Investigation of energy characteristics of CuBr+HBr laser with lowered energy contribution in a discharge

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Investigation results on energy characteristics of CuBr+HBr lasers of large active volume with an externally heated active zone of the gas-discharge tube are presented for cases of the laser operation with different excitation schemes. It is shown that external heating by traditional pumping schemes does not affect significantly the laser output parameters. At the same time, the laser of such construction is able to maintain the required temperature regime of active medium independently of the pumping mode; this allows lasing in gas-discharge tubes of large volume at a low pumping power, as well as realization of the train operation mode. Based on experiments with trains, it is shown that escape of Cu from a discharge in the inter-pulse period is connected with CuBr reduction. The CuBr reduction rate constant in discharge afterglow is found to be $5 \cdot 10^3$ s^{-1}.

Introduction

It is well-known that energy characteristics of metal vapor lasers are determined mostly by the excitation pulse parameters,[1–3] which essentially depend on pumping circuit features. As it is shown in Ref. 2, the use of the voltage increase circuits in a gas discharge tube (GDT) with magnetic pulse compression (circuits with pulse transformer and the capacitive voltage doubling) for Cu vapor laser pumping allows more than twofold increase of the lasing efficiency.

Comparative study of pumping features of Cu and CuBr+H_2 lasers[4] has shown that the CuBr+H_2 lasing power decreases insignificantly (by less than 10%) when changing from the voltage doubling circuit with magnetic pulse compression to the direct pumping circuit, while the Cu laser power is decreased twofold. The use in the CuBr+H_2 laser pumping of the Blumlein doubling circuit, free of magnetic pulse compression lines and circuits with interacting contours pumping,[5,6] allows the increase of the lasing power and efficiency (as compared to the direct circuit), comparable with the similar increase in case of Cu laser.[2]

The model study of the mode of the lowered energy contribution in a discharge by means of short-time change of reserve capacities, carried out for Cu [Ref. 7] and CuBr [Ref. 8] lasers, have shown that the energy contribution lowering allows an enhancement of the lasing efficiency. Such a mode does not allow the active medium temperature to be maintained during a long time; therefore, there appears an idea to design so-called "laser with low energy contribution in a discharge," i.e., with insufficient energy for maintaining stable laser operation. Hence, the external heating is required.

The CuBr laser active element was designed, construction of which allowed maintaining the temperature in the GDT active zone and gas mixture composition independently of the power input into a discharge. Such design allows widening of the range of pumping conditions up to realization of the "expectation" mode, when pumping pulses stop for a long time (seconds or minutes), as well as the train mode, when inter-pulse period varies from 0 to about 100 pulse-repetition periods.

The idea to use the trains of periodically repetitive excitation pulses to study the properties of an active medium, containing copper salt vapors, was earlier realized in a CuCl vapor laser.[9,10] In Ref. 9, the trains were formed according to the condition f/S = const, where f is the pulse repetition frequency in a train, S is the train on-off time ratio. The suggested technique allowed us to vary the train pulse frequency conserving the level of the input mean power. This gave us the opportunity to study a long excitation pulse train, instead of the double pulse excitation mode. However, this method prevents from arbitrary variation of train parameters, because the laser temperature regime changes when f/S varies.

The CuCl laser with an active GDT volume of 30 cm × 8 mm was studied in Ref. 10 under conditions that active medium relaxation in the inter-pulse periods was determined by diffusion processes towards a wall. The external heating was used and the lasing was excited by paired trains with controllable parameters. Such excitation procedure, like in our work, allowed us to minimize the effect of excitation conditions on the thermal behavior of the active element.

According to Ref. 11, introduction of an optimal concentration of HBr (about 0.2 Torr) into CuBr laser active elements is similar to hydrogen addition, which essentially improves frequency and energy parameters of the laser (twofold and more). This is favored by the current delay relative to voltage and

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by an increase of discharge voltage at GDT electrodes due to more effective relaxation and recombination of the active medium in the inter-pulse period.

However, some discrepancy in results, obtained with different pumping circuits for $CuBr+H_2$ lasers, and a lack of data for CuBr+HBr lasers do not allow an unambiguous conclusion about the influence of different pumping circuits on CuBr+HBr laser energy characteristics. Hence, one of the problems of our work is an experimental study of these characteristics for a CuBr+HBr laser with lowered energy contribution in the discharge at excitation with the use of different pumping circuits. One more problem is the study of influence of the inter-pulse period (pause) length on the discharge characteristics and the lasing of large-active-volume CuBr+HBr laser, excited by periodically repetitive electric trains. Such regime is of interest not only for investigation of active media properties, but for solution of applied problems connected with in-line control for laser radiation.

Experimental technique and measurement equipment

Active element design

A simplified design of the active element under study is shown in Fig. 1.[12]

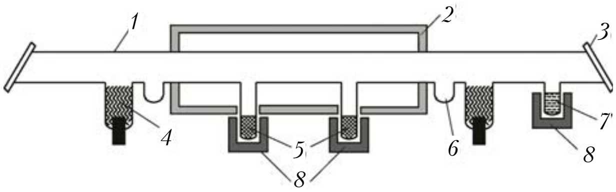

Fig. 1. Design of the active element of CuBr+Ne+HBr laser with low energy contribution in a discharge: GDT (*1*); heat chamber (*2*); windows (*3*); electrodes (*4*); containers with CuBr powder (*5*); traps (*6*); HBr generator (*7*); and heating elements (*8*).

The quartz GDT (*1*) is placed into the heat chamber (*2*), having temperature control tools and allowing the automated maintenance of a preset temperature inside the chamber (GDT outwall temperature). Containers with the working matter CuBr (*5*) are located outside the heat chamber and are heated independently. The reverse HBr generator (*7*) is built into the GDT, its function is not only HBr delivery into the laser active medium but also HBr pumping back into the generator. The HBr concentration is controlled in wide limits by the heater temperature; the addition optimum is determined by the maximum of radiation power. Typical addition value is 0.2–0.3 Torr.[11]

The goal of the design was to heat the GDT with power from the heater and to realize the HBr dissociation and excitation through high-voltage pumping pulses. As the result, we expected an augmentation of the pumping efficiency (relative to the energy consumed from the high-voltage source). The GDT of different active volumes were under study: GDT No. 1 has 56 cm active length, 70 cm inter-electrode distance, 35 mm inside diameter, and 540 cm^3 active volume; GDT No. 2 has 91 cm active length, 105 cm inter-electrode distance, 38 mm inside diameter, and 1032 cm^3 active volume. The pressure of the buffer gas Ne was 30 Torr. Some experiments were carried out with GDT No. 3: an active length of 105 cm, an inter-electrode distance of 125 cm, an inside diameter of 58 mm, an active volume of 2774 cm^3, and Ne pressure of 20 Torr.

Pumping circuits

Four pulse formation circuits were used to study energy characteristics of CuBr + HBr laser with low energy contribution in a discharge (Fig. 2). In all circuits, the resonance charging of the storage capacitor was used to increase the voltage at *C1* (*C2*) relative to the power source. Pulse hydrogen thyratron TGI1-1000/25 with air heating (at an average handling power less than 2 kW) and water heating (at more than 2 kW) was used as a key controllable element.

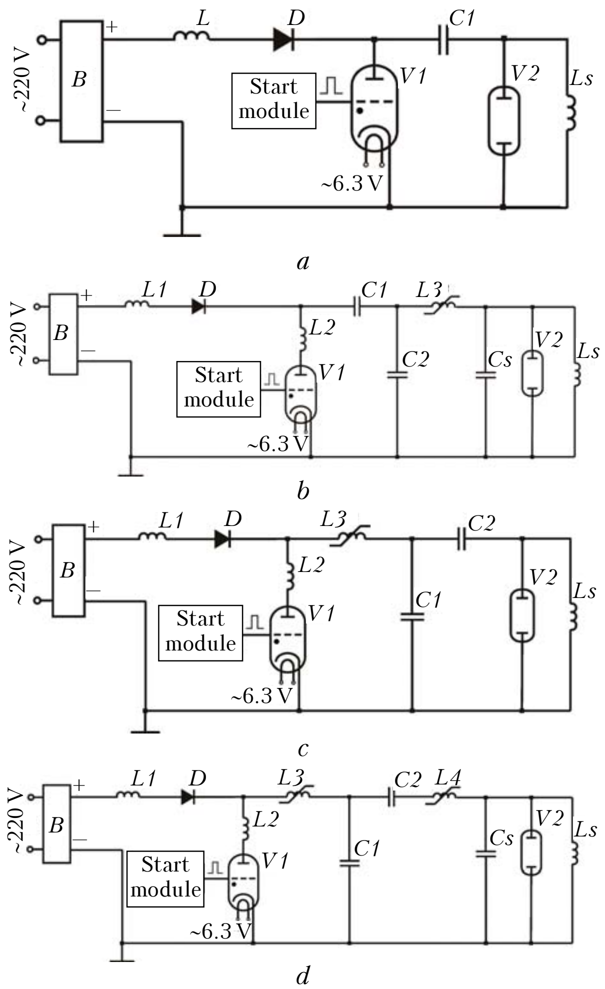

Fig. 2. CuBr+Ne+HBr laser pumping circuits: direct discharge circuit of the storage capacitor (*a*); circuit with magnetic pulse compression without voltage doubling (*b*)[13]; Blumlein voltage doubling circuit (*c*)[5,13]; voltage doubling circuit with magnetic pulse compression (*d*).[2]

The thyratron is excluded from the discharge contour in circuits with magnetic pulse compression (MPC), Blumlein voltage doubling, and voltage doubling with MPC. In contrast to the direct circuit, the switch time characteristics do not virtually affect the processes in the discharge contour. In addition, requirements to the switch are abated and its operation life increases. When forming pulse in circuits with MPC, the duration of current passing through the thyratron and voltage front buildup was 400–600 and 150–200 ns, respectively, which is about two times higher than the characteristic time of circuits without magnetic compression. A false throttle *L3* served for 20–40 ns limiting of current through the thyratron till its complete activation. A recharge period for *C1* and *C2* capacities was set with the help of the air throttle *L2*.

Parameters of MPC units were determined by the equations and technique, described in Refs. 13–15. Exact parameters of saturated-core chokes were selected while adjusting the circuit. Ring ferrite cores (2000 HM ferrite mark) were used as the magnetic conductor material. To maintain the temperature conditions of the cores, saturation inductances *L3* and *L4* were placed into a reservoir with cooling liquid (transformer oil). Heating energy losses of the magnetic conductor were determined by the calorimetric method; they were less than 150 W at the 1.8-kW power, consumed from the rectifier.

Measurement equipment

The current, voltage, and lasing pulses were measured with the Rogovski coil, low-inductance TBO resistor divider, and coaxial photocell FK-22, respectively. Recorded signals were sent to a Tektronix TDS3032 oscillograph. The radiation power was measured with an IMO-2 power meter and the GDT wall temperature – with a Chromel-Alumel thermocouple.

Energy characteristics of CuBr+HBr lasers

Figure 3 shows dependences of the average lasing power P_{av} on the consumed power P_r for CuBr + HBr lasers with low energy contribution into the discharge at different pumping circuits.

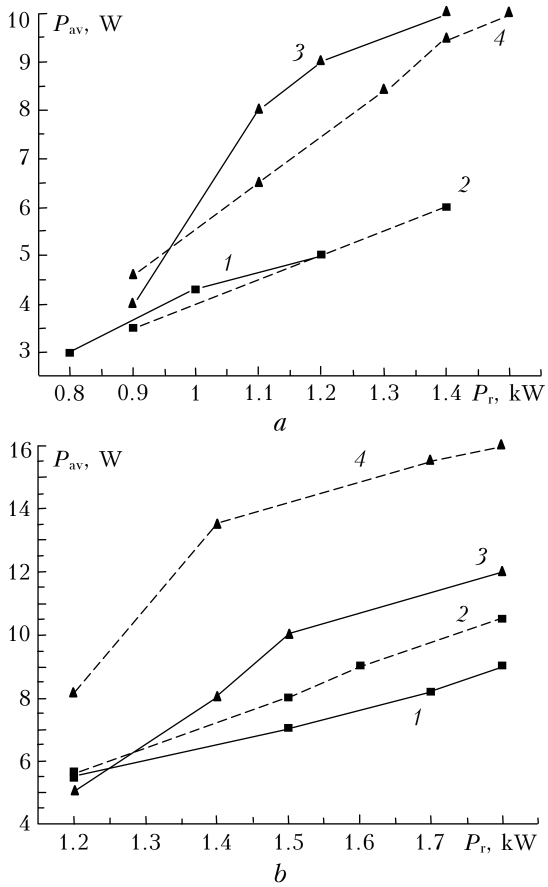

Fig. 3. Lasing power as a function of the high-voltage-rectifier-consumed power: GDT1 (*a*) and GDT2 (*b*). Curve *1* corresponds to the direct circuit, *2* – to the circuit with MPC, *3* – to the voltage doubling circuit, and *4* – to the voltage doubling circuit with MPC.

The value of storage capacities *C1* and *C2* was 750 pF for GDT Nos. 1 and 2 and 1300 pF for GDT No. 3. The physical efficiency factors of lasers were calculated from voltage, current, and lasing oscillograms in two cases: a) when taking into account the energy, input into the discharge for the total current pulse life time η_c and b) when accounting for the energy, input into the discharge from the current flow beginning to the end of the lasing pulse η_l. By the rectifier η_r, the efficiency was calculated as the ratio of average radiation power to rectifier-consumed one. Maxima of P_{av}, P_r, η_c, η_l, and η_r are given in the Table below for each circuit.

Pumping circuit	GDT No.	Diameter, mm	P_{av}, W	P_r, kW	η_r, %	η_c, %	η_l, %
Storage capacitor direct discharge	1	35	5	1.2	0.42	0.61	0.73
	2	38	9	1.8	0.50	1.2	1.6
	3	58	15	2.4	0.63	–	–
With MPC	1	35	6	1.4	0.43	0.70	0.85
	2	38	10,5	1.8	0.58	2.27	2.25
Blumlein voltage doubling	1	35	10	1.4	0.70	1.55	2.10
	2	38	12	1.8	0.67	2.56	3.50
Voltage doubling with MPC	1	35	10	1.5	0.67	2.26	3.10
	2	38	16	1.8	0.90	4.02	5.00
	3	58	24	2.4	1.0	–	–

As it follows from the obtained results, the highest radiation powers and efficiency factors are obtained in voltage doubling circuits, where much higher voltage is applied to GDT at the same power consumed from the high-voltage rectifier. Hence, excitation of Cu upper working levels is more effective as compared to the circuits free of voltage doubling. Real voltage doubling only in the presence of HBr addition turned out to be a feature of CuBr+HBr lasers. The highest average power was 10 W at 0.7% efficiency for GDT No. 1 and 16 W at 0.9% efficiency for GDT No. 2, calculated by the power, consumed from the high-voltage rectifier (see the Table). A radiation power of 24 W at 1% efficiency, obtained for GDT No. 3, was not maximal, since it did not satisfy to conditions of the optimal gas mixture composition.

As it follows from Fig. 3, circuits with MPC are preferable for the GDT of larger working volume (Fig. 3*b*), while MPC has no positive effect on the average radiation power and efficiency in case of GDT No. 1. (Fig. 3*a*). This can be explained by the fact, that the GDT of larger volume has a larger capacitive component of resistance, therefore, the capacities recharge current in the discharge circuit and the rate of the current rise should be higher to provide for a steeper voltage front at GDT. However, realization of such situation is limited by the rate of thyratron current growth.[16]

The presence of the capacity voltage doubling in the circuit (Fig. 2*d*) of the saturated-core choke *L4* provides for complete recharging of *C2*; then an equivalent capacity (in a series of *C1* and *C2* capacitors) enters into the discharge circuit. Therefore, in case of GDT No. 2, the leading edge and duration of an excitation pulse noticeably decrease, when input of the saturated-core choke and the capacitor *Cs* into the Blumlein circuit, which enhances the lasing conditions. It follows from the comparison of physical efficiency factors, characterizing the efficiency of energy contribution in the active medium for circuits with and without MPC (see Table), that the factor is much higher in the latter case (twofold and more).

A possibility to obtain the lasing in tubes of larger volume at a small power from high-voltage pumping source turned out to be one of the advantages of the laser design with external heating. By means of decreasing the energy in pumping pulses and simultaneous increasing the heater power, i.e., maintaining at a certain level the total power input into GDT, it is possible to obtain relatively high mean lasing power in conditions, at which this would be difficult in case of self-heating active element (see Fig. 3). Despite the low efficiency ($\eta_r < 0.2\%$), the lasing existed at a pumping power of about 500 W for GDT No. 2 and about 300 W for GDT No. 1. The lasing was absent at an input power of 0.8–0.9 kW (GDT No. 1) and almost absent (was equal to tenths of W) at 1.2 kW (GDT No. 2) at full switching-off of the external heating (the heat-insulation level was constant).

Figure 4 shows oscillogramms of the current *I*, voltage *U*, and lasing P_l for conditions with maximal output parameters for voltage doubling circuit with MPC (GDT Nos. 1 and 2). It turned out that maxima of the radiation power and lasing efficiency are observed at clearly pronounced oscillating behavior of the voltage at GDT electrodes, i.e., at evident mismatch of GDT and pumping circuit. It can be supposed that the discharge in a copper halide vapor laser with active additives differs from the discharge in pure metal vapors.

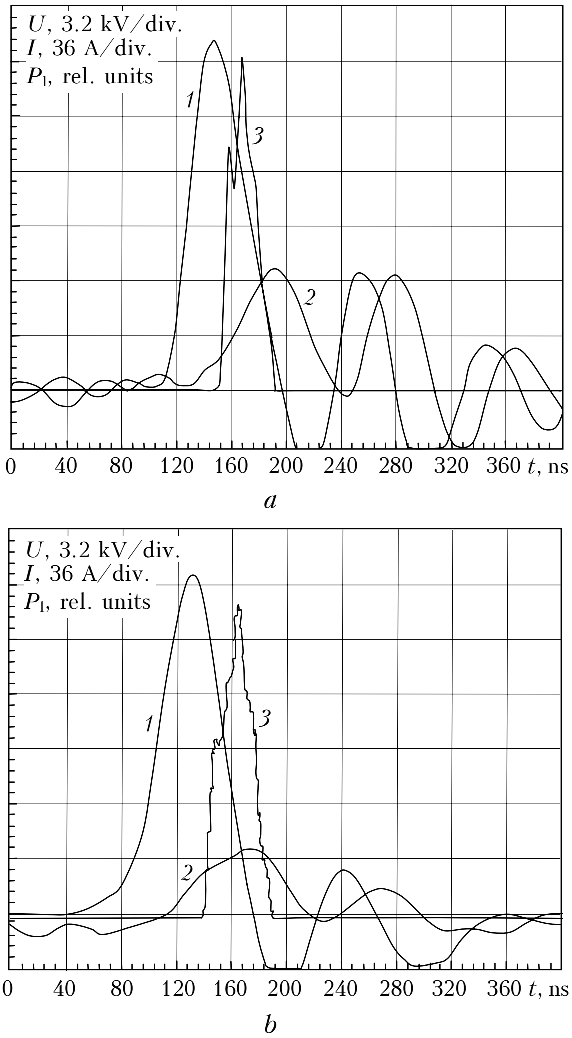

Fig. 4. Oscillogramms of voltage (*1*), current (*2*), and lasing (*3*) for the voltage doubling circuit with MPC: GDT1 (*a*) and GDT2 (*b*).

Hence, the following conclusions can be drawn:

1. External heating allows the lasing in a CuBr laser to be obtained at low pumping powers, at which it is impossible without such heating.

2. At the same time, external heating does not improve essentially output parameters of the CuBr+HBr laser. To obtain a high efficiency, it is necessary to increase the pumping pulse power, input into a discharge, and decrease the heater power.

3. For all pumping circuits, an efficiency factor, calculated for the moment before the lasing pulse termination and for the current flow time, significantly increases the conversion efficiency. Probably, additional means for energy input break, e.g., after lasing termination, would allow the decrease of input pulse power without the efficiency loss.

4. For further increase of output parameters, a detailed study of discharge characteristics in metal halide vapor lasers, particularly, CuBr+HBr lasers, is required.

The train pumping mode

To study plasma relaxation processes in the inter-pulse period and, correspondingly, to determine the influence of the inter-pulse period length on parameters of the pulse and lasing, CuBr+HBr laser was excited with electric pulse trains. The trains are of interest, because allow the study of both "ultra low" (inter-train periods are of several seconds and more) and high (> 100 kHz) pulse repetition frequencies. The former is interesting in view of the study of the Cu diffusion onto the wall and CuBr reduction in the GDT volume; the latter opens a possibility for studying the reasons, limiting the pulse repetition frequency and energy parameters of metal halide vapor lasers. In the case of the self-heating laser, when exciting pulse trains, the energy input into a discharge and, hence, the temperature in the active zone depend on the train parameters (the frequency rate, the number of pulses in a train, the inter-train period).

The design of the active element with low energy contribution in a discharge allowed minimizing the influence of pumping parameters on the laser temperature regime. The GDT No. 1 was studied in conditions of the direct circuit exciting (see Fig. 2*a*), and a storage capacity of 500 pF. The start module was formed of a master oscillator and pulse former for thyratron starting. The master oscillator allowed forming periodic pulse trains with controllable parameters: the pulse repetition frequency and the number of pulses in a train. The inter-train period could be set from 0 (pulse-periodic mode) to 5 ms. The maximal pulse frequency rate in a train (23.3 kHz) was determined by the switch (TGI1-1000/25 thyratron) capabilities. An operation mode with 10–23.3 kHz pulse frequencies in a train was under study.

Figure 5 shows characteristic oscillograms of the voltage, current, and lasing for the train excitation mode.

It is typical for all experiments that the amplitude of the first pulse in current train and lasing trains is less than in the next pulses, and the lasing power steadily increases from pulse to pulse. Lasing pulse duration, virtually invariable, is at the 40-ns level (to base).

According to the existing R-M laser models, the lasing power depends on a number of factors, in particular, on the residual electron concentration and Cu atom concentration in the ground and metastable states to the beginning of excitation pulse. As it follows from Figs. 5*a* and *b*, the electron concentration decreases during the pause to a smaller value than during the inter-pulse period in a train.

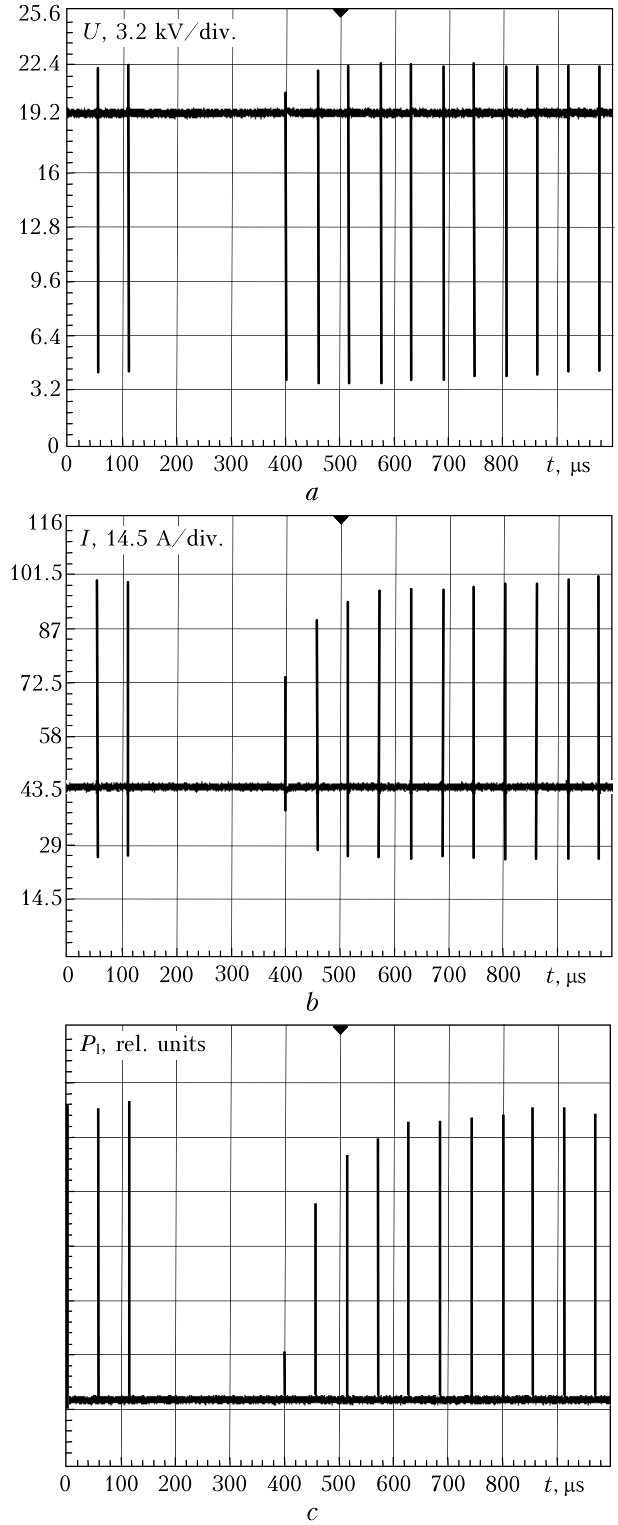

Fig. 5. Oscillograms of voltage (*a*), current (*b*), and lasing pulses (*c*) at the train operation mode with the 17.5-kHz pulse frequency in a train.

It can be supposed that Cu atom concentration in the metastable state also decreases. This means, that conditions for more effective lasing should be created to the beginning of the first pulse, provided the Cu atom concentration in the ground state is invariable (or decreased insignificantly). In 2–3 pulses, the current pulse amplitude attains some equilibrium, which evidences that the prepulse electron concentration is established; however, the lasing pulse amplitude attains its equilibrium (recovers) much later or not at all. This occurs at large intervals between trains and (or) a small number of pulses in a train.

The power decay in the first pulse can be explained by the deficit of free Cu atoms in the discharge, and the lasing power increase from pulse to pulse – by accumulation of the atomic copper. The dependence of peak lasing power P_l on pulse number in a train is shown in Fig. 6*a* for different excitation pulse repetition frequencies at inter-train pauses of 280–300 μs (10–14 pulses in a train).

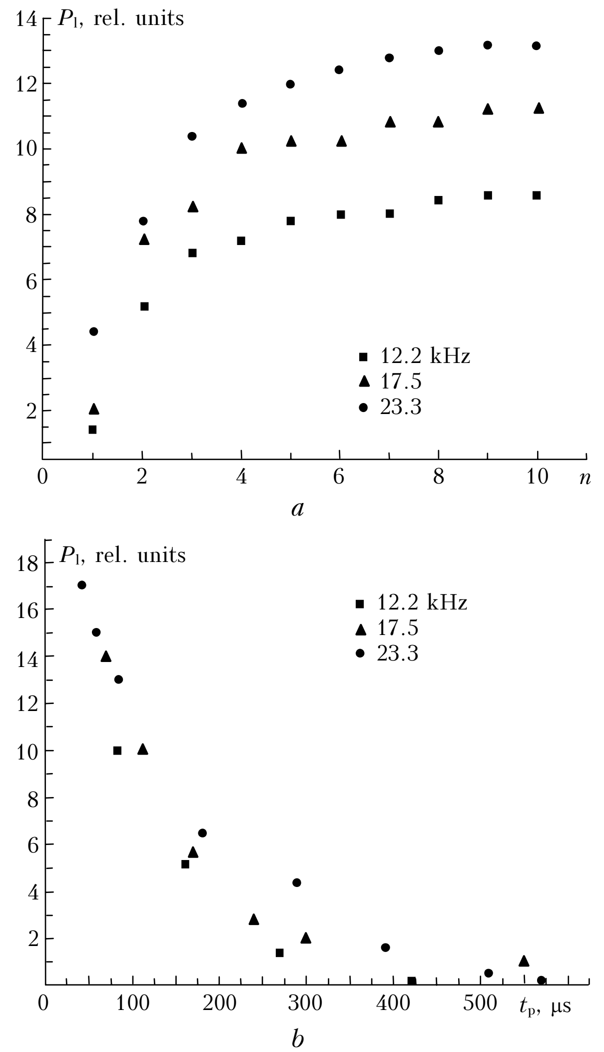

Fig. 6. Peak lasing power P_l as a function of pulse number in a train (*a*) and the peak lasing power in the first pulse in a train P_{l1} as a function of inter-pulse pause accumulating t_p (*b*).

Figure 6*b* shows the peak lasing power in the first pulse of a train as a function of inter-pulse pause. The amplitude of the first pulse of a train near-exponentially decreases, the lasing power in the first pulse *e*-fold falls during a pause of about 200 μs and virtually vanishes during 500–600 μs. On the base of this dependence, the rate constant of escape of Cu atoms from the discharge plasma has been assessed. It is determined by the processes of the copper and bromine compounding into CuBr, as well as by Cu atoms diffusion onto the GDT wall. The assessment is $5 \cdot 10^3\,s^{-1}$. Hence, when exciting the active medium by pulses repeating with a frequency less than 5 kHz, the problem arises in providing for the concentration of Cu atoms, necessary for effective lasing. A pause of 600 μs is a threshold, at which lasing in the first pulse of the next train disappears. When changing the pause length from 600 μs to 5 ms, the lasing was observed, beginning from the second pulse for all pulse repetition frequencies under study. The shape of lasing train envelope was invariable and had a monotone character within the whole range of pauses between repetitive pulse trains, beginning with the minimal delay (the next train continued the previous one) to the maximally possible one in the experimental conditions (5 ms). Amplitudes of only first pulses in trains increased as the inter-train period decreased and (or) pulse number in the train increased.

The inter-train period and the pulse frequency in the train determine the pulse power, set to the end of some train, and the recovery time, i.e., the time, during which the amplitude of lasing pulse attains the equilibrium value. The recovery time is defined as

$$T_r = (N - 1)\,T,$$

where T is the period of pulse succession in a train; N is the number of pumping pulses, after which the lasing power attains some equilibrium value.

The dependence of the recovery time of lasing power amplitude t_r on the inter-train period t_p for different pulse repetition frequencies in a train is shown in Fig. 7.

As it follows from the obtained dependences, there is a residual Cu atoms concentration in the discharge gap to the moment of arrival of the first pulse in the train even at long inter-train periods. The higher is the repetition frequency, the higher is the concentration. Hence, the peak lasing power attains an equilibrium value for a less number of pulses (at a similar pause). The dependence of the recovery time on the inter-train period is evidently nonlinear for each frequency. The bends on the curves show that Cu density decreases much more slowly at a delay of about 600 μs than at shorter delays.

The obtained results have a number of differences from those given in Ref. 10. First, in the shape of train envelope – in Ref. 10 it has a maximum and drops to the train end almost in all presented cases. An excess of the maximum peak power over equilibrium one in a train decreases as the chamber

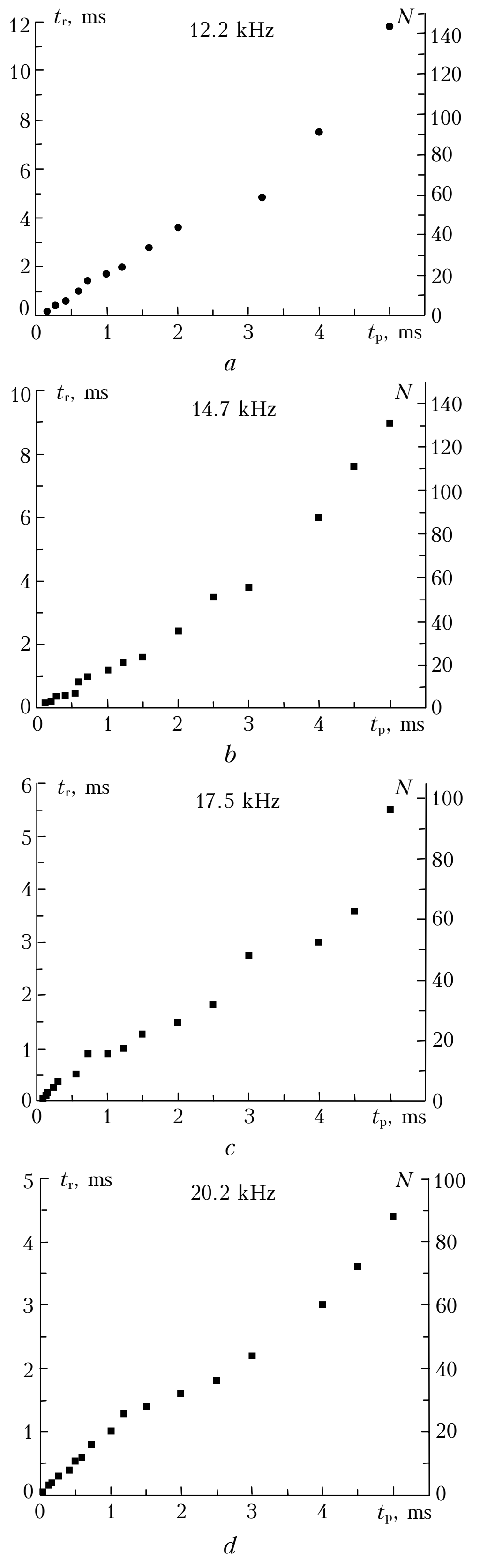

Fig. 7. The recovery time t_r (N pulses), required for attaining the maximum pulse power, as a function of inter-train period t_p at different pulse repetition frequencies in a train.

period does not affect the shape of train envelope in wall temperature rises, and at some temperature the envelope becomes monotonous. Second, the inter-train period in our experiments; all trains in the train sequence have the same shape and the equilibrium value of the lasing power. In Ref. 10, the envelope shape of the second train and lasing power in the train essentially depend on the inter-train period and the number of pulses in the first train. Unfortunately, there is no information on the pared train repetition frequency and, correspondingly, on the delay between the second train in a previous pair and the first train in the next pair. It can be supposed that this delay is much longer than the inter-train pause in a pair.

Naturally, the excitation by periodically repeating trains differs from excitation by single or pared trains. Such character of train formation simulates the regular pulse mode more accurately as compared to train pairs. In our case, the influence of one train to another, connected with the time of CuBr molecules delivery into the working zone, is probably absent, i.e., a sufficient amount of CuBr is always present in the active zone, and transient processes are determined by the CuBr dissociation during the pumping pulse and Cu atoms departure in the inter-pulse period. We have not studied the dependence of train parameters on the temperature into the heater and the temperature of containers filled with CuBr. However, the envelope shape change was not observed while GDT heating up to the working temperature (780 °C).

The differences between our results and those from Ref. 10 are sooner determined by different experimental technique and equipment (GDT size and design, HBr addition) than by the type of halogenide (CuBr or CuCl). Taking into account the similarity of CuBr and CuCl properties, as well as the results of Ref. 17, it can be supposed that the character of lasing pulse trains is similar in similar pumping conditions, GDT sizes and design, as well as the presence (or absence) of HBr addition.

Analyze the process of Cu atoms escape from a discharge. In Ref. 10, where the CuCl laser with GDT of 8 mm in diameter was studied, this process was connected mainly with the Cu diffusion onto the wall. The characteristic diffusion time in the conditions of Ref. 10 was about 160 μs. In our work, the Cu escape from a discharge is considered as two processes, i.e., Cu diffusion on the wall and CuBr reduction into the GDT volume. We have assessed the diffusion time (about 10 ms) for a tube of 35 mm in diameter (the Ne pressure is 30 Torr, gas temperature is 1000 K), using data from Refs. 18–20. The characteristic time of Cu atoms escape, measured by the curves in Fig. 6, is about 200 μs. This witnesses that the diffusion processes in our case do not affect essentially the Cu escape from the discharge. Hence, volume processes, connected with CuBr reduction in the inter-pulse period, prevail, and the obtained rate constant of Cu atoms escape from discharge plasma is in fact the CuBr reduction rate constant.

Conclusion

The use of external GDT heating in traditional pumping circuits has no positive effect on the laser efficiency. The pumping power lowering at corresponding heater power magnification results in reduction of the mean radiation power and efficiency factor.

At the same time, the advantage of the laser design with low energy contribution into a discharge is the possibility of lasing at a low pumping power, which is so low, that the self-heating mode in the GDT of a CuBr+HBr laser of large volume would be hardly realizable when using an active element of traditional design.

The constant of CuBr reduction rate in discharge afterglow has been determined experimentally with pulse trains as $5 \cdot 10^3$ s^{-1}.

The obtained results demonstrate the need in further investigations of the train excitation mode of CuBr laser to gain a deeper insight into physical processes in this laser.

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