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Discharge formation in a copper vapor laser: optimal pumping conditions

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Abstract

The electrophysical process in the discharge circuit of a copper vapor laser (CVL) is investigated. It is shown that the pumping of the active medium of a CVL in gas-discharge tubes (GDT) with electrodes located in cold buffer zones is carried out in two stages. At the first (preparatory) stage, the capacitive components of the laser discharge circuit are charged from the storage capacitor, and at the second stage, the active medium is directly pumped. The transition from the preparatory stage to the pumping stage is carried out as a result of a breakdown. It is shown that breakdown is a transient process of discharge development from a glowing to a non-thermal arc discharge and is characterized by a sharp change in the cathode potential drop across the GDT. The inductance of the discharge circuit is a factor that determines the efficiency of pumping the active medium since the release of the energy stored in the inductance at the preparatory stage provides heating of the cathode spot and determines the conditions for the occurrence of thermal emission of electrons from the GDT cathode.

Keywords: copper vapor laser, breakdown, thermionic emission of electrons

(Some figures may appear in colour only in the online journal)

1. Introduction

Copper vapor lasers (CVLs) have found wide application in nanotechnology, high-speed precision micromachining of materials [1], in medical systems for photodynamic therapy [2], in systems for visual-optical diagnostics and environmental monitoring [3] for remote detection of various substances [4], including using LIDAR systems based on the effect of spontaneous Raman scattering [5]. However, the practical use of CVLs today is limited by the significantly high cost of laser radiation due to the low efficiency of $\sim$1%, which is an order of magnitude lower than predicted [6, 7]. Therefore, the development of new methods and ways of realizing the energy potential of CVL is an urgent task.

The active media of repetitively pulsed CVLs have a high prepulse electron concentration $n_{e0} \sim 10^{13}$ cm^{-3}. Therefore, it was assumed that the development of the discharge under these conditions occurs without a breakdown stage, and a simple oscillatory circuit is used as the equivalent circuit of the laser discharge circuit, in which the electrophysical process can have an aperiodic or oscillatory nature. It is easy to show that the population of metastable states N_m at the front of the excitation pulse is $\sim L_C\ (n_{e0})^2$ in the case of an aperiodic process in the discharge circuit, where L_C is the inductance of the laser discharge circuit. The quality factor of the circuit should increase with increasing n_{e0}, during an oscillatory process, as a result of which the voltage on the active component decreases, which should inevitably lead to a redistribution of the population rates of the laser levels in favor of N_m.

The above indicates the defining role of n_{e0} in limiting the frequency-energy characteristics (FEC) of CVL generation and determines the approaches of choosing the optimal pump parameters. However, as researches have shown, the development of a discharge in gas discharge tubes (GDT) with electrodes located in cold buffer zones (CBZ) is carried out with a breakdown stage [8–13]. The presence of breakdown makes it possible to explain the observed electrophysical process in the

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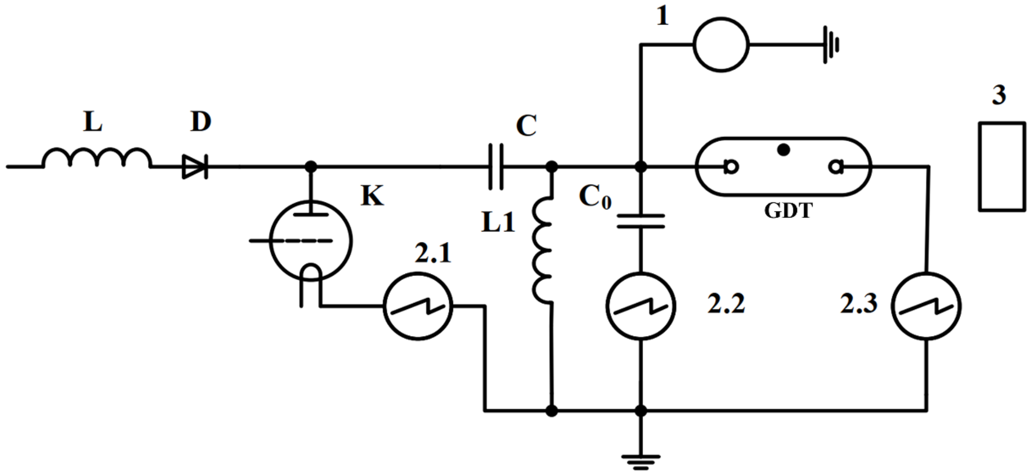

Figure 1. Experimental setup diagram: where GDT—a gas-discharge tube; *K*—thyratron TGI1-1000/25; *L, D*—charging choke and diode, respectively; *L*1—shunt inductance (∼230 μH); *C*—storage capacitor; C_0—peaking capacitor; 1—static voltmeter; 2—voltage divider; 3—current sensors; 4—'OPHIR-NOVA'.

discharge circuit of the laser [11], however, earlier researches did not reveal the mechanism of this process.

The purpose of this work is to elucidate the mechanism of breakdown formation by studying in more detail the electrophysical process in the discharge circuit of a CVL and to determine the optimal conditions for pumping the active medium.

2. Experimental setup

The research was carried out on an experimental setup, the diagram of which is shown in figure 1. In the experiment, a sealed GDT with cylindrical electrodes located in the CBZ at a buffer gas pressure (Ne) of ∼80 Torr was used. The discharge channel of the GDT is made of a BeO-ceramic tube with an inner diameter of 10 mm and a length of 40 cm. KVI-3 capacitors were used as storage and peaking capacitors, and a TGI1-270/12 thyratron was used as a switch. The GDT self-heating mode was carried out at a power consumption from a ∼900 Watt rectifier. To more accurately assess the energy characteristics of the laser, the capacitance of each capacitor used in this work was measured, since the permissible deviation of the capacitance from the nominal value for the KVI-3 capacitors is ±20%, therefore, further in the work, not the nominal capacitance value of a capacitor is given, but their measured values. A Tektronix DPO-4034B oscilloscope monitored current and voltage pulses. The average output radiation was measured with an OPHIR-NOVA power meter.

Figure 2 shows oscillograms for the pulse repetition rate (PRR) of the excitation $f = 10$ kHz and the voltage at the high-voltage rectifier $U_v \sim 3$ kV ($C = 3.45$ nF, $C_0 = 350$ pF) after the laser reaches a stationary state with an average output power of ∼890 mW. These are typical values for CVLs oscillograms of current pulses 1 flowing through the GDT, voltage 2 on the GDT, and generation 3. Additionally, there are oscillograms of current 4 flowing through the thyratron and current 5 for charging (5.1) and discharging (5.2) C_0. Current 4, flowing through the thyratron, consists of two parts 4.1 and 4.2: 4.1 is the charging current C_0 (preparatory stage of pumping) and 4.2 is the discharge current of the storage capacitor at the stage of pumping the active medium.

3. Experimental results

The oscillograms in figure 2 illustrate the two-stage process of the formation of an inverted population in an active medium. At the preparatory stage, the peaking capacitor C_0 is charged from the storage capacitor. The current through the switch drops to zero after C_0 is charged, and the pumping of the active medium is determined by the energy input from C_0 during its discharge. In this case, the energy remaining in the storage capacitor is deposited into the active medium after the generation pulse and does not directly affect the breakdown formation process. Consequently, a breakdown should form during the charging of C_0, and the most informative stage is the initial stage of the process, shown in figure 2(b) with higher temporal resolution. Obviously, under these conditions, it is possible to increase the practical efficiency of the laser by 'cutting off' the energy input from the storage capacitor after charging C_0 using a controlled switch [14].

The electrophysical process in the discharge circuit of the laser did not change with increasing capacitance C_0. An increase in the amplitude of the current flowing through the thyratron during C_0 charging, the charging current, and C_0 charging time was observed, as well as a decrease in the average generation power and an increase in the reverse voltage U_{rev}. at the anode of the thyratron. In figure 3 shows the dependences of the charging current amplitude ($I_{peaking}$) of C_0 1, the half-width 2 (Δt) of the charging current pulse of C_0, the reverse voltage U_{rev}. at the anode of the thyratron 3 and the voltage on the GDT 4 on the capacitance C_0. The voltage to which the capacitor is charged is proportional to the amount of charge q stored in the capacitor:

$$U = q/C = I_{peaking.}\Delta t/C. \quad (1)$$

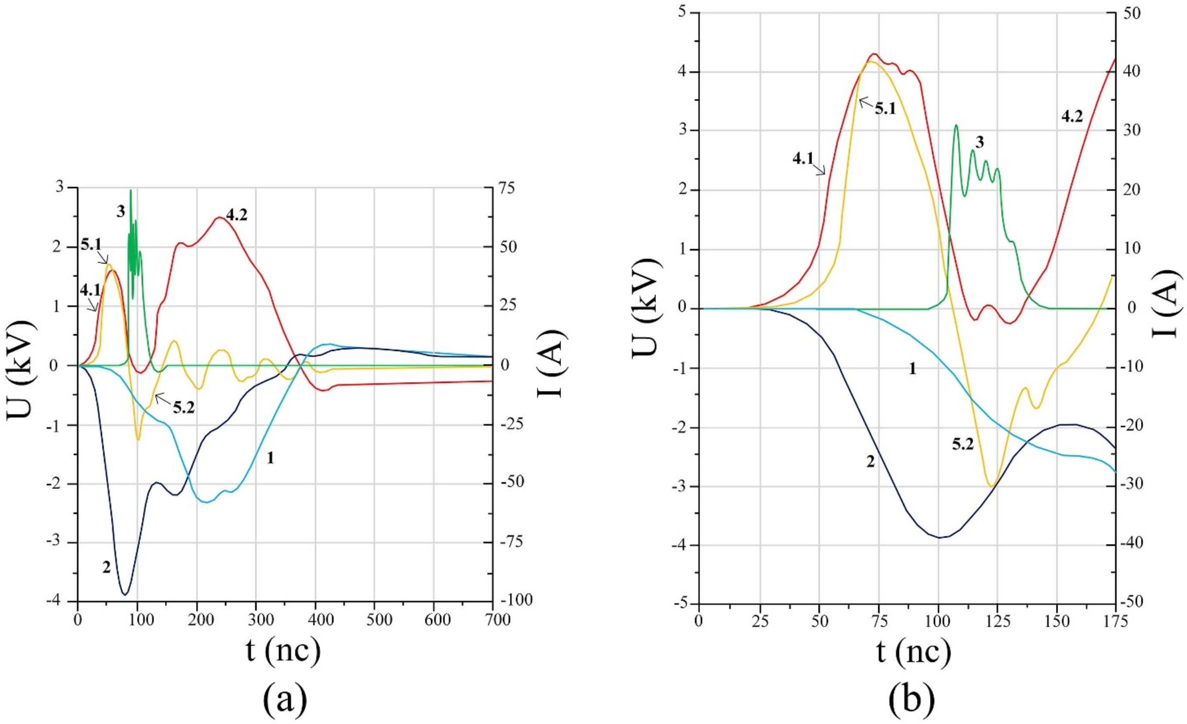

Figure 2. Oscillograms of current pulses (1) flowing through the GDT, voltage (2) on the GDT, generation (3), a current flowing through the thyratron (4), and current (5) for charging and discharging C_0, where $f = 10$ kHz, $U_v \sim 3$ kV, $C = 3.45$ nF and $C_0 = 350$ pF.

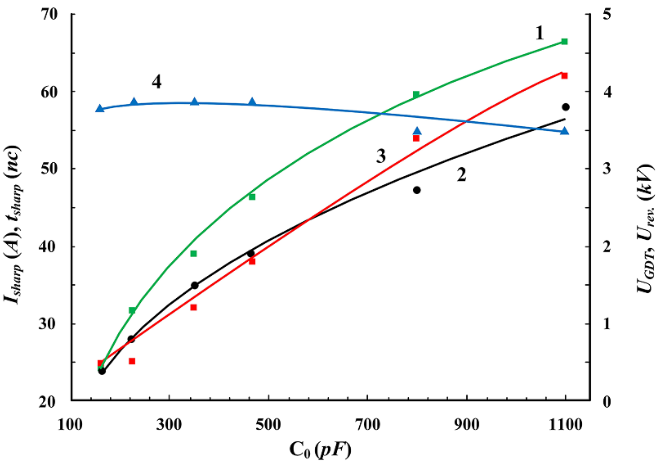

Figure 3. Dependences of the charging current amplitude (I_{peaking}) of C_0 (1), the half-width (Δt) of the charging current pulse of C_0 (2), the reverse voltage U_{rev}. at the anode of the thyratron (3) and the voltage on the GDT (4) on the capacitance C_0.

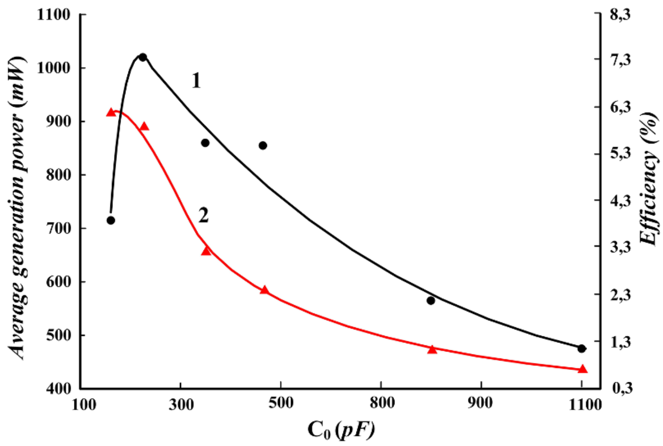

Figure 4. Dependence of the average output power (1) and pump efficiency (2) on the capacitance value C_0.

The voltage values calculated by this formula to which C_0 is charged from the storage capacitor coincide with the measured voltage values across the GDT. Consequently, the voltage across the GDT reflects the voltage value up to which C_0 is charged, and the voltage rise time on the GDT reflects the time of C_0 charging. Figure 4 shows the dependence of the average output power ($P_{\text{gen.}}$) 1 and the pumping efficiency (η) 2 (relative to the energy stored in C_0) also on the capacitance C_0.

Maximum $P_{\text{gen}}. \sim 1020$ mW and $\eta \sim 5.9\%$ are realized at $C_0 \sim 225$ pF. However, the practical efficiency of the CVL was $\sim$0.1% under these pumping conditions. This is because the bulk of the energy initially stored in the storage capacitor is deposited into the active medium after the generation pulse. The observed dependences of the electrophysical (figure 3) and energy characteristics of the laser (figure 4) are due to the sequential discharge process of the peaking and storage capacitors. The storage capacitor is discharged under these conditions through a medium with high plasma conductivity, the conductivity of which increases with increasing capacitance C_0. This causes an increase in the quality factor of the discharge circuit and leads to an increase in the reverse voltage at the thyratron anode in the presence of inductance in the discharge circuit, which was (according to estimates from the captured oscillograms) $L_c \sim 0.7\ \mu$H.

An analysis of the results obtained and the observed dependences suggest that the energy characteristics of the laser can be increased by choosing the optimal value of the capacitance C_0 with the minimum circuit inductance—(C_0—GDT) and introducing an additional inductance (L_{add}) into the discharge circuit between the storage and peaking capacitors. The role of the storage capacitor under these conditions is to ensure the charging of C_0 and to maintain the thermal regime of the laser operation. As is known, for efficient pumping of the active medium of a CVL, it is necessary to form an excitation pulse with a duration commensurate with the lifetime of the population inversion [15], which is realized when the first of the above conditions are satisfied. Maximum $P_{gen.} \sim 1020$ mW and ∼5.9% were experimentally realized at $C_0 \sim 225$ pF when the discharge time of C_0 was ∼40 ns with a lasing pulse duration of ∼35 ns. The need to introduce L_{add} is determined by the fact that the elements of the discharge circuit (including the switch) do not affect the process of discharging C_0 at the GDT. However, at the preparatory stage, a significant fraction of the energy stored in the storage capacitor is spent on work to shift the charge during the charging of C_0. For example, 50% of the energy stored in the storage capacitor will be spent on work to shift the charge under conditions when $C = C_0$. Insertion L_{add} into the discharge circuit of the laser allows resonant charging of C_0 from a storage capacitor. This process should ensure the charging of C_0 to a higher voltage, reduce the energy consumption for work on the shift of the charge when charging C_0, and, as a consequence, realize higher energy characteristics of laser emission.

Reducing the capacity of the storage capacitor makes it possible to increase the voltage across the high-voltage rectifier or excitation PRR while maintaining the thermal regime of the laser operation, which provided an increase in the average output power without changing the character of the electrophysical process in the circuit. $R_{gen.} \sim 1250$ mW and $\eta \sim 4.5\%$ are realized at pump parameters ($C = 2.17$ nF, $C_0 = 225$ pF, $f = 10$ kHz, $U_v = 3.7$ kV, $U_{rev.} \sim 1$ kV). It should be noted that the average output power at the given pump parameters, without the peaking capacitance, was $P_{gen.} \sim 870$ mW ($U_v = 3.6$ kV, $U_{rev.} \sim 1.8$ kV). $R_{gen.} \sim 1580$ mW and $\eta \sim 3.8\%$ are realized at pump parameters ($C = 1.1$ nF, $C_0 = 225$ pF, $f = 17.5$ kHz, $U_v = 4$ kV, $U_{rev.} \sim 2$ kV). However, the possibility of increasing the FEC of laser radiation by reducing the capacity of the storage capacitor is very limited. This is because thyratrons have a rather narrow region of stable operation with the upper boundary of $U_{rev.} \sim 5$ kV [16]. The storage capacitor is charged from the high-voltage rectifier through the charging inductor L (see figure 1) to a voltage of $\sim 2U_v + U_{rev,}$ which causes an increase in voltage to which the storage capacitor is charged with an increase in U_{rev}. For this reason, we failed to provide a self-heating mode of laser operation at $C = 800$ pF ($f = 26$ kHz), since the reverse voltage at the thyratron anode reached ∼5 kV and the voltage to which the storage capacitor was charged at ∼12 kV at a power consumption of high-voltage rectifier ∼750–800 W.

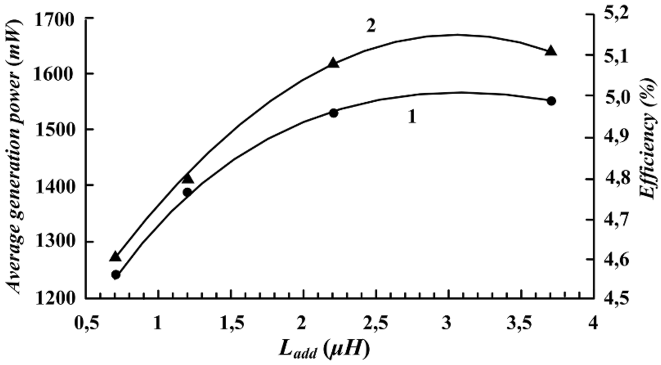

Figure 5. Dependence of the average output power (1) and pump efficiency (2) on the inductance of the discharge circuit.

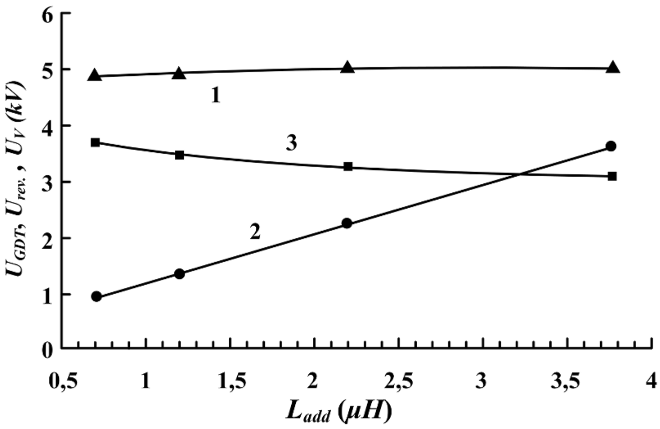

Figure 6. Dependence of voltage on GDT (1), reverse voltage $U_{rev.}$ at the anode of thyratron (2) and the voltage at the high-voltage rectifier (3) on the inductance of the discharge circuit.

Measurement of the electrophysical and energy characteristics of the laser with the insertion $L_{add.}$ into the discharge circuit was carried out at an excitation PRR of 10 kHz ($C = 2.17$ nF, $C_0 = 225$ pF) after the laser reached a stationary lasing mode at a power consumption from a high-voltage rectifier of ∼900 W. Figure 5 shows the dependences of the average output power 1 and pumping efficiency 2 (relevant to the energy stored in C_0) on the inductance of the discharge circuit (the indicated value of $\sim 0.7\ \mu$H corresponds to the intrinsic inductance of the discharge circuit in the absence of L_{add}). Figure 6 shows the dependence of the voltage on the GDT 1, reverse voltage $U_{rev.}$ at the anode of the thyratron 2 and the voltage at the high-voltage rectifier 3 on the inductance of the discharge circuit.

Studies have shown that the power consumption from the rectifier increased with the insertion of L_{add} into the circuit, which led to overheating of the active medium. It was necessary to reduce the voltage on the high-voltage rectifier (figure 6(3)) to maintain the laser operation's thermal region with an increase in the inductance L_{add}. An increase in $U_{rev.}$ was observed (figure 6(2)) at the thyratron anode under these pumping conditions with an insignificant change

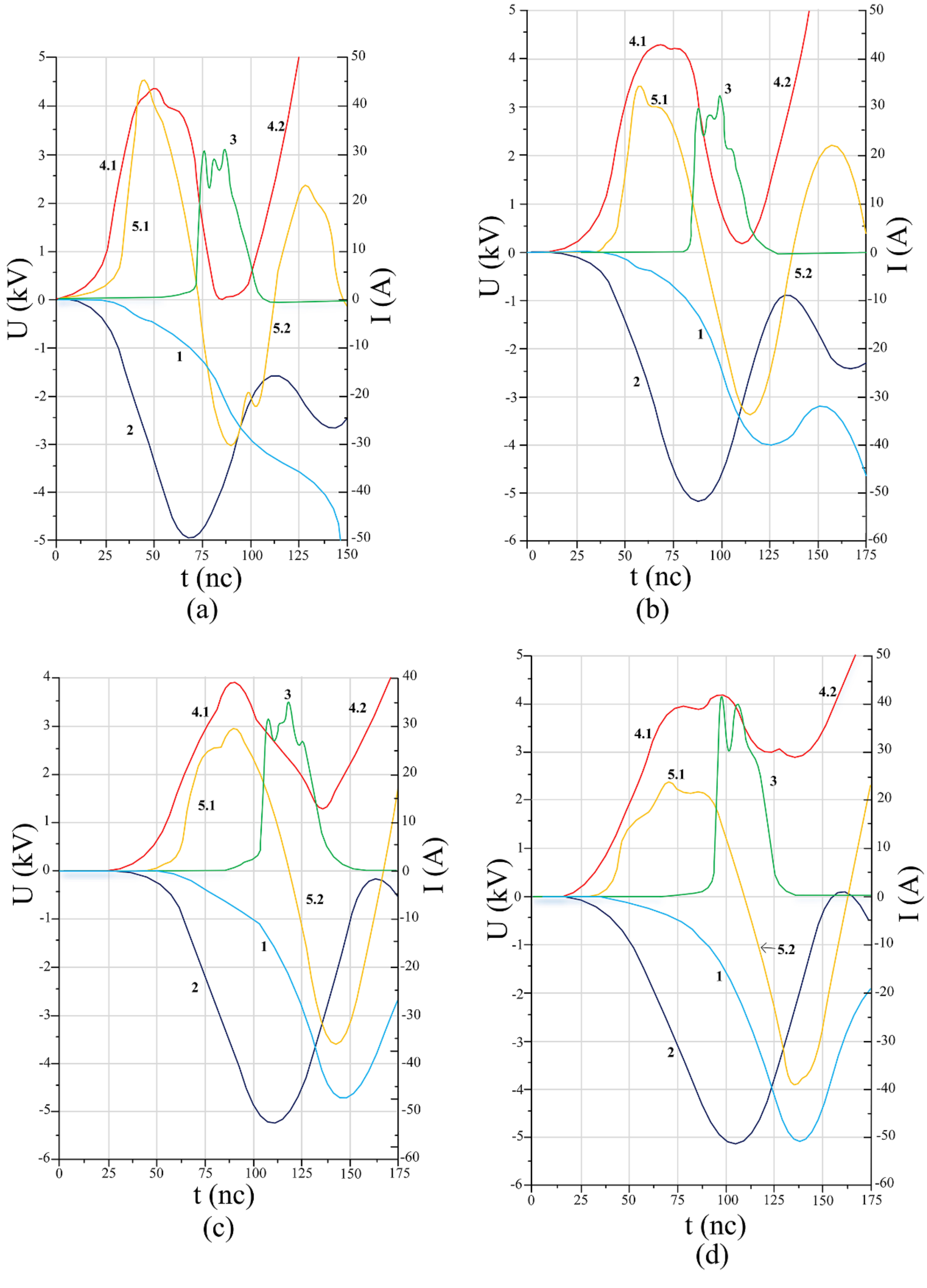

Figure 7. Oscillograms of current pulses (1) flowing through the GDT, voltage (2) on the GDT, generation (3), a current flowing through the thyratron (4), and current (5) for charging and discharging C_0 for the initial pumping stage of the laser active medium. a—$L_{add.} = 0$; b—$L_{add.} \sim 0.5$ μH; c—$L_{add.} \sim 1.5$ μH; d—$L_{add.} \sim 3$ μH.

in the voltage across the GDT (figure 6(1)), while an increase in the average output power (figure 5(1)) and pump efficiency (figure 5(2)) relative to the energy stored in C_0 was observed. However, as the analysis of the captured oscillograms showed, the observed increase in the average output power is because the current flowing through the switch did not drop to zero during the charging of C_0 and the summation of currents from two circuits formed by the storage and peaking capacitors was observed on the GDT (figure 7).

4. Discussion

The pumping of the active medium in the GDT with electrodes located in the CBZ is carried out in two stages. At the preparatory stage, C_0 is charged from the storage capacitor, and the active medium is pumped during the discharge C_0. The transition from the preparatory stage to the pumping stage occurs as a result of a breakdown, which is formed during the charging of C_0.

To analyze the processes in an electrical circuit, according to the theory of electrical circuits, it is necessary to draw up its equivalent circuit. As an equivalent circuit, when developing a kinetic model of the active medium of a CVL, a simple oscillatory circuit or a more complex two or three circuit is used see, for example [17, 18], and a satisfactory result is obtained when testing the kinetic model using the experimentally captured oscillograms of current pulses flowing through the GDT and the voltage across the GDT. The problem arises when simulating the current flowing through the thyratron, since a positive result for the complete set of recorded oscillograms (see figure 2) can be obtained only under the assumption of a breakdown in the GDT [11].

The active medium (the geometrical dimensions of the active medium in the GDT are determined by the thermally insulated discharge channel) is isolated from the electrodes by CBZ in which metal vapors are absent. Neutralization of charges in the interpulse period in such GDT designs occurs in the process of bulk three-particle recombination in the active medium and due to dissociative recombination in the buffer zones. Since the rate of dissociative recombination is higher than the three-particle recombination, it was assumed [10] that the breakdown should be observed under conditions of complete plasma recombination in the CBZ. The results of our studies do not confirm the above, since no change in the electrophysical process in the discharge circuit of the laser was observed both during the heating of the active medium to the operating temperature and when the PRR of the excitation and the parameters of the pump pulses were varied over a wide range. Nevertheless, the currents flowing through the thyratron and the GDT should differ significantly in the presence of breakdown, which is due to the process of charging C_0 from the storage capacitor. This is demonstrated by the results of studies and the results of works [8, 9, 11–14], which indicates the presence of a process that is similar to a breakdown or accompanies it.

The breakdown is one of the most important discharge processes, which begins with a certain number of random or artificially injected electrons to stimulate the process. The presence of $n_{e0} \sim 10^{13}$ cm^{-3} in the active medium of a CVL determines the possibility of a discharge development without a breakdown stage. However, the electrical circuit must be closed for a discharge to occur in a gaseous medium or plasma, which is ensured by the emission of electrons from the cathode. In this case, it is desirable (for efficient pumping of the active medium of a CVL) to ensure the emission of electrons from the GDT cathode at a minimum cathode voltage drop, which can be realized under thermionic emission conditions, when the GDT cathode or the cathode spot on the electrode is heated to a temperature of $T_k \sim 2000°$ K, then is when the discharge has all the features of a non-thermal arc discharge. It follows from this that to implement effective pumping, it is necessary to heat the cathode to a temperature of $\sim T_k$ by placing it, for example, in the hot zone of the discharge channel of the GDT of a CVL, where the operating temperature is $\sim T_k$. It should be noted that similar designs of GDT were used in studies for example [19–21], and showed high efficiency, but the most widely used so far are GDT with electrodes located in the CBZ.

The location of the electrodes in the CBZ, where the gas temperature is ∼450° K–600° K, provides the possibility of rapid cooling of the cathode spot on the electrode (after the excitation pulse) in a time of ∼1 μs due to the high thermal conductivity of the cathode material. Consequently, it can be assumed that at the preparatory stage of pumping in such GDT structures, the process of heating the cathode spot on the electrode to a temperature of $\sim T_k$ is realized. A question arises—what is the mechanism of this process? The answer to this question is given by an analysis of the experimental results.

At the preparatory stage of pumping, C_0 is charged from the storage capacitor and energy ($E_{L_k} = L_k I_{max}^2/2$) is stored in the inductance of the discharge circuit when the charging current in the circuit rises. The release of stored energy in L_c should ensure the process of further charging C_0. However, a GDT which has a resistance (R_{GDT}) that cannot be infinitely large, is connected parallel to C_0. Since the release time of stored energy in L_c, $\tau \sim L_C/R_{GDT}$, this process must provide heating of the cathode spot. Actually, the beginning of current flowing through the GDT was recorded with a delay relative to the beginning of the voltage pulse (figures 2 and 7); when the voltage across the GDT was ∼0.3–1.5 kV, depending on the pumping conditions, but a noticeable increase in current was always observed from the moment the stored energy in L_c began to be dumped. The appearance of the current flowing through the GDT reflects the moment when the electric circuit is closed and the glow discharge is ignited. The GDT resistance at this moment should be $R_{GDT} \sim 0.5$–1 kΩ, while the resistance of the active medium is two times less. Therefore, the specified voltage ∼0.3–1.5 kV reflects the cathodic potential drop at which a glow discharge is ignited, and the current flowing through the GDT at this time is a phantom current [8, 11], which allows us to hypothesize a possible a breakdown mechanism. From the gas discharge physics point of view, this is the development of a discharge from an anomalous glow discharge to a non-thermal arc discharge during the heating of the cathode spot on the electrode to the temperature at which thermal emission of electrons from the cathode occurs and is characterized by a sharp change in the cathode potential drop. From the electrophysics point of view, this is a sharp change in the conductivity (by two orders of magnitude) of the GDT during the heating of the cathode spot, which determines the possibility of characterizing this process as a breakdown. The inductance of the discharge circuit under these conditions of discharge development is a factor that determines the efficiency of pumping the active medium since the release of the stored energy in the inductance at the preparatory stage provides heating of the cathode spot and determines the conditions for the occurrence of thermal emission of electrons from the GDT cathode. However, the determining factor is not the magnitude of the inductance in the laser discharge circuit, but the stored energy in the inductance. This leads to two possible pumping modes of the active medium of a CVL for realizing a high average output power, which can be conventionally called modes of reduced and increased energy input.

The mode of decreased energy input is realized under pumping conditions when the current flowing through the switch drops to zero after charging C_0 (figures 2 and 7(a), (b)). The optimal pumping conditions for this mode are determined by the choice of parameters: voltage across the storage capacitor, capacitance C_0, and inductance L_c. This pumping mode makes it possible to increase the average lasing power only by increasing the excitation PRR. As studies have shown, there is a potential possibility of increasing the excitation frequency by 10–15 times due to 'cutting off' the energy input from the storage capacitor after charging C_0 using a controlled switch [14]. The transition to the mode of increased energy input is carried out as a result of an increase in the voltage across the storage capacitor when the current flowing through the switch does not drop to zero after charging C_0. The energy characteristics of a CVL in this mode are determined by the sum of currents from two circuits formed by the storage and peaking capacitors, and the difinig role is played by the first of the circuits listed.

The conventional division of the above methods is determined by the fact that, with comparable pump parameters, the conditions of both the regime of decreased and increased energy input can be realized. Which of the modes is realized under specific pumping conditions can be determined only by controlling the current flowing through the switch. This can be illustrated by the following example. Replacing the TGI1-270/12 thyratron with the TGI1-1000/25 thyratron (with almost two times higher permissible current rise rate) in the pumping circuit (figure 1) makes it possible to halve the charging time of C_0 from the storage capacitor at the preparatory stage. In this case, the charging current C_0, according to (1), will be two times higher, and the stored energy in the inductance of the circuit is four times higher. This provides faster heating of the cathode spot and a transition from one pumping mode to another at comparable voltages across the GDT.

The research has shown that the limitation of the FEC of the CVL lasing is due to the high n_{e0}, regardless of the pumping mode of the laser active medium. This is because, for efficient pumping of the active medium, it is necessary to form an excitation pulse with a duration commensurate with the lifetime of the inversion [15]. These conditions can be realized only by reducing the capacity of the storage or peaking capacitors, depending on the pumping mode. A decrease in the capacitance of the capacitor leads to an increase in the quality factor of the pump circuit and the transition from the aperiodic process of the capacitor discharge to the oscillatory one, which was experimentally observed during the discharge C_0 (see figures 2 and 7). This causes a decrease in the energy input during the formation of the inversion and the efficiency of pumping the active medium. Consequently, for effective pumping of the active medium, it is necessary to form an excitation pulse with a duration commensurate with the lifetime of the inversion under the conditions of the aperiodic process of discharging the capacitor that forms the pumping pulse, then the condition $R_0 > 2\sqrt{L/C}$ must be satisfied, where R_0 is the prepulse resistance of the active medium.

5. Conclusion

(a) The pumping of the active medium in the GDT with electrodes located in the CBZ is carried out in two stages. At the preparatory stage, C_0 is charged from the storage capacitor, and the active medium is pumped during the discharge C_0. The transition from the preparatory stage to the pumping stage occurs as a result of a breakdown, which is formed during the charging of C_0.

(b) Breakdown is the development of a discharge from an anomalous glowing to a non-thermal arc discharge during the heating of the cathode spot on the electrode to the temperature at which thermionic emission of electrons from the cathode occurs and is characterized by a sharp change in the cathode potential drop. From the point of view of electrophysics, this is a sharp change in the conductivity (by two orders of magnitude) of the GDT during the heating of the cathode spot, which determines the possibility of characterizing this process as a breakdown.

(c) The inductance of the discharge circuit under these conditions of discharge development is a factor that determines the efficiency of pumping the active medium since the release of the energy stored in the inductance at the preparatory stage provides heating of the cathode spot and determines the conditions for the occurrence of thermionic emission of electrons from the GDT cathode. However, the determining factor is not the magnitude of the inductance in the laser discharge circuit, but the energy stored in the inductance. This leads to two possible pumping modes of the active medium of a CVL for realizing a high average output power, which can be conventionally referred to as modes of reduced and increased energy input.

(d) For efficient pumping of the active medium, it is necessary to form an excitation pulse with a duration commensurate with the lifetime of the inversion under the conditions of the aperiodic process of discharging the capacitor that forms the pump pulse.

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