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Numerical simulation of a UV He – Ar – N_2 gas-discharge laser

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***Abstract*.** **A detailed nonstationary kinetic model of a gas-discharge He – Ar – N_2 laser on transitions of the second positive $C(^3\Pi_u) - B(^3\Pi_g)$ system of nitrogen is constructed. The main parameters of the laser are optimised for the three UV laser lines at 358, 381, and 406 nm.**

Keywords: *plasma-chemical kinetics, numerical simulation, nitrogen gas-discharge laser, spiral cathode, energy extraction.*

1. Introduction

Small, simple, durable, moderate-power near-UV (350 – 380 nm) lasers, for example, a laser on transitions of the second positive system $C(^3\Pi_u) - B(^3\Pi_g)$ of nitrogen in a mixture with helium and argon can be used in some fields, in particular, in biophysics. The highest output power at these transitions was obtained in papers [1 – 4]. However, X-ray preionisation lasers using mixtures containing aggressive components NF_3 and SF_6 are too clumsy and short-lived to be used for applications of interest to us. Sulphur hexafluoride under normal conditions is a neutral gas and is used as an insulator in electrotechnical industry. However, in an electric discharge in mixtures with rare gases, a chain of plasma-chemical reactions (ion – ion recombination, harpoon reactions, radiative decay of intermediate exciplex molecules) produces atomic fluorine, which is quite aggressive and corrodes the surfaces of a cathode and optical elements.

A specific feature of a nitrogen laser is the population of the upper working $N_2^*(C,\ \upsilon = 0)$ states during direct excitation energy transfer from metastable $Ar^*(3p^5 4s)$ levels of argon (the kinetics of basic processes in this laser is discussed in detail in [5]). Therefore, to provide the efficient energy transfer to the upper working level, it is necessary to pump efficiently the corresponding levels of argon. The metastable levels of argon can be more efficiently pumped in a discharge in a mixture with helium because its working pressure can be considerably higher than that of heavy rare gases. In this connection we studied the He – Ar – N_2 mixture excited by a discharge with a spiral hollow cathode, which is characterised by the hard component of the electron energy distribution function, i.e. belongs to hard ionisers [6]. However, because the aim of this paper is to study theoretically the limiting possibilities of the given active medium, we considered different pressure combinations, in particular, outside the range admissible for our setup, for the same limiting ionisation frequency. This allows us to estimate the prospects for using other types of a hard ioniser (for example, an open discharge [7]) in the future.

2. Kinetic model of a He – Ar – N_2 laser

We developed a detailed nonstationary kinetic model of a He – Ar – N_2 laser. The model took into account the following components of the active medium (Fig. 1): nitrogen molecules N_2; helium He, argon Ar and nitrogen N atoms; the excited $He^*(^1S)$ and He_2^* states of helium, the $Ar^*(4s)$ and Ar_2^* states of argon, and the states $N^*(^2D)$, $N_2^*(A)$, $N_2^*(B,\ \upsilon = 0)$, $N_2^*(B,\ \upsilon = 1)$, $N_2^*(B,\ \upsilon = 2)$, $N_2^*(B,\ \upsilon = 3)$, $N_2^*(B,\ \upsilon = 4)$, $N_2^*(C,\ \upsilon = 0)$ of nitrogen; helium ions He^+, He_2^+, He_3^+, argon ions Ar^+, Ar_2^+, Ar_3^+, and nitrogen ions N^+, N_2^+, $N_2^{+*}(B^2\Sigma_u^+)$, N_3^+, N_4^+, and heteronuclearions $HeAr^+$. In addition, the model considered the development of lasing at wavelengths 337.1, 358, 381, and 406 nm corresponding to the $C(\upsilon = 0) \to B(\upsilon = 0, 1, 2, 3)$ transi-

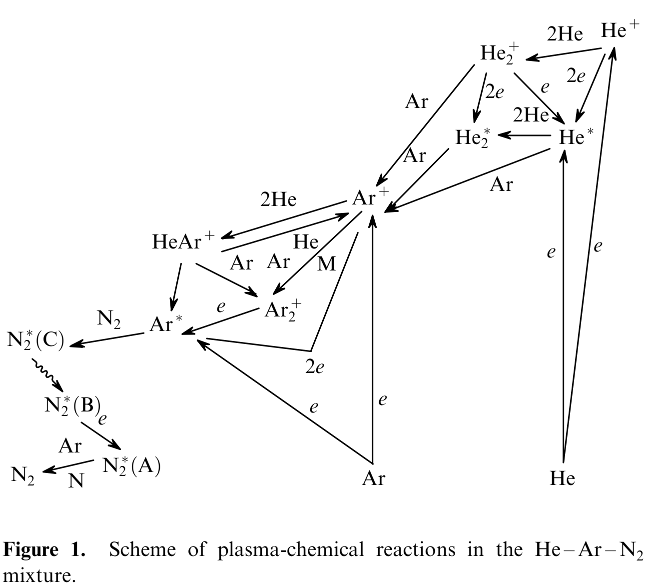

Figure 1. Scheme of plasma-chemical reactions in the He – Ar – N_2 mixture.

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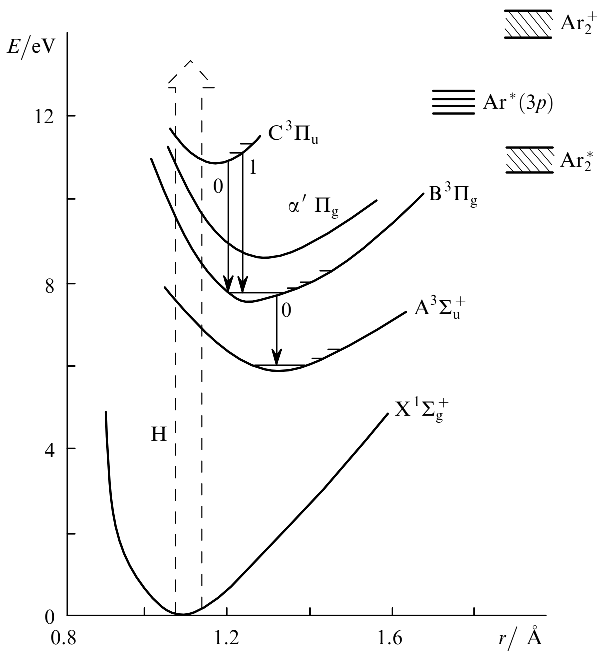

Figure 2. Scheme of the energy terms illustrating the Ar – N_2 laser operation.

tions in nitrogen molecules. The energy terms of a nitrogen molecule are shown in Fig. 2.

The parameters of a pump source were specified for definiteness according to experimental data [6]. A ribbon hollow cathode of diameter 5 mm and ribbon width 1 cm was placed inside a glass discharge tube of diameter 25 mm and length 30 cm. A single bell-shaped discharge pulse had the following parameters: the burning voltage $U = 1-1.5$ kV, the current density $j \leqslant 13$ A cm^{-2}, the pulse duration 3 μs, the pulse repetition rate f could achieve 28 Hz. The cavity length was 100 – 120 cm, and the reflectance of mirrors was close to 100 %.

The stable burning of the discharge is provided when electrons between ionisation collisions acquire from the electric field the energy spent for ionisation, i.e. the relation

$$U/[d(\sigma_{\rm i}^{\rm He}[{\rm He}] + \sigma_{\rm i}^{\rm Ar}[{\rm Ar}] + \sigma_{\rm i}^{\rm N_2}[{\rm N_2}])] > E_{\rm par} \qquad (1)$$

is fulfilled, where $E_{\rm par} \approx 46$ eV is the electron – ion pair formation energy; $[{\rm N}_i]$ are the concentrations of helium, argon, and nitrogen; and $\sigma_{\rm i}$ are the ionisation cross sections for these gases.

In our setup with parameters achieved at present, the relatively stable discharge burning can occur in the He – Ar – N_2 mixture under the condition that the helium pressure does not exceed 100 Torr, while the total pressure of argon and nitrogen does not exceed 14 Torr. Taking into account the gas heating during discharge burning and the gas displacement from the discharge region, the initial working pressure can be even higher.

The approximate volt – ampere characteristic of a stable discharge in our setup is presented in Fig. 3 [6].

3. Numerical simulation results

Calculations were performed by using the parameters of the active medium indicated above. Simulations showed that the output power of the laser increased with increasing j.

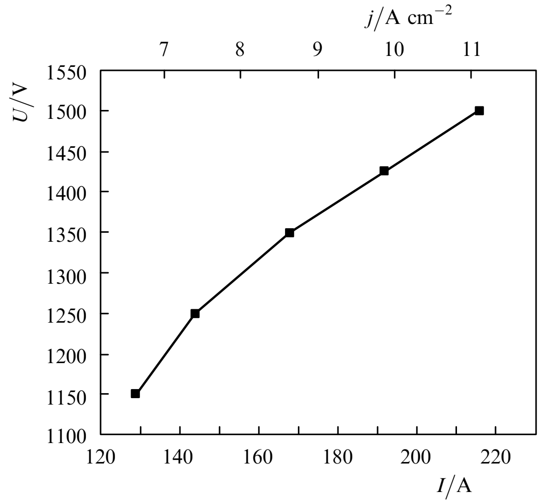

Figure 3. Volt – ampere characteristic of a discharge with a spiral hollow cathode in the N_2 (0.37 Torr) – Ar (2.1 Torr) – He (43 Torr) mixture. The pulse duration is 3 μs, $f = 28$ Hz.

Therefore, calculations were performed for maximal $j = 13$ A cm^{-2} and $U = 1.5$ kV. Under these conditions, the maximum helium ionisation frequency was $v_{\rm i}^{\rm He} = 720$ s^{-1}. All the calculations were performed for this ionisation frequency at the pump pulse maximum. The cavity length was set equal to 1 m and the reflectance of the output mirror was $r = 99.9$ % or 97 % (the second mirror was a highly reflecting mirror). Because lasing has not been obtained in experiments so far, the laser was completely optimised.

The preliminary calculations of the active-medium heating in the discharge region were performed for the repetitively pulsed regime (Fig. 4). It was found that for active-medium temperatures exceeding 600 K, when the heated gas escaped from the discharge volume through slits in the spiral cathode, lasing was quenched due to the decrease in the concentration of particles in the active medium, the corresponding decrease in the energy input and the change in the optimal conditions for lasing. Under typical working conditions for our setup, this occurred after five and smaller discharge pulses. Therefore, to provide stable lasing, the discharge volume should coincide, if possible, with the glass tube volume, i.e. the diameter of the spiral cathode should be approximately equal to the tube

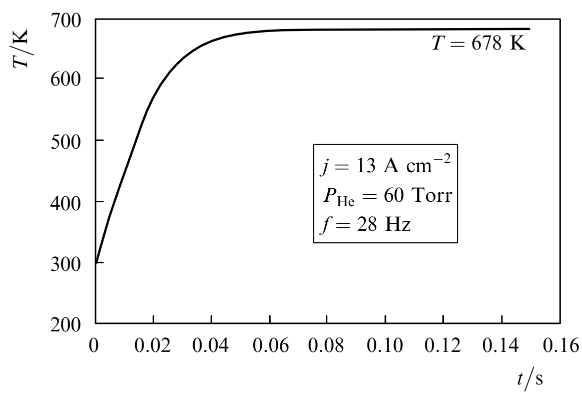

Figure 4. Temperature of the active medium of the He – Ar – N_2 laser in the discharge region during discharge burning.

diameter. We will assume below that the laser operates in the repetitively pulsed regime at the average temperature 600 K.

The main task in the simulation of the laser is to determine the optimal relation between the components of the active medium. In particular, the influence of additions of rare gases into the Ar – N_2 mixture was investigated in some experiments [1, 2]. Therefore, we performed first of all calculations to optimise the composition of the He – Ar – N_2 mixture. Figure 5 presents the dependences of the specific laser radiation energy at three wavelengths on the nitrogen pressure. One can see that the lines at 358 and 406 nm compete with each other. The maxima of the dependences of the output energy at 358 and 381 nm are caused by the collision deexcitation of the lower working levels of transitions at 406 and 381 nm accompanied by the population of the lower working level of the transition at 358 nm:

$$N_2\,(B(v=3)) + N_2 \rightarrow N_2(B(v=2)) + N_2, \quad (2)$$

$$N_2\,(B(v=2,3)) + N_2 \rightarrow N_2(B(v=1)) + N_2. \quad (3)$$

The optimal pressure of nitrogen should be selected in accordance with the required radiation wavelength. Note that the results of calculation in Fig. 5a are presented for the discharge parameters that were already achieved in our setup ($U = 1.5$ kV and $j = 13$ A cm^{-2}), while the results presented in Fig. 5b are obtained for principally possible parameters of the setup satisfying conditions (1) and providing the same ionisation frequency ($U = 2.3$ kV and $j = 18$ A cm^{-2}). When the parameters of the active medium are changed, the required parameters of the discharge can vary, and because of this we used the ionisation frequency as a parameter in our calculations. The required parameters of the discharge could be calculated separately in some cases, if necessary. This also concerns the results presented below. Note that the main pump channel of the upper working level in the entire range of partial pressures of components used in calculations is energy transfer from the metastable states of argon.

Figures 6 and 7 present the dependences of the specific laser radiation energy at different wavelengths on the partial pressures of argon and helium. One can see that the output laser energy increases with pressure in the pressure range under study. This is caused by (i) the increase in the energy input into the active medium with increasing pressure and, correspondingly, in the pump power of the upper working level and (ii) by the excess of collision quenching of the lower working levels by molecular nitrogen over their collision quenching by helium and argon atoms. The working pressure of the laser is determined exclusively by the limiting possibilities of the organisation of a volume discharge in the cathode cavity.

Figure 8 presents the dependences of the specific laser energy extraction on the ionisation frequency. As pointed out above, the energy extraction in the laser increases with increasing pump power.

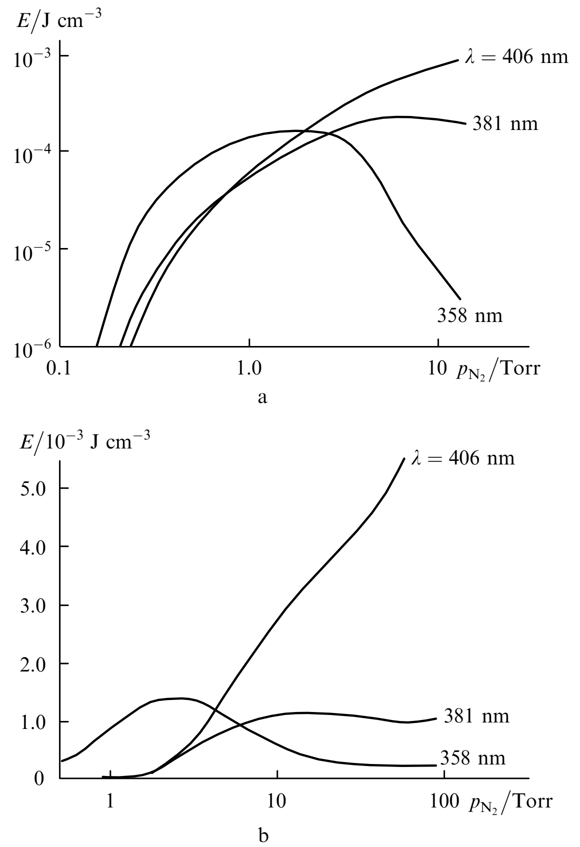

Figure 5. Dependences of the specific laser radiation energy at three wavelengths on the nitrogen pressure for $p_{He} = 43$ Torr, $p_{Ar} = 2.1$ Torr, and $r = 99.9$ % (a) and for $p_{He} = 100$ Torr, $p_{Ar} = 30$ Torr, and $r = 97$ % (b). $v_i^{He} = 720$ s^{-1}, as in Figs 6, 7, 9.

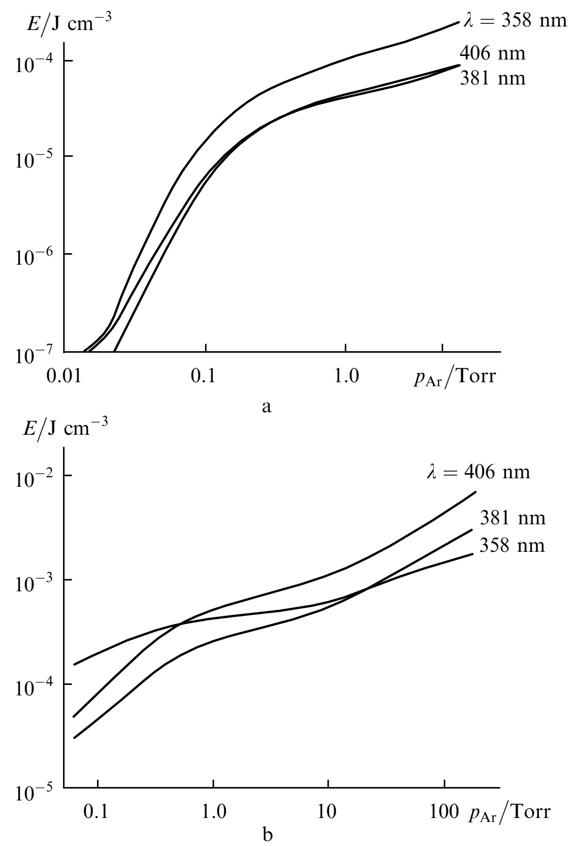

Figure 6. Dependences of the specific laser radiation energy at three wavelengths on the argon pressure for $p_{He} = 43$ Torr, $p_{Ar} = 1$ Torr, and $r = 99.9$ % (a) and for $p_{He} = 100$ Torr, $p_{N_2} = 6.2$ Torr, and $r = 97$ % (b).

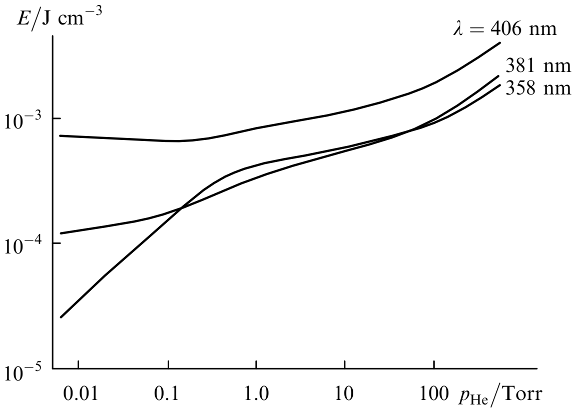

Figure 7. Dependences of the specific laser radiation energy on the helium pressure for $p_{\mathrm{Ar}} = 30$ Torr, $p_{\mathrm{N_2}} = 6.2$ Torr, and $r = 97\,\%$.

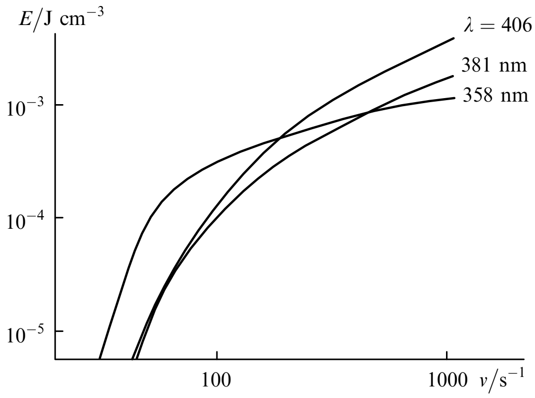

Figure 8. Dependences of the specific laser radiation energy on the ionisation frequency for $p_{\mathrm{He}} = 100$ Torr, $p_{\mathrm{Ar}} = 30$ Torr, $p_{\mathrm{N_2}} = 6.2$ Torr, and $r = 97\,\%$.

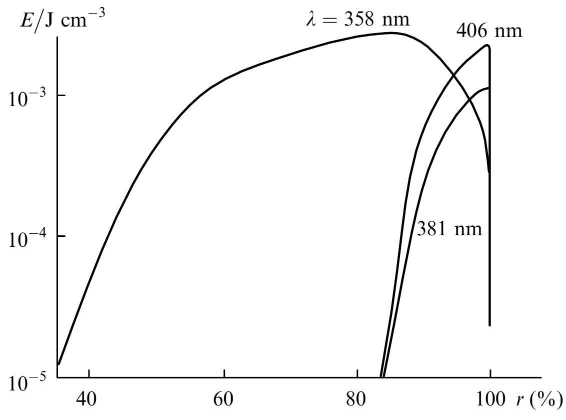

Figure 9. Dependences of the specific laser radiation energy on the reflectance r of the output mirror for $p_{\mathrm{He}} = 100$ Torr, $p_{\mathrm{Ar}} = 30$ Torr, and $p_{\mathrm{N_2}} = 6.2$ Torr.

The optimal reflectances r of the output mirror are 83 % at 358 nm and 99 % at 381 and 405 nm (Fig. 9).

4. Conclusions

The numerical simulation of a nitrogen laser has shown that it is necessary to place a spiral cathode in a glass tube as close as possible to the tube walls. This considerably reduces the displacement of the working gas from the discharge volume of the hollow cathode.

The calculations have shown that lasing can be obtained on the transitions $C(\upsilon = 0) \rightarrow B(\upsilon = 1)$ (358 nm), $C(\upsilon = 0) \rightarrow B(\upsilon = 2)$ (381 nm), and $C(\upsilon = 0) \rightarrow B(\upsilon = 3)$ (406 nm) in nitrogen. No lasing appears on the 337.1-nm $C(\upsilon = 0) \rightarrow B(\upsilon = 0)$ transition, as in experiments [1]. The calculated specific pulse energy was 2 mJ cm^{-3} at the $C \rightarrow B(\upsilon = 1)$ transition, 1.63 mJ cm^{-3} at the $C \rightarrow B(\upsilon = 2)$ transition, and 5.7 mJ cm^{-3} at the $C \rightarrow B(\upsilon = 3)$ transition. The maximum calculated radiation power at 357.7 nm is 0.2 W.

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