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Energy characteristics of a copper vapor laser pumped by a Marx generator: gas discharge tube LT-10Cu

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The energy characteristics of a copper vapor laser pumped by a Marx generator have been studied. It has been shown that the Marx generator allows for a multiple increase in the upper limit of stable operation of thyratrons, proportional to the number of thyratrons used (for two thyratrons, up to a reverse voltage on the thyratron anodes of approximately $\sim 8-10$ kV). Consequently, it ensures pumping parameters for the active medium that cannot be achieved with a single thyratron.

Keywords: Copper vapor laser, Marx generator.

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A copper vapor laser (CVL) is a source of visible radiation with unique frequency-energy characteristics (FECs) that make it irreplaceable in various applications, despite the development of diode-pumped solid-state lasers in the visible range. (without using brackets). The active medium of a CVL is pumped by discharging a storage capacitor through a gas-discharge tube (GDT). Thyratrons are used as switches. One of the factors limiting the frequency-energy characteristics (FEC) of a CVL is the need to maintain the input power in the gas discharge tube (GDT) at a certain level when pump parameters change, so as not to disrupt the laser's thermal operating regime [1,2]. This necessitates a reduction in capacitance of the storage capacitor with an increase in voltage at the thyratron anode or the excitation pulse repetition rate (PRR, f). The Q factor of the laser discharge circuit increases with a reduction in capacitance of the storage capacitor, which leads to an increase in reverse voltage at the thyratron anode and is a significant factor limiting the CVL FECs, since thyratrons have a fairly narrow range of stable operation [3]. As the analysis has shown, a Marx generator can significantly expand the possibilities for optimizing the pump parameters of a CVL. Its operating principle is based on charging capacitors connected in parallel with an electric current, which then switch to a series connection after charging using various switching devices, such as thyratrons [4].

The aim of the study is to evaluate the efficiency of pumping the active medium of a CVL by a Marx generator. An LT-10Cu industrial gas discharge tube (NPP Istok, Fryazino) [5,6] was used in experiments.

Figure 1 shows the pumping circuit of a CVL, illustrating the operating principle of the Marx generator, which uses TGI2-500/20 thyratrons as switching elements.

Storage capacitors C_2 and C_3 are charged in parallel from high-voltage rectifier HV through the corresponding resonant diode charging circuits $L-D$ and shunt inductances L_1 and W_2. Source Tr is connected to thyratron K_2 via filter F, which ensures its decoupling from high-voltage pulses generated when the thyratrons are turned on. This enables the use of heater transformers TN-61 as source Tr for heating the cathode and the hydrogen generator of thyratrons K_1 and K_2. Filter F contains two counter-wound inductances W_1 and W_2 with ~ 20 turns on a ferrite ring ($100 \times 60 \times 15$ mm). W_2 acts as a shunt inductance in the

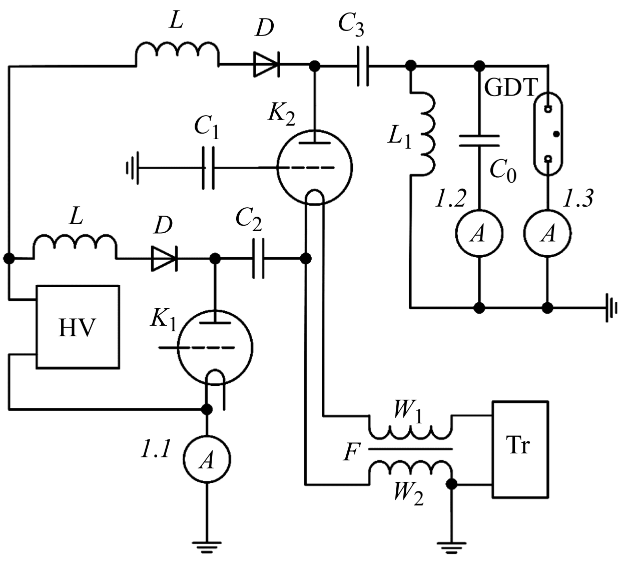

Figure 1. Schematic diagram of a Marx generator for pumping the CVL active medium. K_1 and K_2 — TGI2-500/20 thyratrons; C_1 — KVI-3 capacitor (100 pF); $C_2 = C_3$ — storage capacitors; C_0 — peaking capacitor; $L-D$ — circuit of resonant diode charging of capacitors C_2 and C_3; HV — high-voltage rectifier; L_1 — shunt inductance; GDT — LT-10Cu; F — filter; Tr — heating source for the cathode and the hydrogen generator of thyratron K_2; and *1.1–1.3* — current sensors.

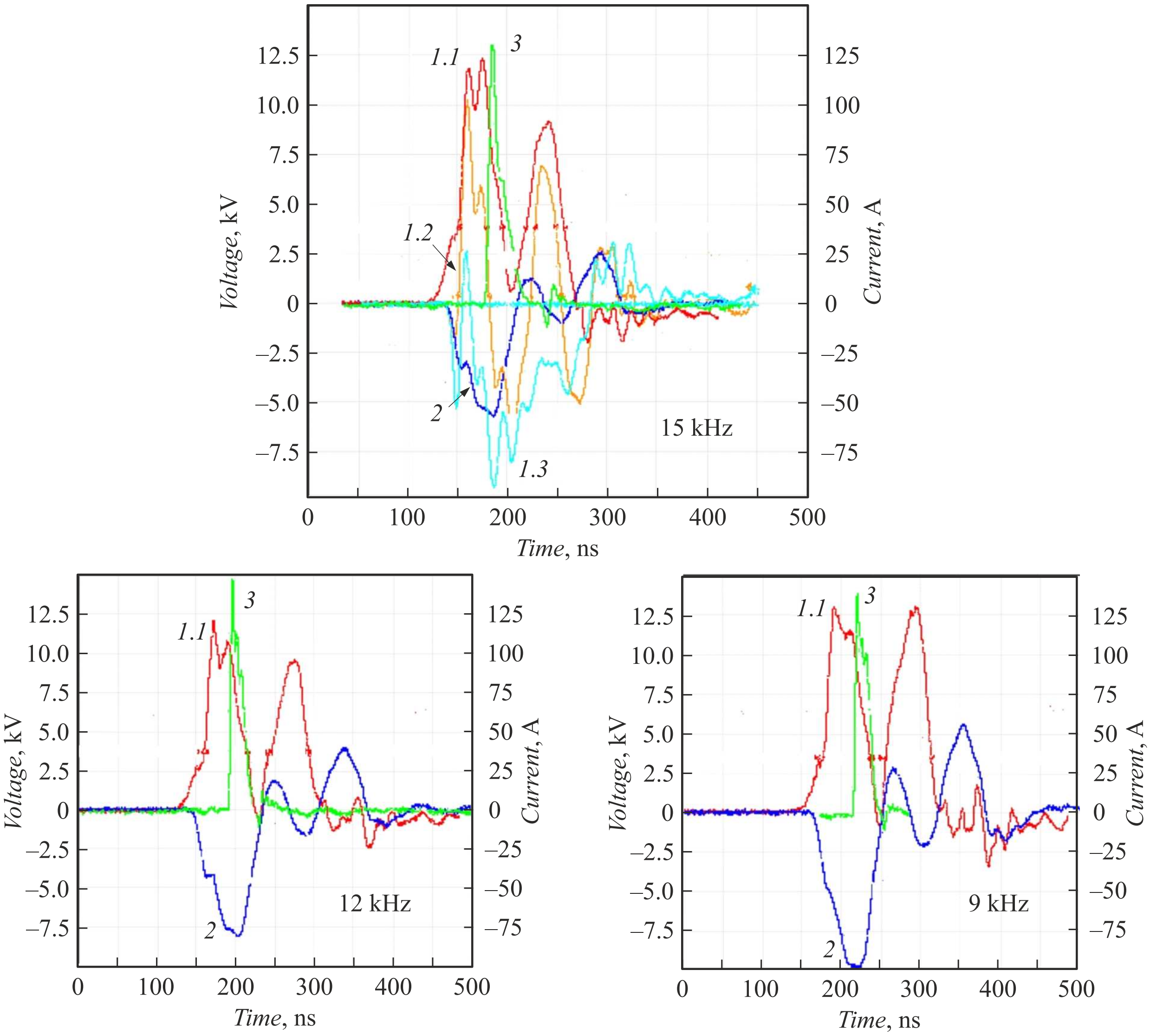

Figure 2. Oscilloscope records of current pulses through the thyratron (*1.1*), the peaking capacitor (*1.2*), and the gas-discharge tube (*1.3*); a GDT voltage pulse (*2*); and a generation pulse ($C_0 = 340$ pF) (*3*).

process of charging the C_2 storage capacitor. Following charging of the storage capacitors, a trigger pulse is sent to the grid of thyratron K_1. Thyratron K_1 is switched on, and storage capacitor C_2 starts to discharge along the $K_1-C_1-K_2$ thyratron grid circuit, charging capacitor C_1 to a voltage at which thyratron K_2 turns on.

Measurements of the energy and current–voltage characteristics of the laser were carried out with $C_2 = C_3 \sim 1.9$ nF (two series-connected capacitors KVI3-3.3 nF and KVI3-4.7 nF), $C_0 = 340$ pF, and a power input of ~ 1.5 kW from the high-voltage rectifier. Figure 2 shows the oscilloscope records of electrophysical parameters of the laser discharge circuit and the generation circuit, which illustrate the process of pumping of the active medium with a change in the excitation PRR. The complete set of obtained oscilloscope records is presented in Fig. 2 for $f = 15$ kHz; at $f = 12$ and 9 kHz, only the oscilloscope records of current pulses through the thyratron, the GDT voltage pulse, and the generation pulse are shown. Figure 3 shows the dependences of GDT voltage, specific energy in a generation pulse, and average generation power on the excitation PRR.

The obtained results revealed that the active medium of the laser is, just as in [7], pumped in two stages. At the preparatory stage, C_0 is charged from series-connected storage capacitors C_2–C_3, and the active medium is pumped when C_0 is discharged.

The transition from the preparatory stage to the pumping stage is initiated by a „breakdown“ in the process of C_0 charging (as in [7]). This indicates that this process of pumping the CVL active medium is typical for gas-discharge tubes with electrodes located in cold buffer zones. The

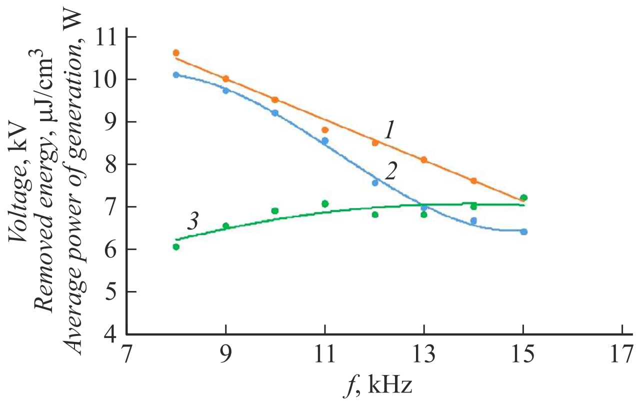

Figure 3. Dependence of the GDT voltage (*1*), the specific energy in a generation pulse (*2*), and the average generation power (*3*) on the excitation PRR ($C_0 = 340$ pF).

oscilloscope records presented in Fig. 2 provide a clear illustration of the above. Generation is achieved when the laser charging circuit current (flowing through the thyratron) decreases, and pumping of the active medium is governed by the energy input from the inductance of the discharge circuit and C_0. Since the two-stage pumping mechanism was discussed in [7], the specifics of pumping by a Marx generator should be examined in more detail. The distinguishing feature of CVL pumping in the self-heating mode is a significant change in reverse voltage at the thyratron anode [3] in the process of GDT heating to the operating temperature, which imposes a certain limit on the storage capacitor capacitance at which the reverse voltage at the thyratron anode remains within the region of stable thyratron operation. The minimum capacitance of the storage capacitors ensuring stable operation of the Marx generator was C_2–$C_3 \sim 1.9$ nF (the capacitance in the active medium pumping circuit was ~ 0.95 nF). Naturally, under these pumping conditions, one needs to adjust the voltage to the changing excitation PRR in order to maintain the self-heating mode of CVL operation. The presented dependences of energy characteristics (Fig. 3) on the excitation PRR demonstrate clearly that the generation pulse energy increases linearly with an increase in GDT voltage. The total voltage with a series connection of storage capacitors after triggering the thyratrons was ~ 17–18 kV at an excitation PRR of ~ 15 kHz and ~ 22–25 kV at a PRR of ~ 8 kHz. Such levels cannot be achieved in a traditional pumping circuit with a single thyratron. The key advantage of the Marx generator is that it allows raising the upper limit of stable operation of two thyratrons to a (total) reverse voltage of ~ 8–10 kV. With an increase in the excitation PRR (Fig. 3), the generation pulse energy decreases, but the average generation power increases. This pattern of variation of energy characteristics is attributable the fact that generation pulse energy $E_{gen} \sim U$, where U is voltage, and the energy stored in the storage capacitors is $E_C = CU^2/2 \sim U^2$. Two options for solving the problem of enhancing the CVL energy characteristics thus become apparent. The first one is related directly to the fact that the Marx generator expands the region of stable operation of thyratrons and allows one to establish self-heating laser operation at a higher power consumption by reducing the thickness of the GDT heat insulator. The second option is enabled by the fact that the active medium is pumped in the process of C_0 discharging. At the preparatory stage of pumping, C_0 is charged. According to [7], it is always possible to choose such capacitance C_0 at which the current through the switch drops to zero after charging C_0, which allows one to „cut off" further energy input into the GDT from the storage capacitor with a controlled switch (e.g., a tacitron). The obtained results revealed (Fig. 2) that this pumping mode is established when the Marx generator is used: the current through the switch drops to zero after charging C_0 (Fig. 2) within the entire range of variation of the excitation PRR and the GDT voltage. The „cutoff" of energy input to the GDT potentially allows one to raise the excitation PRR by an order of magnitude, and the factors limiting the energy characteristics of the laser under these conditions are pre-pulse electron concentration n_{e0} [8] and pre-pulse concentration of copper atoms in the metastable state N_{m0} [9]. Metastable states in the interpulse period relax within ~ 15–$20\,\mu$s in the matched load mode [10], which is also established with a „cutoff" of energy input after the generation pulse. Therefore, N_{m0} should not affect the CVL energy characteristics at an excitation PRR < 50–75 kHz. If we take into account that the main contribution to ionization in the excitation pulse is produced by step processes [11,12] and, according to [7,13], the process of ionization of copper atoms is not observed at the preparatory pumping stage, the „cutoff" of energy input after the generation pulse provides an opportunity to eliminate the main ionization channel in the active medium. This establishes the conditions for increasing the optimum excitation PRR to the specified values of ~ 50–75 kHz in the „cutoff" mode. The above estimates for the „cutoff" mode are only an illustration of the potential to enhance the CVL energy characteristics. The Marx generator has the following advantage over the traditional CVL pumping arrangement with a single thyratron. An increase in voltage at the thyratron anode causes a corresponding increase in average generation power, but the reverse voltage at the thyratron anode also rises in this case. The maximum possible average generation power is achieved at reverse voltages of ~ 5–6 kV at the thyratron anode (the upper limit of stable thyratron operation). However, the service life of the thyratron is ~ 50 h under these pumping conditions, but corresponds to the rated value of ~ 1000 h at a reverse voltage of ~ 3 kV [14]. The level of average generation power corresponding to the maximum value indicated above should be achieved with a total reverse voltage at the anodes of thyratrons in the Marx generator also being around ~ 6 kV. The reverse voltage at the anode of each thyratron will then be ~ 3 kV, and, accordingly, the service life of thyratrons will be $\sim 1000\,\mathrm{h}$, which, considering the cost of thyratrons, is economically advantageous.

The Marx generator expands the region of stable operation of thyratrons, raising the upper limit to $\sim 8-10\,\mathrm{kV}$ (the total reverse voltage at the anode of two thyratrons). This provides an opportunity to pump the active medium at a higher voltage at the gas-discharge tube, and higher values of the generation pulse energy are thus achieved. The results of our experiments and their analysis demonstrated the potential of using Marx generators for pumping the CVL active medium, suggesting the need for further research.

Conflict of interest

The authors declare that they have no conflict of interest.

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