INVESTIGATION OF THE Cu-VAPOR LASER WITH IMPROVED EFFICIENCY

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The efficiency of copper vapor laser (CVL) excitation by a pulse with a short rise time and aperiodic current behavior disrupted at the moment of output pulse termination has been investigated experimentally. Under these conditions of excitation, the efficiency of a CVL is demonstrated to reach ~9%. Preliminary data on processes in the discharge plasma are presented. Based on the results obtained a method of output pulse shape and duration control for CVL has been developed. Reduction of the output beam divergence down to the diffraction limit has been investigated, and an increase of the reduction efficiency from 28% to 83% has been achieved when using the regime of output control instead of a conventional regime. A three time narrower emission spectrum of a dye laser pumped with a CVL operating in the regime of a pulse shape control has been achieved.

INTRODUCTION

Development of copper vapor lasers (CVL) lasts more than 25 years.[1] During this time, laser power has been increased from tens of milliwatts to hundreds of watts, pulse repetition rate being increased from several to hundreds kilohertzs, and efficiency has been improved from tenth to several per cent.[1–7] At the same time, according to recent theoretical results, see e.g. Refs. 5 and 8, the highest possible output characteristics of these lasers have not yet been achieved. First of all, this is true for one of the most important laser parameters, namely, the efficiency. Several ways of efficiency scaling have been proposed in recent years,[9,10] but their feasibility is still problematic. As shown in Ref. 10, the efficient excitation of laser transitions can be achieved if the voltage pulse applied to a gas discharge tube (GDT) exhibits short rise time and disrupts at the moment of laser pulse termination. Moreover, temporal profile of the discharge current should be aperiodic. In this paper, CVL operation in such a mode and efficiency of diffraction limited beam formation for pumping a dye laser are described.

1. EXPERIMENTAL STUDY OF LOW CURRENT EXCITATION MODE OF A CVL

Block diagram of a CVL under study is shown in Fig. 1. Working channel of GDT *3* manufactured from ceramie BeO tube 170 mm long and 6 mm in diameter is filled with a buffer gas neon at 6.7 kPa pressure. Composite gas discharge switch allowed current interruption at a 20 A level. That switch was composed of a TGI1–270/12 thyratron *1* and a TGU1–27/7 tasitron *2* connected in series. Tasitron was initially opened. When thyratron was triggered, a negative pulse closing tasitron was applied trough variable delay line. This enabled us to control excitation pulse duration and to provide interruption of energy input after laser pulse termination.

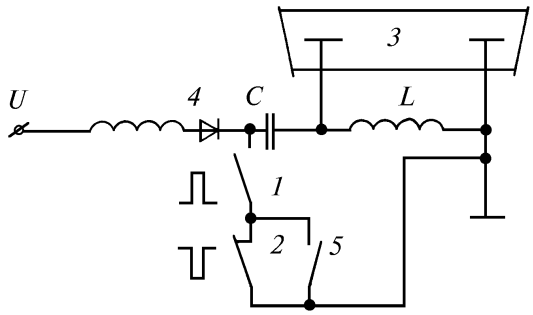

FIG. 1. CVL block diagram: switches 1 and 2, GDT 3, the circuit of a resonant diode charging 4, the storage capacitor C, the charging indictance L, and the vacuum switch 5.

This circuit also allows "to cut" energy loading when after current interruption before the end of laser pulse an additional energy is deposited in GDT from the capacitive storage to maintain thermal regime of CVL. In such a way, excitation conditions of CVL in self-heating regime were optimized.

The most important result obtained in our experiments was the fact that in the regime of current interruption energy deposition into the discharge plasma is significantly lower as compared to the regime with oscillating current, whereas the output power remains at the same level. Efficiency of CVL operation in the regime of complete discharge interruption after

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laser pulse termination reached 9%. Detailed examination of CVL efficiency has not been performed due to limited abilities of the composite switch. In Fig. 2, conventional self-heating discharge corresponds to regime *1* and low current discharge is related to regime *3*. Total discharge emission was observed to be much weaker in the latter case which is similar to that in Ref. 11. Detailed analysis of spectrum of spontaneous emission allowed us to identify channels for the medium relaxation after its excitation and ionization (see Fig. 2, *3*). In the low current regime *3*, emissions originating from higher levels of copper atoms, copper and neon ions are weak. The higher is the emitting level, the less is its excitation. The conclusion about lower degree of ionization of copper atoms can be drawn both from low amplitude of current pulse and from temporal profiles of copper ion lines.

Figure. 2 presents regime with "cut off" current pulse (regime *2*) together with the conventional and low current regimes. The first stage of this regime is low current discharge, and the second one is high current discharge. Total average power loading during both stages is equal to energy deposition in the conventional self-heating regime being 150 W/cm^3. This regime was found to be appropriate for determining contribution of direct and stepwise processes to population of emitting levels. Indeed, time delay between low current and high current stages was only $2\cdot 10^{-7}$ s, and the recombination channel of population of upper levels can be excluded. As it is seen in Fig. 3*b*, recombination affects population of the upper levels in the time range from 10^{-6} to 10^{-5} s.

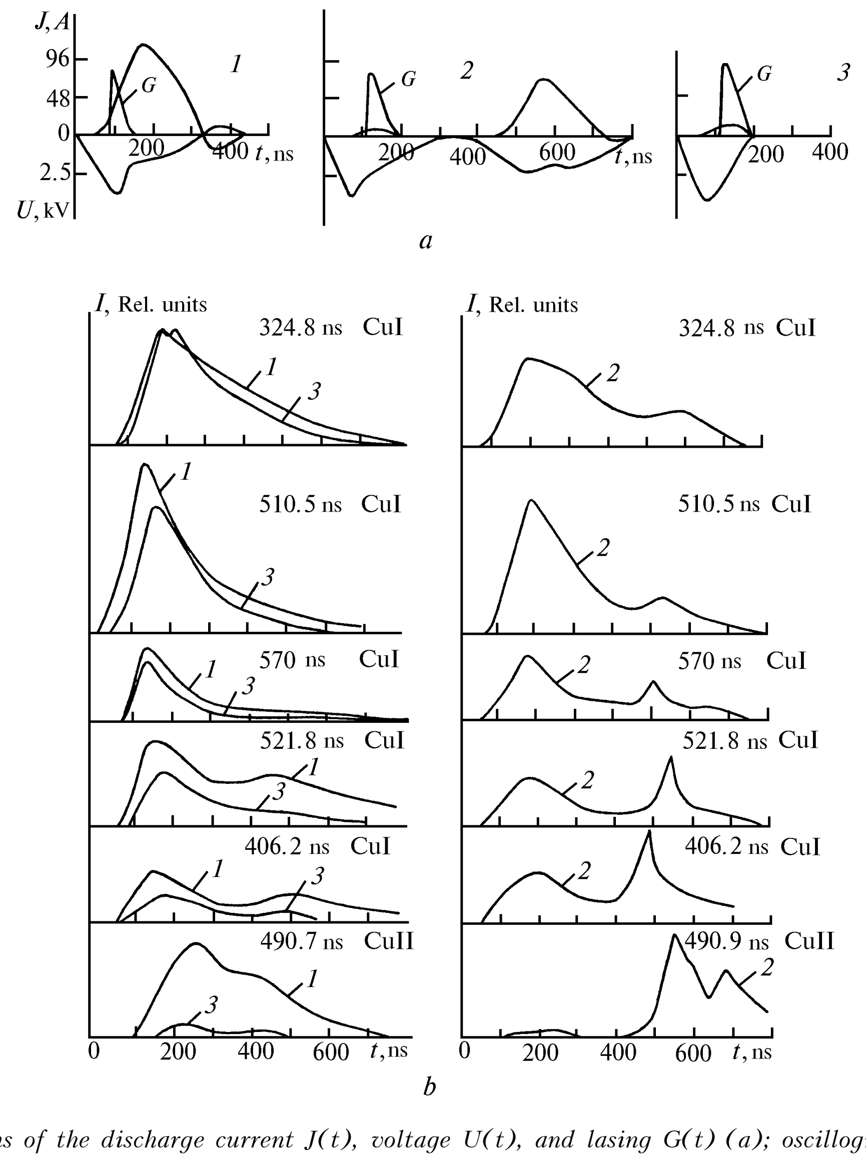

FIG. 2. Waveforms of the discharge current J(t), voltage U(t), and lasing G(t) (a); oscillogram of spontaneous emission I(t) monitored in three regimes of CVL operation: the conventional self-heating discharge (high current discharge) (curve 1); the regime of pulse separation (2), the low current discharge (3).

In a high current discharge, the stepwise excitation of atomic levels lying higher than the first resonance state as well as the stepwise ionization with decay of the upper laser levels was found to be appreciable as it was reported in Refs. 12–14. This fact was clearly seen in our measurements. First, according to the data on intensities of spontaneous emission lines at λ = 510.6, 570.0, and 578.2 nm measured during the discharge stage as well as on laser power obtained in the green and yellow region of spectrum, the stepwise processes limit population of 4*p*-levels. Second, after the laser pulse is terminated, the electron number density strongly increases, and processes of plasma relaxation and deionization are slowed down between the successive excitation pulses. Figure 3*b* illustrates clearly that difference between two regimes is most pronounced in the afterglow. Higher energy deposition in the high current regime leads to a stronger radial inhomogeneity of the discharge and lasing (see Fig. 4).

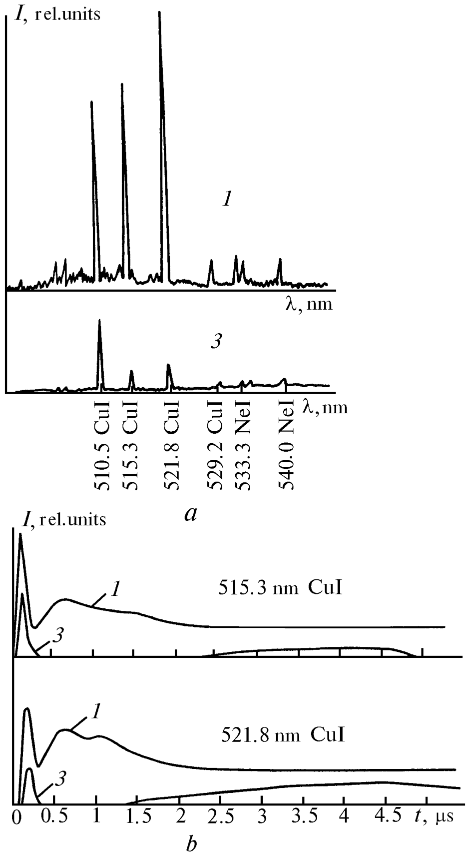

FIG. 3. Total spectrum of plasma emission (a) and its temporal behavior (b) observed from a high current (1) and low current discharge (3).

It should be kept in mind that limitation of the discharge current resulting in a constant discharge voltage and therefore, in a constant electron temperature during the excitation is not simply a reduction of the energy load into discharge plasma but also provides selectivity of the excitation of resonant levels. In the opposite case, this would lead to a reduction of the output power.

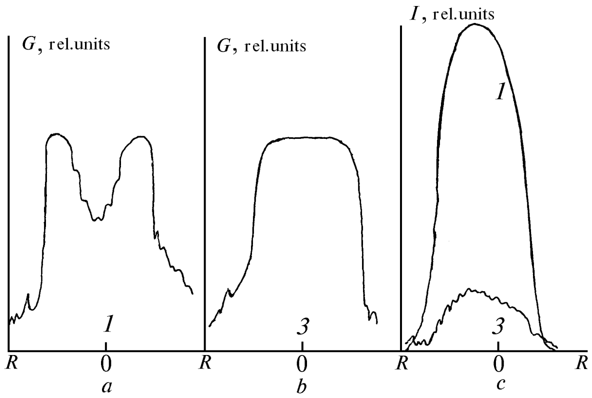

FIG. 4. Radial distribution of laser power and brightness of spontaneous emission in the regimes 1 and 3.

2. RESULTS OF LOW CURRENT CVL KINETICS SIMULATION

Parameters of the low current discharge presented in Fig. 2 together with thermodynamic plasma characteristics (buffer gas pressure $P_{\rm Cu}$ and gas temperature T_g) were used for estimation of the influence of different processes involved in plasma kinetics. The initial values of electron number density and electron temperature before the beginning of excitation pulse were determined from plasma conductivity and graphs presented in Ref. 15 to be $N_e^{(0)} = 2\cdot10^{12}$ cm^{-3}, $T_e = T_g = 0.25$ eV. Concentration of the buffer gas and of metal vapor were $N_e = 3\cdot10^{17}$ cm^{-3} and $N_{\rm Cu} = 2\cdot10^{15}$ cm^{-3}, respectively. Diffusion coefficients are calculated based on the equations derived in Ref. 16. Excitation and ionization rates are deduced from equations of a semi-classical theory.[17] The set of equations of theoretical model described in Refs.10 and 18 was solved numerically.

Figures 5 and 6 present results of calculations. In Fig. 5, temporal profiles of electron number density and number density of copper atoms at lasing levels as well as the electron temperature and energy of stimulated emission are shown. Case (*a*) corresponds to the high current discharge (regime *1* in Fig. 2) and case (*b*) corresponds to the low current discharge (regime *3*).

As is seen from Fig. 5*b*, electron number density in ordinary high current discharge reaches much higher values than in the low current discharge. The degree of ionization at 160 ns approaches 25% and 5%, respectively. This causes lower intensity of ion lines and atomic lines originating from highly excited states (see Figs. 2–3) when the discharge current is limited. Current restriction does not affect dramatically the behavior of laser level population. The difference is in the longer lifetime of the inversion in low current discharge. In ordinary discharge, the populations of lasing levels drop rapidly due to processes of stepwise excitation and ionization that results in a shorter output pulse than in low current discharge. Similar calculations (see Fig. 6) have been carried out for different case (regime *2* with "cutting" of the current). As it follows from these data, the differences between high current and low current discharge remain the same. The energy deposited into the discharge plasma in high current regime is appreciably higher than that deposited into low current regime. At the same time, both experimental data and calculations demonstrate that pulse energy is nearly the same in both cases. Hence, efficiency of the low current excitation is significantly higher.

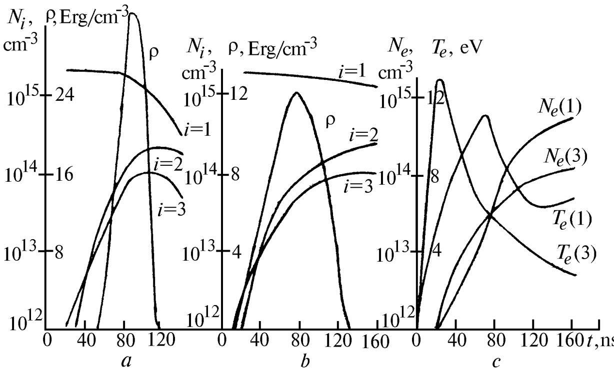

FIG. 5. Calculated temporal behavior of CVL plasma parameters in regime 1(a) and regime 3(b). N_e *and* T_e *versus time in regimes 1 and 3(c).*

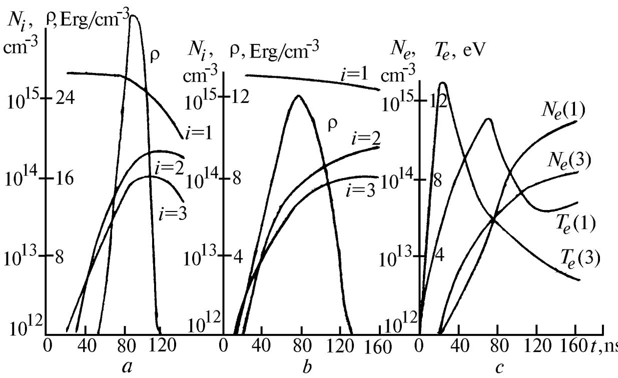

FIG. 6. Calculated temporal behavior of CVL plasma parameters in regime 1(a), and regime 2(b). N_e *and* T_e *versus time in regimes 1 and 2(c).*

Calculated values of the power deposition W_d, laser power W_g, and efficiency η are presented in the table for the discharge conditions related to Fig. 5.

TABLE.

Parameters	Regime	
	Ordinary discharge	Model discharge at a low energy load
P, W	330	30
W, watts	4	2.9
Efficiency, %	1.2	10

Thus, experimental and theoretical results show that appreciable increase in CVL efficiency in the case of limited discharge current could be achieved owing to reduction of energy spent on excitation of the levels higher than 4*p* levels and for ionization of active medium. At the same time, the pumping of lasing levels remains fixed. In this regime, discharge is stable and distribution of the output power over the beam cross section is uniform. Moreover, substantial increase in the pulse repetition rate and specific output power is feasible.

3. FORMATION OF DIFFRACTION LIMITED OUTPUT BEAM FROM A CVL WITH A CONTROLLED TEMPORAL PROFILE OF OUTPUT PULSE

The field of applications of pulsed CVL lasers is widened due to high pulse and average output power and high efficiency of these lasers. High beam divergence related mainly to short pulse duration of 10–20 ns is a problem in these lasers. Under typical experimental conditions, the divergence of output beam from CVL equipped with plane-parallel resonator is two orders of magnitude higher than the diffraction limit. Unstable resonator allows one to reduce the divergence by an order of magnitude. Formation of the diffraction limited beam is connected with significant energy losses due to high gain in active medium, short lifetime of inversion, and large axial dimensions of active zone. Using resonator with $M = 20$, it is possible to decrease the number of light travels in the resonator needed for formation of diffraction limited beam to one or two and to obtain the coefficient of conversion of the output pulse energy to energy of the beam with a diffraction limited divergence of 55% (Ref. 19). However, increase in M value is followed by a monotonic reduction of output power (Ref. 20). Besides, there are technical problems in producing optical elements for an unstable resonator with large M.

According to data from Ref. 19, when an unstable resonator with an optimal M value of 30 (Ref. 20) was used in a CVL with short bell-shaped output pulse exhibiting fast rise time, the coefficient of conversion of laser radiation to diffraction limited beam did not exceed 12% (Ref. 19).

Thus, in typical regimes of a CVL excitation efficient formation of a diffraction limited beam with low energy losses is impossible. Longer laser pulse duration will lead to lower divergence of the output beam. A possibility of increasing the pulse duration from 20 to 130 ns with increase of a storage capacitor in the excitation circuit was shown in Ref. 10. In our experiments, low current excitation resulted in a long laser pulse too. Combination of high current and low current discharge provides control over the shape and duration of laser pulses.

In order to obtain appreciably higher coefficient of conversion of laser radiation to diffraction limited beam, it is necessary to form an output pulse with a very special shape. In particular, its initial part of duration equal to the time of diffraction limited beam formation should have low amplitude. In this case, a fraction of laser energy extracted before the ground mode is established in extremely small and maximum value of the coefficient of laser beam conversion is reliable.

In this section, a possibility of improving the coefficient of conversion using a combination of high current and low current discharges for the control over the shape of laser pulse is studied.

Block diagram of the experimental setup is presented in Fig. 1. When the switch *5* is closed, conventional excitation system of CVL operates (regime *1*). To control the shape and duration of the output pulse, we used TGU1–60/7 and TGU–5/12 tassitrons connected in series. The tassitron *2* was controlled by variation of negative voltage applied to its grid (see Fig. 1). When the voltage bias is equal to zero (switch *5* is opened), tassitron *5* is closed and regime *1* is realized. When the bias voltage applied to the grid is increased, the discharge current through GDT is limited prior and during laser the pulse formation what allows one to maintain the voltage across the GDT during a longer time than in conventional regime and leads to transformation of the output pulse shape (regime *4*).

In our experiments, a GDT with active length L of 100 cm and inner diameter D of 2 cm was used. Preliminary examination of CVL operation with a plane parallel resonator demonstrated that regime of excitation *4* allows one to vary the shape and to increase the duration of the output pulse. When the circuit includes tassitron *2* with zero voltage across, it there is no difference in current, voltage, and laser pulses obtained in this case and in the case of conventional regime of excitation (see Fig. 7 *a*, *b*, regime *1*). An increase in the bias voltage leads to limitation of the current in the beginning of excitation pulse as well as to variation of the shape and duration of voltage and laser pulses (see Fig. 7 *c*, *d*). Further increase in the bias voltage leads to deformation of the laser pulse up to its division in two or more separate pulses.

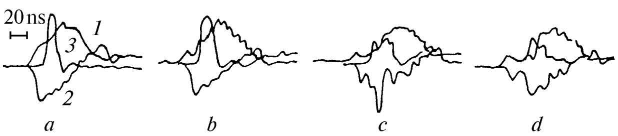

FIG. 7. Waveforms of discharge current (1), voltage (2) and lasing (3) obtained in regime 1(a) and 2 at bias voltage applied to the grid of tassitron of 0 *(b),* 190 V*(c),* 210 V*(d).*

Besides, characteristics of a CVL equipped with an unstable resonator with L = 162 cm and H = 30 were investigated. In this case, the time of diffraction limited beam formation was calculated to be 42 ns (Ref. 21). Measurements were performed at λ = 510.6 nm. Radiation at λ = 578.2 nm was filtered by an interference filter. When the laser operated in the regime *1* the output pulse exhibited characteristic peak structure, its duration being 70 ns end-to-end. The major part of laser energy is released in the first 40 ns (see Fig. 8*a*).

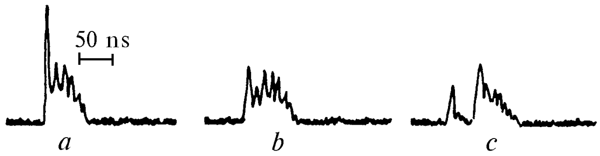

FIG. 8. Waveforms of lasing at 510.6 nm *in regime 1(a) and 2 at bias voltage applied to the grid of tassitron of* 180 *(b) and* 210 V*(c).*

An increase in the bias voltage across the tassitron *2* resulted in a decrease in the output power at the very beginning of the output pulse (Fig. 8*b*), and after that the main part of the energy released. Hence, the increase of the energy of diffraction limited beam (see Fig. 9, curve *1*) was observed. The ratio P_g/P_0 of the average power of diffraction limited beam to the total average output power was determined from the ratio of the area under the oscillographic trace after 42 ns to its total area. Reliability of the technique was checked by direct measurement of the power of diffraction limited beam separated with a spatial filter. Increase in the bias voltage applied to tassitron grid *2* from 0 to 240 V results in an increase of the conversion coefficient from 28 to 83% (see Fig. 9, curve *2*). Though the reduction of the total average power at a constant average energy loading by 22% is evident, an increase in the average power of diffraction limited beam by a factor of two is observed.

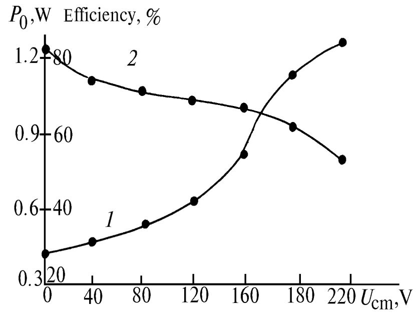

FIG. 9. Relative efficiency (1) and laser power (2) versus bias voltage applied to the grid of a tassitron.

Reduction of the laser power ocurring due to the voltage drop across the tassitron can be compensated for by higher charging voltage. In our opinion, conversion efficiency of 83% is not the upper limit. To increase the fraction of energy of diffraction limited beam, one should control more precisely the initial portion of a laser pulse and pulse duration using pulsed voltage applied to the tassitron.

Thus, its should be pointed out that the main result is a significant increase in conversion coefficient, its value exceed (80%) is observed in the regime of output control with an additional switch. The regime of output control can meet a lot of applications. A possibility of appreciable improvements in spectral characteristics of dye lasers pumped by a CVL with special pulse shape can be considered as an example of such applications.

4. EFFICIENCY OF PUMPING OF DYE LASER BY A CVL WITH CONTROLLED OUTPUT

To make the spectrum of a dye laser radiation narrower, the pumping pulse should have the amplitude of its initial part with duration equal to the time of formation of stationary spectral composition close to the threshold value. In the tailing part of the pump pulse, the main part of energy should be concentrated since it determines the efficiency of wavelength conversion. In our paper, we discuss spectral composition of laser radiation as a function of pump pulse shape. A CVL with a GDT of 2 cm diameter and 60 cm long was used as a pumping source. This laser was fitted with three-mirror unstable resonator with the magnification factor $M = 30$. Dye laser was pumped by radiation at $\lambda = 510.6$ nm filtered using a disperse prism made of TF6 glass. Dye laser with a quasi longitudinal excitation scheme included a cell with dye circulation and a resonator close to a concentric one. Two diffraction gratings of 1200 grooves/nm were used as spectral selectors. Output radiation was extracted in zero order of diffraction at grazing angle. Resonator magnification in the plane of grating dispersion was $H = 32$. Ethanol solution of Rhodamine 6G was circulated through the cell at a speed of 5 m/s.

Figure 10 presents the interference patterns of the spectrum of dye lasing (top) and corresponding waveforms of excitation (bottom) at a pulse repetition rate of 4 kHz. It is seen that current limitation leads to substantial variation of the front of excitation pulse. Total duration of laser pulse is increased, and the shape of excitation pulse becomes closer to the optimal shape. Width of the dye laser spectrum correlates with the variation of excitation pulse shape tending to be narrower when the shape becomes closer to the optimal shape. Figure 11 illustrates the width of spectrum of the dye laser as a function of the value of negative bias voltage applied to the tassitron grid.

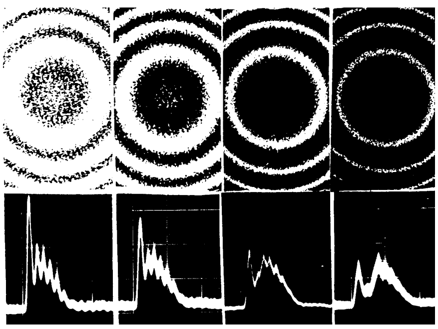

FIG. 10. Spectrograms of dye laser (top row) and corresponding waveforms of CVL excitation (bottom row). Ethanol spacing is 3 cm, *scanning speed is* 50 ns/div.

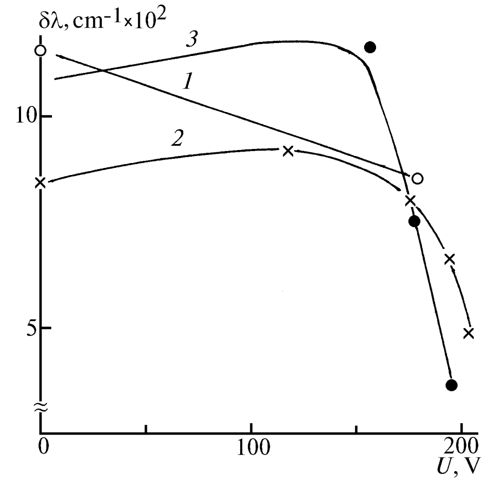

FIG. 11. Dye laser spectrum width as a function of discharge current limit in GDT of CVL. Curves 1, 2, and 3 were obtained at resonator lengths of dye laser of 100.80 and 60 cm respectively.

Curves *1*, *2*, and *3* have been obtained at resonator lengths of 100, 80, and 60 cm, respectively. Minimum width of the spectrum measured is $0.037\ \text{cm}^{-1}$ at the resonator length of 60 cm. Use of pumping by a CVL with output control leads to narrowing of the dye laser spectrum by a factor of three. Spectrum narrowing in the regime *4* was observed together with the reduction of the background level in the laser pulse. It was about 40% in conventional regime, and reduced to 12% in the regime *4*. It should be pointed out also that we did not reach the minimum possible width of spectrum of a dye laser. The technique of output control did not allow precise variation at the initial portion of the excitation pulse and did not provide high reproducibility of the results. In our further experiments, we intend to provide active pulsed control of the regime of discharge current limitation in order to widen capabilities of this technique.

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