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CuBr laser with a reduced energy input into a discharge

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Abstract. The operation of a CuBr laser with a small volume of the active medium for a reduced energy input into a discharge was studied. It was shown that switching the commutator to a smaller operating capacitor for a short time permits a 2.3-fold reduction (relative to the typical operating mode) of the power supplied to the discharge without sacrificing any output laser power. By the application of an additional 'dissociating' pulse, a stationary mode of laser operation was realised, whereby the pump pulse energy was lowered by a factor of 10 without loss in the output power.

1. Introduction

A typical operating mode of present-day repetitively pulsed metal vapour lasers (MVLs) is self-heating involving the heating of the working volume (and the metal) produced by the same pump pulses. In metal halide lasers for a pulse repetition rate from several to several tens of kilohertz, each pulse performs three functions: dissociates molecules (in particular, of copper bromide), heats the working volume, and accomplishes excitation.

These lasers are hard to optimise in several parameters simultaneously. At the same time, it is obvious that their efficiency can be improved by either augmenting the output power or reducing the input power (the latter way is best suited for designing compact efficient MVLs). In particular, in the case of a copper vapour laser, Soldatov et al. [1] showed that rapidly limiting the discharge current at the stage of its build-up permits the power introduced into the discharge to be substantially lowered without a reduction in the output laser power. In this case, the physical laser efficiency (relative to the pump) may be as high as 9%. True, this mode is not stationary, since the power inputted into the discharge proves to be insufficient to ensure the required density of copper vapour.

The passage to high pump pulse repetition rates in MVLs also implies a reduction of the energy deposition in each individual pulse to maintain the average power introduced into the discharge at the same level as at low repetition rates. At the same time, a consideration of our and data from the literature on the lasing characteristics of pure-metal vapour lasers operating at high repetition rates (around 100 kHz) suggests that the HF mode is realised in the active elements with small diameters (below 1 cm) and volumes (below 10 cm^3); in this case, the specific (per unit volume) power inputted into the discharge $W_{\text{sp}} = 50 - 100$ W cm^{-3} and the efficiency does not exceed tenths of one percent [2 – 4]. At the same time, in tubes of medium or large diameter (over 2 cm) for pump pulse repetition rates of 5 – 15 kHz, the efficiency of lasers using vapour of metals and their compounds attains 1 – 3%; in this case, $W_{\text{sp}} = 3 - 10$ W cm^{-3} [5 – 8].

Metal halide lasers require lower operating temperatures than pure vapour lasers. This allows one to reduce the power introduced into the discharge, provided it is sufficient for efficient dissociation of the molecules and the pumping of the working levels. Taking advantage of this fact, we were able to realise stable lasing in a CuBr laser at high pulse repetition rates (up to 300 kHz) for $W_{\text{sp}} = 10$ W cm^{-3}. The maximum output pulse repetition rate was obtained in a gas-discharge tube (GDT) 1.4 cm in diameter. The maximum repetition rate and the laser efficiency lowered as the diameter of the discharge channel was reduced. We attribute this to a sharp increase in the energy deposition to the discharge in narrow tubes, with the effect that the discharge conditions may recede from those optimal for lasing. In particular, this may lead to excessive ionisation of the working copper atoms [9].

It would appear natural that a further increase in the output-pulse repetition rate and the efficiency of small-volume MVLs would be associated with lowering W_{sp}. That is why the objective of this work is to investigate the feasibility of operation of a CuBr laser with a discharge channel less than 1 cm in diameter for a reduced energy input into the discharge.

By a reduced energy input, we mean one for which the adverse effects of energy input into the discharge (overheating, excessive ionisation) are minimised, while the efficiency of excitation of the upper working levels is not lowered. The notion 'reduced energy input' is meaningful when we are considering a short-pulse periodic pumping of small-volume active elements. In large-diameter tubes, a low-energy deposition (per unit volume of the active medium) does occur, as noted above.

2. Experimental results and discussion

We performed experiments on a CuBr laser mainly with two GDTs: No. 1 (6 mm in diameter, 20-cm-long active region) and No. 2 (8 mm and 20 cm). The GDTs were made of silica;

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they differ in design from the tubes described in Ref. [9] in that they are supplimented with additional thermal insulators to investigate the operation at a reduced energy input. An external thermal insulator was used in tube No. 1 and an internal thermal insulator, in tube No. 2.

The results were analysed using the data previously obtained for a small-volume Cu laser [1]. The buffer gas was spectrally pure neon at a pressure $p_{\mathrm{Ne}} = 30 - 100$ Torr. Prior to charging a GDT with copper bromide, the GDT was outgassed in the atmosphere of argon and then, neon. After charging with CuBr, the tube was 'trained' to yield a stable output laser power. Note that the average output power increased in the course of 'training', attained a maximum, and then fell off somewhat to assume the stationary value. We attribute this behaviour to the evacuation of the greater part of hydrogen, which is always present as a small uncontrollable impurity.

The discharge was excited using the circuits shown in Fig. 1. Fig. 1a shows a typical circuit for the direct capacitor discharge through a GDT and a switch (a thyratron at frequencies below 20 kHz and a tasitron at higher frequencies, up to 100 kHz in this work); switch K_3 is closed in the normal state. A VV-20 high-voltage vacuum relay was used as the K_3 switch. Opening the K_3 switch permits the discharge to be promptly switched to a smaller working capacitor and ensures operation in the mode of reduced energy input.

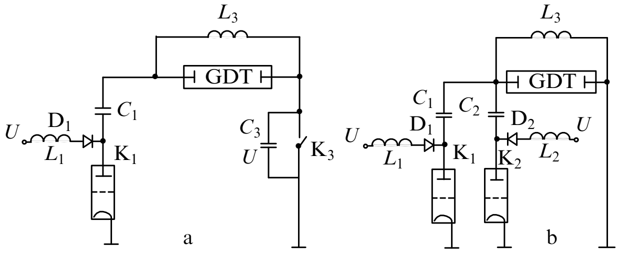

Figure 1. Circuits of the experimental facility in the usual mode (switch K_3 is closed) and with a reduced energy input (switch K_3 is open) (a) and with a double-pulse pumping (b): L_1, D_1, L_2, and D_2 are the charging inductors and diodes; L_3 is the inductive shunt; C_1 and C_2 are the working capacitors; C_3 is the additional capacitor; K_1 and K_2 are the commutators; and K_3 is the switch.

The circuit shown in Fig. 1b is intended to produce, along with the excitation (and partly dissociating) pulse, an additional higher-power pulse, which ensures primarily the dissociation of the molecules of copper bromide and heating of the working volume of the GDT. The circuit shown in Fig. 1b also enables a realisation of a conventional alternate initiation of the thyratron switches to increase the operating pump-pulse repetition rate up to 50 kHz without the use of a tasitron generator.

Fig. 2 shows current, voltage, and output pulses of a CuBr laser in the conventional operating mode and in the mode of reduced energy input for a pump-pulse repetition rate of 50 kHz employing a GDT with an internal thermal insulator (GDT No. 2). The mode of reduced energy input is not stationary: In this case, the GDT cools down slowly and the output power falls off. However, more important is that at the instants of time immediately following the change-over to a smaller working capacitor, the output laser power does not change when the energy input was reduced by more than a factor of two. A further reduction in the energy input into the discharge causes the oscillation to cease. We attribute it to an inadequate degree of dissociation of copper bromide molecules and, hence, a low density of the working atoms prior to the next pump pulse.

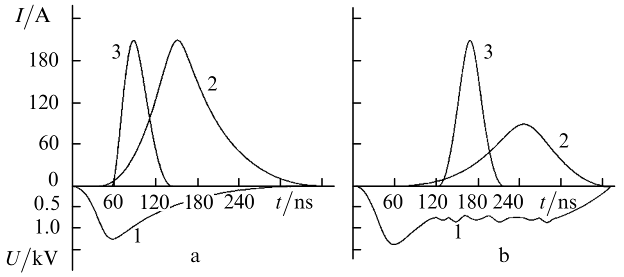

Figure 2. Voltage (1), current (2), and output (3) pulses in the usual mode of pumping a CuBr laser (a) and in the mode of reduced energy input (b) for a GDT No. 2 ($f = 50$ kHz, $C_1 = 3.0$ nF, $C_3 = 0.47$ nF, $p_{\mathrm{Ne}} =$ 30 Torr) and a power inputted into the GDT of 252 (a) and 112 W (b)

Fig. 3 is a schematic representation of the energy input into the discharges realised in copper and copper bromide vapour lasers of the same volume. The mode of reduced energy input (an order of magnitude lower than the typical one) was described in Ref. [1]. A similar situation occurs for a bromide laser, with the only difference being that the required density of copper bromide is determined by the external heating of containers with copper halide. After a significant reduction of the energy input in a Cu laser [Fig. 3a (2)], the density of copper atoms required for efficient lasing, which is determined by the temperature on the inside of the GDT wall, will be provided (for a short period of time) by the preceding self-heating. The remaining specific power (several Watts per cubic centimetre) inputted into the discharge proves to be sufficient for pumping the working states [1].

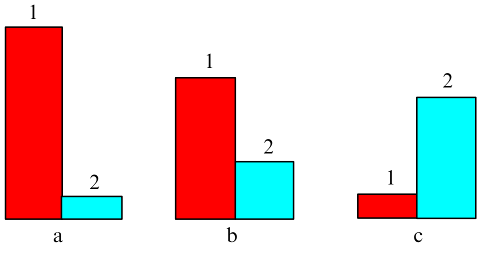

Figure 3. Schematic representation of the energy input into the discharge for a Cu (a) and a CuBr laser (b) in the conventional mode (self-heating for a Cu laser) (1) and in the mode of reduced energy input (2), as well as in the mode of CuBr laser pumping by doubled pulses (1 is the energy input of the exciting pulse, and 2 is the energy input of the dissociating pulse).

A somewhat different situation takes place for a CuBr laser. Fig. 3b (2) schematically shows the minimum energy input to ensure the density of copper atoms required for lasing by dissociating the molecules of copper bromide (for a lower energy input, no lasing occurs).

Let us estimate the energy (and the power) required for the dissociation of 10^{15} cm^{-3} copper bromide molecules per cubic centimetre (we assume that $N_{0\mathrm{Cu}} = 10^{15}$ cm^{-3} is the number density of copper atoms in the ground state typical for lasing). The specific dissociation energy is $D_{0\mathrm{CuBr}} =$ 78 kcal mol^{-1} [10], the energy needed for the dissociation of a single molecule is $D_{01} = 5 \times 10^{-19}$ J = 3.2 eV, and the energy necessary for the dissociation of 10^{15} cm^{-3} molecules is D ($N_{\text{CuBr}} = 10^{15}$ cm^{-3}) $= 5 \times 10^{-4}$ J cm^{-3}. If it is assumed that the Cu_3Br_3 molecules make up a greater part of the molecules [11], the energy required to produce 10^{15} copper atoms in a unit volume is 8×10^{-4} J cm^{-3}. From the above estimates, it follows that the energy input into the discharge should exceed some threshold energy input $(5 - 8) \times 10^{-4}$ J cm^{-3} if the pulse-to-pulse accumulation of copper atoms is disregarded.

Having analysed the data obtained, we made an attempt to provide the required degree of dissociation of CuBr molecules by using an additional 'dissociating' pulse (Fig. 4b). We managed to accomplish this by discharging two working capacitors alternately into the discharge gap by means of two parallel thyratron switches initiated with some time delay (see Fig. 1b). The first pulse in Fig. 4b is the 'pump pulse' (and, naturally, a partially dissociating one), and the second is the 'dissociating' pulse, which mostly provides the required dissociation. For tube No. 2, the power introduced during the first pulse is $W_1 = 36$ W ($W_{1\text{sp}} = 3.6$ W cm^{-3}). Accordingly, the energy input provided by the excitation pulse is 3.6×10^{-4} J cm^{-3}.

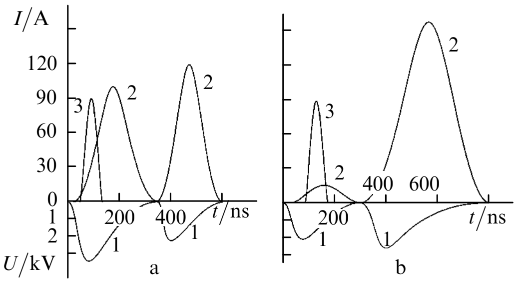

Figure 4. Voltage (1), current (2), and output (3) pulses for a CuBr laser (GDT No. 2) pumped by double pulses ($p_{\text{Ne}} = 30$ Torr) in the mode similar to the self-heating mode for $C_1 = C_2 = 1.5$ nF, $W = 300$ W (a) and in the mode of reduced energy input (relative to the excitation pulse) for $W = 300$ W, $W_1 = 36$ W, $C_1 = 0.22$ nF, and $C_2 = 3.0$ nF (b).

The low repetition rate (10 kHz) in this experiment was adopted purposefully for the following reasons. To ensure that there occurs no accumulation of Cu atoms from one dissociating pulse to another, the relaxation time τ_r for the density of copper atoms should be shorter than the interpulse period, i.e., less than 10^{-4} s. According to the estimates given in Ref. [11], this time τ_r caused by recombination and diffusion to the wall is, for gas-discharge tubes less than 1 cm in diameter, pressures of the neon buffer gas of tens of Torr, and optimal temperatures of bromide copper containers, shorter than 10^{-4} s. The τ_r value measured [12] under experimental conditions close to ours was 5×10^{-5} s, assuming that the discharge plasma loses copper atoms during the interpulse period owing to recombination by the scheme

$$Cu + Br_2 \rightarrow CuBr + Br\ . \qquad (1)$$

In this case, the energy input into the discharge associated with the dissociating pulse is, for the data shown in Fig. 4, 2.6×10^{-3} J cm^{-3}, which safely exceeds the threshold energy input estimated above. This scheme permits the energy input during the first (pumping) pulse to be reduced tenfold without loss in the output laser power, which means an increase in the physical efficiency (efficiency relative to the pump). For GDT No. 2, the total power introduced into the discharge in this double-pulse scheme amounts to 300 W, which affords a steady (in time) repetitively pulsed lasing. A model representation of this mode is given in Fig. 3c.

Note that our reasoning is valid for the lifetimes of copper atoms in the working volume (due to recombination and diffusion to the wall) $\tau_r \leqslant 10^{-4}$ s, i.e., in small-diameter GDTs (below 1 cm). In tubes of a larger diameter, these times may be substantially longer, with the effect that the required densities of copper atoms in the ground state may be attained (due to accumulation) at pump-pulse repetition rates of over 10 kHz and an energy input of less than 10^{-4} J cm^{-3} per pulse.

3. Conclusions

Therefore, it is possible to realise the mode of reduced energy input for a small-volume CuBr laser. When an additional ('dissociating') pulse is provided, a steady repetitively pulsed lasing is realised with a high pumping efficiency.

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