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Copper bromide vapour laser excited by an electron beam

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Abstract. **Lasing on self-terminating copper atom transitions is obtained for the first time by pumping the Ne–CuBr mixture by regular pulses and by a pulse train of low-energy electron beams formed in an 'open' discharge. In these regimes in a range of experimental conditions, a growth of power and radiation energy is demonstrated with an increase in the electron beam current and pulse repetition rate. In a double pulse excitation regime, the lasing energy is completely recovered in ~2.5 μs. In a central zone of the active element where CuBr molecules are totally dissociated, the specific lasing energy of ~44 μJ cm^{-3} is obtained at a physical efficiency of 8.5%.**

Keywords: *copper bromide vapour laser, electron beam.*

1. Introduction

Nonequilibrium plasma produced by an external ioniser, which may be a beam of fast neutral or charged particles, is a promising active medium for gas lasers. For the first time, electron-beam excitation of lasers on working substances with a high concentration of active particles has been suggested in [1]. Main works on electron-beam excitation of gaseous media were carried out with relativistic electron beams (EBs) having an energy of above 200 keV both for direct pumping of lasers (see, for example, [2]) and for stabilising discharges in high-pressure gases (see, for example, [3]). As applied to lasers on self-terminating metal atom transitions this method was considered in [4]. In that paper, it was assumed that the limiting efficiency of electron-beam pumped lasers may reach 10%. In [5], it was reported about lasing on self-terminating copper atom transitions $4p\,^2P^o_{3/2}–4s^2\,^2D_{5/2}$ at $\lambda = 510.6$ nm and $4p\,^2P^o_{1/2}–4s^2\,^2D_{3/2}$ at $\lambda = 578.2$ nm in a copper vapour laser (CVL) pumped by an EB with the energy $w \approx 500$ keV, current $I \approx 3$ kA, and FWHM current pulse duration $\tau_I \approx 60$ ns. At a neon pressure $p_{\rm Ne} \approx 0.02–0.5$ atm, the energy of laser radiation $w_{\rm las}$ and physical efficiency of lasing η (the lasing efficiency relative to the energy deposited to the medium) reached ~30 mJ and ~1.5%–3%, respectively. These parameters are far from the expected values, because the pumping occurred due to interaction of the vortex electric field induced by the EB with plasma rather than due to the direct EB action.

The employment of relativistic EBs generated in vacuum and gas diodes for pumping gas lasers (an average pressure of the active medium is from several to dozens of Torr) entails great technical and physical difficulties. A noticeable difference of pressures in an EB source and laser requires complicated separating systems for introducing the EB into the active medium. On the other hand, in order to completely absorb the energy of a relativistic EB in a medium with a pressure of ~10 Torr, the length of the active medium should be several hundred metres. Obviously, excitation of active media by low-energy EBs substantially simplifies the experimental assembly, and the EB should be generated directly in the active volume – in a gas-vapour medium.

Advantages of exciting active media of metal vapour lasers by low-energy EBs (with an energy of up to 5 keV) as compared to conventional excitation by gas discharges have been demonstrated in [6]. In lasers on self-terminating transitions in manganese and lead atoms, the pump power P, optimal pulse repetition rate $f_{\rm opt}$, and average laser power $P_{\rm las}$ are greater by two orders of magnitude than under the EB pumping. This is related to the fact that in the case of EB pumping the mechanism limiting laser frequency–energy characteristics changes if the influence of the pre-pulse electron concentration in plasma is eliminated (its role is reduced).

Modelling of CVL operation in [7, 8] has demonstrated that if He(Ne)–Cu mixtures are excited by a low-energy EB, the specific radiation energy may reach ~360 μJ cm^{-3} at the lasing efficiency $\eta \sim 5\%–16\%$, and an average laser power per unit length can be higher than 1 kW m^{-1}. This noticeably exceeds characteristics obtained presently in gas-discharge CVLs.

In a He(Ne)–Cu active medium excited by fast electrons formed in a hollow cathode discharge, lasing on more than 50 lines of the copper ion spectrum has been realised [9]; the main mechanisms for producing the required concentration of copper atoms and the inverted population were cathode sputtering and charge exchange on buffer gas ions, respectively. There were attempts to obtain lasing on self-terminating copper atom transitions [10]; however, the lasing characteristics were poor. To our knowledge, experiments on lasing on copper atom lines with low-energy EBs have not been continued. Seemingly, this is related to technical difficulties in fabricating the corresponding laser cells.

In this connection, in the present work we study the possibility of exciting copper vapours obtained in the process of CuBr molecule dissociation by low-energy EBs.

2. Experimental setup and main results

Experiments were carried out with a Ne–CuBr mixture. The relatively low working temperature of copper bromide

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(500–600 °C) gives a chance to employ EBs formed in an 'open' discharge [11] as a method of energy action.

The laser cell design and schematic diagram of the power supply are given in Fig. 1. In a vacuum-tight quartz case there was a cylindrical cathode, for which a copper tube with an internal diameter of 5.5 cm was used. A 20-cm-long coaxial anode was aligned with the cathode and was fabricated from a molybdenum mesh with a transparency $\mu = 92\%$. A cathode-anode distance formed an accelerating gap with a length of 3 mm. Copper bromide was placed either directly on the internal surface of the cathode or in special quartz containers on the anode grid; the containers did not affect stability of EB production. The required pressure of CuBr vapours was provided by external heating of the laser cell; at high pump powers the system operated in the self-heating regime.

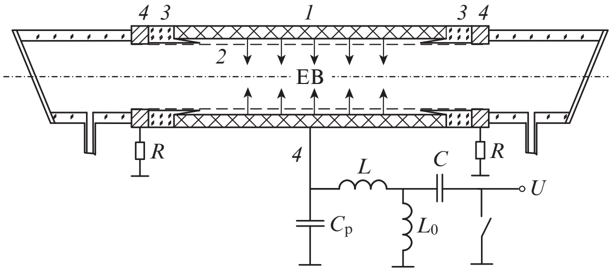

Figure 1. Laser cell and schematic diagram of the power supply: (*1*) cathode; (*2*) anode grid; (*3*) dielectric isolators; (*4*) power points.

Importantly, the molybdenum mesh was covered by a dense copper film, which protected the mesh against corrosion and destruction due to chemical interaction of molybdenum and bromine.

The power supply comprised a peaking capacitor C_p = 13.2 nF that was charged from a storage capacitor C = 14.6 nF through a thyratron TGI1-1000/25. Various excitation regimes were used for exciting a gas-vapour mixture: by regular pulses with a pulse repetition rate $f \approx 1-3$ kHz; by a pulse train with a duration of ~1 ms and a train sequence frequency of 50 Hz, and fixed frequency of pulses f = 10 kHz; by double nanosecond pulses from two independent sources with a tunable delay ΔT between them and a common pulse repetition rate of 3 kHz.

At increasing the voltage U across the accelerating gap at a neon pressure $p_{\rm Ne} > 3$ Torr, a converging EB was formed in the cell. In the range $p_{\rm Ne} \approx 3-20$ Torr at U = 8 kV the discharge current, which is actually equal to the EB current, reached ~2 kA. An increase in the copper bromide vapour $p_{\rm CuBr}$ to ~1 Torr weakly affected the EB parameters. The limiting values of the EB current were determined by arising instability and sparking on the cathode.

In exciting a Ne–CuBr gas-vapour mixture in the regular pulse regime with f = 0.8–3 kHz at the pressures of neon $p_{\rm Ne} \approx 7-20$ Torr and copper bromide $p_{\rm CuBr} \approx 0.1-1$ Torr and voltage $U > 5$ kV ($I > 700$ A), lasing has been obtained at λ = 510.6 and 578.2 nm. In threshold conditions with respect to the copper bromine pressure, lasing occurs in a near-anode zone. As the pressure elevates, the radiation intensity at the cell centre increases, whereas at the periphery it falls. In the optimal conditions the diameter of the radiation spot $d_{\rm las}$ is ~3 cm and the intensity distribution in the central part of cell is almost uniform. This intensity distribution is determined by the radial character of the injected EB and by the degree of dissociation of CuBr over the cell cross section. Since the path length for electrons calculated according to the methods from [12] is ~25 cm, which is noticeably greater than the cell diameter, electrons perform several oscillations across the cell cross section experiencing substantial scattering. Thus, about half the radiation power is concentrated in a central zone with a diameter $d_{\rm m} \approx 1.2$ cm.

Oscillograms of voltage U, discharge current I, and laser radiation pulse are given in Fig. 2. Good matching between the laser cell and pump generator allows one to characterise the power deposited to the discharge by a dependence $P(t)$. In the conditions of Fig. 2 close to optimal for lasing, the energy deposited to the cell is ~220 mJ. A typical FWHM duration of the laser pulse $\tau_{\rm las}$ is ~20 ns at the EB current pulse duration $\tau_I \approx 33-40$ ns.

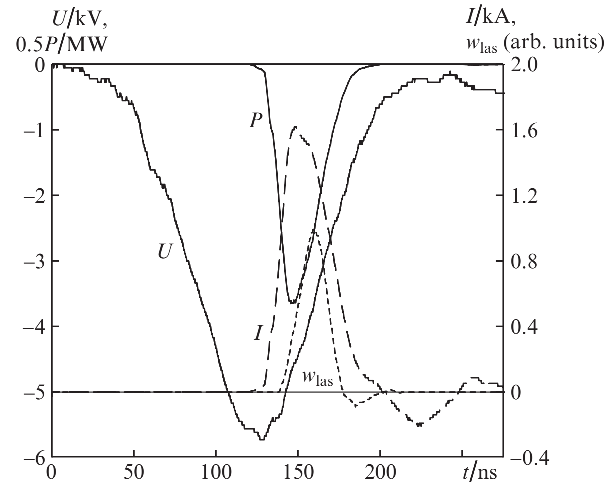

Figure 2. Oscillograms of the pulses of voltage U, current I, pump power P, and lasing energy $w_{\rm las}$ at $p_{\rm Ne} \approx 9$ Torr, f = 2 kHz.

In Figs 3 and 4 one can see dependences that characterise energy parameters of lasing. The dependence of the average power on the current $P_{\rm las}(I)$ (Fig. 3) is increasing, $P_{\rm las}$ rising faster than the current amplitude. From Fig. 4 one can see that an increase in the pulse repetition rate f and, correspondingly, the pump power P results in a higher laser power $P_{\rm las}$ and energy $w_{\rm las}$.

At pulse repetition rates exceeding 3 kHz and higher energy of the exciting pulse, the optimal temperature regime for copper bromine was broken, and constructive features of the laser cell could not provide a required degree of cooling. In turn, the optimal frequency of gas-discharge CuBr-laser operation is above 20 kHz [13, 14], which is related to the necessity of obtaining an atomic copper vapour from dissociated CuBr molecules and maintaining the required concentration of copper atoms to the instant of the next excitation pulse arrival. Thus, further experiments were carried out with the laser excited by a train of pulses. At a train duration of ~1 ms and the repetition rate of 10 kHz, the active medium was excited by 10 pulses. Lasing was observed starting from second (third) excitation pulse; and starting from the fourth and later pulses the lasing amplitude was stabilised and constant to the end of the train. The laser power $P_{\rm las}$ recalculated to the regime of regular pulses is ~10 W (50 W m^{-1}) (Fig. 4). Obviously, the pulse repetition rate f = 10 kHz limited by the

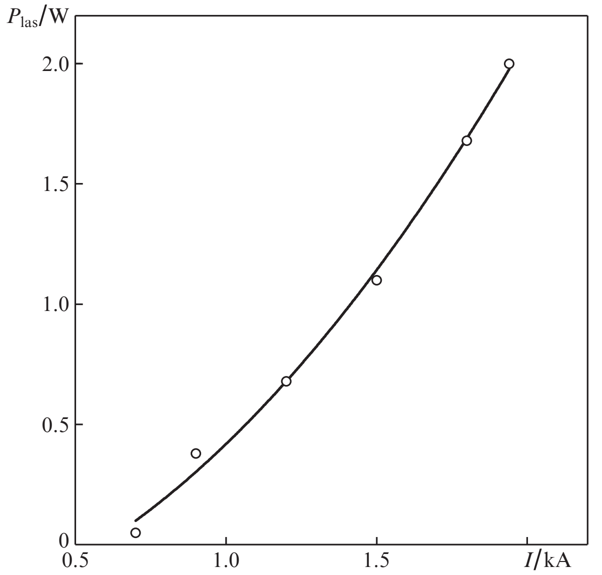

Figure 3. Average laser power P_{las} vs. current I at $p_{Ne} \approx 9$ Torr, $f = 2$ kHz.

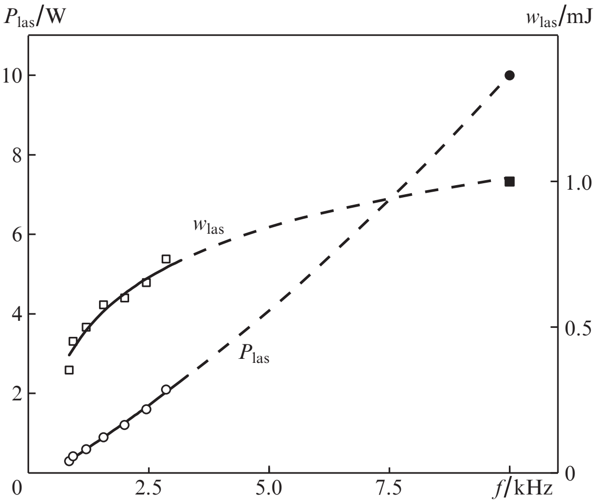

Figure 4. Average laser power P_{las} and lasing energy w_{las} vs. pulse repetition rate f in the regimes of regular pulses (light dots) and train of pulses (dark dots).

pulse source is also far from optimal both for the CuBr pressure and for the conditions of producing the inverted population.

For finding the limiting frequency characteristics of the electron-beam pumped CuBr laser we have studied the excitation of the laser by double pulses of nanosecond duration. Curve (*1*) in Fig. 5 shows the relative lasing energy of the second pulse w_{las2}/w_{las1} as it approaches the first pulse. One can see that lasing arises after $\Delta T \approx 0.65$ μs, and to the moment of ~1.5 μs the relative energy reaches 0.9 of the maximal value. For comparison, in this figure one can see a similar dependence (*2*) for the gas-discharge CuBr laser at $U = 8$ kV measured in the case where influence of the electron concentration existing prior to the pump pulse arrival is neutralised [13]. These results are comparable with data on the electron-beam pumped lead laser [curve (*3*)] [8] in which lower lasing levels are efficiently deactivated by electrons. All these dependences are similar and demonstrate the fact that, in the conditions where the electron concentration existing prior to the pump pulse arrival has no effect on the frequency-energy characteristics and the rate of electron deactivation is sufficient to efficiently deplete a lower laser level, the lasing is recovered in a time interval $t = 1-3$ μs. This makes possible laser operation at high frequencies.

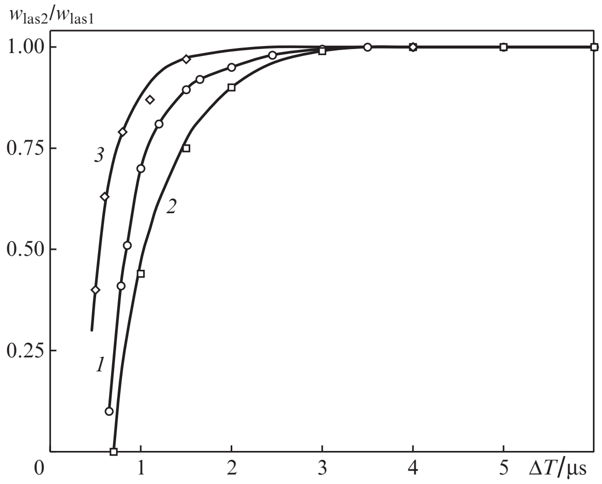

Figure 5. Lasing recovery in (*1*, *2*) CuBr and (*3*) Pb lasers [6]. Excitation is performed by (*1*, *3*) an EB and (*2*) gas discharge in the conditions of neutralised influence of the electron concentration [13].

3. Discussion of results

Obtaining lasing in a Ne–CuBr active medium excited by low-energy EBs and demonstration of actually absent limitations on a pulse repetition rate make it possible to verify modelling results [7] and realise high-power and efficient electron-beam pumped copper lasers.

Analysis of this possibility can be performed using the data from Figs 4 and 5. It follows from [13] that if the rate of lasing recovery after the termination of a previous pulse is determined by the rate of deactivation of the metastable state (MS), then the following relationship is valid

$$\frac{\Delta W_{\Delta T}}{W_0} = \frac{g_r n_{ms0}}{(g_r + g_{ms}) n_{ph0}}, \tag{1}$$

where W_0 and n_{ph0} are the specific lasing energy and the number of photons emitted from a unit volume in the case when they are independent of frequency f; $\Delta W_{\Delta T}$ is the relative change of the lasing energy in the delayed pulse at instant ΔT after the termination of the previous pulse [Fig. 5, curve (*1*)]; g_r and g_{ms} are the total statistical weights of upper and lower states, respectively; and n_{ms0} is the pre-pulse concentration of the MS.

For the central part of the cell with an almost uniform intensity distribution, the value of n_{ph0} determined at $f = 10$ kHz is 1.21×10^{14} cm^{-3}, which corresponds to the energy extraction $W_0 \approx 44$ μJ cm^{-3}. From this value and formula (1) we obtain $n_{ms0}(\Delta T) = 3.23 \times 10^{14} \Delta W_{\Delta T}/W_0$ [Fig. 6, curve (*1*)]. Similarly to other self-terminating lasers, it comprises a fast part followed by a retarded rate of the MS decay. The first part is determined by the rate of MS deactivation by electrons [15] and the following part – by gradual convergence of electron

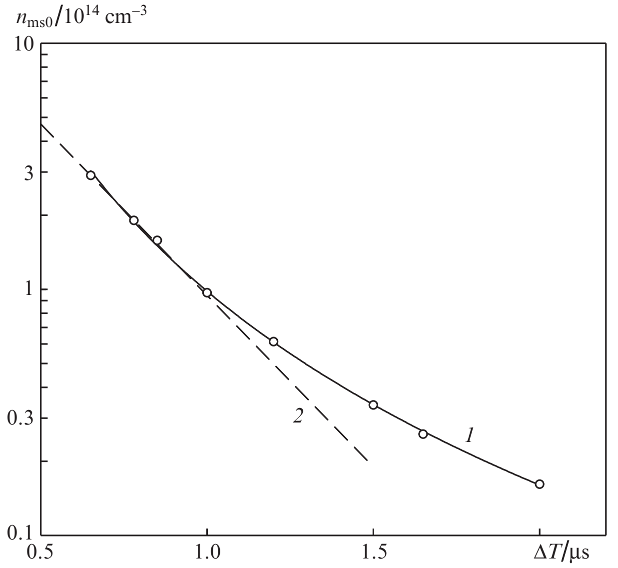

Figure 6. (*1*) Dependence $n_{ms0}(\Delta T)$ and (*2*) its approximation.

and gas temperatures. Taking the constant of electron deactivation k_e equal to 1.8×10^{-8} cm^3 s^{-1} [16], one can find that in near afterglow the electron concentration is $n_e = 1/(\tau k_e) = 1.68\times10^{14}$ cm^{-3}, where $\tau = 0.33$ μs is determined from the slope of the straight line (*2*) in Fig. 6.

When a working medium is pumped by the EB, all heavy particles are ionised. However, to the instant $t = 0.5-1$ μs, Ne and Br ions in the recharge reactions transfer the charge to Cu$^+$ ions; hence, the specific energy deposited to the central zone of active medium can be calculated by the formula

$$w_p = E_i n_e/\eta_w, \tag{2}$$

where E_i = 7.72 eV is the ionisation energy of the copper atom; η_w is the part of the EB energy spent to produce secondary electrons, which depends on the relationship between the total energy losses and ionisation losses.

Presently, the value of η_w for the Ne–CuBr mixture is not known. We may estimate its lower limit from the following backgrounds. The ratio of energy losses dw/dx to the ionisation cross section σ_i for inert gases is approximately constant [12, 17, 18]. The energy spent to produce an electron–ion pair falls in transferring from He to Ne, Ar, Kr, and Xe (see, for example, [2, 19]). Hence, in more heavy – as compared to helium – gases, part of the energy spent on ionisation is greater. According to [2], this value is ~3/4. Detailed calculations of η_w for helium have been performed in several works and yield the value from 0.33 [7] to 0.55 [20, 21]. Introduction of copper vapours increases η_w from 0.33 to 0.46, and for the ratio of helium and copper concentrations $n_{Cu}/n_{He} = 10$, we have $\eta_w \approx 0.38$ [7]. For Cu and Br atoms, as for inert gases, the ratios dw/dx to σ_i are almost equal; hence, the number of electron–ion pairs for dissociated copper bromide is twice that for copper. Finally, for estimates we take the value $\eta_w \approx 0.4$, which is a lower estimate for this parameter.

From (2) one obtains that the specific energy deposited to active medium is $w_p = 0.52$ mJ cm^{-3}. At the energy extraction of ~44 μJ cm^{-3} the physical lasing efficiency is $\eta \approx 8.5\%$. From experiments follows that the laser intensity rapidly falls with a distance from the central zone with $d_m \approx 1.2$ cm to periphery, and at a distance of ~0.9 cm from the anode, lasing does not develop. There are two reasons for this: nonuniform pumping and reduction of the dissociation degree near cell walls, which is typical for gas-discharge CuBr lasers [13, 14]. Taking into account nonuniform pumping, which in average over volume is twice less than in the central part, the total pump energy is ~106 mJ per pulse, i.e., twice less than the energy stored in the peaking capacitor (~220 mJ for the conditions of Fig. 2). The energy losses are related to the fact that, on the one hand, the anode grid has limited transparency and, on the other hand, the path length of the electron beam is multiply longer than the cell diameter. Hence, electrons experiencing oscillations across the cell waste a substantial part of their energy on the grid. Thus, after three oscillations corresponding to half the path length, part of the EB current is left equal to $\mu^6 \approx 0.61$ of the initial value.

4. Conclusions

The results of the investigations show that, under electron-beam excitation of the Ne–CuBr mixture in an 'open' discharge, a high specific lasing energy is realised at a physical efficiency of ~8.5%, which is close to the parameters calculated in [7] for an electron-beam pumped copper laser. The lasing energy of the CuBr laser is an increasing function of the pulse repetition rate to, at least, f ~ 10 kHz. The specific energy in this case reaches ~44 μJ cm^{-3} in a central zone with a diameter of ~1.2 cm. Under double-pulse excitation, lasing of the second radiation pulse arises in 0.65 μs and completely recovers in 2.5 μs. Thus, it is reasonable to expect creation of efficient kilowatt, electron-beam pumped lasers both on the Ne–CuBr mixture and on the pure Ne–Cu mixture.

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