

DISCUSSION

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On the simulation of a copper vapour laser with hydrogen admixtures

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***Abstract*. The results of computer simulation of a pulsed copper vapour laser with hydrogen admixtures presented in [1 – 4] are discussed. It is pointed out that the simulation technique used in these papers has a number of serious drawbacks. In particular, it is shown that the prepulse electron temperature obtained with its help is much lower than the temperature of the wall of the gas-discharge tube, which is in direct contradiction with the thermodynamics. Possible reasons for the erroneous results obtained in these works are discussed.**

Keywords: *pulsed copper vapour laser, effect of hydrogen admixtures, computer simulation.*

In a large article published by A.M. Boichenko et al. in Quantum Electronics [1], a theoretical model of a copper vapour laser (CVL) with hydrogen admixtures was described and the results of calculations of lasing and pulse discharge plasma parameters were presented. The same problem was also considered in subsequent publications of these authors [2 – 4]. All these publications used the same model having the following basic features.

(i) In most cases, the processes proceeding in a pulsed power supply system are not simulated, and a current pulse $J(t)$ passing through the gas-discharge tube (GDT), measured in the regular pulse mode, is used. The authors use $J(t)$ to calculate the volume-averaged plasma and lasing parameters. For this purpose, some initial conditions are specified and iterations are carried out for the same value of $J(t)$, i.e., the processes in excitation pulses and in the intervals between pulses are successively calculated until the results no longer vary from pulse to pulse. The obtained results were termed by the authors as *self-consistent*.

(ii) The equations for gas temperature T_g are not solved and the values of T_g are not indicated in the papers.

The results of simulation in [1, 2] are compared with the results of simulation of the same lasers in [5, 6]. The statement by the authors of [1, 2] about a good agreement of results with those obtained in [5, 6] is not justified in our opinion. The limited volume of this communication does not allow a comprehensive analysis of the results presented in [1 – 4], and a detailed account is presented in [7]. We shall consider here only the results of calculaton of the prepulse electron temperature T_e and population densities $N(^2D)$ of the lower laser levels that have caused the maximum objections.

In most cases, the electron temperatures T_e calculated in [1 – 4] are much lower than the reasonable estimates of T_g and often even lower than the GDT wall temperature T_w. For example, Table 1 presents the results of calculations from Refs [3, 4] pertaining to the 'Kristall-LT-40' laser. One can see that as the concentration of hydrogen, and hence the value of T_w, increases, the temperature T_e decreases continuously, remaining below T_w and T_g all the time. One can see from Table 1 that low values of T_e lead to low prepulse values of $N_{D_{5/2}}$ (see Table 1), which are always lower than the equilibrium values corresponding to T_w. Thus, the values of T_e and $N_{D_{5/2}}$ calculated in [3, 4] are obviously erroneous and simply contradict the laws of thermodynamics. The results of simulation presented in [1, 2] also contain analogous errors, although they are not so noticeable in this case.

Table 1. Prepulse values of T_e and population densities of metastable copper levels for various hydrogen admixtures for the 'Kristall LT-40' laser.

Parameter	$N_{H_2}/10^{16}$ cm^{-3}					
	0	0.0827	0.32	1.6	2.0	3.2
$N_{Cu}/10^{15}$ cm^{-3}	1	1.277	1.424	1.587	1.765	2
T_e/eV	0.145	0.147	0.13	0.121	0.116	0.103
T_e/K	1683	1590	1509	1404	1346	1195
T_w/K	1773				1825	
$N_{D_{5/2}}/10^{11}$ cm^{-3}	2.5	1.85	1.42	0.958	0.791	0.543
$N_{D_{5/2}}/10^{11}$ cm^{-3} *	3.36				7.608	
T_g/K (estimate [7])					$\geqslant 4300$	

* Equilibrium values corresponding to T_w.

It is astonishing that the authors have failed to notice, nor tried to explain these features in their results of simulation. One would expect that they should have at least explained the process responsible for lowering of the population of metastable levels below the equilibrium population for T_w and T_g. It can be assumed that the authors set T_g equal to T_w (this in itself should lead to serious errors), which resulted in low values of the prepulse T_e. However, this does not explain why the calculated values of T_e are lower than T_w.

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First of all, the question arises why simulation leads to the values of $T_e(0)$ much lower than T_g as well as T_w. This can be explained by two reasons: either some significant electron cooling process is considered in the equation but the inverse process of heating is neglected, or the simulation technique itself may have serious faults. The first of these reasons was not revealed in the papers. Consider the possible flaws in the simulation technique.

It should be noted at once that the model used in [1–4] cannot be considered as *self-consistent*. A certain concept of a self-consistent model has evolved in the world literature. In papers [5, 6, 8–12], where these models are described, the initial conditions for the main parameters of the problem are specified (T_w, N_{Ne}, GDT parameters, characteristics of the pulsed power supply, etc.). The characteristics of excitation pulses are then calculated by iteration in the series of pulses and the kinetics is simulated on this basis, i.e., the values of $T_e(t)$, $n_e(t)$, T_g, population of levels, lasing pulse, and other parameters are calculated. These calculations are performed during the excitation pulse and in the period between pulses until the results no longer vary from pulse to pulse, i.e., until the regular pulse regime is established.

As the number of pulses increases, the gas is heated. This leads to a change in the density of the buffer gas and copper, gradients of T_g, T_e and n_e appear, the values of $n_e(0)$, $T_e(0)$ and their gradients increase, and corresponding changes in kinetics take place. This is accompanied by a considerable change in the parameters $J(t)$ and $U(t)$ of the excitation pulse [13–15], matching of the power supply system with GDT, etc. These processes are interrelated to a large extent. All these variations are calculated in the *self-consistent* models, i.e., the real process of transition to regular pulses is simulated.

In contrast to such an approach, the authors of [1–4] use in their calculations the current pulse $J(t)$ corresponding to the already established regular pulse regime. This current pulse is used in iterations for calculating the prepulse values of the quantities required for calculations. Such iterations do not correspond to any real process since they start from the steady-state regime in which the parameters of the problem no longer vary from pulse to pulse. Such iterations may not lead to correct values of the prepulse parameters.

Serious deviations from the self-consistent model are also due to the fact that the gas temperature was not calculated by the authors of [1–4]. However, it is well known that calculations of T_g are essential since the CVL operation depends considerably on T_g.

In summary, it must be stated that the method of simulation of copper vapour lasers employed by the authors of [1–4] and based on the use of a current pulse measured in the regular pulse regime obviously leads to erroneous values of the prepulse electron temperature. In most cases, this value proves to be much lower than T_g and even T_w. Since the plasma relaxation in a copper vapour laser is determined by three-body recombination, which depends strongly on T_e, it can be concluded that the calculation of $n_e(0)$ is erroneous as well.

Since the laser operation depends considerably on the prepulse parameters, other results and the conclusions drawn in [1–4] must contain serious errors. In particular, the conclusion about mechanism of the effect of hydrogen admixtures and about the factors restricting the attainable pulse repetition rate cannot be treated as justified. Note that the conclusions made in [1, 2] about the mechanism of hydrogen admixture effect differ from those of other authors, including those who used much more substantiated self-consistent models. On the whole, the simulation technique employed in [1–4] is a clear step backward from the previously published self-consistent models [5, 6, 8–12].

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