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Excitation and relaxation of metastable atomic states in an active medium of a repetitively pulsed copper vapour laser

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Abstract. **The influence of a pre-pulse population of copper atom metastable states and their sub-population at a current pulse edge on the copper vapour laser pulse energy is studied under optimal temperature conditions. Experiments have been performed with active elements of a commercial laser having an internal diameter of a discharge channel of 14 and 20 mm. It is found that at a pulse repetition frequency of 12–14 kHz, corresponding to a maximal output power, the reduction of the energy due to a residual population of metastable states is by an order of magnitude less than due to their sub-population at a current pulse edge. The modelling based on the experimental results obtained has shown that in the case of an active element with an internal diameter of 14 mm, a decrease in the pulse leading edge from ~25 ns to 0.6 ns does not reduce the laser pulse energy up to the repetition frequency of ~50 kHz at an average output power of 70 W m^{-1} and efficiency of ~11 %.**

Keywords: *copper vapour laser, lasing, lasing efficiency, pre-pulse electron concentration, pre-pulse concentration of metastable levels.*

Active progress in investigations and development of copper vapour lasers (CVLs), caused first of all by important works on laser isotope separation in 80–90 years of the XX century [1, 2] slowed down to the beginning of the XXI century. The fall of interest in CVLs is explained by two main facts: the loss of competitive advantages as compared to solid-state lasers with diode pumping and conversion to the second harmonic, and the absence of a further increase in the output power and lasing efficiency. The rise in the output power P_{lg} has stopped at a level of approximately 100 W m^{-1} [3–5] [P_{lg} is the average output power per unit length of the laser active element (AE)], whereas the first repetitively pulsed CVL had a power of P_{lg} ≈ 20 W m^{-1} [6], and the actual efficiency has still remained at the level of about 1 %. Slightly greater values of the parameters have been reached for kinetically enhanced lasers, the active medium of which comprised various molecular additives [7]. In particular, Le Guyadec et al. [8] reported on obtaining the efficiency of $\eta \approx 3.8\%$ at $P_{lg} \approx 90$ W m^{-1}, and in [9] the power of $P_{lg} \approx 150$ W m^{-1} was reached at a small diameter (D = 38 mm) of a gas-discharge channel of the AE as compared to D = 80–90 mm in [3–5, 7, 8]. In a CVL with a small power P_{lg} the observed efficiency was $\eta \approx 5\%–9\%$ [10–12]. However, these parameters are far from the values predicted for optimal excitation conditions [13–15].

In our opinion, the lack of progress in the development of CVLs is partially associated, in addition to the reasons mentioned above, with the insufficient understanding of the processes occurring in an active medium of a laser operating at a high pulse repetition frequency f. Mechanisms limiting the average output power P_{av}, which is an extreme function of f, were discussed for a long time. Originally, it was assumed that with increasing frequency f, the pre-pulse concentration of metastable states (MS) of copper atoms n_m^0 also increases [16], which at $f \approx 10$ kHz in the AE with D = 20 mm [17] will be so high that it starts limiting the P_{lg}. Hence, the development of high-power CVLs followed the way of increasing the AE diameter [18], which resulted in the average output power of $P_{av} \approx 600$ W m^{-1} per single laser element [19] at typical frequencies of $f \approx 5–6$ kHz. However, with increasing frequency, in AEs with the diameter of above 80 mm, the pre-pulse electron concentration n_e^0 also increases due to an insufficient rate of plasma recombination in a time interval between pulses. The result is that in exciting an active medium by pulses of duration of approximately 100 ns, the skin-effect prevents pumping of the entire active volume [18] and limits P_{lg} to the value of approximately 100 W m^{-1}.

It was suggested previously [20] that the insufficient recombination rate in the active volume of the laser increases the undesired MS population at a current pulse edge in the AE of any diameter due to drawbacks of laser power supply systems. Later it was shown that the rate of de-excitation of the MS in near afterglow is so high [21] that the residual population of the MS cannot be the principal reason for the reduction of P_{lg} and η, including the output power of at least $P_{lg} \approx 50$ W m^{-1} in the AE with D = 20 mm [15]. In order to overcome the limitations related to the influence of n_e^0, it was suggested [20] to introduce hydrogen into a working Cu–Ne mixture, which accelerates recombination. Development of this direction has yielded the parameters of CVLs mentioned above.

One more way to overcome the influence of n_e^0 is excitation of CVLs by rectangular pulses [13, 14] with a sub-nanosecond leading edge [22]. In the context of recent realisation of such a possibility by using kivotrons [23, 24] and substantial material and technical costs needed for creating CVL operating in the repetitively pulsed regime, one should critically estimate the state of investigations concerning mechanisms limiting f and η. These investigations seem more actual in view of the fact that recent works [25–27] revitalise the

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hypothesis on the decisive role which $n_{\rm m}^0$ plays in limiting $P_{\rm lg}$ and η. It is asserted that the influence of $n_{\rm e}^0$ is only revealed in lasers with the AE in which electrodes are mounted in a hot zone where the concentration of copper atoms is high. In commercial lasers and most laboratory CVLs, the electrodes are mounted in a cold zone. In the latter case, due to possible specific features of the equivalent circuit of CVL excitation first suggested in [28], the populations of MSs slowly relax. According to [25–27], these populations limit f and $P_{\rm lg}$.

The analysis performed in [25–27] is based on data about relaxation of the populations of MSs and about these populations at the leading edge of a current pulse obtained in [17]. This is the only work with such data, and the analysis of mechanisms limiting f in a number of publications and other literature is based on it. However, data in [17] have been obtained in studying one of the first laser AEs (UL-101). Drawbacks of this element were mentioned in a monograph of the developers [29]. In particular, imperfect heat insulation of the working channel requires a high-power pumping, which, in turn, leads to a strong mismatch between the pumping and the AE, and to a high population of MSs in the near (3–5 μs) afterglow (which is greater by almost two orders of magnitude than in optimised lasers [15]). Modern commercial CVLs [29] possess substantially greater $P_{\rm lg}$ and η, and for this reason the conclusions in [17], based on investigations of the AE with D = 20 mm, are not applicable to other lasers with the same diameter of the AE and better output parameters.

In the present work, we study the influence of the concentration $n_{\rm m}^0$ on energy parameters of the CVL and make a comparison with the effect of the sub-population of MSs at a current pulse edge due to the pre-pulse concentration $n_{\rm e}^0$ and imperfect power supply of the laser. To solve this problem we have studied the system comprising a master oscillator (MO) and a power amplifier (PA) with commercial 'Kulon' and 'Kristall' AEs [29]. The study has been conducted on an experimental base of RPC 'Istok' with 'Kulon 15' (GL-206D) and 'Kulon 20' (GL-206I) AEs at a neon working pressure of $p_{\rm Ne}$ = 300 and 220 Torr, respectively. The diameter of a discharge channel of the 'Kulon' AE is D = 14 mm; the channel length is $L_{\rm ch}$ = 49 and 62.5 cm, respectively; the length of end zones (a distance from a tube face to a cathode) is 3.6 cm; and the power of power supply, consumed from a rectifier, is $P_{\rm p}$ = 1.7–1.8 kW and 1.9–2 kW, respectively. The excitation circuit was thoroughly described in [29]. The parameters of the 'Kristall' AE are as follows: D = 20 mm, $L_{\rm ch}$ = 93 cm, $p_{\rm Ne}$ = 250 Torr, $P_{\rm p}$ = 2.9–3.2 kW.

The master oscillator is based on the GL-206D AE placed in an unstable resonator with the magnification M = 200. The output power of the MO under optimal conditions in both the lines λ_1 = 510.6 nm (green line) and λ_2 = 578.2 nm (yellow line) was 4–5 W, and the base-level duration of the laser pulse was 13–14 ns. In Fig. 1 one can see an average output radiation power of a system comprising the MO and the PA, based on the GL-205A AE, versus a density of the average power at the amplifier input $P_{\rm in}/S$ ($P_{\rm in}$ is the average output power of the MO, and S is the cross section of the active element of the PA). At $P_{\rm in}/S$ > 200 mW cm^{-2} and f = 12.5 kHz (or at a density of a pulse power exceeding 16 μJ cm^{-2}) the population inversion in the PA is completely depleted, i.e., it operates in a saturated regime. The absorption probability $n_{\rm p}\sigma_{\rm a}$ for the green and yellow lines is, respectively, 3.2 and 2, i.e., the total bleaching is observed in the absorption range ($n_{\rm p}$ is the number of photons emitted per pulse across 1 cm^2, and $\sigma_{\rm a}$ is the cross section of absorption at the working transitions [30]).

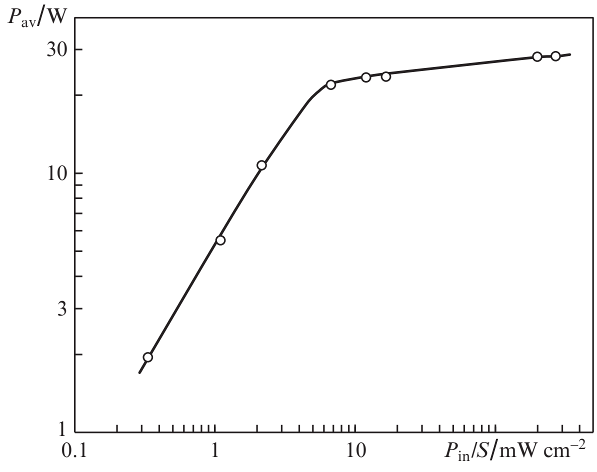

Figure 1. Average output power $P_{\rm av}$ of the CVL with a PA based on the GL-205A AE vs. average power density $P_{\rm in}/S$ at the amplifier input.

Figure 2 shows the dependence of the average output power $P_{\rm av}$ for the GL-206D AE operated in the amplification regime on the time shift Δt of the radiation pulse of the MO relative to the amplification maximum in the PA. The plus sign of Δt means that the MO pulse is ahead of the amplification maximum in the PA, and the minus sign means a lag. The value of Δt corresponding to the 'ideal' synchronisation, i.e., the maximal $P_{\rm av}$, is assumed to be zero. Also shown are the oscillograms of the voltage and current pulses and of the laser pulse at the output of the PA. The base-level duration of the light pulse is ~35 ns. If the PA operates in an oscillation regime, the base-level duration is ~41 ns, and the pulse starts earlier than in the amplification regime. The difference is explained by the fact that the duration of the MO pulse is shorter than the time of population inversion existence in the PA. At f = 13.6 kHz, the total output power of the PA is ~17.6 W, from which 3.2 W corresponds to the radiation of the MO and the rest 14.4 W – to the radiation of the PA with an approximately equal power distribution between the green and yellow radiation lines. Taking into account the reflection

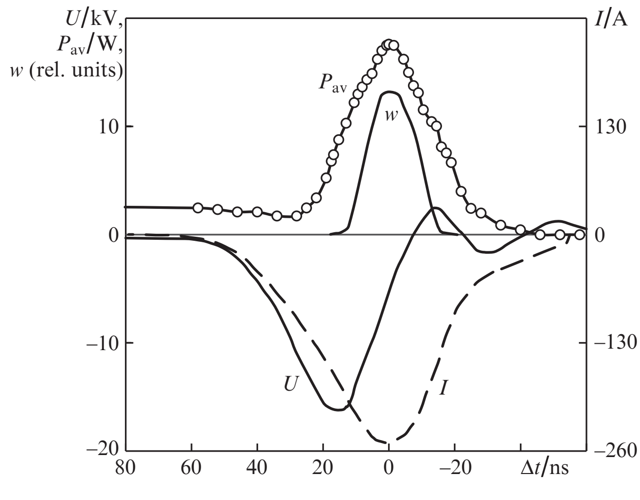

Figure 2. Oscillograms of the voltage U and current I pulses and of an amplifier laser pulse (w), and the dependence of the output power $P_{\rm av}$ in the case of the GL-206D AE on a time shift of the MO pulses relative to the amplification maximum in the PA at f = 13.6 kHz.

from the outcoupling mirror ($r \approx 0.106$), the power 'extracted' from the PA is ~8.05 W in each of the lines.

One can see from Fig. 2 that amplification in the PA with the ideal synchronisation ($\Delta t = 0$) starts with a delay relative to the current pulse. Obviously, the delay is related to a fulfilment of the following condition: the population of the resonance state (RS) should exceed that of the MS. The latter is comprised of the pre-pulsed population of the MS n_m^0 and of MS population at the leading edge of a current pulse. Curves in Fig. 2 allow one to compare the influence of these factors on P_av. One can see that the dependence of P_av on Δt is clearly separated into four ranges: 1) P_av is independent of Δt ($\Delta t >$ +58 ns); 2) P_av falls (+58 ns > Δt > +22 ns); 3) gain is registered (+22 ns > Δt > –24 ns); and 4) the radiation of the MO is totally absorbed ($\Delta t <$ –46 ns). In switching off the pumping of the PA, the absorption in the PA falls due to the convergence of the parameters T_g and T_e (T_g and T_e are gas and electron temperatures, respectively), at the beginning rapidly, and then (in ~1 ms) slowly, which is explained by cooling of the AE, the reduction of the copper atom concentration and, respectively, of MS population.

Consider range 1. The input and output power distributions are as follows: the input power is 4 W, the output power is ~2.5 W, the power lost on mirrors due to the Fresnel reflection is 0.71 W, and ΔP_a = 0.79 W is absorbed in the PA (including ΔP_a1 = 0.71 W in the green line and ΔP_a2 = 0.08 W in the yellow line). This absorption is related to the pre-pulse concentration n_m^0. Since the experiment (Fig. 1) was performed under the total bleaching conditions, the RS and MS populations, prior to MO pulse passing (n_r^0 and n_m^0) and after it (n'_r and n'_m), obey the relations:

$$n^0_\mathrm{r1,r2} + n^0_\mathrm{m1,m2} = n'_\mathrm{r1,r2} + n'_\mathrm{m1,m2},$$
$$n'_\mathrm{r1} = n'_\mathrm{m1}(g_\mathrm{r1}/g_\mathrm{m1}) = 0.667n'_\mathrm{m1}, \qquad (1)$$
$$n'_\mathrm{r2} = n'_\mathrm{m2}(g_\mathrm{r2}/g_\mathrm{m2}) = 0.5'_\mathrm{m2},$$

where $g_{\alpha i}$ are the statistical weights of the corresponding levels, and indices 1 and 2 refer to the transitions in copper atoms $^2\mathrm{P}^0_{3/2}-{}^2\mathrm{D}_{5/2}$ at λ_1 = 510.6 nm and $^2\mathrm{P}^0_{1/2}-{}^2\mathrm{D}_{3/2}$ at λ_2 = 578.2 nm, respectively. Prior to MO radiation pulse passing we have $n_\mathrm{r}^0 = 0$, and in view of (1) for the green and yellow lines it follows that

$$n^0_\mathrm{m1} = 1.667n'_\mathrm{m1}, \quad \Delta n_\mathrm{m1} = n^0_\mathrm{m1} - n'_\mathrm{m1} = 0.4n^0_\mathrm{m1},$$
$$n^0_\mathrm{m2} = 1.5n'_\mathrm{m2}, \quad \Delta n_\mathrm{m2} = n^0_\mathrm{m2} - n'_\mathrm{m2} = 0.33n^0_\mathrm{m2}. \qquad (2)$$

In turn, under the condition of total bleaching the following expression is valid

$$\Delta n_\mathrm{m1,m2} = \Delta P_\mathrm{a1,a2}/(h\nu_{1,2}fV), \qquad (3)$$

where $h\nu_1$ = 2.43 eV is the energy of quanta for λ_1 = 510.6 nm, and $h\nu_2$ = 2.14 eV – for λ_2 = 578.2 nm; f = 13.6 kHz; $V \approx$ 75 cm^3 is the volume of the PA active element. It follows from (2) and (3) that $n^0_\mathrm{m1} = 4.47\times10^{12}$ cm^{-3} at ΔP_a1 = 0.71 W, i.e., the pre-pulse population of the copper MS $^2\mathrm{D}_{5/2}$ is less by a factor of approximately 3.4 than in [17] at f = 10 kHz ($n^0_\mathrm{m1} \approx 1.51\times10^{13}$ cm^{-3}). However, the value of P_lg in the present work is thrice greater, which also testifies that excitation in [17] was not optimal. In a similar way, one obtains $n^0_\mathrm{m2} \approx 0.8\times10^{12}$ cm^{-3} for the level $^2\mathrm{D}_{3/2}$.

A variation of the output energy W of the PA pulse due to the influence of n^0_m is calculated by using the method from [15]:

$$\frac{\Delta W}{W} = \frac{g_\mathrm{r} n^0_\mathrm{m}}{(g_\mathrm{r} + g_\mathrm{m}) n^0_\mathrm{ph}}, \qquad (4)$$

where n^0_ph is the specific number of photons 'extracted' from the PA in the regime when n_ph is independent of f. Measurements performed at f = 8 kHz in similar temperature conditions and pump pulses, give the following concentrations: $n^0_\mathrm{ph1} = 3.21\times10^{13}$ cm^{-3} for λ_1 = 510.6 nm and $n^0_\mathrm{ph2} = 3.16\times10^{13}$ cm^{-3} for λ_2 = 578.2 nm (the output powers of the PA with the allowance made for losses on windows are P_av1 = 7.5 W and P_av2 = 6.5 W, respectively). Thus, we have $\Delta W/W \approx 5.6\%$ for λ_1 = 510.6 nm and ~1.1% for λ_2 = 578.2 nm. The overall variation of energy due to the influence of the pre-pulsed MS concentration is ~3.4%, which coincides with data from [15] for optimised lasers.

In [17], at an almost thrice lower power P_lg and four times less specific laser pulse energy, the value of n^0_m is approximately three times greater. By assuming $n^0_\mathrm{ph} \approx 9\times10^{12}$ cm^{-3} and $n^0_\mathrm{m} \approx 1.5\times10^{13}$ cm^{-3} we obtain $\Delta W/W = 66.7\%$. Hence, in [17] P_lg is really limited by a high concentration of n^0_m. However, this limitation is not related to physical properties of the medium of the CVL AE but to its technical imperfection. This is why, as mentioned above, the conclusion of [17] cannot be extended to other more perfect lasers.

For determining the influence of the sub-population of the MS at the leading edge of a pump pulse on the laser pulse energy we will consider two ranges of the dependence $P_\mathrm{av}(\Delta t)$: +58 ns > $\Delta t \geqslant$ +30 ns and +30 ns $\geqslant \Delta t >$ +25 ns (at Δt = +25 ns, the medium in the PA becomes transparent). At Δt = +30 ns when attenuation of the input radiation is maximal we have the following power distribution in the PA: 4 W at the input and 1.73 W at the output, losses on windows are 0.64 W, and losses on absorption in the medium ΔP_a = 1.64 W (including 1.33 W in the green line and 0.31 W in the yellow line). According to relationships (2) and (3), at Δt = +30 ns the copper MS $^2\mathrm{D}_{5/2}$ is populated to the concentration of $n_\mathrm{m1} \approx 8.38\times10^{12}$ cm^{-3}, and the copper MS $^2\mathrm{D}_{3/2}$ – to $n_\mathrm{m2} \approx 2.68\times10^{12}$ cm^{-3}. Hence, for the green line at this instant the influence of the MS sub-population at the current pulse edge on the laser pulse energy becomes equal to the influence of the concentration n^0_m; for the yellow line the reduction of energy due to the sub-population is trice greater than due to n^0_m.

As the pump pulse evolves, the populations of the MS still continue to increase with increasing RS population. At $\Delta t \approx$ +25 ns, the populations of the MA and RS become equal (per unit statistical weight), and then the medium becomes amplifying. By using data from Fig. 2 we will calculate an increase in the populations of the working levels for the transition $^2\mathrm{P}^0_{3/2}-{}^2\mathrm{D}_{5/2}$ with λ_1 = 510.6 nm, because the influence of n^0_m on this transition is stronger than on the transition $^2\mathrm{P}^0_{1/2}-{}^2\mathrm{D}_{3/2}$ with λ_2 = 578.2 nm.

In the general case, at the edge of a current pulse without lasing and with neglected spontaneous decay, MS and RS populations obey the equations

$$\dot{n}_\mathrm{m} = n_\mathrm{e} n_\mathrm{Cu} k_\mathrm{em} - n_\mathrm{e} n_\mathrm{m} k^\mathrm{s}_\mathrm{em} + n_\mathrm{e}(n_\mathrm{m} k_\mathrm{mr} - n_\mathrm{r} k_\mathrm{rm}),$$
$$\dot{n}_\mathrm{r} = n_\mathrm{e} n_\mathrm{Cu} k_\mathrm{er} - n_\mathrm{e} n_\mathrm{r} k^\mathrm{s}_\mathrm{er} + n_\mathrm{e}(n_\mathrm{r} k_\mathrm{rm} - n_\mathrm{m} k_\mathrm{mr}), \qquad (5)$$

where k_{er} and k_{em} are the rate constants for exciting the RS and MS; k_{er}^{s} and k_{em}^{s} are the constants of a stepwise depopulation of the RS and MS, respectively [31]; k_{rm} and k_{mr} are the constants of working level mixing related to the principle of detailed balance; and n_e and n_{Cu} are the concentrations of electrons and copper atoms. In turn,

$$n_e = j/(ev_{dr}), \qquad (6)$$

where j is the current density; v_{dr} is the electron drift velocity dependent on the reduced electric field strength E/N (E is the electric field strength and N is the concentration of particles). By assuming that E/N in the present work is determined by neon [32] and using the approximation $v_{dr} = 0.455\times10^6(E/N)^{0.908}$ (v_{dr} is measured in cm s^{-1} and E/N – in units of 10^{-7} V cm^2) obtained from data [33], from initial parts of U and I oscillograms in Fig. 2 we find that $n_e^0 \approx 5.4\times10^{13}$ cm^{-3} is independent of U and I up to approximately 6 kV and 25 A, respectively. Interestingly, the constancy of n_e at the beginning of the pumping is, seemingly, specific for 'Kulon' and 'Kristall' active elements [29]. This is confirmed by oscillograms from [34], which look like those in Fig. 2.

The electron temperature T_e at the leading edge of a current pulse can be found from data in [31, 32]. As follows from [32], the temperature T_e is invariant relative to the parameter $E/(px^{1/2})$, where $x = 10^3 n_{Cu}/n_{Ne}$, and p is the mixture pressure. The values of $E/(px^{1/2})$ in [31] are close to those in the present work [n_{Cu} has been found from the condition $n_{Cu} = (g_0/g_{m1})n_{m1}\exp[\Delta E/(kT_g)] = 1.7\times10^{15}$ cm^{-3}, where g_0 is the statistical weight of the ground state of the copper atom; n_{m1} is the population of the copper level $^2D_{5/2}$ calculated by formula (4) immediately after switching off the pumping; ΔE is the energy of this level; and $T_g = 1650\,°C$ equals to the temperature of a wall of an AE discharge channel]. Taking into account that the effective voltage, which affects E and v_{dr}, differs from the voltage applied to AE by the value of $L(dI/dt)$, where dI/dt is the experimental value found from the oscillogram in Fig. 2, and $L = 0.3$ μH is the inductance of the tube, we obtain the variation of T_e as the pump pulse evolves (Fig. 3a).

The main data on the rate constants of processes are taken from [31]. The control experimental parameters for testing the correctness of the solution to system (5) are the MS population at $\Delta t = 30$ ns (in the domain of a maximal absorption) as well as the RS and MS populations and energy extraction in the approximation of saturated power in the maximum inversion. The concentrations n_r, n_m, and the power P_{av} calculated in the approximation of saturated power are presented in Fig. 3b as functions of Δt. One can see that at $\Delta t = 30$ ns (at the maximal absorption), $n_m = 7.6\times10^{12}$ cm^{-3} and $n_r = 1\times10^{12}$ cm^{-3}, which well agrees with experimental results. This confirms that system of equations (5) with the constants of processes taken from [31, 32] correctly describes the kinetics of populating the working levels at the initial stage of a pump pulse. Note that by the time $\Delta t = 30$ ns the contribution of stepwise processes and of working level mixing by electrons is negligible.

Figure 3b shows that at $\Delta t \approx 22$ ns when $n_r/g_r = n_m/g_m$ (that is, the medium becomes optically transparent) we have $n_{m1} = 1.8\times10^{13}$ cm^{-3}. In view of (4) we obtain $\Delta W/W = 22.4\%$ or a reduction of the radiation energy by 29%. In this value, 5.6% corresponds to the energy fall due to the pre-pulse concentration n_m^0, and the rest 23.4% – due to the MS sub-population at the edge of a current pulse. Thus, already by this instant, the energy reduction due to the sub-population is

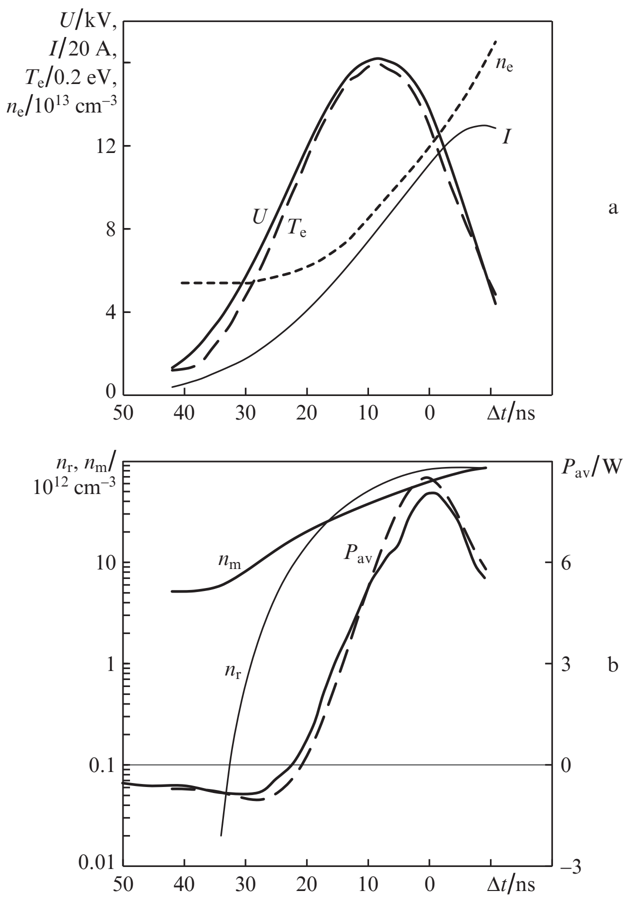

Figure 3. Pump and output characteristics of the GL-206D AE at $n_e^0 \approx 5.4\times10^{13}$ cm^{-3}: (a) oscillograms of voltage U and current I pulses, and dependences of the electron concentration n_e and temperature T_e on Δt; (b) time dependences of the populations n_r (RS) and n_m (MS) and of the output radiation power P_{av} at $\lambda_1 = 510.6$ nm (solid curve is the experiment; dashed curve is the calculation).

4.2 times greater than due to n_m^0. An 'echo' of this sub-population still affects the value of inversion in the course of further evolution of the pump pulse, because at $\Delta t = 22$ ns the temperature is $T_e = 2.15$ eV and $k_{er}/k_{em} = 1.9$. The mostly favourable conditions in our experiment are realised at the instant $\Delta t = 8.4$ ns when $T_e = 3.19$ eV and $k_{er}/k_{em} = 3.5$. By this time, the MS is populated to $n_{m1} = 4.1\times10^{13}$ cm^{-3}, which results in a reduction of the radiation energy by $\Delta W = 0.44W$ or by a factor of 1.8 as compared to the case where the population of the MS at the edge of a current pulse can be neglected. The highest energy is realised at $\Delta t = 0$ and equals 8.51 W, which is greater than the experimental value by ~9%. This difference is explained, first of all, by inaccurate data on rate constants of the processes, mainly of stepwise depopulation of the RS, and by nonuniform distributions of temperature and copper concentrations along the tube. A certain discrepancy between the calculated and experimental data on P_{av} values in the range $\Delta t < 30$ ns is explained, on the one hand, by the fact that the experimental duration of the MO pulse is ~14 ns, whereas the radiation of the MO in the calculations is considered as a strobe pulse. On the other hand, oscillogram records at the initial stage are inaccurate because of a stray interference.

To estimate finally the influence of n_e^0, we will calculate the value of P_{lg} at $n_e^0 \approx 1.8\times10^{13}$ cm^{-3}, which corresponds to a time interval of 125 μs between pulses. The population of the MS n_{m1}^0 is taken, as previously, equal to 4.47×10^{12} cm^{-3}.

Oscillograms of voltage and current pulses, temporal dependences of n_r and n_m, and the output power in the saturated regime are presented in Fig. 4. One can see that at the maximum of the pre-pulse absorption ($\Delta t \approx 28$ ns), the radiation power of 0.073 W at the wavelength $\lambda_1 = 510.6$ nm is lost, which is approximately 10 times less than in the case of $n_e^0 \approx 5.4\times10^{13}$ cm^{-3}. By the instant $\Delta t \approx 20$ ns when $n_r/g_r = n_m/g_m$ the concentration is $n_{m1} \approx 1\times10^{13}$ cm^{-3} as compared to $n_{m1} \approx 2\times10^{13}$ cm^{-3} in the case of $n_e^0 \approx 5.4\times10^{13}$ cm^{-3}. At the maximum of the population inversion, the output power is $P_{av} = 12.4$ W in terms of $f = 13.6$ kHz and the laser pulse energy is greater than at $n_e^0 \approx 5.4\times10^{13}$ cm^{-3} by a factor of 1.46.

Thus, in the considered experimental conditions ('Kulon 15' AE) with the power supply employed in [29], the reduction of the laser pulse energy at $f = 13.6$ kHz due to n_e^0 is greater than due to n_m^0 by a factor of 8.2. Under further reduction of the time interval between pulses, n_e^0 rises substantially faster than n_m^0 [14]; hence, the relative role of n_e^0 becomes stronger. An increase in the inductance of power supply circuits has the same effect.

Data presented in Fig. 5 for the GL-206I AE at the frequency $f = 13.6$ kHz are similar to those in Fig. 2. This AE is longer by 28% than the GL-206D AE. The energy has raised by a factor of 1.36. In GL-206I, the current amplitude is $I \approx 310$ A as compared to $I \approx 260$ A in GL-206D. The distribution of the MO power is as follows: 5 W at the input of the PA, 3.5 W at the output of the PA in the range $\Delta t > +60$ ns, losses on windows are ~1 W, losses in the PA are $\Delta P_{av1} = 0.5$ W at $\lambda_1 = 510.6$ nm and $\Delta P_{av2} = 0.06$ W at $\lambda_2 = 578.2$ nm, and losses in the weak absorption zone are 0.81 W at $\lambda_1 = 510.6$ nm and 0.19 W at $\lambda_2 = 578.2$ nm. Similar calculations show that in the green line the reduction of the laser pulse energy $\Delta W/W$ due to n_m^0 is 2.2%, and due to the population of the MS at the edge of a current pulse prior to the instant of maximal inversion it is 31% or 1.45 times greater, which is 20 times higher than the reduction of laser pulse energy due to n_m^0. Thus, the GL-206I AE is better matched with a laser power supply system than the GL-206D [15]; this is confirmed by the higher efficiency. Actually the same results have been obtained with the GL-205A AE at the power of $P_{av} = 45$ W and frequency $f = 12$ kHz (Fig. 5b). They agree with earlier data on the GL-206B AE of the same diameter [15]. Hence, the reduction of the laser pulse energy caused by the pre-pulse concentration of electrons n_e^0 due to a limited rate of electron heating at the current pulse edge in the AE of this type exceeds

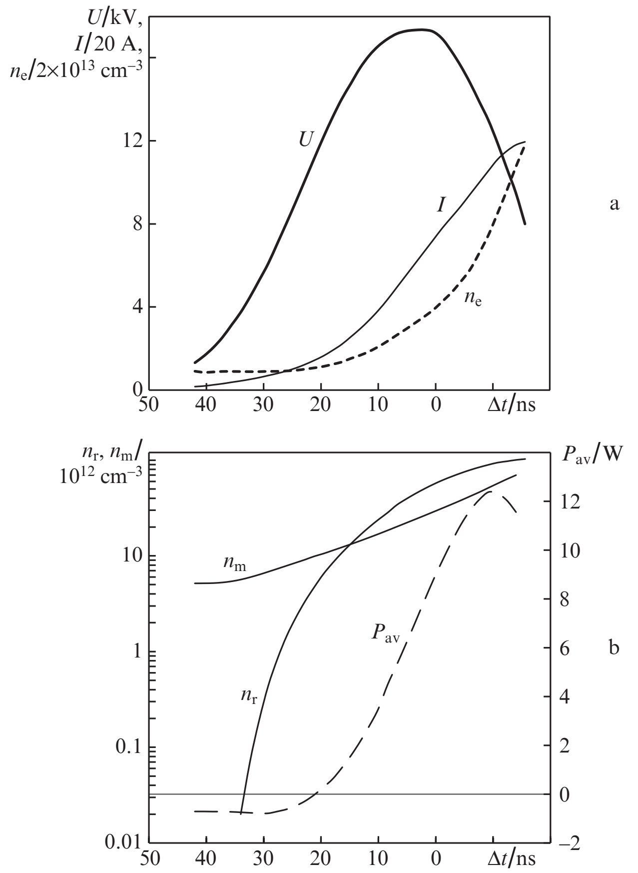

Figure 4. Pump and output characteristics of the GL-206D AE at $n_e^0 \approx 1.8\times10^{13}$ cm^{-3}: (a) oscillograms of voltage U and current I pulses as well as the time dependence of the electron concentration n_e in the amplification regime; (b) time dependences of the populations n_r (RS) and n_m (MS) and of the output radiation power P_{av} at $\lambda_1 = 510.6$ nm.

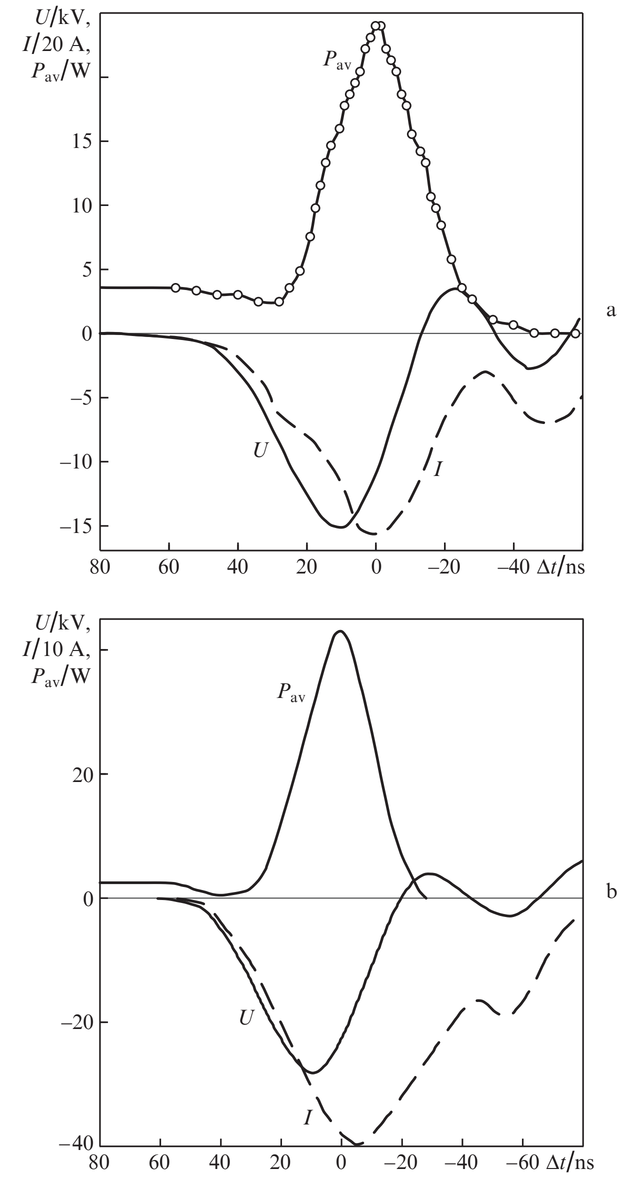

Figure 5. Oscillograms of voltage U and current I pulses, and time dependences of the output power P_{av} for (a) the GL-206I AE at $f = 13.6$ kHz and (b) the GL-205A AE at $f = 12$ kHz.

the reduction due to the pre-pulse population of the MS by more than an order of magnitude.

Hence, there is no difference between the mechanisms limiting frequency–energy characteristics of CVLs with different arrangements of electrodes, for example, in commercial lasers [29] and lasers investigated in [15, 20]. This was earlier shown in [35] based on data about real characteristics of a CVL active medium.

In view of the results obtained, it is interesting to estimate characteristics of the CVL for further technical improvement of excitation systems, in particular, by shortening the leading edge of the voltage pulse to ~0.6 ns as compared to ~25 ns in the present work (at the level of 0.1–0.9). Let us assume that the GL-206D AE is used at $n_e^0 = 5.4\times10^{13}$ cm^{-3}, $n_{Cu} = 5\times10^{15}$ cm^{-3} (the copper vapour pressure is 1 Torr), and p_{Ne} = 300 Torr. We choose the temperature T_e = 3 eV, at which k_{er}/k_{em} = 3.13 ($k_{er} \approx 3.6\times10^{-8}$ cm^3 s^{-1}, $k_{em} \approx 1.15\times10^{-8}$ cm^3 s^{-1}). Such a temperature is realised at $E/N = 18.8\times10^{-17}$ V cm^2, which corresponds to the effective voltage U = 13.8 kV, v_{dr} = 6.53×10^6 cm s^{-1} and I = 87 A (the active resistance of the AE is 160 Ω). The tube and a backward conductor should be designed in such a way that their impedance was also 160 Ω. Under these conditions, one can obtain the current leading edge in the AE equal to the switching time of the kivotron ~0.6 ns at $U \approx 14$ kV [22–24]. The duration of the pumping is chosen from the condition that by the end of the excitation pulse we have $n_r k_{er}^s \approx 0.1 k_{er} n_{Cu}$, which corresponds to the final population of the RS $n_r^f = 5.2\times10^{13}$ cm^{-3} and the duration of the pump pulse $\tau = n_r^f/(n_{Cu} k_{er} n_e) \approx 5.3$ ns. The population of the MS by the end of the pump pulse is $n_m^f = n_m^0 + n_{Cu} k_{em} n_e$. Since the concentration n_{Cu} in this case is approximately three times greater than in the above considered examples, we have $n_m^0 = 1.52\times10^{13}$ cm^{-3} and $n_m^f = 3.25\times10^{13}$ cm^{-3}.

At such concentrations n_r^f and n_m^f, the specific number of emitted photons per pulse is $n_{ph} = 1.82\times10^{13}$ cm^{-3}, which for λ_1 = 510.6 nm corresponds to the output power of 0.46 W kHz^{-1}. Similarly, for λ_2 = 578.2 nm we obtain 0.28 W kHz^{-1}. Then we assume that on switching off the pumping, in the process of electron cooling and stepwise ionisation all excited copper atoms are ionised in a time interval of ~100 ns [15]. Under this assumption, the final electron concentration is $n_e^f \approx 1.5\times10^{14}$ cm^{-3}. Plasma returning to the initial concentration $n_e^0 \approx 0.54\times10^{14}$ cm^{-3} takes ~20 μs [14]. Consequently, with the considered pump parameters, the laser pulse energy is constant up to a frequency f = 50 kHz, i.e., the output power P_{av} reaches the value of 36 W (more than 70 W m^{-1}). The lasing efficiency calculated by the formula $\eta = P_{av}/(IU\tau f)$ is about 11.3%.

Summarising, we may conclude that the output power and lasing efficiency of modern commercial lasers are limited by imperfect power supply systems, which is revealed via a parasitic population of the MS at the edge of a current pulse. The employment of kivotrons or other switching devices and a rectangular pump pulse with the leading edge of ~0.6 ns may increase the lasing efficiency by an order of magnitude and more at a substantially increase in the output power.

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