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Peculiarities of pumping of copper vapour and copper bromide vapour lasers

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***Abstract*. Lasing and peculiarities of pumping of a copper vapour laser with a commercially produced 'Crystal' LT-40Cu active element and of a CuBr laser with a large-volume experimental active element are studied experimentally. It is shown that the efficiency of lasers with an average radiation power up to 50 W relative to the energy supplied to the active medium during useful pumping achieves 4 %. It is found that the stage of useful pumping of the central part of the laser tube is preceded by a partial breakdown of the discharge gap and the charging of parasitic capacitances. A distinguishing feature of the pumping of a CuBr laser as compared to the Cu laser is that the inductance of the leads from the pump oscillator to the active element and the inductance of the pump oscillator can be increased, while the average radiation power remains unchanged.**

Keywords: *copper and copper bromide vapour lasers, pumping, lasing.*

1. Introduction

Self-terminating metal vapour lasers have gone through a long path of evolution since their fabrication in the 1960s. Their practical application in the devices for remote sensing of the atmosphere, in laser navigation systems, bathymetry, precision processing of metals, image intensifiers, etc. [1 – 4] is determined to a considerable extent by the realisation of the self-heating mode of operation [5]. In this class of lasers, the copper vapour laser (CVL), which provides high-power output with the efficiency above 1 % in the green (510.6 nm) and yellow (578 nm) spectral regions, is the most efficient. Several companies in UK, France, USA, and Russia manufacture commercial sealed active elements for copper vapour lasers operating in the self-heating mode. In particular, the State Research and Production Enterprise 'Istok' (Fryazino, Moscow oblast) produces high-power active elements for CVL of 'Kristall' series with an average radiation power (for both lines) from 20 to 50 W and a service life up to 1000 h and longer [6, 7].

Apart from the study and developments of CVLs (providing the required vapour pressure in them by self-heating), new methods for introducing the working substance into the active zone were always sought. The most important of these methods at the present stage is the one based on the dissociation of chemical compounds of metals in a pulse-periodic discharge. Copper halogenide vapour lasers (CHVLs) have a number of advantages over CVLs. In contrast to the CVL temperature (1600 °C), their working temperate is 400 – 600 °C, which makes it possible to considerably simplify the construction of the laser tube and to reduce their cost as well as the time required for the development of lasing.

A detailed comparison of the parameters of copper bromide and chloride vapour (CuBr and CuCl lasers) with the parameters of CVLs having discharge tubes of the same size [8] showed that CuBr and CuCl lasers are not inferior to a copper vapour laser in the efficiency and the radiation power. This fact determined the subsequent investigations aimed at creating powerful CHVLs along with CVLs. The fabrication of a CuBr laser producing over 100 W of power was reported for the first time in Ref. [9]. The highest output power obtained at the present time in a CuBr laser was 120 W for an efficiency of 2.5 % when a small amount of hydrogen was added to the basic buffer gas (neon) [10].

It should be noted that admixtures of hydrogen produce a positive effect not only on the output power and efficiency, but also on the quality of the output beam [11]. Sealed-off versions of a CuBr laser, including those with a large active volume, which have a service life up to 1000 h, have already been built [12, 13]. Thus, CHVLs may seriously compete with CVLs in the nearest future after solving some technical problems, in particular, as applied to the isotope separation problems [14].

In this work, we study experimentally the peculiarities of pumping of a high power CVL with a standard 'Kristall' LT-40Cu active element and of a CuBr laser with a large-volume experimental active element, which can operate in the sealed-off regime. The working pump pulse repetition rate (10 kHz) was determined by the technical conditions of application of the lasers in a specific laser system [15]. We investigated the possibility of improving the efficiency of the CVL operation, the peculiarities of pumping of Cu and CuBr lasers, and the possibility of using CuBr lasers along with Cu lasers for isotope separation.

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2. Experimental setup and methods of current and voltage measurements

The experimental setup is shown schematically in Fig. 1. The pump oscillator circuit is similar to that used by the designers of sealed-off 'Kristall' LT-40Cu commercial tubes. A detailed description of these active elements and the pumping scheme is given in Refs [6, 7]. The active length of the 'Kristall' LT-40Cu discharge tube was $l = 120$ cm and its diameter was $d = 2$ cm. The discharge tube of the CuBr laser has the active length 150 cm and diameter 5.8 cm. A detailed description of the self-heated active element of the CuBr laser is given in Ref. [12]. The experiments for both active elements were made with a 3 – 5.5 kW electric power supply from the mains and for a pulse repetition rate of 10 kHz.

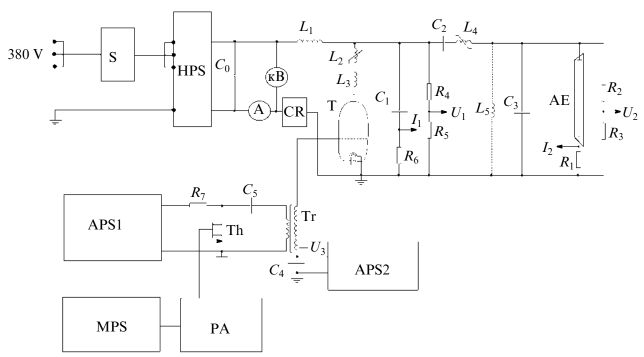

Figure 1. Scheme of a pump oscillator for a copper vapour laser: (S) Starter; (HPS) High-voltage power supply; (CR) Current relay; (T) Thyratron; (AE) Active element; (APS1, APS2) Auxiliary power supplies; (MPS) Master pulse oscillator; (PA) Pulse amplifier; (Tr) Transformer; (Th) Thyristor; (U_1) Voltage across C_1; (U_2) Voltage across the AE; (I_1) Current through C_1; (I_2) Current through the AE; (U_3) Bias voltage at the thyratron grid.

It should be noted that a pulse repetition rate of 10 kHz is optimal for the Cu laser because the maximum output radiation power is achieved at this repetition rate. As for the CuBr laser, it follows from the results obtained by other authors [13] and our preliminary experiments on the pumping of the CuBr laser by an electron-tube oscillator that the average radiation power increases almost linearly with the pulse repetition rate in the range from 10 to 20 kHz. Accordingly, the output powers given below are close to the maximum values for the Cu laser with such a geometry and half as large as the maximum output power for the CuBr laser.

We can briefly describe the operation of the pump oscillator as follows. The capacitor C_0 is charged from the mains to a voltage of 3 – 10 kV through a rectifier which charges capacitors C_1 and C_2 through the inductance L_1. The maximum charging voltage for capacitors C_1 and C_2 reaches a value twice as large as the charging voltage for an appropriate choice of the inductance of the choke, capacitances C_1 and C_2, and for low ohmic losses (for a given pulse repetition rate). After the actuation of the thyratron T, the capacitor C_1 starts recharging through inductances L_2 and L_3, and the thyratron T. An increase in the voltage across the choke L_4 leads to its saturation and to the charging of C_3 from C_1 and C_2. This is followed by a breakdown of the laser chamber.

In some experiments, the additional choke L_5 assembled from 22 ferrite rings of mark M2000HM1 having a size 28/16/9 mm was placed between the capacitor C_3 and the laser chamber. The charging voltage for C_1 and C_2 is determined by an ohmic divider $R_4 - R_5$ or by a capacitive divider. The shunt R_6 or a Rogowki loop were used for detecting current in the circuit of the capacitor C_1, while the current in the laser tube circuit was detected using the shunt R_1 or a Rogowski loop. Note that the current in the circuit of the capacitor C_1 prior to saturation of the choke L_4 coincides with the current in the thyratron circuit. The signals from the shunts and dividers were fed to a Tectronix TDS220 oscilloscope. The average radiation power was measured at the green and yellow lines simultaneously with an IMO-2 calorimeter with an attenuator put in front of it. The shape of the radiation pulse was determined with a FEK-22 vacuum photodiode.

3. Experimental results and discussion

In the course of the experiments, we optimised the capacitances of the storage and peaking capacitors, inductances and materials of the chokes, as well as the layout of the laser tube, thyratorn, chokes and capacitors. The optimisation of the pump oscillator is a multifaceted problem and requires the attainment of simultaneous optimal operation of all the elements. Note that an improvement of the parameters of one of the elements may decrease the average radiation power due to misalignment of the entire system.

3.1 Cu laser

The best results were obtained for the following parameters of the pump oscillator (see Fig. 1).

1. The single-turn water-cooled choke L_4 was composed of 51 ferrite rings of mark M2000HM1 and size 28/16/9 mm, while the three-turn choke L_2 was air-cooled and consisted of six ferrite rings of size 32/20/6 mm separated by 2-mm air gaps. The inductance and capacitances were $L_5 = 380$ μH, $C_1 = 1000$ pF, $C_2 = 1940$ pF, and $C_3 = 300$ pF. The output power obtained for these parameters was 37 W in both lines for 3.9 kW power extracted from the rectifier and a pulse repetition rate of 10 kHz. The voltage across the discharge tube was 27.6 kV and the maximum current passing through the tube was 470 A. The replacement of the magnetic choke L_2 with the above-mentioned parameters by a water-cooled single-turn magnetic choke consisting of 22 ferrite rings of mark M2000HM1 (size 28/16/9 mm) and the inclusion of a thyratron with the inductance $L_3 = 0.85$ μH increased the average output power to 40 W for a 3.6 kW rectifier power. The maximum voltage across the discharge tube was 27.6 kV again, and the maximum current passing through the tube was 460 A. An increase or a decrease in the capacitance of the peaking capacitor C_3 led to a decrease in the output power in this regime.

2. The single-turn water-cooled choke L_4 was composed of 150 ferrite rings of mark M1000HM3 and size 20/10/5 mm, while the choke L_2 consisted of 25 ferrite rings of the same kind. The inductance and capacitances were $L_3 = 1.7$ μH, $C_1 = C_2 = 1000$ pF, and $C_3 = 200$ pF. The maximum output power was 37.9 W for 4.8 kW power extracted from the rectifier and a pulse repetition rate of 10 kHz. The introduction of the additional choke L_5 increased the average output power to 39.6 W for a 5.2 kW power extracted from the rectifier.

The obtained parameters correspond to the best output radiation parameters achieved in commercial tubes of this type by the designers using such schemes [6, 7]. For example, the average output power attained by the manufacturer for a given tube (according to the technical specifications) is 39 W.

In our opinion, the most important result of our work is the peculiarities of a Cu vapour laser discovered by us, in particular upon the introduction of the additional choke L_5. Fig. 2 shows the oscillograms of the voltage across the laser tube, the current passing through the tube, and the radiation pulse. The current and voltage pulses were changed by varying the parameters of the electric circuit of the pump oscillator. An analysis of the oscillograms of the discharge current through the tube shows a decrease in the current in all oscillograms after 20 – 50 ns, followed by its repeated increase (at approximately maximum voltage). Lasing occurs only at the trailing edge of the voltage pulse during a repeated increase in the discharge current, even if the first peak of the current pulse is approximately identical to the second current peak upon the lasing onset (Fig. 2b). As the duration of the leading edge of the voltage pulse decreased, the dip in the current pulse became not so pronounced but lasing still began at the trailing edge of the voltage pulse (Fig. 2c).

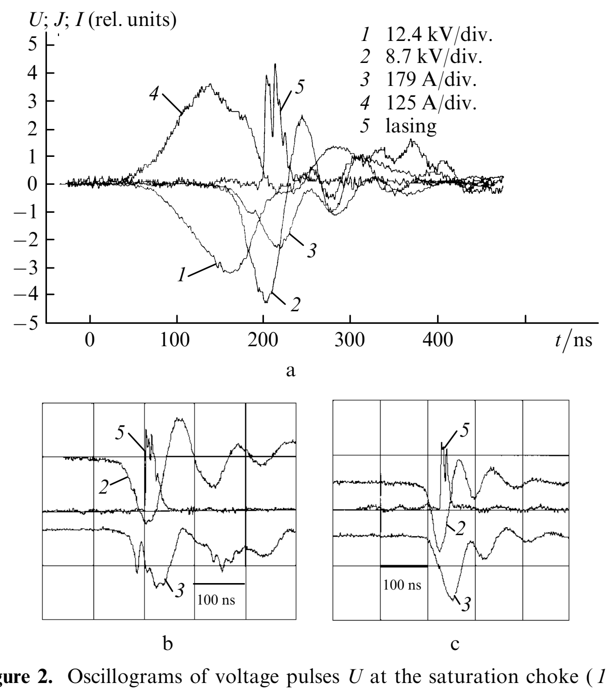

Figure 2. Oscillograms of voltage pulses U at the saturation choke (*1*) and at the laser tube (*2*), of current I through the laser tube (*3*) and through the thyratron (*4*), as well of emission intensity I (*5*) in the green and yellow lines (simultaneously) of the Cu laser for $C_1 = 1000$ pF (a – c), $C_2 = 1000$ (a), 1940 (b) and 1000 pF (c), $C_3 = 200$ (a, c) and 400 pF (b); the power extracted from the rectifier is 4.4 (b) and 5.2 kW (c); the output power is 28 (a) and 38 W (b).

The following dynamics of gas breakdown in the tube was observed upon variation of the voltage across the tube. For low voltages, a partial breakdown is observed in the laser tube, and upon an increase in the voltage supplied to the tube, the gas-discharge plasma propagates from the potential electrode (in the case under study, from the cathode) to the anode. The main discharge glow is concentrated at the inner wall of the laser tube. We believe that the first peak of the current through the tube is due to the partial breakdown and is associated with the charging of a parasitic capacitor. One plate of this capacitor is formed by the plasma at the surface of the central ceramic tube, and partially at output quartz branch pipes from the 'Kristall' L-40Cu tube, as well as at the inner surface of the outer ceramic cladding. The second plate of the parasitic capacitor is formed by the outer cylindrical metal screen covering the laser tube and serving as the reverse current lead.

After charging of this capacitor, the current passing through the tube decreases and its subsequent increase occurs after the breakdown in the central part of the laser tube. This results in a decrease in the voltage across the tube, an increase in the energy contribution to the active medium, and the onset of lasing. Obviously, the useful pumping begins only upon a repeated increase in the current through the tube and ends with termination of the lasing pulse. Accordingly, the lasing efficiency, calculated relative to the energy pumped into the plasma during this period, is much higher. Apparently, the partial breakdown in the tube during charging of the parasitic capacitor also plays a positive role, providing the formation of a volume discharge in the central part of the tube due to illumination.

A comparison of the average radiation power obtained for various pumping regimes shows that the radiation power is maximal upon shortening the voltage pulse front at the laser tube (Fig. 2c). The minimum duration of the voltage pulse front in our experiments was about 30 ns, the average output radiation power being 40 W in this case. However, upon shortening the voltage pulse front, the rectifier voltage should be increased to provide a stable operation of the laser, which usually leads to an increase in power extracted from the rectifier and to an increase in the losses in the pump oscillator elements (chokes, thyratron).

It is quite important to analyse the limiting lasing efficiency of a copper vapour laser. The 9 % physical efficiency obtained in a small-size tube (diameter 6 mm, length 170 mm) pumped with a break in the energy contribution upon the termination of the lasing pulse was reported in Ref. [16]. However, an additional heating of the laser tube is required in this case. The results of our investigations show that the lasing efficiency calculated from the oscillograms of voltage across the discharge plasma and of current during the lasing pulse is rather high ($\sim$ 4 %) even for tubes of a medium size (diameter 20 mm, length 1200 mm). Considerably lower lasing efficiencies relative to the power extracted from the rectifier are due to losses in the pump oscillator, the need to ensure a heating of the laser tube to the working temperature, and losses occurring during the formation of a homogeneous discharge in the central part of the tube.

3.2 CuBr laser

Testing of a CuBr laser was performed under a 25 Torr pressure of the buffer gas (neon), including neon with small admixtures of hydrogen (from 0.05 to 0.3 Torr). In the absence of hydrogen, the output power was 22 W (pulse repetition rate 10 kHz) for $C_1 = 22$ pF, $C_2 = 1170$ pF ($C_3 = 0$) and the power supply voltage of 8.8 kV. Upon addition of hydrogen (0.2 Torr), the output power increased to 48 W for $C_1 = 700$ pF, $C_2 = 1170$ pF, and the power supply voltage of 10 kV. The output power reduced to 35 W upon a variation of the pump parameters ($C_1 =$

1000 pF, $C_2 = 1940$ pF, $C_3 = 300$ pF, 8.4 kV from the power supply), mainly due to a decrease in the power supply voltage. A further increase in the partial content of hydrogen leads to a decrease in the output power. It was found that the addition of hydrogen increases the delay of the current pulse relative to the applied voltage pulse.

Thus, small admixtures of hydrogen cause the lasing to begin at lower currents and higher voltages. Apparently, hydrogen (most likely, its compounds formed in the discharge) considerably improves the situation. This is possible due to a more rapid relaxation of the active medium of the CuBr laser in the period between the pulses [17, 18], as well as to the positive action of the electronegative molecules (of the type HBr) during the excitation pulse [18]. A similar effect was observed earlier for the nitrogen laser. For example, it was shown in Ref. [19] that additions of electronegative gases increase the time for which a high voltage can be sustained in the discharge gap (slow down the voltage drop), which increases the duration of useful pumping and of the lasing pulse. This effect is observed in lasers for which the duration of the current pulse exceeds the voltage drop time in the discharge gap. Because the pumping time in a copper bromide laser increases, the effect of the inductance of the pump oscillator and the inductance of the leads from the oscillator to the active element decreases.

Measurements of the ratio of powers of the green (510.6 nm) and yellow (578.2 nm) lines (Fig. 3) showed that this ratio varies from 3 : 1 (for output powers less than half the maximum value) to 2 : 1 (for maximum average output power). Fig. 4 shows the radial distribution of the total beam power for an average radiation power of 48 W (in the presence of hydrogen). The additions of hydrogen lead to a redistribution of the radiation intensity (with a maximum glow at the discharge axis), and the effective diameter of the laser beam decreases to $\sim 0.7d$ for an optimal addition of hydrogen (0.2 – 0.3 Torr). For considerable additions (more than 0.5 Torr), the discharge contraction is observed.

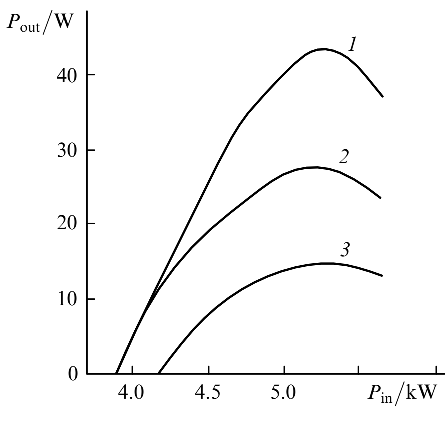

Figure 3. Dependences of the total average output power P_{out} of a Cu laser for both lines (curve *1*); as well as for the green (510.6 nm, curve *2*) and yellow (578.2 nm, curve *3*) lines on the power P_{in} extracted from the rectifier.

Measurements of currents and voltages showed that, as in the case of a Cu laser, two current peaks are observed. The first one is apparently related to a primary partial breakdown in the tube and charging of the parasitic capacitance (consisting of the discharge plasma in the axial region at the first stage of discharge and the reverse current lead). However, this effect is manifested less strongly in the CuBr laser. The lasing pulse emerges in this case only after a voltage drop in the gap (Fig. 5).

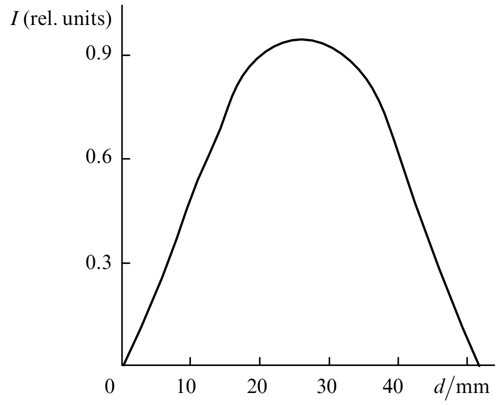

Figure 4. Radial distribution of the total output power of a CuBr laser for a 5.2-kW power extracted from the rectifier, a pulse repetition rate of 10 kHz, an average output power of 48 W, $C_1 = 700$ pF, $C_2 = 1170$ pF, and $C_3 = 0$.

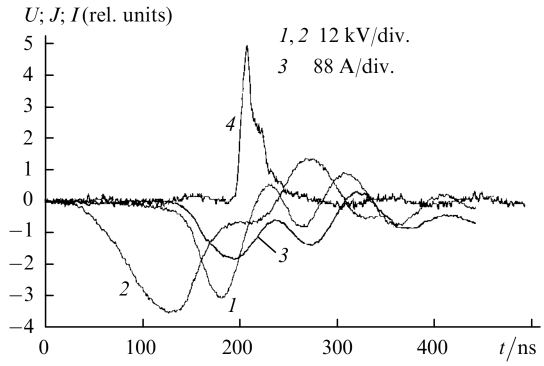

Figure 5. Oscillograms of the voltage across the laser tube (curve *1*) and across the saturation choke (curve *2*), as well as of the current (curve *3*) and emission (curve *4*) for a CuBr laser at a buffer gas (neon) pressure of 25 Torr (with 0.2 Torr admixture), 8.4-kV voltage across the rectifier, an average discharge current of 0.6 A, a pulse repetition rate of 10 kHz, an average output power of 35 W, and $C_1 = 1000$ pF, $C_2 = 1940$ pF, $C_3 = 300$ pF.

4. Conclusions

Experimental studies of pumping and emission in copper and copper bromide vapour lasers showed that average radiation powers of 40 – 50 W are obtained using the standard scheme of the pump oscillator including a thyratron and a magnetic key. The total output power in the green and yellow lines in the commercial 'Kristall' LT-40Cu tube is ~ 40 W. The introduction of an additional choke between the laser tube and the peaking capacitor makes it possible to increase the voltage build-up rate in the discharge gap and may increase the average output power. The breakdown of the laser tube occurs in two stages. In the first stage, a partial breakdown occurs (parasitic capacitors are charged during this period). During the second stage, the breakdown of the central part of the tube and useful pumping take place. Lasing begins at the stage of voltage drop across the tube during the repeated increase in the current through the tube.

The physical efficiency in a copper vapour laser is quite high in tubes of a medium size and reaches 4 %. We believe that it is difficult to further increase the output power (by more than 20 %) in the 'Kristall' LT-40Cu tubes only by improving the pump oscillator; however, a considerable increase in the total lasing efficiency is possible if a better thermal insulation of the tube is provided. In our experiments, we observed that a preliminary heating of the tube leads to a stable growth of the lasing power upon a decrease in the power extracted from the rectifier. In one of the regimes without the additional choke L_5, a decrease from 4.5 to 3.2 kW in the power extracted from the rectifier due to a lowering of the charging voltage from 6.8 to 6 kV resulted in the increase in the average output power from 34 to 40 W, and the practical lasing efficiency (relative to the power extracted from the rectifier) was 1.25 %.

The pumping of the CuBr laser differs from that of the copper laser in less stringent requirements imposed on the pump pulse and in a considerably larger duration of the lasing pulse. Thus, the use of a pumping circuit without a compression line results in a decrease in the Cu laser power by half, and in an insignificant (less than 10 %) decrease in the power of the CuBr laser (in the presence of hydrogen). In our opinion, this effect is due to the influence of the electronegative gases on the electric field in the discharge plasma, as was observed earlier in the CuBr laser and the nitrogen laser. The additions of electronegative gases slow down the voltage drop in the discharge gap and increases the time for which a high electron temperature is maintained in the plasma. The useful pumping time and the lasing pulse duration increase in this case.

The output characteristics (average radiation power 48 W and practical efficiency ~ 1 %) achieved for the CuBr laser are by no means the highest for lasers of this type because they were obtained for much lower pump pulse repetition rates than the optimal values. Note that the linear powers introduced in the discharge (per unit length) are close for both types of lasers, while the specific powers per unit volume are an order of magnitude lower for the CuBr laser than for the Cu laser. This considerably reduces the risk of an excessive ionisation of the active medium. A further increase in the output power and efficiency of sealed active elements of the CuBr laser is achieved by using higher pump pulse repetition rates (up to 20 kHz) and preserving hydrogen in the form of a small controllable impurity. At the same time, it can be assumed in view of the running time (of more than 100 h in the lasing regime) and the invariability of the output parameters in the sealed version of the active element over a period of three months that hydrogen in the active element is bonded into compounds of the HBr type and does not leave the quartz tube in this form.

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