Effect of active medium prepulse parameters on the copper vapor laser performance

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The effect of the active medium prepulse parameters on the frequency and energy characteristics of a copper vapor laser (CVL) is considered. The process of relaxation of the lower laser levels in the inter-pulse period is shown to be the main physical factor determining the pulse repetition frequency of the laser. Fast relaxation of the lower levels determines the high energy potential of CVL. The prepulse electron density is, in essence, a technical factor limiting the efficiency of pumping the active medium. The effect of the prepulse electron density is caused by many reasons. In combination, they can determine a significant dependence of the CVL energy characteristics on the prepulse electron density. The revealing and excluding of these reasons will enhance the CVL performance.

Introduction

One of the main parameters determining the energy characteristics of the copper vapor laser (CVL) is the repetition frequency *f* of laser pulses. At present, we know two factors limiting this parameter. Petrash with co-authors[1–3] attribute the main limitation to relaxation processes of lower laser levels in the inter-pulse period.

To the contrary, Bokhan with co-authors[4–8] believe that the limitation is caused by a high prepulse concentration of electrons n_{e0} due to the finite rate of the recombination process in plasma. A high value of n_{e0} prevents the fast electron heating because of the presence of inductance in the laser discharge circuit, and this leads to populating the lower laser levels at the leading front of the pump pulse and re-distribution during the pump pulse of population rates of the upper and lower laser levels in favor of the latter.

Specialists dealing with investigation of CVL hotly debate which of these reasons is decisive. The effect of n_{e0} can be caused by the following. The electron temperature in the CVL active medium, which determines the population rates of laser levels, follows the variation of the field strength at the active component *R* of the gas-discharge tube (GDT) impedance.[9,10]

The rate of the field strength increase at *R* is determined not only by the switch open time and the voltage across the charge-storage capacitor, but also by parameters of the laser discharge circuit.[11] This stipulates the dependence of the voltage rise rate across *R* and, correspondingly, the electron temperature on the n_{e0} magnitude. However, direct measurements of the kinetics of CVL working levels in the double-pulse mode fail to support the statements that the relaxation rate of metastable levels does not affect the lasing parameters and that lasing characteristics are limited by the population of these levels in the pump pulse.[2] Under the conditions of this work, just the prepulse population of the metastable level mostly determines lasing characteristics at short delays.

Despite direct measurements of the working level kinetics, in recent papers[12,13] Boichenko and Yakovlenko considered the inversion quenching mechanism in CVL due to high prepulse electron density, which occurs at some critical electron density $n_{e\,\mathrm{cr}}$. If the prepulse electron density exceeds $n_{e\,\mathrm{cr}}$, then the electron temperature during the plasma-heating pulse fails to achieve the values needed for lasing. In essence, these papers resume the discussion concerning this issue.[12–16]

The urgent need in obtaining an unambiguous answer to this question is dictated, first of all, by the necessity to assess the CVL energy potential. This, in turn, determines promises and ways for further development of self-terminating lasers. To answer the question, we must determine the conditions, under which the population of lower laser levels at the pump pulse front exists and is a significant factor limiting the inversion in CVL or it is absent and there are another "limiting channels" caused by n_{e0}.

1. Excitation of lower laser levels

During the pump pulse, the population inversion is generated in the CVL active medium:

$$\Delta N = N_\mathrm{r} - (g_\mathrm{r}/g_\mathrm{m})N_\mathrm{m}, \qquad (1)$$

caused by the population difference between the upper and lower laser levels (here N_r and N_m are populations of resonant and metastable states; g_r, g_m are the corresponding statistical weights of these states). The predominant population of lower laser levels by prepulse electrons at the leading front of the pump pulse takes place as long as the electron temperature is lower than 1.7 eV and the rate of population of the lower laser levels exceeds that of the upper ones.[17,18] To answer the question whether the population of the lower laser levels at the pump pulse front is a significant or decisive limiting factor, it is necessary to determine the conditions, under which the population of these levels changes by ΔN for the time of the electron temperature rise to 1.7 eV. The comparison of these conditions with the conditions typical of CVL will allow us to judge the presence of the limitation.

The idea of the experimental check consisted in the following. As it was noted, the electron temperature determining the population rates of laser levels follows the variation of the field strength at R of the GDT impedance. Predominantly, lower laser levels in CVL are populated (by the prepulse electrons) until the electron temperature achieves 1.7 eV. Simultaneously, the active medium is heated. In this period, the ionization process in plasma can be neglected. It is obvious that the energy deposited into the active medium for this time is only a part of the total energy deposited for the pump pulse. If before every pump pulse, an extra pulse is generated to populate only the lower laser levels up to populations, terminating the lasing in the main pump pulse, that is, the condition is fulfilled:

$$\Delta N \le n_{e0} N_{\mathrm{Cu}} \langle \sigma_{\mathrm{m}} \upsilon \rangle \tau, \qquad (2)$$

(where N_{Cu} is the density of copper atoms in the ground state; $\langle \sigma_{\mathrm{m}} \upsilon \rangle$ is the constant of the population rate of the lower laser levels; τ is the duration of the extra pulse), then from the ratio of the energy deposited by the extra pulse ($Å_{\mathrm{d}}$) to the energy deposited by the pump pulse ($Å_{\mathrm{n}}$) we can judge whether or not the population of the lower laser levels at the pump pulse front is a significant factor. At $E_{\mathrm{d}} / E_{\mathrm{n}} \ge 1$ this limitation is absent; at $E_{\mathrm{d}} / E_{\mathrm{n}} < 1$ it can be considered as really possible.

The experimental check was carried out, using the CVL with UL-102 GDT, having the discharge channel with 2 cm inner diameter and 40 cm length. Neon was used as a buffer gas. The experimental setup is shown schematically in Fig. 1.

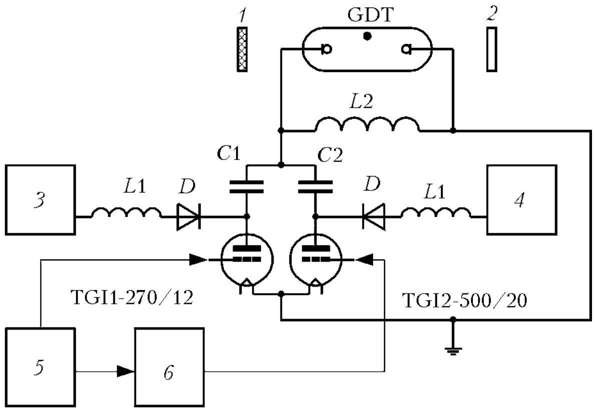

Fig. 1. Experimental setup: cavity mirrors *1*, *2*; rectifier of additional power supply *3*; rectifier of the pump source *4*; master oscillator *5*; regulable delay line *6*; charge-storage capacitors *Ñ*1, *Ñ*2; charging choke *L*1 and diode *D*; shunt coil *L*2.

The TGI2-500/20 and TGI1-270/12Â thyratrons were used as switches, forming the pump and extra pulses. The investigations were carried out at the following parameters: charge-storage capacitors *Ñ*1 = *Ñ*2 = 2.2 nF; f = 10 kHz; the rectifier voltage of 4.9 kV; mean consumed current of 340 mA; the rectifier voltage and mean consumed current of the additional power supply of 1 kV and 40 mA. The maximal mean output power of the plane-parallel cavity laser in the established thermal mode and at the delay between pulses longer than 10 μs was ~ 5 W.

2. Experimental results

Two experimental series have been conducted. The first series demonstrates the dependence of laser energy characteristics on the relaxation of lower laser levels in the inter-pulse period, while the second one shows the effect of the prepulse electron concentration.

The experiments conducted have shown that the mean output power decreases from 5 W to 0 at shortening the delay between the extra and pump pulses, as shown in Fig. 2.

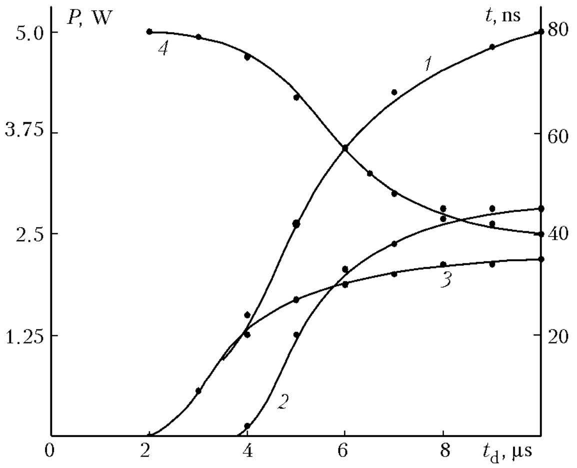

Fig. 2. Variation of the total mean output power (*1*), mean output power at λ = 510.6 nm (*2*) and λ = 578.2 nm (*3*), the lasing delay with respect to the beginning of the pump pulse (*4*) versus the delay t_{d} between the pulses.

At λ = 510.6 nm, the mean output power decreases sharper. The radial distribution of the laser radiation density changes. With decrease of the inter-pulse delay, first the transition to the ring structure of lasing at λ = 510.6 nm begins, then the lasing vanishes, and with further decrease of the delay the similar pattern is observed at λ = 578.2 nm. The lasing at the both lines vanishes completely at ~ 2 μs delay between pulses. This experiment demonstrates a peculiarity of f limitation due to the lower laser level relaxation in CVL. If this were the only reason for lasing limitation, then the limitation would show itself starting from f ~ 100 kHz and limiting f could achieve ~500 kHz. But actual restrictions of energy characteristics in UL-102 GDT are observed at pumping f much lower than 100 kHz.

The ratio of the energy deposits in GDT indicates that the condition $E_d / E_n < 1$ is fulfilled and the population of the lower laser levels at the pump pulse front can be considered as a really possible limitation. Moreover, the lower laser level population in the extra pulse can significantly exceed ΔN, because, according to Eq. (2), it is proportional to the extra pulse duration. The inversion quenching in the active medium occurs at equalizing the laser level populations

$$\Delta N = n_{e0} N_{\mathrm{Cu}} \langle \sigma_m \upsilon \rangle \tau. \qquad (3)$$

To satisfy this condition, the extra and pump pulses were partly overlapped (as shown in Fig. 3) until the moment of the lasing appearance in the pump pulse. The lasing appeared again in the pump pulse at ~120 ns delay between the beginning of the extra pulse and the beginning of the pump pulse, which made up about one third of the extra pulse duration.

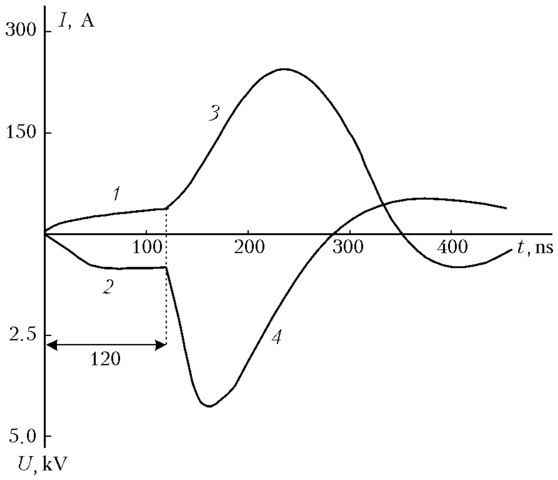

Fig. 3. Current (*1*, *3*) and voltage (*2*, *4*) pulses of the extra pulse (*1*, *2*) and the pump pulse (*3*, *4*) at the delay between pulses equal to 120 ns.

Because the power consumed from the extra rectifier was ~40 W, with allowance for the loss in the switch, the energy deposit of ~10–30 W into the active medium proves to be sufficient for inversion quenching in the laser. Knowing ΔN, N_{Cu}, n_{e0}, at $\tau = 120$ ns, we can estimate from Eq. (2) the constant of the population rate of metastable levels in the extra pulse. Since the direct measurement of ΔN, N_{Cu}, and n_{e0} was not carried out in the framework of this work, we can present only a rough estimate of $\langle \sigma_m \upsilon \rangle$, using the typical CVL parameters: $\Delta N \sim \sim (2\text{–}2.4) \cdot 10^{13}\ \mathrm{cm}^{-3}$, $N_{\mathrm{Cu}} \sim 2 \cdot 10^{15}\ \mathrm{cm}^{-3}$, $n_{e0} \sim 10^{13}\ \mathrm{cm}^{-3}$, for which we obtain $\langle \sigma_m \upsilon \rangle \sim (0.8\text{–}1.0) \cdot 10^{-8}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$.

The results obtained allow us to presume that the population of the lower laser levels at the pump pulse front is a significant limiting factor.

3. Results and discussion

According to Ref. 11, the time of the voltage rise across R of the GDT impedance is determined by the time constant L/R (where L is the GDT inductance) in case of circuits with partial discharge of the charge-storage capacitor and by the frequency of free oscillations in the laser discharge circuit in case of circuits with complete discharge of the charge-storage capacitor. Consequently, the time of the voltage rise across R at the initial moment, until the electron temperature achieves 1.7 eV, must increase proportionally to n_{e0} variation, and the population of lower laser levels must vary proportionally to n_{e0}^2. This is also indicated by the obtained experimental results. However, direct measurements of kinetics of the CVL working levels do not confirm such dependence.[2]

The observed contradiction between the obtained experimental results and direct measurements can be explained by the presence of some additional conditions in a real laser (ignored in Ref. 11), which lead to sharpening of the voltage rise front at the active component of the GDT impedance. Actually, the GDT is considered in Ref. 11 as a load consisting of L and R connected in series. Only the GDT discharge channel can be considered as such a load, beyond which, in cold buffer zones, cylindrical electrodes are placed. In addition, the GDT has its own capacitance $C_s \sim 0.1\text{–}0.2$ nF (Ref. 19).

Because in this paper we consider the initial stage of the discharge development, it is necessary to take into account a change in time of resistance of the near-cathode area and cold end zones free of copper. Analysis of the processes shows[20] that just the initial stage of development of the pulsed discharge, used in the CVL pumping, plays an important role in excitation of the levels and generation of nonstationary inversion. Unfortunately, the processes on CVL electrodes and in the cold near-electrode region are poorly known. Therefore, within the framework of this analysis, to be noted is only the experimentally observed delay of the current pulse with respect to the voltage under typical conditions of the CVL operation.

The presence of the delay stipulates a possibility of charging the GDT capacitor or the peaking capacitor, which is often used for this purpose, up to the voltage comparable (as shown by the computer simulation) with the voltage across the charge-storage capacitor. If the further process at the electrodes and in the near-electrode zones is developed avalanche-like, then, by analogy with Ref. 11, it can be considered as a unit response. The rate of voltage rise across the GDT discharge gap is determined by the frequency of free oscillations in the circuit consisting of L, R, and C_s elements. This determines a significant sharpening of the voltage front at the active component of the GDT impedance.

The discrepancy between the conclusions on the mechanism of f limitation[2,4] can be likely explained just by design differences in the gas-discharge tubes. At the same time, the population of the lower laser levels at the pump pulse front by the prepulse electrons is quite probable; it can be called the "limitation channel." This channel can be decisive, if the transient process on the electrodes and in the near-electrode zones develops slowly, that is clearly demonstrated by the experimental results. However, removal of the channel does not mean that the effect of the prepulse electron concentration is excluded. Without going into details, note only the well-known fact that the Q-factor of an oscillatory circuit increases with the decreasing resistance.

In the case under consideration, the absolute value of the electron temperature decreases with n_{e0} increase, thus leading to re-distribution of the population rates of the upper and lower laser levels in favor of the latter. Consequently, there must exist $n_{e\,\mathrm{cr}}$, at which the electron temperature during the plasma-heating pulse fails to reach values needed for lasing.[12,13] In fact, these arguments return us to the initial positions.

4. Decisive role of prepulse population of lower laser levels. Limiting repetition frequency of laser pulses

To answer the fundamental question, we refer to Refs. 12 and 13, in which the nature of limitations is considered with the use of a simple kinetic model, based directly on the experimental dependences of time behavior of the current density, as an example. This allows us to obtain a simple estimate of the critical electron density.

As a necessary condition for population inversion, the well-known limitation from below on the electron temperature was used. The kinetic model of a vapor mixture ionization by a pump pulse includes equations for density of copper and neon ions N_{iCu}, N_{iNe}:

$$\frac{\mathrm{d}N_{\mathrm{iCu}}}{\mathrm{d}t} = k_{\mathrm{iCu}} n_e (N_{\mathrm{Cu}} - N_{\mathrm{iCu}}), \qquad (4)$$

$$\frac{\mathrm{d}N_{\mathrm{iNe}}}{\mathrm{d}t} = k_{\mathrm{iNe}} n_e (N_{\mathrm{Ne}} - N_{\mathrm{iNe}}), \qquad (5)$$

where $n_e = N_{\mathrm{iCu}} + N_{\mathrm{iNe}}$ is the electron density; k_{iCu}, k_{iNe} ($\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$) are the ionization rate constants of copper and neon atoms; N_{Cu} and N_{Ne} are the densities of heavy particles (copper and neon). The copper and neon ionization rates were assumed equal to the rate of excitation of resonant states, which is valid in the mode of quasistationary ionization, when each excitation event is accompanied by the event of the excited state ionization.[12] This form of description of the processes in the active medium is most illustrative for determination of the conditions limiting the energy characteristics, rather than the causes.

Equations (4) and (5) are written for the process of direct ionization of copper and neon atoms. The rate of direct ionization at least for the copper atoms is almost two orders of magnitude lower than the rate of de-excitation of the resonant levels into the ionization state. Therefore, the mode of quasistationary ionization is determined by the processes of stepwise ionization, when every excitation event is accompanied by the event of de-excitation into the state of ionization mostly from the resonant copper levels.[21] Consequently, Eq. (4) should be written in the form

$$\frac{\mathrm{d}N_{\mathrm{iCu}}}{\mathrm{d}t} = k_{\mathrm{iCu}} n_e (N_{\mathrm{Cu}} - N_{\mathrm{iCu}}) + k_{\mathrm{riCu}} n_e N_{\mathrm{rCu}}, \qquad (6)$$

$$\frac{\mathrm{d}N_{\mathrm{rCu}}}{\mathrm{d}t} = k_{\mathrm{r}} n_e (N_{\mathrm{Cu}} - N_{\mathrm{iCu}}) - k_{\mathrm{riCu}} n_e N_{\mathrm{rCu}}, \qquad (7)$$

where k_{iCu}, k_{riCu}, and k_{r} are the rate constants of direct ionization (from the ground state), stepwise ionization (from the resonant states) of copper atoms, and the excitation of resonant levels, respectively; N_{rCu} is the population density of the copper atom resonant states.

The validity of description of the physical process in the active medium by Eqs. (6) and (7) is indicated by the experimental results shown in Fig. 2. If the conditions of active medium pumping do not vary during the pump pulse, the rates of excitation and ionization processes remain unchanged as well. A change of delay between the pump and extra pulses leads to a change in the prepulse population of the lower laser levels and in the threshold conditions for lasing. This causes the observed delay in the appearance of lasing and a change of the output energy, because the population of the resonant states is bounded above by the stepwise processes of de-excitation into the ionization state.

This character of variation of the delay and laser pulse energy is observed in the case shown in Fig. 4, provided the delay between the pulses remains constant and equal to ~ 120 ns, but the rectifier voltage of the extra power supply varies or the delay between pulses shortens to their complete overlapping. In this case, the prepulse population of the lower laser level varies due to the change of $\langle \sigma_m \upsilon \rangle$ or τ.

The above real processes (6) and (7) in the active medium determine the presence of a certain time before the quasistationary ionization, during which electrons can be heated up to the temperature higher than 1.7 eV and lasing in CVL can be obtained. If we introduce Eqs. (6) and (7) into the system of equations presented in Refs. 12 and 13 and estimate the main causes of limitation, then we obtain a similar result: the presence of the critical electron density $n_{e\,\mathrm{cr}} \sim 10^{14}\ \mathrm{cm}^{-3}$, but a somewhat different conclusion, namely, at these values the CVL efficiency becomes virtually zero.

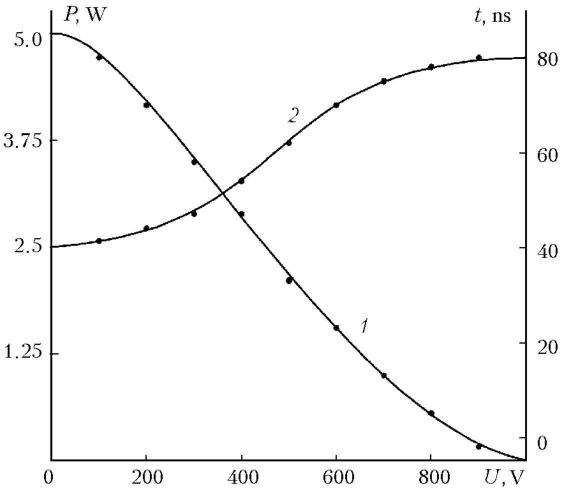

Fig. 4. Mean output power (*1*) and delay of the lasing pulse (*2*) as functions of rectifier voltage of the extra power supply.

Actually, if the thermal mode of CVL operation is neglected, when carrying out the investigation by the method of double pulses, then we can change the pumping conditions in the second pulse, for example, through changing the voltage across the charge-storage capacitor, and obtain lasing at $n_{e0} \sim n_{ecr}$ and $N_m \sim 0$. However, because the population of the upper laser levels is limited in the pump pulse by the process of their de-excitation into the ionization state, we cannot obtain lasing at any pump conditions, if the initial population of the lower laser levels is high. That is, by analogy, there must be a critical prepulse population of the lower laser levels N_{mcr}, at which the lasing in CVL is impossible. Just this determines the fact that the prepulse population of the lower laser levels is the fundamental cause for the limitation of f in CVL.

Redistribution of rates of populating upper and lower laser levels in favor of the latter with the increase of n_{e0} forms another "channel of limitation" of the CVL efficiency, which also cannot be the main decisive factor of f limitation, because it is always possible to form such pumping conditions, at which the degree of ionization of the active medium just in the pump pulse is lower that n_{ecr}. Therefore, the laser efficiency decreases with the increase of f, but the limiting laser pulse repetition frequency, determined by the process of relaxation of the lower laser levels, achieves hundreds of kHz (Ref. 22). In this case, a significant difference (almost tenfold) in the estimate of limiting f values between the above results and the results of Ref. 2 looks unexpected.

The kinetics of CVL working levels was measured in Ref. 2 in the double-pulse mode. The lasing vanished at the inter-pulse delay of 15 μs, when the prepulse population of the metastable level N_{m0} achieved $\sim 4.0 \cdot 10^{13}$ cm^{-3}. The causes for high N_{m0} value were not analyzed, because it was assumed to be determined by the metastable level relaxation in the inter-pulse period. At the same time, it was noted that the experiments were conducted with the ordinary pump circuit. It is well-known that in such circuits (regardless of the switch used: lamp or thyratron) the interpulse currents, caused by the charge of the charge-storage capacitor, pass through the active medium.[23] In addition, immediately after the pump pulse, the extra energy stored in the shunt coil is deposited into the active medium.[19] The total energy deposited into the active medium after the pump pulse can restrict the relaxation of the lower laser levels and provide for the high value of N_{m0}.

The computer simulation of this process has shown that this energy deposit maintains the voltage of ~50–70 V across the plasma for 10–12 μs after the pump pulse, and its duration is determined by the charging time of the charge-storage capacitor. Although the duration of the energy depositing into the active medium corresponds to the inter-pulse delay, it is far from obvious that the extra energy deposition will affect significantly the process of relaxation of the lower laser levels at such field strength. To check this assumption, a continuous voltage was applied to the active medium of CVL operating in the repetitively pulsed mode (Fig. 5). The investigations were carried out with GL201 GDT (discharge channel of 20 mm in diameter and 80 cm in length). A TGI1-1000/25 thyratron was used as a switch. The additional capacitor Ñ2 = 10^4 μF served a filter capacitor of the extra rectifier, the voltage from which was applied to GDT.

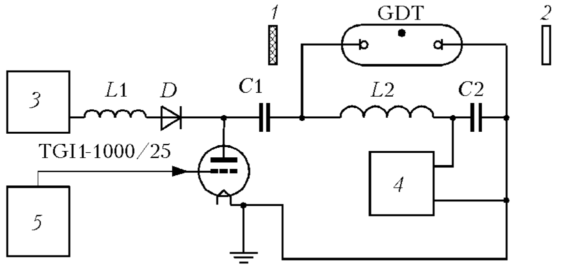

Fig. 5. Experimental setup: cavity mirrors *1* and *2*; power supply rectifier *3*; extra power supply *4*; master oscillator *5*; charge-storage capacitor Ñ1; filter capacitor Ñ2 of extra power supply *4*; charging choke *L*1 and diode *D*; shunt coil *L*2.

As the voltage at the extra rectifier varied from 0 to 60 V, the laser pulse amplitude changed from its maximal value to zero at the following pumping parameters: Ñ1 = 2200 pF; f = 12 kHz; voltage of the high-voltage rectifier of ~5.6 kV; consumed current from the high-voltage rectifier of ~450 mA. The character of the voltage dependence of the mean output power at the extra rectifier corresponded to that shown in Fig. 4. As the voltage increased to 60 V, the lasing changed more sharply at λ_1 = 510.6 nm than at λ_2 = 578.2 nm. The radial lasing profile changed too.

The experimentally observed result demonstrates clearly the effect of the energy deposited into the active medium after the pump pulse on the relaxation process of the lower laser levels. This process is in fact determined by the plasma electron component, and, correspondingly, it can be considered as an additional channel for limitation of the CVL efficiency. Its effect can be removed through removing the additional energy deposited into the active medium after the pump pulse with the use of, for example, the pumping circuit proposed in Ref. 23. Limiting f of lasing was estimated in the laser operating in the repetitively pulsed mode with the inter-pulse gap of 100 μs. The charging time of the charge-storage capacitor was 70–75 μs. In this case, there was no energy deposition into the active medium for 25–30 μs immediately before the pump pulse, and, consequently, the results obtained demonstrate the relaxation effect of the lower laser levels in a pure form.

Conclusions

The presented experimental results and their analysis suggest that the main cause limiting the CVL pulse repetition frequency is the prepulse population of the lower laser levels. This allows us to break the "vicious circle" of the many-year discussion concerning this problem. The statement that the prepulse electron density is the decisive factor limiting the CVL efficiency indicates the need of further investigation into the issue, because its manifestation depends on many causes, which, in combination, determine a significant n_{e0} dependence of the CVL energy characteristics. Revealing of these causes ("channels of limitation") allows us to select the corresponding conditions to remove their negative effect.

It can be believed that the removal of every channel of limitation is a step to achievement of the limiting CVL energy characteristics, which are determined by the process of relaxation of the lower laser levels in the inter-pulse period. Elucidation of causes leading to appearance of the channels of limitation opens a possibility for purposeful modernization of laser equipment. Thus, the channel causing the population of the lower laser levels at the pump pulse front determines the need in modernization of laser tubes, while the redistribution of the population rates of laser levels in favor of the metastable levels determines the need in further optimization of the excitation conditions. The limitation of the relaxation rate of the lower laser levels in the inter-period stipulates the need in modernization of excitation circuits. One more well-known limitation channel can be added to the above-said. It is caused by the fact that, as the prepulse electron concentration increases, the rate of rise and the amplitude of the current in the laser discharge circuit increase as well. If these parameters exceed the maximum permissible values for the switch, then the switch itself becomes the limiting factor.[24] The presence of this limitation channel determines the need in development of switches with the current rise rate of > 10 kA / μs.

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