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Comments to the note by G.G. Petrash on the paper 'On the simulation of a copper vapour laser with hydrogen admixtures'

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***Abstract*. The remarks on the results published in [1 – 4] on the simulation of a copper vapour laser with hydrogen admixtures are analysed. It is shown that these remarks do not affect the conclusions made in our papers, and many of them are simply erroneous.**

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

G.G. Petrash concludes in his note that the results of our papers [1 – 4] are not justified and our model and simulation technique is an obvious step backward compared to the results of earlier papers [5 – 11]. Moreover, he asserts that our conclusion about the mechanism of hydrogen admixture effect differs from those of other authors, 'who used much more substantiated self-consistent models'. These statements are erroneous. Let us start with the last statement.

G.G. Petrash has not given in his note any examples showing a discrepancy between the results published in [1 – 4] and [5 – 11], while we have presented in [1, 2] a comparison of our results with the data from other publications. In particular, our conclusions agree with those made in [5, 6, 10] concerning the role of heating during laser operation at low repetition rates (these are the only operating conditions considered in [5, 6, 10]). The effect of rapid quenching of metastable copper atoms by vibrationally excited hydrogen molecules is discussed in [12, 13] as well as in our publications.

Consider now the statements made by G.G. Petrash in an attempt to prove that our results are 'not substantiated'.

(i) It is stated that our simulation cannot be treated as self-consistent. In the opinion of G.G. Petrash, the concept of self-consistent model lies in the specification of general parameters corresponding to an idle laser at first, followed by the observation of a passage to the operation regime. Naturally, nobody follows such an approach on account of the futility of such calculations and the enormous amount of time required for this purpose. Indeed, the passage to the operation regime in experiments requires more than an hour. The statement made by Petrash that 'the real process of transition to regular pulses is simulated' in [5 – 11] is not true.

(ii) According to G.G. Petrash, the process of iterations for calculating the prepulse values of the concentration of different reagents cannot be used because 'such iterations do not correspond to any real process'. This statement is wrong. The iterations need not correspond to a real process, but must converge to the correct solution. Note that iterations are also used in papers [5, 6], which are set as examples to us by G.G. Petrash.

We have used in our studies the experimental time dependence of current corresponding to steady state conditions. The prepulse values of concentration and electron temperature are iteratively matched with the values calculated for the end of the interval between pulses. It is much more reliable to specify the experimentally measured current pulse in these cases than to simulate the electric circuit for which, moreover, the data are usually insufficient. By the way, we also simulate the electric circuit whenever it is required [1].

(iii) It is also stated that 'serious deviations from the self-consistent model are also due to the fact that the gas temperature T_g is not calculated in [1 – 4]'. However, the gas temperature T_g in fact remains unchanged during a pulse. It is easier and more reliable not to calculate this temperature, and use the experimentally obtained value in the model.

(iv) It is mentioned that the gas temperature T_g is not indicated in the papers. This is indeed true for publications [1, 2]. As a matter of fact, the value of T_g is most important only for determining the prepulse population density of copper atoms in the ground state. While comparing the results of calculations based on our model with the theoretical and experimental results presented in [5, 6], we chose in our calculations the prepulse values of the copper atom concentration in the ground state equal to their values in these very publications. We believe this approach to be more reliable.

The value $T_g = 0.146$ eV used by us in some kinetic calculations in [1, 2] was indeed somewhat lower than the real gas temperature. Therefore, we recalculated the prepulse parameters of various reagents as well as the lasing energy for $T_g = 0.215$ eV. It turned out [4] that the values of lasing energy differ from the earlier values by about 1%. The results of recalculations were presented to G.G. Petrash last year in the thesis [14] (see Tables 1 and 2). The reason behind the insensitivity of the lasing energy to the gas temperature is due to the above-mentioned correct choice of the prepulse copper concentration. As expected, a verifica-

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Table 1. Initial values of plasma reagents obtained in self-consistent calculations [1, 2] at a frequency of 12 kHz ($N_{Cu} = 8 \times 10^{14}$ cm^{-3}; $N_H = 10^{15}$ cm^{-3} for all cases where N_{H_2} is nonzero). Gas temperature $T_g = 0.146$ eV was used in simulations of kinetics.

Parameters of plasma and lasing energy	$N_{H_2}/10^{16}$ cm^{-3}					
	0	0.165	0.33	1.65	3.3	4.95
$N^+_{Ne}/10^{12}$ cm^{-3}	6.25	6.13	5.96	4.25	2.8	2.02
$N^+_{Cu}/10^{13}$ cm^{-3}	1.96	1.9	1.79	1.2	0.835	0.67
$N_{D_{5/2}}/10^{11}$ cm^{-3}	7.54	7.38	6.31	1.94	0.965	0.74
$N_{D_{3/2}}/10^{11}$ cm^{-3}	1.06	1.01	0.866	0.21	0.0823	0.0533
$N^{min}_{Cu}/10^{14}$ cm^{-3}	4.91	5.07	5.2	5.73	5.98	6.16
T_e/eV	0.171	0.17	0.165	0.1465	0.146	0.146
$N_{H^-}/10^9$ cm^{-3}	–	1.63	2.01	2.36	1.8	1.54
$N_{CuH}/10^{10}$ cm^{-3}	–	7.98	11.9	6.35	1.83	0.775
$N_{H_2}/10^{14}$ cm^{-3} ($v = 1$)	–	0.77	1.39	2.8	1.85	1.09
$N_{H_2}/10^{11}$ cm^{-3} ($v = 2$)	–	2.9	4.77	4.08	0.801	0.149
$E_t/10^{-6}$ J cm^{-3}	3.00	2.95	2.92	2.72	2.45	2.20
$E_{510}/10^{-6}$ J cm^{-3}	2.14	2.1	2.09	1.95	1.77	1.61
$E_{578}/10^{-6}$ J cm^{-3}	0.86	0.85	0.833	0.765	0.674	0.59

N o t e. Here and in Table 2, E_t is the total specific lasing energy, E_{510} is the specific lasing energy at a wavelength of 510.6 nm, E_{578} is the specific lasing energy at a wavelength of 578.2 nm, N^{min}_{Cu} is the minimum copper concentration during the excitation pulse. The lasing energy at various gas temperatures ($T_g = 0.146 - 0.215$ eV) varies by about 1 % for the same copper atom densities in the ground state.

Table 2. Initial values of plasma reagents obtained in self-consistent calculations [1, 2] at a frequency of 12 kHz ($N_{Cu} = 8 \times 10^{14}$ cm^{-3}; $N_H = 10^{15}$ cm^{-3} for all cases where N_{H_2} is nonzero). Gas temperature $T_g = 0.215$ eV was used in simulations of kinetics.

Parameters of plasma and lasing energy	$N_{H_2}/10^{16}$cm^{-3}					
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$N^+_{Ne}/10^{13}$ cm^{-3} $N^+_{Cu}/10^{13}$ cm^{-3}	3.3	3.2	3.06	2.08	1.3	0.92
$N_{D_{5/2}}/10^{12}$ cm^{-3}	6.7	6.6	5.6	1.7	0.86	0.66
$N_{D_{3/2}}/10^{11}$ cm^{-3}	9.5	9.1	7.7	1.9	0.74	0.48
$N^{min}_{Cu}/10^{14}$ cm^{-3}	4.9	5.1	5.2	5.7	6.0	6.2
T_e/erV	0.225	0.224	0.223	0.22	0.217	0.216
$N_{H^-}/10^9$ cm^{-3}	–	2.5	3.1	3.6	2.7	2.3
$N_{CuH}/10^{11}$ cm^{-3}	–	2.2	3.2	1.7	0.51	0.21
$N_{H_2}/10^{14}$ cm^{-3} ($v = 1$)	–	0.84	1.5	3.1	2.02	1.2
$N_{H_2}10^{11}$ cm^{-3} ($v = 2$)	–	5.6	9.2	7.9	1.5	0.287
$E_t/10^{-6}$ J cm^{-3}	3.00	2.90	2.92	2.72	2.40	2.20
$E_{510}/10^{-6}$ J cm^{-3}	2.1	2.1	2.1	1.9	1.7	1.6
$E_{578}/10^{-6}$ J cm^{-3}	0.9	0.8	0.82	0.8	0.7	0.6

tion proved that all the results obtained in [1, 2], including the specific values of the critical densities of metastable states, remain valid.

(v) According to G.G. Petrash, the electron temperature T_e in our works is lower than the gas temperature T_g at the end of the interpulse period, which, in his opinion, contradicts the laws of thermodynamics. It should be clarified here that, first, T_e is not lower than T_g in our papers [1, 2], and the rows 3, 4, 6 and 7 in the table presented by Petrash do not contain our data. Second, we have used the kinetic coefficients satisfying the detailed balancing principle, which rules out contradiction with the thermodynamics.

As a matter of fact, T_e may become lower than T_g for some time for a comparatively large concentration of molecular impurities [3–5], and this is not in contradiction with the thermodynamics. The matter is that the excited vibrational states of hydrogen molecule vanish due to chemical reactions considered in models [3–5]. As a result, the excitation of vibrations by electrons is not compensated entirely by the reverse transitions and this leads to a nonequilibrium cooling of electrons.

Note that the electron temperature is lower than the gas temperature in calculations made in [5], whose correctness is not disputed by Petrash. What is more, this publication is set as an example. An analysis of Figs 8, 9 in [5] carried out using the relation between T_g and the concentration of copper atoms in the ground state [9] shows that the gas temperature along the axis of the tube in these calculations is higher than the electron temperature ($T_g > 0.22$ eV, $T_e < 0.19$ eV).

Thus, we have considered all the comments made by G.G. Petrash regarding our publications [1–4]. All the general critical remarks made by him are simply not correct. The authentic particular remarks were taken into consideration by us earlier and it was shown that they do not affect the conclusions made in our works.

References

1. Boichenko A.M., Evtushenko G.S., Yakovlenko S.I., Zhdaneev O.V. *Laser Phys.*, **13**, 1231 (2003).
2. Boichenko A.M., Evtushenko G.S., Zhdaneev O.V., Yakovlenko S.I. *Kvantovaya Elektron.*, **33**, 1047 (2003) [*Quantum Electron.*, **33**, 1047 (2003)].
3. Boichenko A.M., Evtushenko G.S., Zhdaneev O.V., Yakovlenko S.I. *Opt. Atmos. Okean.*, **16**, 1036 (2003)].
4. Boichenko A.M., Evtushenko G.S., Yakovlenko S.I., Zhdaneev O.V. *Laser Phys.*, **14**, 1031 (2004).
5. Carman R.J., Mildren R.P., Withford M.J., Brown D.J.W., Piper J.A. *IEEE J. Quantum Electron.*, **36**, 438 (2000).
6. Cheng C., Sun W. *Opt. Commun.*, **144**, 109 (1997).
7. Carman R.J., Brown D.J.W., Piper J.A. *IEEE J. Quantum Electron.*, **30**, 1876 (1994).
8. Carman R.J., in *Pulsed Metal Vapour Lasers*. Ed. by C.E. Little, N.V. Sabotinov. (Dordrecht: Kluver Academic Publishers, 1996) pp 203–214.
9. Carman R.J. *J. Appl. Phys.*, **82**, 71 (1997).
10. Ivanov V.V., Klopovskii K.S., Mankelevich Yu. A., Motovilov S.A., at al. *Proc. SPIE Int. Soc. Opt. Eng.*, **4747**, 128 (2002).
11. Marshall G.D. *Kinetically Enhanced Copper Vapour Lasers. PhD Thesis* (Clarendon Laboratory, Oxford, 2002).
12. Garcia-Prieto J., Ruiz M.E., Poulain E., Ozin G.A., Novaro O. *J. Chem. Phys.*, **81**, 5920 (1984).
13. Carman R.J., Mildren R.P., Piper J.A., Marshall G.D., Coutts D.W. *Proc. SPIE Int. Soc. Opt. Eng.*, **4184**, 215 (2001).
14. Zhdaneev O.V. *Ph.D. dissertation* (Tomsk: Tomsk Polytechnical University, Institute of Optics of Atmosphere, Siberian Branch, Russian Academy of Sciences; Moscow: General Physics Institute, Russian Academy of Sciences, 2004).