measured lasing parameters. Nevertheless, due to the recent hot discussion about the mechanisms restricting the pulse repetition rate F (see, for example, [46–52]), it is useful to verify the validity of expressions (3), (4), (9), and (10) by performing controlled experiments and independent computer calculations. In Ref. [40], the threshold lasing conditions were determined at a low concentration N_{e0} for a Pb laser (the $7s\,^3P_1^0 - 6p^2\,^1D_2$ transition at 722.9 nm). It was found that, for $w_{las} = 10^{-6}$ J cm^{-3} ($N_{ph0} = 3.64 \times 10^{12}$ cm^{-3}), the threshold density of metastable states was $N_{ms}^{th} = 0.9 \times 10^{13}$ cm^{-3}, i.e., $N_{ms}^{th} = 2.47 N_{ph0}$, whereas, according to expression (4), $N_{ms}^{th} = 2.67 N_{ph0}$. Therefore, the accuracy of measurement of N_{ms}^{th} is 8 %. An acceptable agreement (within 15 % – 20%) was observed for the reduction of lasing at intermediate values of $\Delta W/W$ and for a 1.5-μm Ba laser as well [41]. The computer calculation of a beam copper laser for $N_{e0} = 0$ [17, 18] gives the values of $\Delta W/W$ and N_{ms}^{th} that exactly coincide with those calculated from expression (3).

Therefore, the method for determining of the effect of N_{ms0} developed in this paper is confirmed with good accuracy by experiments and computer calculations. Thus, we confirmed the conclusion of papers [40–52] about a weak effect of N_{ms0} on the frequency–energy characteristics of a Cu laser.

6. Conclusions

The study performed in this paper gave the following results.

(i) The maximum population of metastable states and their relaxation in the afterglow in a copper vapour laser very strongly depend on the degree of matching of a power supply with the laser tube and, hence, on the laser efficiency. This leads to the differentiation of the mechanisms of restriction of the frequency–energy parameters of the laser. In a well-matched highly efficient laser, an increase in the output power with increasing pulse repetition rate is predominantly restricted by a high prepulse electron concentration. In the case of poor matching and low lasing efficiency, the output power can be mainly restricted sometimes by a high prepulse concentration of metastable states.

(ii) An addition of hydrogen to the active mixture and increasing neon pressure improve the degree of matching, which is one of the reasons for reducing the metastable-state population N_{ms} in the afterglow. In these cases, the contribution of N_{ms} to the reduction of lasing does not exceed 10 % even for linear lasing powers of 50–100 W m^{-1}. This value can be substantially increased by improving the parameters of the power-supply pulse, first of all by shortening the leading edge of the voltage pulse and its duration.

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