Characteristics of inductive coaxial copper vapour lasers

Vycheslav. M. Batenin[1], Mishik. A. Kazaryan[2], Vyacheslav. T. Karpukhin[1], Nikolay. A. Lyabin[3], Mikhail. M. Malikov[1], Victor. I. Sachkov[4], Ivan. N. Feofanov[2]

[1] Joint institute for high temperatures, Russian academy of sciences, 127412, Moscow, Russia
[2] P. N. Lebedev physical institute, Russian academy of sciences, 119991, Moscow, Russia
[3] Research and production corporation "Istok", 141190, Fryazino, Moscow Region, Russia
[4] Siberian physical-technical institute, Tomsk state university, 634050, Tomsk, Russia

ABSTRACT

We present new results on numerical investigation of characteristics of pulse-periodic inductive copper vapour lasers. In these lasers pump pulses are trains of high-frequency (~ 30 MHz) current oscillations repeated at a frequency of 2-17 kHz. An inductive laser with an annular working volume of 1.7 l was considered and its possible output parameters were studied. We analyze specific features of working medium excitation in an HF-discharge; diversity of the obtained laser pulse shapes and possible applications are discussed as well.

Copper vapour laser, inductive pumping, HF-discharge, lasing pulses.

1. INTRODUCTION

The physical model of pulse-periodic electrodeless inductive copper vapour lasers (ICVLs) and the first results of numerical investigations were described in a number of publications[1-4]. In these works we have demonstrated the possibility to achieve high output characteristics of ICVLs comparable to those of conventional copper vapour lasers pumped by a longitudinal electrode discharge. The dependence of the dynamics of plasma parameters and radiation pulse shapes of ICVLs on the frequency of damped HF-oscillations of pump current f_{tr} was investigated in our previous work[5]. In the present study for a fixed frequency of f_{tr} = 30 MHz the influence of the pump train repetition rate f and other specified parameters on the pulse shape and pulse energy characteristics was investigated. It should be noted that to date there has been no experimental implementation of such laser. Radiation dynamics and laser kinetics of an ICVL has not been studied for an HF-discharge yet. Therefore, numerical investigations providing new information on potential radiation parameters for ICVLs are of scientific and practical interest.

2. NUMERICAL EXPERIMENT AND DISCUSSION

A schematic diagram of the ICVL with a several-turn-inductor and annular discharge volume of 1.7 l is presented in fig. 1. Geometrical parameters are the following: the inductor radius is 6 cm, the radii of the walls of the annular discharge chamber are 3.5 cm and 2.5 cm, the length is 90 cm. These dimensions and the number of inductor turns N govern the inductance of the inductor, the inductance of the plasma "turn" and mutual inductance. The frequency of damped high-frequency current oscillations in the train f_{tr} depends on each inductance involved as well as on the value of the storage capacitance C. The laser cavity was composed of two plane mirrors positioned at the faces of the discharge chamber. Their reflectivities were of typical values with 0.97 for the cavity end mirror and 0.07 for the output mirror. The distance between the mirrors was equal to 130 cm.

In the initial version of the calculations the following parameters were prescribed: N = 1 (one-turn inductor solid along the chamber length), neon pressure was 250 Torr, concentration of copper atoms was $1.53 \cdot 10^{15}$ cm^{-3}, the storage capacitance was C = 1.5 nF with $U(0)$ = 35 kV applied voltage, pump pulse (train) repetition rate was f = 10 kHz. The frequency of current oscillations in the train f_{tr} was ~ 30 MHz for this version. With the stated parameters the average power W_{av} of the ICVL radiation was close to maximum and equal to 165 W with the physical efficiency being $\eta_{ph} \approx$ 3.5%.

XIII International Conference on Atomic and Molecular Pulsed Lasers, edited by
Victor F. Tarasenko, Andrey M. Kabanov, Proc. of SPIE Vol. 10614, 1061405
 · doi: 10.1117/12.2303584

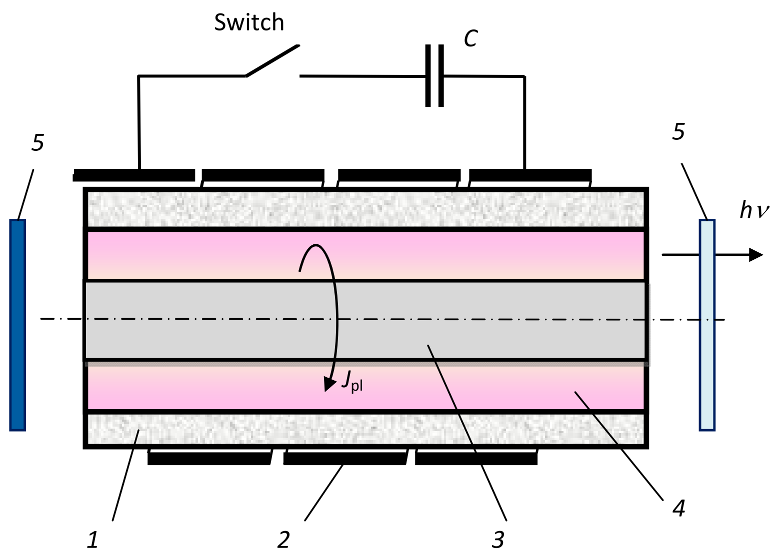

Fig. 1. Design of ICVL. *1*– heat insulation, *2* – inductor turns, *3* – central ceramic insert, *4* – annular discharge chamber, *5* – optical cavity mirrors.

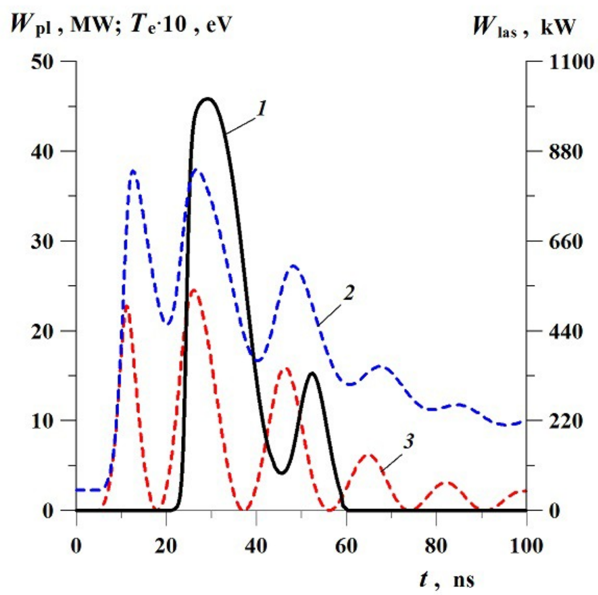

Fig. 2. Plasma parameters and laser radiation pulse (total radiation from two lasing lines at 0.51 μm and 0.578 μm): *1* – W_{las}, *2* – T_e, *3* – W_{pl}; $U(0) = 35$ kV, $f = 10$ kHz, $f_{tr} = 30$ MHz.

The dynamics of the Joule heat released in the plasma $W_{pl}(t)$, electron temperature $T_e(t)$ and output power pulses $W_{las}(t)$ is shown in fig. 2. It can be seen that the power W_{pl} reveals pulsations with a doubled frequency $2f_{tr} = 60$ MHz.

For each pulsation W_{pl} higher rates of injection of energy into the plasma are achieved as compared to those specific to conventional electrode-based CVLs with long (~ 200-250 ns) nonperiodic pump pulses. It should be noted that at the initial stage (~ 0-60 ns) up to ~ 70% of the electric energy injected into the plasma is released. All these factors facilitate the rise of inverse population and increase in the laser efficiency. On the other hand, pronounced oscillations of the electron temperature which are in time to W_{pl} pulsations appear and pulsations of the lasing power W_{las} arise (see fig. 2).

The dynamics of plasma parameters, the dynamics of radiation pulses and their interdependencies with regard to an ICVL are described in detail in the literature[5]. It was demonstrated that the oscillations of T_e do not inhibit the rise and maintenance of inverse population for self-terminating transitions between the laser levels of copper atoms. At times longer than ~ 60 ns (see fig. 2) generation of pulsed laser radiation is stopped as the temperature T_e drops below 2 eV and the population rate for electron impact-induced population of the upper laser level becomes smaller than the corresponding rate for the lower laser level.

Changing the train repetition rate f and the voltage at the capacitance $U(0)$ had a great effect on the plasma parameters, radiation pulse shape, peak pulse power, average power W_{av} and physical efficiency η_{ph}. The dynamics of W_{las} (for 0.51 μm lasing line) and T_e for three values of f and two values of $U(0)$ are presented in fig. 3. The other parameters were fixed. For low repetition rates $f = 2$ kHz (figs. 3a,d) a long-duration laser pulse W_{las} (up to 70-90 ns) containing 3-5 peaks was observed. For these peaks the spacing frequency was ~ 60 MHz.

With increasing f a faster decrease in T_e occurred (figs. 3b,c and figs. 3e,f) and the number of the peaks was decreased. With high rates f ~ 12-17 kHz for each current train it is possible to achieve a single smooth lasing pulse W_{las} with a narrow width at half-maximum of about 5-10 ns (figs. 3c,f).

The comparison between figs. 3a,b,c and figs. 3d,e,f reveals that the increase in the voltage $U(0)$ results in the decrease of the lasing pulse duration and the number of peaks as well.

It should be noted that the dependencies of W_{las} on f and $U(0)$ obtained for the second lasing line (0.578 μm) are identical with those presented in fig. 3. However, due to a small time shift between these two radiation pulses the total pulse at two wavelengths can exhibit additional peaks for small values of f (fig. 4a). This fact is not related to the dynamics of the inverse population for each lasing transition.

For $U(0) \approx$ 30-40 kV and high values of f total peak power (summed over two lasing lines) of short (5-10 ns) single pulses exceeds 1 MW (fig. 4b). Total values of the average power W_{av} and physical efficiency η_{ph} for two lasing lines (0.51 μm and 0.578 μm) of the ICVL are presented in table 1. These values correspond to the variants in fig. 3. It can be seen that with fixed $U(0)$ (and equal energy input in the pulse[5]) the power W_{av} reaches its maximum with a certain optimal value of f, whereas the physical efficiency η_{ph} drops significantly with the growth of f.

It should be noted that the increase in the lasing pulse duration with the decrease of the repetition rate f and the voltage applied to the tube takes place in a conventional (electrode-based) CVL with a nonperiodic discharge as well (see the review in the corresponding reference[6]). However, such pronounced regular (with frequency of tens of megahertz) pulsations of the intensity W_{las} are not observed. Possible generation of long-duration radiation by an ICVL can be useful for the development of a laser system for monitoring distant objects[7, 8]. Additionally, pulsed character of W_{las} may draw attention of the researchers involved into the development of high-resolution diagnostic techniques.

Smooth ICVL-produced radiation pulses with short durations of ~ 5-10 ns, high peak power exceeding 1 MW and repetition rates of 10-15 kHz can find application in diagnostic techniques based on the light scattering effect[7, 9].

The solution of the heat problem reveals that for low rates $f \leq$ 2-4 kHz, specified thickness of heat insulation ~ 2.5 cm and its effective thermal conductivity higher than 0.15 W/m·K the amount of the heat released in the plasma W_{pl} is not enough for self-heating and temperature maintenance of the inner wall. In this situation, similarly to the case of conventional CVLs, additional heating of the wall by an individual energy source will be required to implement such variants of an ICVL.

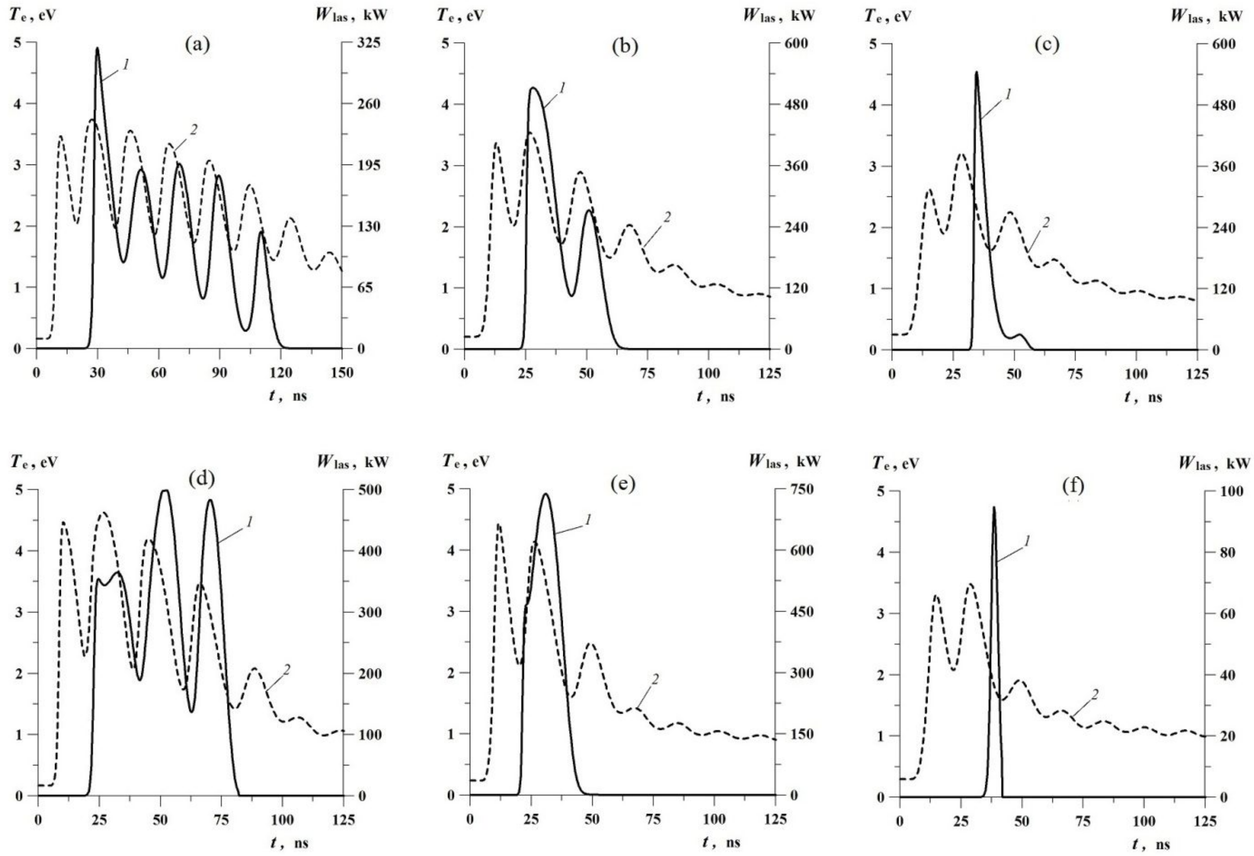

Fig. 3. Pulses W_{las} – *1* (for 0.51 μm lasing line), T_e – *2*; f_{tr} = 30 MHz: (a), (d) f = 2.0 kHz; (b), (e) f = 9.0 kHz; (c), (f) f = 16 kHz; (a), (b), (c) $U(0)$ = 28 kV and (d), (e), (f) 45 kV.

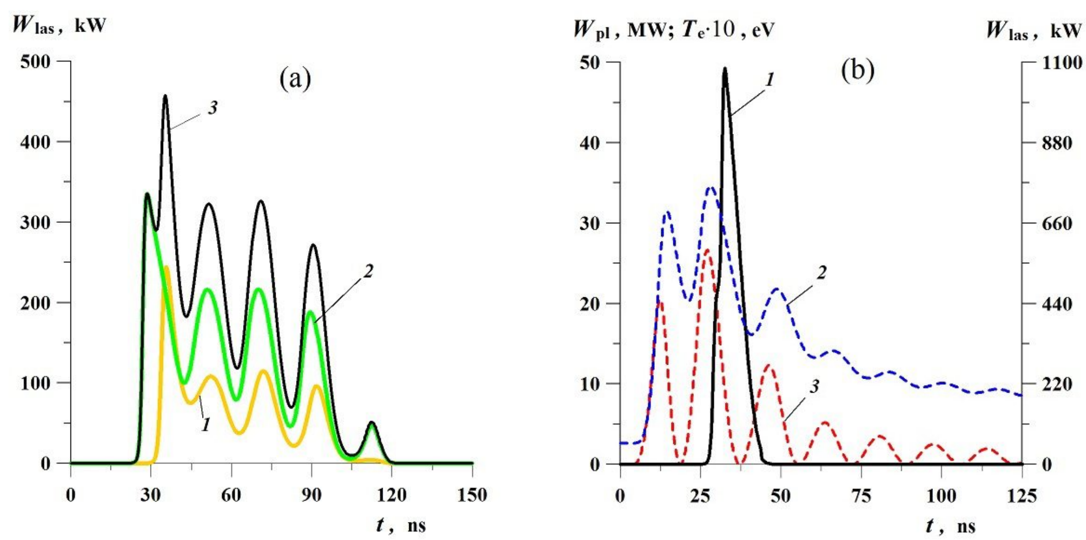

Fig. 4. Lasing pulses W_{las} for f = 10 kHz, f_{tr} = 30 MHz; (a): $U(0)$ = 28 kV, corresponding to 0.578 μm lasing line – *1*, to 0.51 μm lasing line – *2*, in total (0.51 μm and 0.578 μm) – *3*; (b): $U(0)$ = 35 kV, W_{las} (for 0.51 μm and 0.578 μm) – *1*, T_e – *2*, W_{pl} – *3*.

Table.1. Average laser power and efficiency (corresponding to variants in fig. 3).

U, kV	f, kHz	W_{av}, W	η_{ph}, %
28	2.0	34	5.2
	9.0	132	4.6
	16.0	100	2.1
45	2.0	57	4.0
	9.0	160	2.4
	16.0	55	0.7

3. CONCLUSION

The possibility to efficiently pump a copper vapour laser by a high-frequency discharge was demonstrated. In the numerical experiments for 1.7 l volume of the discharge chamber the maximum value of the physical efficiency was ~ 6 % with the maximum average output power W_{av} being as high as 170 W.

The possibility to obtain laser radiation W_{las} pulsating with the frequency of HF-oscillations of the Joule heat power release W_{pl} (~ 60 MHz) in the pump train was revealed. Such radiation pulses ("trains") were realized with a low repetition rate f of pump pulses (~ 2-2.5 kHz). The average laser power W_{av} was ~ 35-60 W with the physical efficiency of ~ 4.0-5.2% and the duration of the radiation pulse was increased to 70-90 ns.

In general, a more complicated and specific behaviour is observed for plasma kinetic parameters in an ICVL and for radiation pulses as compared to a conventional electrode-based CVL.

This work was supported by the Russian Foundation for Basic Research under project No. 17-08-00410 a.

REFERENCES

[1] Malikov, M. M., Kazaryan, M. A. and Karpukhin, V. T., "On the Possibility of Efficient Pumping of Copper Vapor Lasers by a Pulse-Periodic Inductive Discharge," Bull. Lebedev Phys. Inst. 42(5), 138-143 (2015). © Allerton Press, Inc., 2015. ISSN 1068-3356.
[2] Batenin, V. M., Kazaryan, M. A., Karpukhin, V. T., Lyabin, N. A. and Malikov, M. M., "Design and Physical Features of Inductive Coaxial Copper Vapor Lasers," Plasma Phys. Rep. 42(11), 1057-1065 (2016). © Pleiades Publishing, Ltd., 2016. ISSN 1063-780X.
[3] Batenin, V. M., Kazaryan, M. A., Karpukhin, V. T., Lyabin, N. A., Malikov, M. M., and Sachkov, V. I., "Excitation of coaxial copper vapor lasers by a pulse-periodical inductive discharge," Atmos. Ocean Opt. 29(2), 112–120 (2016).
[4] Kazaryan, M. A., Malikov, M. M., Karpukhin V. T. and Lyabin, N. A., "The use of Inductive Discharge for Laser Pumping of a Copper Vapor," J. Phys. Conf. Ser. 826, 012003 (2017). doi:10.1088/1742-6596/826/1/012003.
[5] Batenin, V. M., Kazaryan, M. A., Karpukhin, V. T., and Malikov, M. M. "Copper Vapor Laser Pumped by Pulse-Periodic High-Frequency Discharge," High Temp. 55(5), (2017). © Pleiades Publishing, Ltd. ISSN 0018-151X.
[6] Gubarev, F. A., Fedorov, V. F., Fedorov, K. V., Shiyanov, D. V. and Evtushenko, G. S., "Copper bromide vapour laser with an output pulse duration of up to 320 ns," Quantum Electron. 46(1), 57-60 (2016).
[7] Evtushenko, G. S., Kazaryan, M. A., Torgaev, S. N., Trigub, M. V. and Shiyanov, D. V. [High speed brightness amplifiers based on metal vapor induced transitions], STT Publishing, Tomsk, "Radiation. Beams. Plasma" Series, Part 1 (2016).
[8] Buzhinskij, O. I., Otroshchenko, V. G., Slivitsky, A. A. and Slivitskaya, I. A., "Videoscope on the basis of copper vapor laser for spatially-temporal diagnostics of tokamak discharge chamber internal components," Plasma Devices and Operations 11(3), 155-160 (2003).
[9] Burlakov, V. D., Zuev, V. V., Evtushenko, G. S., El'nikov, A. V., Marichev, V. N. and Pravdin, V. L., "Metal-vapor lasers for applications to sensing of atmospheric aerosol," Atmos. Ocean Opt. 6(3), 326-331 (1993).