Pulse-periodic HF induction-type discharge for pumping lasers on self-terminating transitions

V M Batenin\textsuperscript{1}, V T Karpukhin\textsuperscript{1}, M M Malikov\textsuperscript{1}, M A Kazaryan\textsuperscript{2}

\textsuperscript{1} Joint Institute for High Temperatures, Russian Academy of Sciences, 13 Bd. 2 Izhorskaya str. 125412 Moscow, Russia

\textsuperscript{2} P N Lebedev Physical Institute, Russian Academy of Sciences, 53 Leninskiy Prospekt, 119991 Moscow, Russia

e-mail: mmalikov@oivtran.ru

Abstract. We present the results of numerical investigation regarding the physical processes in the working medium of a copper vapour laser pumped by trains of high-frequency ($f_{tr} \approx 30$ MHz) current oscillations with $f \approx 10$ kHz repetition rates. An electrodeless discharge achieved by employment of an induction-type process, which is new for this type of lasers, was considered. Elimination of the electrodes in the design of such inductive copper vapour laser will, in principle, provide a means to increase the lifetime and reliability of sealed discharge tubes and reduce their costs.

1. Introduction

The possibility to efficiently pump the working medium (Ne+Cu) of an inductive copper vapour laser (ICVL) using high-frequency discharge was first demonstrated in [1−4]. In the present work we used the physical model and computer codes developed in [2, 3]. These results provide a means to obtain self-consistent values of all plasma, electric, kinetic and heat parameters in the stationary operation mode. The goal of the present study is to reveal physical conditions and technical specifications that would provide the improvement of the ultimate output parameters of gas-discharge lasers based on self-terminating atomic transitions of copper. The basic approach involves numerical modeling of kinetic and thermal processes in discharge plasma with simultaneous solution of the differential equation system describing the electric circuit of induction pumping.

2. Results and discussion

We consider the design of the ICVL (figure 1a) with a one-turn inductor (6 cm in diameter) which is solid along the tube length. The working medium is disposed in an annular volume limited by two cylinders (5 and 7 cm in diameter and 90 cm in length). Numerical experiments were conducted with predefined values of the storage capacitance $C=1.5$ nm, initial voltage at this capacitance $U(0)=35$ kV, neon pressure $P_{Ne}=250$ Torr, temperature of the inner wall $T_{in}=1823$ K (concentration of copper atoms was $1.5 \times 10^{15}$ cm$^{-3}$). The calculated value of the gas temperature in the middle of the working gap did not exceed 2140 K, which is allowable for laser operation.
The calculated ring current pulse $J_2$ and active voltage pulse (over one azimuthal turn) $U_{ac}=J_2 R_{pl}$ are presented in figure 1b. The dynamics of the plasma resistance $R_{pl}(t)$, electron temperature $T_e(t)$ and electron concentration $n_e(t)$ as well as the Joule heat power $W_{pl}(t)=J_2^2(t) R_{pl}(t)$ released in the plasma is shown in figure 2a. It can be seen from the figure that $J_2$ and $U_{ac}$ pulses appear as trains of decaying HF oscillations. This behaviour is due to the fact that the inductance of the inductor, inductance of the plasma turn and its resistance are much lower than the inductance and resistance of the discharge circuit involving electrodes in a conventional copper vapour laser (CVL) operating with the same storage capacity.

![Diagram](image1.png)

**Figure 1.** (a): Schematic representation of ICVL: 1 – inductor, 2 – heat insulation, 3 – ceramic insert, 4 – plasma; (b): Current $J_2$ – 1 and voltage $U_{ac}$ – 2 pulses.

![Diagram](image2.png)

**Figure 2.** Plasma parameters and laser emission pulse at wavelength of 0.51 μm. (a): 1 – $T_e$, 2 – $n_e$, 3 – $W_{pl}$, 4 – $R_{pl}$; (b): 1 – $W_{las}$, 2 – $T_e$, 3 – $W_{pl}$. 
Consequently, the power $W_{pl}$ reveals pulsed character with a doubled pulse frequency $2f_{tr}$ (figures 2a and 2b). In this case, higher rates of injection of energy into the plasma can be achieved (in every pulse) as compared to the conventional electrode-based CVL with a long (~250 ns) nonperiodic pump pulses. It should be noted that at the initial stage of ~0 – 50 ns the value of $R_{pl}$ is increased by a factor 2 – 3 (figure 2a) due to the growth of the frequency of elastic collisions between electrons and atoms resulting from a rapid increase of $T_e$. At this time interval the growth of $n_e$ is slow and cannot inhibit the growth of $R_{pl}$. The latter is associated with the fact that the characteristic ionization time of the medium is shorter than the period of HF oscillations of the pump current. Due to this behaviour of the plasma up to ~70% of the electric power pumped into the plasma is released at the considered time interval. All of this gives rise to inverse population and increases the laser efficiency.

On the other hand, we observe pronounced pulsation of the electron temperature $T_e$ which is in time to $W_{pl}$, alongside with that, pulsations of the lasing power $W_{las}$ may appear (see figures 2a and 2b). According to our calculations such oscillations of $T_e$ do not affect the rise and maintenance of inverse population for self-terminating transitions between laser levels. This is due to the fact that on the drop of $T_e(t)$ in the oscillations the population rate for the upper laser level $n_r$ still exceeds the population rate for the lower laser level $n_m$ as for the upper level the rate of its electron impact-induced depopulation to the above levels and to the continuum is decreased. This dynamics of $n_r$ and $n_m$ is clearly seen in figure 3a at the time interval from approximately 7.5 ns to 23 ns.

![Figure 3. Dynamic behaviour of operating level populations and inverse population obtained for 0.51 μm laser emission. (a): 1 − $T_e$, 2 − $n_m$, 3 − $n_r$; (b): 1 − $D$, 2 − $T_e$.](image)

At the same time interval we observe a rapid growth of inverse population $D(t)=(n_r-n_m\cdot g_r/g_m)$ (see figure 3b), which reaches its maximum at $t\approx 23$ ns (here $g_r$ and $g_m$ are statistical weights of the levels). It should be noted that the gain constant in the working medium of the laser is proportional to the value of $D$ (in $D>0$ region). For $t\geq 23$ ns a small rapid drop of the population of the upper laser level $n_r$ is observed (figure 3a) alongside with a drastic (almost to zero) fall of the $D$ value (figure 3b). Therefore, laser gain constant drops as well. This is due to the rapid evolution of the lasing pulse at the considered time instants (see figure 2b) and, consequently, to intensive depopulation of the upper laser level to the lower one by virtue of induced transitions. However, the following pulsation of $T_e$ (at $t\sim 50$ ns time scales) again results in a substantial growth (peak) of the $D$ value (figure 3b) and, consequently, it results in the appearance of a second peak in the laser pulse (figure 2b). The subsequent (at $t\geq 60$ ns) pulsations of $T_e$ do not give rise to $D$ and $W_{las}$ peaks as the temperature drops...
below 2 eV and the rate constant for the electron impact-induced excitation of the upper laser level of copper atoms becomes smaller than the corresponding constant for the lower laser level.

In our ICVL optimization calculations [5] for the specified physical and geometrical parameters \((U(0), C, f_{tr}, f, T_{in}, P_{Ne}, \text{and others})\) we managed to find the regions that provided from five to six peaks of the inverse population \(D\) and emission \(W_{las}\) that followed with a frequency of \(2f_{tr}\) within the pump train. In these conditions the total duration of the lasing pulse grew up to \(\sim 80\) ns. Such laser generation was obtained in the numerical experiments when low values of the pre-pulse concentration of electrons \(n_e(0)\) were involved. In other regions of the specified parameters for high values of \(n_e(0)\) the inverse population \(D\) and the emission \(W_{las}\) contained a single peak. The width of the emission peak (at half-maximum) was \(\sim 5 - 8\) ns and its amplitude exceeded 1 MW.

3. Conclusion

In general, the dynamic behaviour of the kinetic parameters and laser generation of the ICVL pumped by HF current pulse trains reveal a more complicated and diverse character as compared to a conventional copper vapour laser. The calculations predict a number of new effects and features of laser generation. It should be noted that in the present work the output power was as high as 170 W for the discharge chamber volume of 1.7 l with physical and technical efficiencies being equal to 3.7% and 1.9%, respectively. Certainly, all the conclusions drawn here require experimental verification. However, even now it is possible to argue that the obtained results may serve as the ideological basis for future applications in the development of analogous lasers based on self-terminating transitions of other metal atoms as well as for designing various state-of-the-art devices involving HF discharge, such as plasmotrons, low-temperature plasma, etc.

The results of the numerical experiments demonstrate the potential for the development of efficient ICVLs and their practical applications.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project no. 17-08-00410.

References

[1] Malikov M M, Kazaryan M A and Karpukhin V T 2015 Bull. Lebedev Phys. Inst. 42 138
[2] Batenin V M, Kazaryan M A, Karpukhin V T, Lyabin N A and Malikov M M 2016 Plasma Phys. Rep. 42 1057
[3] Direktor L B, Karpukhin V T and Malikov M M 2014 High Temp. 52 428
[4] Kazaryan M A, Malikov M M, Karpukhin V T and Lyabin N A 2017 J. Phys. Conf. Ser. 826 012003
[5] Batenin V M, Kazaryan M A, Karpukhin V T and Malikov M M 2017 High Temp. 55