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The influence of ignition method on laser output of pulse hollow cathode copper ion laser

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A new method of preionization has been applied in pulse hollow cathode Cu^+ laser. The 30% increase of laser output power and lower ability of arc formation has been obtained. Discussion of this effect based on sputtering theory and on microphotographs of cathode surface is included.

1. Introduction

Hollow cathode lasers operating on sputtered metal vapors are those which produce laser lines in 220–2000 nm region. In a hollow cathode Cu^+ discharge, upper laser levels are populated mainly during charge transfer collision processes between ground state buffer gas ions and ground state metal atoms, sputtered during the electrical discharge [1]. To be effective this process requires currents of high density (of the order of 1 A/cm²). Cooling of the discharge tube electrodes is a considerable technical problem: to obtain a suitable laser operation pulse action is commonly used.

Regular and stable pulse laser operation requires some amount of ions in the interelectrode space before every pumping pulse. The aim of this paper is to present results of investigations of the influence of methods of producing these ions on the output power of hollow cathode Cu^+ laser. Two methods of preionization were examined:

i) The continuous low current glow discharge of 20 mA/cm² density (called the sustain current) as a background for high current pumping pulses – to our knowledge is the only method of preionization used up to date [2–4].

ii) High voltage, pulse, electrodeless discharge. This discharge causes ionization of the buffer gas in the tube, which initiates the main current pulse discharge.

It has been found that the second method is more advantageous: the 30% increase of laser output power, considerable reduction of hollow cathode contamination and lower ability of arc formation were observed.

2. Experimental

The laser consisting of a water-cooled 55 cm long copper cathode with the slot 2×6 mm, facing the segmented steinless-steel mesh as the anode, was employed. Both electrodes were mounted in a cylindrical vacuum pyrex tube. The mixture of He and Ar gases at the pressure ratio 20:1 and the pressure of 2 kPa (15 Torr) flowed through the laser tube, the rate of flow being 100 Pa dm^3s^{-1}. A thyristor power supply unit produces current pulses of regulated duration and intensity (mostly 1 ms pulses up to 30 A were used). In addition, a continuous low current sustain discharge could be applied to get the first method of preionization. The second method operates, when 5 KV, 70 μs pulses produced by an ignition coil are delivered to an additional electrode wound around the laser tube. These ignition pulses were synchronized with the main pumping pulses. Due to the segmented anode a continuous sustain discharge, when required, could be applied only to a part of the discharge tube.

In our resonator the generation of laser action was achieved for 780.8 nm transition. In order to compare the efficiency of both preionization methods the equal magnitudes of pumping pulses were applied (Fig. 1).

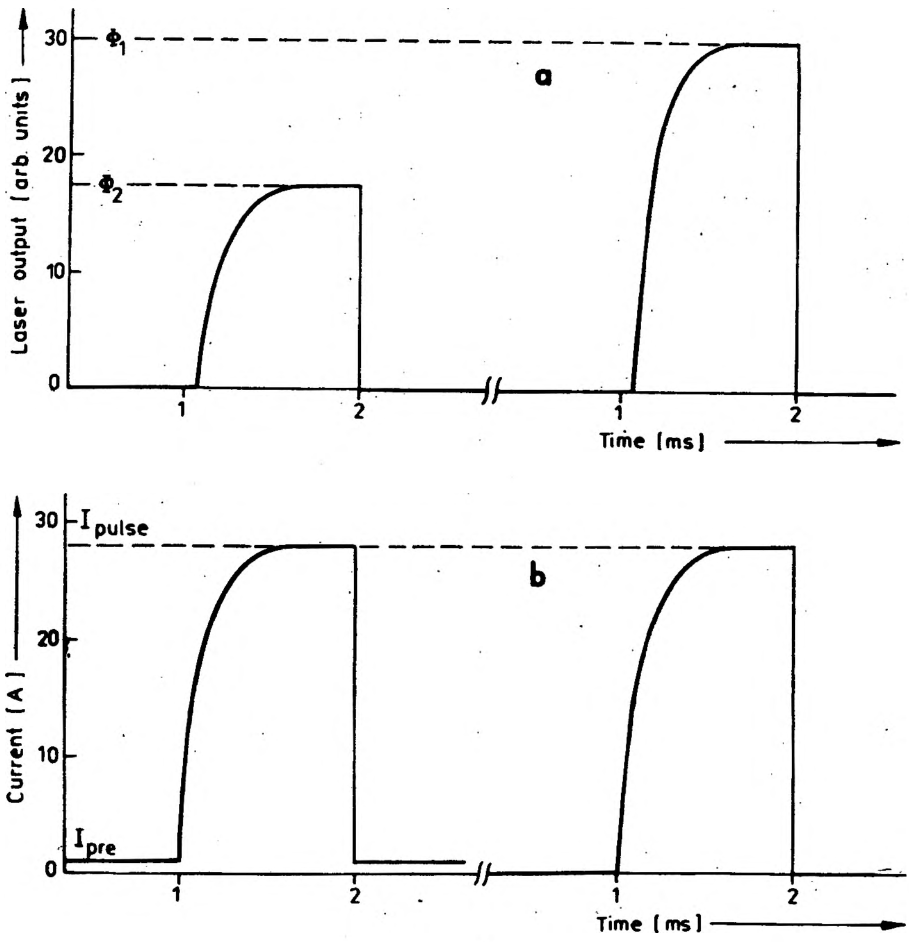

Fig. 1. Laser output pulses produced by applied current with (a) and without (b) sustain current preionization

3. Results and discussion

It has been found, that the application of pulse preionization method with pumping current pulses 15–30 A results in the laser output power at least 30% higher than the output power obtained with the sustain current preionization method. Figure 2 is the illustration of laser power changes when two methods of preionization were successively used. In this figure Φ_1 is, like in Fig. 1, the laser output power obtained when the pulse preionization was used. For a chosen resonator configuration $\Phi_1 = 100$ mW at $I_{\text{pulse}} = 26$ A was achieved, threshold current being 3 A. After switching to the continuous preionization (at the moment t_1) initially rapid, then slower output power decrease was observed. The new power level Φ_2, becomes fixed after few minutes. It has to be noticed that

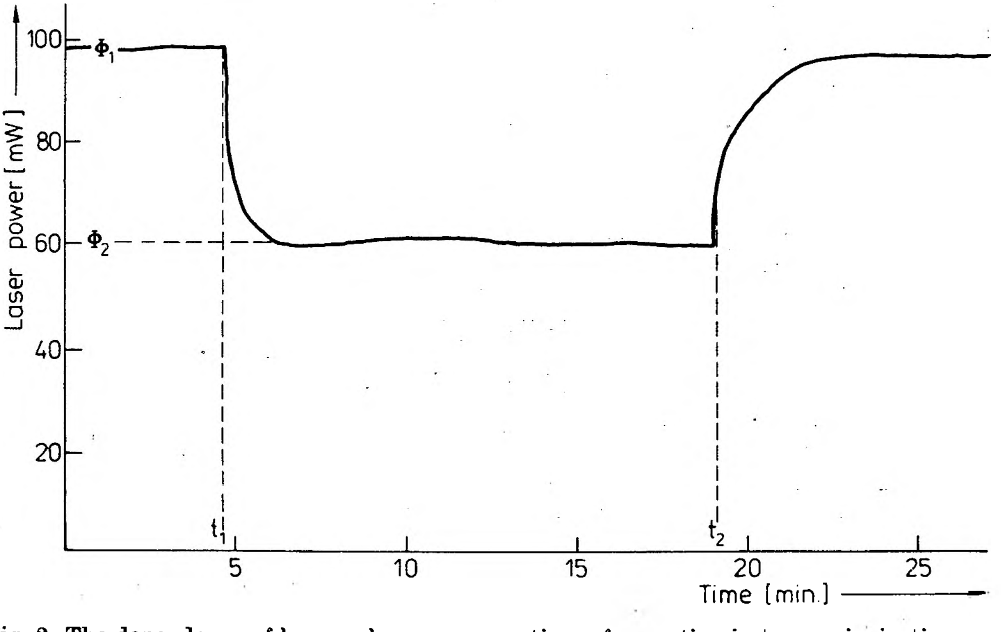

Fig. 2. The dependence of laser pulses power vs. time of operation in two preionization conditions (sustain current of 1 A was applied between t_1 and t_2)

long lasting operation does not change the picture. After switching back to the pulse ignition method (at the moment t_2) the output power becomes again Φ_1. It has been also noticed that the time of increase (or decrease) of laser power is getting shorter when the repetition rate of laser operation increases. It has been further found that the relative power $\eta = (\Phi_1 - \Phi_2)/\Phi_2$ increases with the increase of preionization current and decreases with the increase of the repetition rate.

Because both of the preionization methods can operate independently, they may be applied simultaneously. In that case the lower level Φ_2 of the output power is obtained. It means that the sustain low current glow discharge affects negatively the laser efficiency in hollow cathode lasers.

The laser power drop observed in the presence of continuous low current discharge can be caused by the increase of resonator losses, mainly due to deposition of the metal layer or Brewster windows, increase of the copper ion density in the lower laser level and decrease of copper ion density in the upper laser level. The periodic rise and fall of the output power, as illustrated in Fig. 2, rules out the increase of resonator losses. The discussed laser transition terminates in $Sp^3F_4^0$ level. The mean life time of this level is short, which causes its neglegible population. As a result, the decrease of the population rate of the upper laser level is the main reason of the observed laser power drop.

The discussed laser is the system with small gain. In that case the output power Φ is proportional to the mean density of copper ions $N(Cu^+)^*$ in the upper laser level $Cu^+(6s\,^3D_3)$. The excitation of this state is achieved in the charge transfer process

$$He^+ + Cu \rightarrow He + (Cu^+)^* + \Delta E,$$

in which

$$\overline{N(Cu^+)^*} = K \cdot \overline{N(He^+)N(Cu)} \tag{1}$$

where K is the charge transfer rate constant.

Because $\Phi \sim \overline{N(Cu^+)^*}$ it follows that

$$\eta = (\Phi_1 - \Phi_2)/\Phi_2 = \left[\frac{[\overline{N_1(He^+)}\,\overline{N_1(Cu)} - \overline{N_2(He^+)}\,\overline{N_2(Cu)}]}{[\overline{N_2(He^+)}\,\overline{N_2(Cu)}]}\right] \tag{2}$$

where indices 1 and 2 are correlated with the appropriate preionization conditions. In particular, the index 1 refers to the pulse preionization and index 2 to the sustain current glow discharge preionization.

Three simultaneously occurring processes, i.e., production of these ions in the electron – helium collisions, diffusion to the cathode and charge – transfer process, influence the resultant density of helium ions $N(He^+)$. With the increase of the current density the last process leads to the saturation in the very high current density region [5]. In our laser system operating under moderate discharge conditions the charge transfer process efficiency is too small to be limited by the saturation of the density of helium ions. In this case $N(He^+)$ does not depend on $N(Cu)$ and is a function of efficiency of both, the ionization of helium atoms in collisions with fast electrons and deionization on the cathode surface. The concentration of fast electrons in the discharge region for fixed current density may be influenced by some gaseous impurities desorbed from the cathode surface. With the assumption that preionization may influence the desorption rate of gaseous impurities it could be expected that after a long lasting laser operation with d.c. discharge (sustain current preionization) the cathode should be purified and the laser power drop should disappear. There exists experimental evidence that prolonged laser operation with sustain current preionization does not cause the disappearance of the laser power drop. So it seems reasonable to assume that the gaseous impurities release is not a factor which leads to considerable decrease of helium ionization. It means that, in a good approximation, the density of helium ions does not depend on the preionization method used. In that case (2) may be reduced to

$$\eta = [\overline{N_1(Cu)} - \overline{N_2(Cu)}]/\overline{N_2(Cu)}. \tag{3}$$

Sputtering of metal atoms into the hollow cathode discharge volume is mainly due to the bombardment of the cathode surface by metal ions. So, the density of these atoms in the given discharge conditions depends only on the effective sputtering yield because of the relation

$$N(Cu) = [\xi(Cu^+) - 1]A \tag{4}$$

where $\xi(Cu^+)$ — sputtering coefficient, and A — quantity depending on the pumping current density, the cathode configuration and atomic parameters [5]. Then, putting (4) into (3) we get

$$\eta = [\xi_1(Cu^+) - \xi_2(Cu^+)]/[\xi_2(Cu^+) - 1], \tag{5}$$

which means that just the different values of sputtering coefficients in both discharge conditions, initiated by different preionization methods, are responsible for the discussed drop of laser power. Elementary analysis of (5) leads to a conclusion that even small changes of sputtering coefficient cause substantial changes of the output power of the hollows cathode lasers.

The only factor which can affect the values of sputtering coefficients is the state of the surface of the cathode slot which was examined under different working conditions with the scanning electron microscope Novoscan 30 with the 10 nm resolution. Several specimens of the cathode exposed simulataneously to different preionization methods were examined. This was possible due to the special construction of the segmented anode. The specimens, being smooth copper foils, were fastened tight to the surface of the cathode slot. Figure 3 illustrates a fragment of the cathode surface which was exposed for 3 hours to the action of both main discharge and sustain current. The distinctive feature of this surface is the presence of large amount of cone-shaped forms. In this case the cones occupy about 5% of the surface. Their number is much smaller when pulse ignition is applied: the cones occupy less than 1% of the surface. It is worth-while to note that the number of cones, as presented in Fig. 3, can be reduced by treating of such a surface with a high current pulse discharge together with pulse ignition preionization. There is a remarkable coincidence between the creation and destruction of cones and power changes.

Discussion about the origin of such cones which evolve on ion-bombarded Cu surface was summarized by KELLY and AUCIELLO [6], it, however, does not concern entirely the case of hollow cathode operation.

All the presented observations lead to the conclusion that the low sustain current discharge laser pulses favours cone formation on the cathode surface. Explanation of this effect requires more detailed investigations. Nevertheless, basing on the results achieved, it is possible to state the correlation between the presence of cones and laser output power. The observed surface structure

Fig. 3. Microphotography of Cu-cathode surface after exposure to 30 A current pulses with 1 A sustain current. Some cone-shaped forms may be observed

of the cathode results from sputtering and homogeneous redeposition of Cu atoms simultaneously. It has to be emphasized that atoms which are engaged in the build-up of cones do not participate in the discharge process. The latter causes the decrease of Cu vapour density in the laser active region, and, because of the decrease of charge transfer reaction efficiency, the lowering of laser output power.

As a practical advice it can be stated that in order to achieve a proper action of a hollow cathode copper ion laser device, such working conditions have to be found, in which the formation of cones be minimized. As a final comment, it should be noted that proposed new method of preionization seems to be also advantageous for other than Cu^+ pulse hollow cathode lasers.

4. Summary

It has been shown experimentally that the method of preionization substantially influences the hollow cathode Cu^+ laser output power. A new method of preionization is proposed which gives a better laser performance manifested in higher output power and in decrease of arc formation ability.

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Влияние способа зажигания на выходную мощность импульсного лазера с полым катодом

Применено новую методику преионизаций лазера с полым медным катодом. Получено 30% повышение выходной мощности лазера также замечено повышение устойчивости к образованию дуговых разрядов. Дискуссия опирается на теории распыления полого катода. Приложена микрофотография поверхности катода.