The use of Inductive Discharge for Laser Pumping of a Copper Vapor
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Results of numerical simulation re presented for copper vapor laser (CVL) excitation by a pulse-periodical inductive discharge. A CVL realization with a coaxial discharge chamber is studied. It was shown that a coaxial chamber is better matched with specific features of inductive pumping method than an ordinary cylindrical chamber. High lasing output characteristics are obtained in numerical experiments, which confirms possibility of efficient pumping CVL by a new inductive method.

Key words: copper vapor laser, inductor, transformer, inductive discharge, coaxial chamber, numerical simulation, laser kinetics.

INTRODUCTION

Study of various methods for exciting an active medium of lasers on self-contained transitions of metal atoms [1] is associated with a tendency to enhance output characteristics and obtain certain technical and operational advantages. A pulse-periodical inductive discharge of the transformer type was suggested long ago for exciting gas lasers [2-4]. This method was successively employed in [5-7] and other works for pumping lasers on atom and molecular working media. For the first time the inductive method was tested for exciting copper vapor laser in experimental work [8], and, although lasing was not observed, this work stimulated further investigations. First results of numerical experiments [9, 10] on exciting CVL by an inductive discharge confirmed the possibility of creating such lasers. Note that the nonelectrode inductive excitation is interesting from fundamental point of view as well. For example, in certain conditions, pulsed magnetic fields arising in plasma may change spectroscopic and electric characteristics of discharge plasma. In this work we present results of numerical simulation of operation of an inductive copper vapor laser (ICVL) with a coaxial chamber. The results are compared to those of work [10] where a cylindrical chamber was used. Physical conditions and constructive parameters are discussed, in which efficient lasing may be reached.

PHYSICAL MODEL AND PROBLEM STATEMENT

A simplest ICVL construction with pulse-periodic pumping by inductive discharge is shown in Fig. 1a. Storage capacitor $C_s$ discharges through switch to inductor $L$, which is a conti-
nuous turn around the heat-insulating volume 2. The active volume (copper vapor and neon) is
arranged in a coaxial gap $\Delta r = (r_2 - r_1)$ between a central ceramic insertion 3 of radius $r_1$ and
external wall of the discharge chamber 4 of radius $r_2$. A pulsed magnetic field of the inductor
creates a vortex electric field $E_r(r,t)$ and azimuthal conduction current in plasma of working mi-
xture. In this case, the conductor is considered as a primary coil of transformer (without core) and
the plasma turn is a secondary coil. A specific feature of ICVL distinct from induction lasers [5-7]
mentioned above is a thick heat insulator, which increases a distance from the plasma turn to the
inductor and substantially reduces the coupling coefficient $K_c$ of a transformer negatively affect-
ing operation of the latter. Other features of ICVL are: high pulse repetition frequency of pumping
(dozens kHz) and comparatively low pre-pulse resistance of plasma ~1 Ohm·cm. To produce in-
verted population of working levels it is necessary to rapidly deposit electric energy into plasma
for a time lapse of ~10 – 100 ns. The temperature of walls 3 and 4 of the discharge tube should be
1900 K, which is needed for maintaining the copper vapor pressure. A pressure of buffer neon gas
is 01-1 atm.

In Fig. 1b one can see a simplified schematic diagram of the pulsed inductive pumping of
the transformer type (with purely inductive coupling of coils). Here $L_1$ and $J_1$ are the inductance
and current of the primary circuit, $L_2$ and $J_2$ are the inductance and current of the plasma turn. The
values of $L_1$, $L_2$ and mutual inductance $M$ were calculated by the formulae from [11]. The electric-
al resistance of the switch $R_{sw}(t)$ was described by the model function capable of specifying the
switching duration and Joule loss in the primary circuit of the transformer. The ohmic resistance
$R_1$ of inductor was taken into account. The initial voltage $U_m(0)$ across the storage capacitor and
the initial inductance $L_{in}$ were prescribed.

From known differential transformer equations [12] and the Kirchoff laws one can derive
the system of equations for the scheme in Fig. 1b.
Resistance of plasma turn $R_{pl}(t)$ depends on the specific electric conductivity $\sigma(r,t)$ and the radial current density distribution in plasma $j(r,t)$. All these values including $R_{pl}(t)$ sharply vary during the exciting pulse. For finding $R_{pl}(t)$ system of equations (1) should be solved in conjunction with equations describing physical processes and $\sigma(r,t)$ in non-equilibrium plasma of working medium. For this purpose we used the model and software of conventional CVL developed earlier [13-15]. A basis of the CVL model was the system of equations describing kinetics of the population of excited atomic levels, electron concentration, balance of electron energy. Also, equations of developing induced emission in an optical plane resonator were used. The model comprised a specially developed method for calculating thermal parameters of working medium and high-temperature elements of laser construction. A large number of energy levels of copper and neon atoms were taken into account as well as a series of elementary processes. Note that in a steady state (with respect to a pulse repetition frequency) regime, the self-consistent values of all plasma parameters were numerically calculated, as well as specific conductivity $\sigma(t)$, current and voltage (in the primary and secondary circuits). The power of Joule heat release was determined, as well...
as electron and gas temperatures, radiation power, and laser efficiency. Note that equations in model [13, 14] are written in zero-dimensional approximation, that is, all plasma parameters including \( \sigma(t) \) are averaged over plasma volume, and transport processes are taken into account approximately. Hence, into the balance of electron energy we put an average power of Joule heat release \( w \) equal to

\[
w = \frac{1}{V_p} \int (\sigma E^2) dV_p \approx \frac{J^2 \cdot R_{\text{rel}}(t)}{V_p},
\]

(here \( V_p \) is the working volume). On the other hand, in order to establish relationship between the effective resistance of plasma turn \( R_{\text{pl}}(t) \) and specific average conductance \( \sigma(t) \) by using (2) one should know the radial dependence of vortex electric field and conductance in a cylindrical volume. There are many works (e.g., [16-18]) devoted to calculation of radial distribution of electric parameters in plasma of inductive discharge. For a conductive solid cylinder the induced vortex field \( E_\phi(r,t) \) in plasma has a maximum near external wall and falls to zero at the cylinder axis. In the case of a hollow cylinder (coaxial plasma volume, see Fig. 1a), the value of \( E_\phi(r,t) \) does not fall to zero on internal wall \( (r = r_1) \) and in the case of weak skin-effect \( (\delta \gg (r_2 - r_1)) \) weakly varies [17] (here, \( \delta \) is the depth of field penetration into a conductive medium). Hence, in a coaxial discharge chamber, more homogeneous plasma can be produced than in a cylindrical chamber, which is a positive factor for lasing. In addition, in this case, description of plasma processes by zero-dimensional model is more reasonable. It will be shown below that employment of coaxial chamber gives a chance to substantially increase the coupling coefficient \( K_c \) of transformer.

In [17, 18], formulae for calculating \( R_{\text{pl}}(t) \) are given as applied to solid or hollow cylinders with uniform conductivity \( \sigma \) and arbitrary penetration depth \( \delta \). The expressions comprise complicated combinations of Bessel functions of the first- and second kinds. Those are rather cumbersome and we omit them here. At \( \delta \gg (r_2 - r_1) \) the expressions for \( R_{\text{pl}}(t) \) take an obvious form [17]. For the solid and hollow cylinders we have, respectively

\[
R_{\text{rel}}(t) \approx \frac{4\pi}{\sigma \ell_{\text{tp}}}, \quad R_{\text{rel}}(t) \approx \frac{4\pi}{\sigma \ell_{\text{tp}}} \left( \frac{r_2^2 + r_1^2}{\ell_{\text{tp}}^2} \right).
\]

Here, \( \ell_{\text{tube}} \) is the length of plasma volume (tube).

In real conditions, plasma conductance is not uniform. In this case, there are no analytical solutions for distributions of electrical parameters. Values of fields \( E_\phi(r,t) \), current densities \( j_\phi(r,t) \), \( \sigma(r,t) \) and total resistance \( R_{\text{pl}}(t) \) are found numerically by solving combined non-stationary one-
dimensional electromagnetic problem and non-stationary one-dimensional equations describing non-equilibrium double-temperature plasma. A detailed review of such calculation models of inductive plasma heating one can find in [16, 18]. In [18], authors recommend to employ formulae similar to (3) as a first approximation. In the present work we will limit ourselves, as was mentioned, to zer-dimensional model of plasma processes and equations (2), (3) combining plasma conductivity with system (1) for electric transformer design.

In numerical simulations we have considered two variants of ICVL construction with coaxial chambers, differing in dimensions and coupling coefficients $K_c$ (see Table). For the basis in the first variant of ICVL we have taken parameters corresponding to ordinary commercial active element LT-30Cu [19]: the working volume is $V_w\approx 280$ cm$^3$, diameter of external envelope is $\sim 10$ cm, nominal value of storage capacitor is $C_{st}=0.5$ nF, and initial voltage across it $U_{in}(0)=28$ kV. The second variant differ by greater geometrical dimensions, volume of the coaxial discharge chamber ($V_w=1410$ cm$^3$) and values of storage capacitor $C_{st}$. In both the variants, the pressure of neon equal to 250 millimeters of mercury, temperature of internal wall $T_4=1823$ °K, copper vapor concentration $1.5\cdot10^{15}$ cm$^{-3}$ were similar and approximately corresponded to the parameters of working medium in LT-30Cu. The pumping pulse repetition frequency was 10 kHz. Inductance $L_{cm}$ of switch circuit was taken $0.5L_1$, resistance $R_1$ of the primary transformer circuit with the skin-effect for copper conductor taken into account was $10^{-3}$ Ohm. The coupling coefficient was calculated by the known formula $K_c = M/\sqrt{L_1L_2}$. The duration of pumping current pulses $\tau_p$ was determined in calculations by the instant when 98-99% of the initial (stored in $C_s$) energy was converted to Joule heat in plasma and on resistances of the switch and primary circuit. In this case the balance equation for electric energy was used [12]:

$$\frac{C_sU_{in}^2(0)}{2} = \left[ \left( L_n + L_1 \right) J_1^2 + \frac{L_2J_2^2}{2} - MJ_1J_2 + \frac{C_sU_{in}^2}{2} \right] + \int_0^\tau \left[ J_2^2 \cdot R_{ns} + J_1^2 \cdot R_{ns} + R_1 \right] dt$$

(4)

The value of $R_{pl}(t)$ was chosen such that 30-40% of stored energy was lost in the primary circuit and in switch, and 70-60% in plasma. Such a proportion is typical for exciting an ordinary CVL with a thyratron switch. Hence, in numerical experiments with inductive pumping we have provided pulsed specific energy deposition into plasma approximately equal to that of ordinary CVL. This approach was chosen to objectively compare CVLs of both the types. In the present work we consider a solid single-turn inductor shown in Fig. 1a.

RESULTS OF NUMERICAL SIMULATION
In the first variant of ICVL (see Table), the inductor of radius $r_{ind}$ directly covers the external envelope of the active element of LT-30Cu and the thickness of heat insulation $\Delta r_{hi} = (r_{ind} - r_{2})$ of active element is reduced from 4 cm to 2.5 cm; in this case the value of $K_c$ is 0.47. Note that in using LT-30Cu with ordinary cylindrical working volume without changing the heat insulator thickness; the value of $K_c$ was only 0.18 [10]. In the second variant, the thickness of heat insulation remains 2.5 cm, however, the inductor radius $r_{ind}$, radius of coaxial plasma volume $r_{2}$, and the lengths of tube (and inductor) $\ell_{tube}$ are increased. As one can see from Table, this also increases $K_c$ to 0.53.

Table. 1. Variants of geometrical and electrical-technical parameters of ICVL.

| Var. No. | $r_1$ cm | $r_2$ cm | $\Delta r_{pl}$ cm | $r_{ind}$ cm | $\Delta r_{hi}$ cm | $\ell_{tube}$ cm | $V_w$ cm$^3$ | $L_1$ nH | $L_2$ nH | $M$ nH | $K_c$ |
|----------|----------|----------|---------------------|---------------|---------------------|-----------------|----------|----------|----------|----------|--------|
| 1        | 2        | 2.5      | 0.5                 | 5             | 2.5                 | 40              | 280      | 25       | 3.6      | 4.4      | 0.47   |
| 2        | 2        | 3.0      | 1.0                 | 5.5           | 2.5                 | 90              | 1410     | 13       | 1.9      | 2.6      | 0.53   |

DISCUSSION

Calculations and results presented [10] show that in the inductive excitation of CVL, the pumping current pulse is a train of high-frequency oscillations with the period of 10-30 ns. whereas in ordinary CVL the pulse of current has a shape close to aperiodic discharge with a duration of 150-200 ns. High frequency of current oscillations is related with that the inductance of plasma turn, inductance of the inductor, and the coefficient of coupled induction are by two-three orders of magnitude less than the inductance of the discharge circuit in conventional CVL with longitudinal discharge between electrodes (at similar $V_w$). Note that the effective resistance of plasma $R_{pl}$ is less by approximately two orders of magnitude than the resistance of longitudinal discharge in ordinary CVL (at similar values of $\sigma$). The latter is related with a large transversal cross-section of azimuth current and short length along current (for a single azimuth run). By these parameters the considered coaxial ICVLs are closer to so-called CVL with transversal discharge (see, e.g., [20]).

CONCLUSION

Results of numerical study [9, 10] and the present work confirm possibility of creating efficient CVL excited by pulse-periodic inductive (non-electrode) discharge. Preliminary calcula-
tions show that at a higher coupling coefficient one can reach the power and efficiency of emission typical for conventional CVLs.

ICVL with coaxial discharge chambers may have even higher coupling coefficients. In the numerical experiments discussed above, high radiation power was obtained at the level of 100 W, substantial efficiency of about 5% and technical efficiency of 1.5-3% were attained. These calculated efficiencies are higher than efficiencies of ordinary CVLs operated on pure mixtures of copper and neon. Analysis performed in the present work shows that in the whole coaxial discharge chambers are better suited for creating ICVLs on this bases than cylindrical chambers.

For estimating prospects for creating efficient ICVLs and employing them in practice it is necessary to thoroughly study operation of such lasers and optimize them with respect to the main physical and technical prescribed parameters with the aim of determining limiting output characteristics. Employment of inductive pumping, probably, will help solving the problem of long-term service time and reliability of sealed-off laser elements. Creation of efficient ICVLs substantially expands the range of CVL applications in industry, precious micro-treatment of materials [19], in selective technologies, physical investigations, diagnosing multi-phase gas flows [21, 11], medicine etc.

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