Effect of hydrogen admixtures on the performance characteristics of Kristall LT-40 active element of a copper-vapor laser

A.M. Boichenko,[1] G.S. Evtushenko,[2,3] O.V. Zhdaneev,[2,3] and S.I. Yakovlenko[1]

[1] *Institute of General Physics, Russian Academy of Sciences, Moscow*
[2] *Tomsk Polytechnic University, Tomsk*
[3] *Institute of Atmospheric Optics,*
Siberian Branch of the Russian Academy of Sciences, Tomsk

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The earlier developed detailed kinetic model of the Cu–Ne–H_2 laser active medium is applied to theoretical analysis of experiments carried out at the Istok State Research & Production Enterprise (Fryazino, Moscow Region, Russia) with a Kristall LT-40 active element. The model's capability of describing adequately a wide range of experimental conditions has been demonstrated.

Introduction

Fabrication of up-to-date systems for high-speed recording of optical information, microprocessing of materials, remote sensing of the atmosphere, laser isotope separation, and many other applications require development of highly sophisticated lasers operating in the visible spectral region. This class of lasers includes the lasers generating at transitions from resonance to metastable levels of atoms and metal ions. These lasers combine high pulse and mean output power, high repetition frequency of pump pulses, and excellent quality of the output beam, along with the possibility of generating ultraviolet radiation at ion transitions, as well as high reliability and long service life.

One of the key points in the history of these lasers was the use of hydrogen admixture to the active medium of a copper vapor laser that was proposed in Ref. 1. Besides, the extension of the range of optimal frequencies was achieved in Ref. 1 owing to the admixture of molecular hydrogen. It is now impossible to determine exactly the time, starting from which hydrogen has been used as an active admixture, because hydrogen is released by an active element and often was present in the discharge, but remained beyond the control of researchers. The targeted study of positive effects caused by hydrogen admixtures has led to significant improvement of both frequency and power characteristics of lasers along with the increase in the quality of output beam (see, e.g., Ref. 2).

The positive effect of hydrogen added to a laser active medium was noticed in 1980 (Ref. 1) as early; nevertheless, now (more than 20 years later) the commonly accepted point of view concerning the mechanisms of influence of the hydrogen admixture does not yet exist. There are about ten hypotheses concerning this issue, and each of them is based on one or another experiment or theoretical result. The detailed analysis of these hypotheses can be found in Refs. 3 and 4.

As has already been mentioned, because of uncontrollable hydrogen adsorption and emission by the active element, its purposeful use as an active admixture is difficult, especially, under industrial conditions. In this connection, the Pulsed Technologies Enterprise (Ryazan, Russia) recently has started production of hydrogen generators to be installed in active elements of metal and metal compound vapor lasers in order to carry out controllable hydrogen addition (or removal) to the active medium. The first versions of hydrogen generators made from titanium sponge saturated with hydrogen degraded quite quickly because of chemical reactions with halogen-containing gases.[5] The next versions used nickel and palladium selective membranes to overcome this problem.[6] It has recently been reported that the Istok State Research & Production Enterprise (Fryazino, Russia) began batch production of Kristall LT-30, -40, -50, and -70 sealed-off active elements with hydrogen admixture,[7] which allowed almost 1.5 times increase in the output power with the use of a thyratron switch.

To analyze the effect of hydrogen admixtures on the performance characteristics of a copper vapor laser, we have developed a detailed nonstationary kinetic model.[3,4] For a comparison of the model results with the experiment, we used the data of Refs. 2, 8, and 9, in which the working pressure ranged from 30 to 40 Torr. Commercially available Kristall LT-30, -40, -50, and -70 sealed-off active elements (Istok, Russia) have much higher neon pressure, in particular, 180 Torr for Kristall LT-40. So, now it is possible to test the developed kinetic model against the experimental results under considerably different working conditions and thus to check our earlier conclusions concerning the mechanisms of influence of hydrogen admixtures on the processes in the laser active medium under these conditions.

1. Kinetic model

The detailed description of the kinetic model of Cu–Ne–H_2 laser can be found in Refs. 3 and 4. The model developed allows analysis of time variations in the volume-average populations of the copper atomic levels as well as molecular and atomic hydrogen levels, the density of copper and hydrogen ions, electron temperature, and the intensity of laser radiation at the green and yellow lines of the copper atom, etc.

In this study, we used the experimental dependence of the current in the gas-discharge tube (GDT) presented in Refs. 10–12 for the Kristall LT-40 active element.

Nonstationary equations for the concentrations of various reagents of the plasma of the laser active medium and balance equations for the electron temperature (a total of 39 equations) were solved consistently using the PLAZER software.[13,14] The model includes a total of about 200 kinetic reactions.

2. Comparison with the experiment

Below we compare the results of simulation with the experimental data presented in Ref. 7. The experiments have been conducted at the Istok State Research & Production Enterprise with Kristall LT-40 active element equipped with a thyratron switch; the GDT parameters used in the calculations are given below.

Table 1. GDT parameters[7]

Length of the active medium, cm	123
GDT diameter, cm	2
Pump pulse repetition frequency, kHz	10
Neon pressure, Torr	180

Of the greatest interest is to compare the experimental and theoretical dependences of the mean output power on the amount of hydrogen admixture. In Ref. 7 it was mentioned that the introduction of a hydrogen admixture led to heating of the GDT wall. This must increase the copper concentration in the laser active medium. At the optimal concentration of molecular hydrogen (4–6%) the increase in the temperature was about 50 K (up to 1823 K) as compared with the temperature of 1773 K corresponding to no hydrogen admixture in the medium. In the calculations, it was assumed that the GDT temperature increases linearly with the increase of the hydrogen admixture, and the 50 K increase corresponded to the 5% admixture. The initial concentration of copper in the ground state in the calculations was determined from its relation[15] to the GDT temperature

$$\log\frac{N'_{\rm Cu}}{N_{\rm Cu}} = 0.4477(T_{\rm g}'^{0.7261} - T_{\rm g}^{0.7261}) - 0.03698(T'_{\rm g} - T_{\rm g}),$$

where $N_{\rm Cu}$ is the initial concentration, in $\rm m^{-3}$, $T_{\rm g}$ is the GDT initial temperature, in K; $N'_{\rm Cu}$ and $T'_{\rm g}$ are the finite values.

Unfortunately, Ref. 7 does not present the oscillograms of the GDT current and voltage pulses at different hydrogen admixtures in the active medium, and it is only indicated that the amplitude of the discharge current decreases, while the peak value of the voltage pulse increases. Note that the decrease of the current amplitude at addition of various admixtures was observed in different experiments (see, for example, Ref. 2).

In the simulation, we used two dependences of the current on the concentration of hydrogen admixtures. In the first case, the time behavior of the current was assumed constant, corresponding to the current without hydrogen admixtures. In the second case, the dependence was assumed constant for admixtures up to 5%, and for the last value of 8% the maximum current value decreased in such a way, that the qualitative behavior of the calculated and experimental output energy was identical (Fig. 1). For this purpose, it turned out sufficient to decrease the maximum current value by 30%. So, the decrease of the maximum current value needed for description of the experimental data proves to be reasonably acceptable.

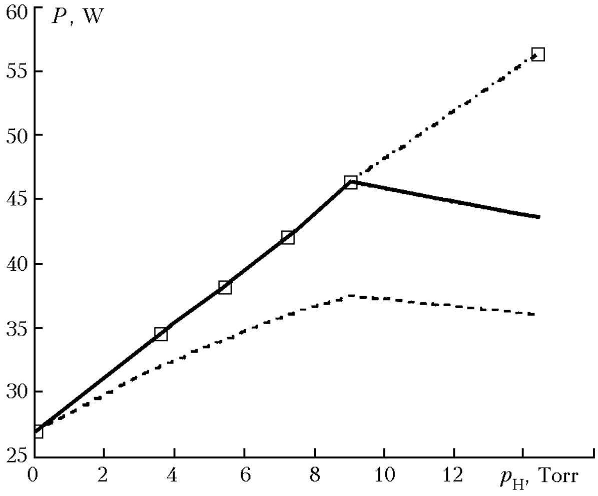

Fig. 1. Dependence of the mean output laser power on the pressure of the hydrogen admixture. Experiment (dashed curve), calculation (dash-and-dot curve and squares) at constant dependence of GDT current on time; for the last value of hydrogen admixture (8%) the GDT current value decreased by 30% (see Table 2) (solid curve).

The experiment with a Kristall LT-40 active element was conducted at the pump pulse repetition frequency of 10 kHz and the parameters of the active medium significantly different from those in Refs. 3 and 4. How does this change in the active medium parameters affect the earlier[3,4] conclusion that the mechanisms of influence of the hydrogen admixture are different at different pump pulse repetition frequencies?

Recall that in Refs. 3 and 4 it was shown that at high frequencies ($f \gg 10$ kHz) the output laser power increases due to a decrease in the pre-pulse concentration of electrons and copper atoms in the metastable state, as well as the increase in the rate of recovery of the copper concentration in the atomic ground state.

When operating at low repetition frequencies ($f \sim 10$ kHz), the mechanisms mentioned above become insufficient. The increase in the output laser power occurs due to the increase in the concentration of copper atoms in the active medium because of GDT heating at addition of the hydrogen admixtures and simultaneous decrease of the pre-pulse concentration of atoms in metastable states due to quenching of these levels by molecules in the vibrationally excited states.

This conclusion proved to be also valid under the experimental conditions considered in this paper. Without the increase in the copper atoms concentration, the decrease of the pre-pulse concentrations of electrons and copper atoms in the metastable states turned out insufficient to compensate for energy loss due to inelastic processes with participation of hydrogen.

As an illustration, Table 2 presents the initial calculated values of the plasma parameters for different concentration of the hydrogen admixture with regard for the change in the concentration of copper atoms in the ground state. The increase in the content of the hydrogen admixture in the laser active medium leads to a monotonic decrease in the pre-pulse concentration of electrons and copper atoms in the metastable states. As this takes place, the initial concentration of all vibrationally excited hydrogen molecules decreases because of a decrease in the pre-pulse electron temperature, and the pre-pulse concentration of vibrationally excited hydrogen molecules, as well as copper atoms in the metastable states, at the low pump pulse repetition frequency, can be well estimated by the Botzmann distribution. Note that the concentration of CuH molecules in the active medium is low. For illustration, Fig. 2 depicts the time behavior of the electron concentration and temperature, as well as the population of copper atoms in the ground state.

Conclusion

The earlier developed kinetic model of the active medium of a copper-vapor laser with hydrogen admixtures has been used for theoretical analysis of operation of a Kristall LT-40 active element.[7] The experimental conditions taking place in this element differ widely from those considered in Refs. 3 and 4.

As some hydrogen admixtures are added to the active medium of the copper vapor laser, one can observe the decrease in the maximum value of the current through the GDT. The same is observed for addition of molecular hydrogen.[7] A good agreement was obtained between the experimental and calculated dependences of the mean output power on the percentage of the hydrogen admixture at a reasonable decrease of the maximum current value in the calculations (see Fig. 1).

Table 2. Pre-pulse values of plasma reagents at the frequency of 10 kHz

Parameter	$N_H = 0$, $N_{H_2} = 0$ cm^{-3}	$N_{H_2} = 8.27 \cdot 10^{14}$ cm^{-3}	$N_{H_2} = 3.2 \cdot 10^{15}$ cm^{-3}	$N_{H_2} = 1.6 \cdot 10^{16}$ cm^{-3}	$N_{H_2} = 2 \cdot 10^{16}$ cm^{-3}	$N_{H_2} = 3.2 \cdot 10^{16}$ cm^{-3}
N_{Cu}, cm^{-3}	$1 \cdot 10^{15}$	$1.277 \cdot 10^{15}$	$1.424 \cdot 10^{15}$	$1.587 \cdot 10^{15}$	$1.765 \cdot 10^{15}$	$2 \cdot 10^{15}$
I, A	400	400	400	400	400	300
N_{Ne^+}, cm^{-3}	$8.43 \cdot 10^{12}$	$6.95 \cdot 10^{12}$	$5.32 \cdot 10^{12}$	$4.65 \cdot 10^{12}$	$3.83 \cdot 10^{12}$	$2.09 \cdot 10^{12}$
N_{Cu^+}, cm^{-3}	$8.44 \cdot 10^{12}$	$5.73 \cdot 10^{12}$	$5.92 \cdot 10^{12}$	$4.61 \cdot 10^{12}$	$4.3 \cdot 10^{12}$	$3.69 \cdot 10^{12}$
$N_{D5/2}$, cm^{-3}	$2.52 \cdot 10^{11}$	$1.85 \cdot 10^{11}$	$1.42 \cdot 10^{11}$	$9.58 \cdot 10^{10}$	$7.91 \cdot 10^{10}$	$5.43 \cdot 10^{10}$
$N_{D3/2}$, cm^{-3}	$2.82 \cdot 10^{10}$	$1.88 \cdot 10^{10}$	$1.32 \cdot 10^{10}$	$7.85 \cdot 10^{9}$	$5.99 \cdot 10^{9}$	$3.34 \cdot 10^{9}$
T_e, eV	0.145	0.137	0.13	0.121	0.116	0.103
N_H, cm^{-3}	–	$1.36 \cdot 10^{15}$	$1.71 \cdot 10^{15}$	$2.31 \cdot 10^{15}$	$2.64 \cdot 10^{15}$	$3.1 \cdot 10^{15}$
N_{H^-}, cm^{-3}	–	$9.6 \cdot 10^{8}$	$7.96 \cdot 10^{8}$	$6.01 \cdot 10^{8}$	$5.16 \cdot 10^{8}$	$3.67 \cdot 10^{8}$
N_{CuH}, cm^{-3}	–	$2.47 \cdot 10^{10}$	$1.17 \cdot 10^{10}$	$2.39 \cdot 10^{9}$	$1.64 \cdot 10^{9}$	$4.69 \cdot 10^{9}$
N_{H_2}, cm^{-3} ($\nu = 1$)	–	$1.31 \cdot 10^{14}$	$1.06 \cdot 10^{14}$	$6.33 \cdot 10^{13}$	$4.47 \cdot 10^{13}$	$2.24 \cdot 10^{13}$
E_{510}, J/cm^3	$2.14 \cdot 10^{-6}$	$5.86 \cdot 10^{-6}$	$6.45 \cdot 10^{-6}$	$7.04 \cdot 10^{-6}$	$7.71 \cdot 10^{-6}$	$7.37 \cdot 10^{-6}$
E_{578}, J/cm^3	$0.86 \cdot 10^{-6}$	$3.06 \cdot 10^{-6}$	$3.43 \cdot 10^{-6}$	$3.83 \cdot 10^{-6}$	$4.24 \cdot 10^{-6}$	$3.97 \cdot 10^{-6}$
E_t, J/cm^3	$3.00 \cdot 10^{-6}$	$8.92 \cdot 10^{-6}$	$9.88 \cdot 10^{-6}$	$10.9 \cdot 10^{-6}$	$12 \cdot 10^{-6}$	$11.3 \cdot 10^{-6}$

Note. The initial values of the plasma reagents are obtained by a consistent calculation. E_t is the total specific output energy per single pulse; E_{510} is the specific output energy at the wavelength of 510.6 nm; E_{578} is the specific output energy at the wavelength of 578.2 nm.

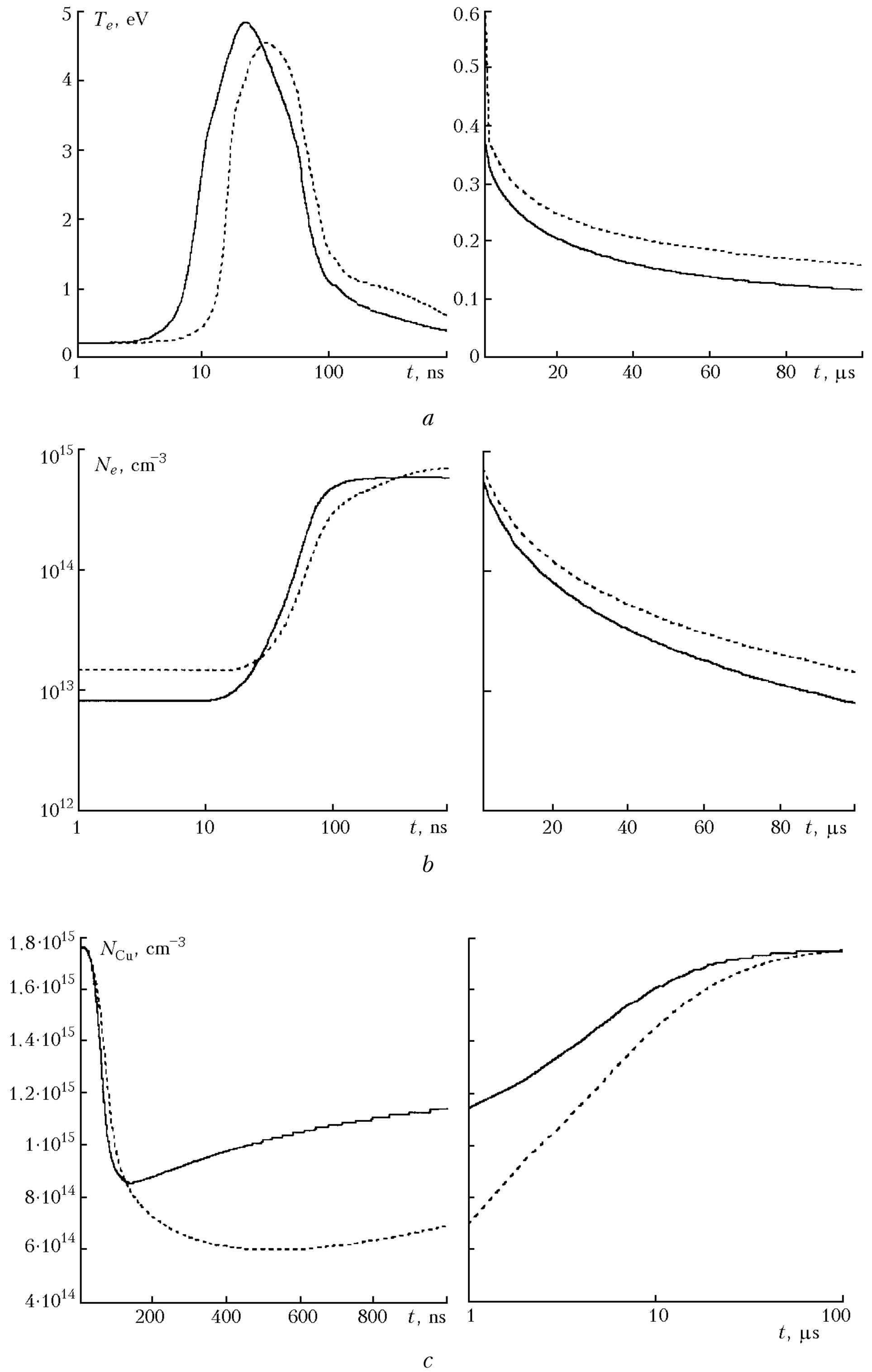

Fig. 2. Time behavior of the electron temperature (*a*) and concentration (*b*), as well as the concentration of copper atoms in the ground state (*c*) during the pump pulse and in the interpulse gap (solid curve corresponds to the initial concentrations N_{H_2}= 5%, N_{Cu} = $1.765 \cdot 10^{15}$ cm^{-3}; while the dashed curve is for N_{H_2} = 0%, N_{Cu} = $1 \cdot 10^{15}$ cm^{-3}). The GDT parameters are presented in Table 1, the pre-pulse values of the plasma reagents used in the calculations are presented in Table 2.

The conclusions in Refs. 3 and 4 on the mechanisms of improving the performance characteristics of copper vapor lasers with hydrogen admixtures have been confirmed under the conditions significantly different from those considered in Refs. 3 and 4.

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