NUMERICAL SIMULATION OF A He-Ne-Ar-H_2 LASER PUMPED BY A HARD IONIZER

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A detailed nonstationary kinetic model of the Penning plasma laser based on neon in mixture He-Ne-Ar-H_2 *(*λ = 585.3 nm*) considering the influence of nitrogen admixtures has been developed. The model describes adequately the experimental results on e-beam and nuclear pumping of* He-Ne-Ar, Ne-H_2, *and* He-Ne-Ar-H_2 *mixtures obtained by different experimental groups and allows one to optimize the laser with a high degree of reliability.*

INTRODUCTION

In the last few years many papers have evolved devoted to the study of the Penning neon plasma laser with e-beam or nuclear pumping. Experimental and theoretical study of plasma chemical and radiative processes in active medium of this laser is currently in progress (for more details, see Ref. 1). This calls for revision and considerable modification of existing kinetic models of He-Ne-Ar and Ne-H_2 lasers. In this paper, modified kinetic models and results of numerical simulation of these lasers with e-beam and nuclear pumping considering the influence of small nitrogen admixture concentration are presented.

Since nuclear pumped He-Ne-H_2 (Ref. 2) and Ne-H_2 (Ref. 3) lasers as well as improved performance characteristics of He-Ne-Ar laser with small additions of hydrogen[4,5] have already been reported, we have developed and examined a model of He-Ne-Ar-H_2 laser operation under the influence of nitrogen admixtures.

KINETIC MODEL

Our calculations were based on the modified kinetic model of a He-Ne-Ar laser at $3p'[1/2]_0$ – – $3s'[1/2]_1$ transition of neon atoms with λ = 585.3 nm (Refs. 6–9). More accurate values of rate constants of the main plasma chemical reactions were used, new important processes were included, and some extra reactions were excluded. In analogy with Refs. 6–9, the following species were considered in the model: He^*, Ne^*, Ar^*, Ar^{**}, Ne_2^{**}, Ne_2^*, He_2^*, $HeNe^*$, Ar_2^*, He^+, Ne^+, Ar^+, He_2^+, Ne_2^+, Ar_2^+, He_3^+, Ne_3^+, Ar_3^+, and $HeNe^+$. The level-to-level kinetics of neon atoms included four groups of atomic states: ($3s$, $3s'$), ($3p$, $3p'$), ($4s$), and ($5s$) and two individual levels $3p'[1/2]_0$ and $3s'[1/2]_1$.

Influence of mixture composition as well as of resonator and pumping parameters on laser output was examined by numerical modeling. Since the effect of nitrogen admixtures was of interest, our model also included the following species: N^+, N_2^+, N, and N_2.

In addition to the above-enumerated species, the kinetic model of the He-Ne-Ar-H_2-N_2 laser included H^+, H_2^+, H_3^+, $H_2(v)$, H, HeH^+, He_2H^+, HeH_2^+, NeH^+, Ne_2^+H, ArH^+, Ar_2H^+, ArH_2^+, HeH^*, NeH^*, Ne_2H^*, and ArH^*. Rate constants were presented mainly in Refs. 8, 10, and 11.

Particle number density balance equations were solved together with equations for gas and electron temperatures. Thus, the number of equations reached 47, and the number of plasma chemical reactions reached 300. Software package PLASER was used in our calculations.[12,13]

RESULTS OF CALCULATIONS

The model developed was verified in experiments with Ne laser operating at λ = 585 nm in mixtures He-Ne-Ar, Ne-H_2, and He-Ne-Ar-H_2 and pumped by e-beams of nanosecond or microsecond duration as well as in experiments with nuclear pumping (see Ref. 1 for more details).

Let us now turn to the discussion of results. Figure 1 shows laser output power versus argon pressure in gas mixtures of different purity simulating experimental conditions described in Refs. 14–16. Optimal argon pressure is determined, on the one hand, by higher degree of depopulation of the lower laser level at higher argon pressure and, on the other hand, by de-excitation of the upper laser level through the Penning reaction on argon as well as by competition of the reactions of binary and three-particle charge transfer from Ne_2^+ to Ar with reaction of dissociative recombination that pumps the upper laser level. Charge transfer dominates at low pump power, whereas de-excitation through the Penning reaction affects laser kinetics at high pump power. It is also seen that a small amount of nitrogen at a level within 0.001–0.01% causes essential drop of laser output power.

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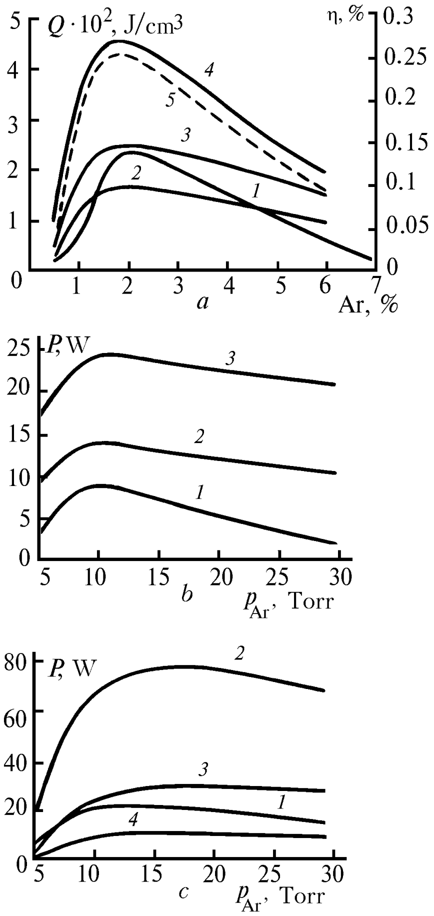

FIG. 1. Output parameters of He-Ne-Ar *laser* (λ = 585.3 nm) *versus partial argon pressure for e-beam pumping at* j = 0.24 A/cm^2, $\tau_{0.5}$ = 30 μs, E_e = 200 keV, *and* p = 2 atm. *Neon content is* 12% *(a). Curve 1 shows experimental data of Ref. 15, curves 2, 3, and 4 show results of our calculations for* [N$_2$] = 5.7·10^{15} cm^{-3} *(2 and 3) and* 0 *(4) and coefficient of absorption losses* $\varkappa^-$ = 10^{-4} *(2) and* 10^{-5} cm^{-1} *(3 and 4), and curve 5 shows laser efficiency calculated under conditions corresponding to curve 4.*

Nuclear pumping at p_{He} = 1 atm, $\bar{\Phi}$ = 1.3·10^{15} n/cm^2·s, ν = 0.13 s^{-1}, p_{Ne} = 30 Torr, $\tau_{0.5}$ = 3 ms, L = 150 cm, d = 2.8 cm, *and* V = 900 cm^3 *(b). Curve 1 shows experimental data obtained in Ref. 14, curves 2 and 3 illustrate results of our calculations for* [N$_2$] = 2.7·10^{15} *(2) and* 0 cm^{-3} *(3) and* $\varkappa^-$ = 10^{-5} *(2) and* 0 cm^{-1} *(3).*
Nuclear pumping at p_{He} = 2 atm, p_{Ne} = 30 Torr, $\bar{\Phi}$ = 2.5·10^{15} n/cm^2·s, ν = 0.088 s^{-1}, V = 1900 cm^3, L = 2 m, *and* d = 5.5 cm *(c). Curve 1 shows experimental data of Ref. 16, curves 2–4 show results of our calculations for* [N$_2$] = 2.5·10^{14} *(2) and* 5.2·10^{15} cm^{-3} *(3 and 4) and* $\varkappa^-$ = 10^{-5} *(2 and 3) and* 10^{-4} cm^{-1} *(4).*

The best agreement between experimental and calculation data is achieved when He is 99.99% pure, Ne - 99.99%, and Ar being 99.9% and absoption losses due to mirrors and active medium are less than 1%.

The optimal argon pressure depends on pump power and nitrogen concentration. Its value decreases with increase of nitrogen concentration and decrease of pump power.

Figure 2 illustrates results of comparison between theoretical and experimental data on the power gain in He-Ne-Ar(–H$_2$) mixture as a function of pump power. Experimental curve was borrowed from Ref. 17. The qualitative and quantitative agreement is seen to be satisfactory.

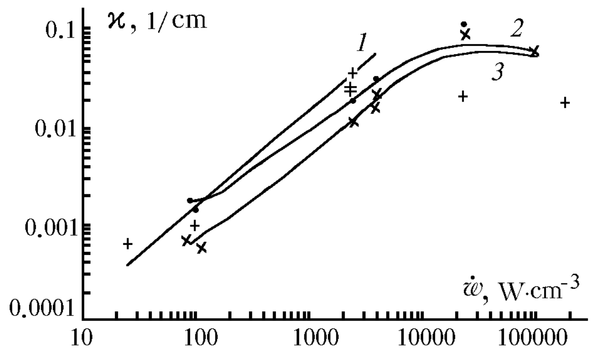

FIG. 2. Power gain as a function of pump power. Experimental data of Ref. 17 are denoted by pluses. Calculation results in 99.999% *pure mixture are shown by dots and in* 99.99% *pure mixture - by crosses. Curve 1 approximates the experimental data of Ref. 17, curve 2 - calculations in* 99.999% *pure mixture, and curve 3 - calculations in* 99.99% *pure mixture.*

Effect of small additions of hydrogen on the output characteristics of He-Ne-Ar laser was studied in Refs. 4, 5, and 18. Aleksandrov et al.[4,18] assumed that hydrogen admixture causes reduction of absorption losses in the active medium. Lomaev et al.[5] concluded that hydrogen admixture did not influence the absorption. At the same time, they concluded that the power gain changes after addition of hydrogen. It should be pointed out that the above-mentioned experiments were carried out with different pump powers and should be considered separately.

Laser operation in Ref. 5 was probably affected by nitrogen admixture in laser chamber. For instance, power gain values of 6·10^{-4} and 1.6·10^{-3} cm^{-1} were measured in He-Ne-Ar gaseous mixture without and with hydrogen, respectively. Our calculations demonstrated that in the absence of hydrogen, $\varkappa_0$ = 6.2·10^{-4} cm^{-1} in He-Ne-Ar mixture of 99.99% purity and $\varkappa_0$ = 1.69·10^{-3} cm^{-1} in the same mixture of 99.999% purity. When 0.4 Torr of hydrogen was added to the latter gaseous mixture, which corresponded to the experimental conditions of Ref. 5, our model predicted $\varkappa_0$ = 1.61·10^{-3} cm^{-1}. Only insignificant change in the absorption was evident from our calculations under experimental conditions of Ref. 5.

Thus, we concluded that the effect of nitrogen admixtures may be more pronounced than that of small additions of hydrogen. To provide correct estimation of the contribution of small additions of hydrogen to He-Ne-Ar laser output characteristics, careful control of the purity of gaseous mixture is necessary. In our opinion, experimental data available are insufficient for final conclusion about the effect of small additions of hydrogen into He-Ne-Ar mixture, especially for values of the pump power density typical of nuclear pumping.

Adverse effect of hydrogen revealed in our model calculations under experimental conditions of Ref. 5 is related to the reaction of charge transfer from Ne_2^+ to H_2. This results in reduction of population rate of the upper laser level and depopulation of the upper laser level through the Penning reaction. It should be noted that small addition of hydrogen causes only insignificant variation of population of the lower laser level. Hence, influence of small additions of hydrogen is similar to that of nitrogen. The only difference is in charge transfer rate from Ne_2^+ that is much higher for nitrogen.

This reaction affects the value of unsaturated power gain rather than the value of the absorption losses. This conclusion is indirectly confirmed by measurements of the absorption losses reported in Ref. 5. When hydrogen is added in the He-Ne-Ar mixture, no change in absorption losses is observed.

Increase in power gain reported in Ref. 5 is apparently related to higher degree of purity of hydrogen-containing gaseous mixture.

It should be mentioned that our kinetic model gives optimistic rather than pessimistic result for hydrogen-containing mixture.

The reverse situation was observed in Refs. 4 and 18. Indeed, they were characterized by high-power pumping and gaseous mixture of high purity (99.995%). The effect of nitrogen trace concentration was insignificant under such conditions. However, due to high-power pumping high number density of metastable argon was reached Ar^*(~ $4\cdot10^{14}$ cm^{-3} at p_{H_2} = 0.003 Torr). Though absorption cross section at λ = 585 nm for these species is rather small (we used σ^- = $5\cdot10^{-19}$ cm^2), small additions of hydrogen (at a level of 0.4–0.8 Torr) have pronounced effect on output pulse shape (see Fig. 3). It should be pointed out that though calculations demonstrated only slight change of peak power, a noticeable increase in laser efficiency from 0.24 to 0.36% was observed under conditions indicated in Ref. 18.

Effect of hydrogen additions on the efficiency of He-Ne-Ar laser with nuclear pumping under optimal conditions is illustrated by Fig. 4. It is seen that at a pump power density of about 150 W/cm^3, laser efficiency first slightly increases with increase of hydrogen pressure up to 1 Torr, and then at higher pressure of hydrogen it drops rapidly. These results were obtained for a pure gaseous mixture when the nitrogen concentration did not exceed 10^{14} cm^{-3}.

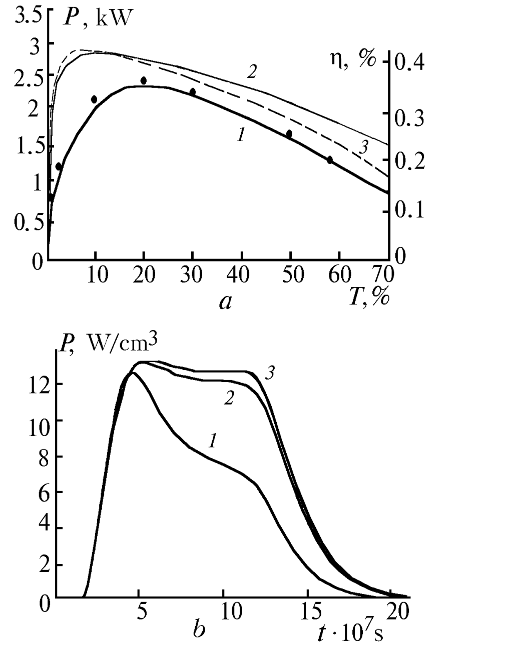

FIG. 3. Lasing characteristics of He-Ne-Ar-H_2 *laser. Output power and laser efficiency (a) versus resonator transmission T at* p_{He} = 3 atm, p_{Ne} = 200 Torr, p_{Ar} = 30 Torr, p_{H_2}= 0.8 Torr, *and* j = 1.2 A/cm^2. *Curve 1 is for experiments reported in Ref. 18, curve 2 shows calculation results, and curve 3 shows calculated laser efficiency.*
Calculated laser pulse shapes (b) under conditions of experiments reported in Ref. 4: p_{He} = 3 atm, p_{Ne}= 200 Torr, p_{Ar} = 15 Torr, *and* p_{H_2} = 0.003 *(1),* 0.4 *(2), and* 0.8 Torr *(3).*

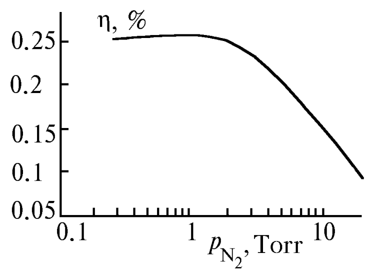

FIG. 4. Effect of small additions of hydrogen to He-Ne-Ar *gaseous mixture on laser efficiency at* p_{He} = 1.5 atm, p_{Ne} = 40 Torr, p_{Ar} = 15 Torr, *and* $\dot{w}$ = 150 W/cm^3.

Figure 5 shows threshold characteristics of He-Ne-Ar(H_2) laser. It is seen that for a photon lifetime in resonator of 1 μs, absorption losses of 10^{-6} cm^{-1}, and nitrogen concentration of 10^{14} cm^{-3} (in fact, such conditions are ideal), laser threshold pump power density in He-Ne-Ar mixture is as low as 3 W/cm^3. However, nitrogen or hydrogen admixtures cause appreciable increase in laser threshold pump power density. Even more pronounced effect is observed in

He-Ne-H_2 mixture. When helium partial pressure is 0.5 atm, neon partial pressure is 300 Torr, and that of H_2 is 30 Torr (optimal conditions for neon laser performance) an addition of nitrogen with concentration at a level of 0.01% leads to increase of laser threshold pump power density up to 250 W/cm^3.

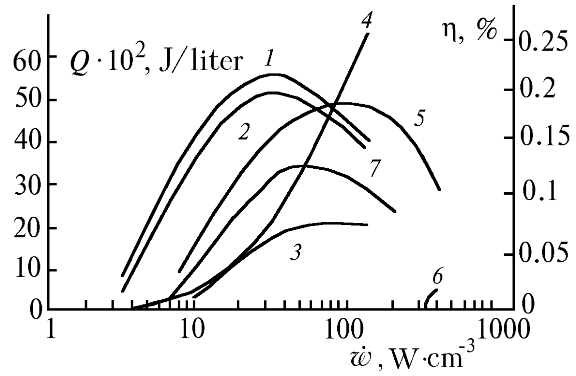

FIG. 5. Output energy density Q and efficiency of nuclear pumped neon laser versus pump power. Curve 1 shows output energy density in He-Ne-Ar *mixture at* p_{He} = 1.5 atm, p_{Ne} = 30 Torr, p_{Ar} = 15 Torr, $[H_2] = 10^{14}$ cm^{-3}, $[N_2] = 10^{14}$ cm^{-3}, *and* $\varkappa^- = 10^{-6}$ cm^{-1}. *Effective photon lifetime in resonator is* 1 μs. *Curve 2 shows laser efficiency under the same conditions; curve 3 corresponds to the same conditions except for* $[N_2] = 4.2\cdot10^{14}$ cm^{-3} (99.999%); *curve 4 is calculated* at $[N_2] = 4.2\cdot10^{15}$ cm^{-3} (99.99%); *curve 5 is obtained at* p_{H_2} = 0.5 Torr, *purity of the gas mixture of* 99.999%, *and* $\varkappa^- = 10^{-5}$ cm^{-1}; *curve 6 shows the laser efficiency in* He-Ne-H_2 *mixture at* p_{He} = 0.5 atm, p_{Ne} = 300 Torr, p_{H_2} = 30 Torr, $\varkappa^- = 10^{-6}$ cm^{-1}, *and* $[N_2] = 10^{14}$ cm^{-3}, *effective photon lifetime in resonator of* 1 μs; *curve 7 corresponds to the same conditions except for purity of gaseous mixture being* 99.99%.

CONCLUSION

1. Nitrogen admixtures at a level of rated gas purity have been shown to affect appreciably the neon laser output characteristics. Gases of high purity and thoroughly cleaned laser chamber should be used for improved Penning neon plasma laser performance. Two-fold increase in lasing characteristics can be obtained in this case.

2. Numerical optimization of He-Ne-Ar-H_2 laser operation has been carried out. When this mixture is pumped by e-beam of duration τ = 10 ns, the best laser performance can be obtained under the following conditions: helium pressure p_{He} = 300 Torr, argon pressure p_{Ar} = 60 Torr, transmission of output mirror T = 50%, active medium length L = 1 m, pump power density $\dot{w}$ = 400 kW/cm^3, and pump energy density 2.5 mJ/cm^3. In this case, laser efficiency of energy conversion in active medium is 0.4%. With 60 μs e-beam pumping, the optimal conditions are as follows: p_{He} = (1.5–2) atm, p_{Ne} = 150 Torr, p_{Ar} = 30 Torr, T = 30%, L = 1 m, p_{H_2} = 1 Torr, and $\dot{w}$ = 1.5 (without H_2) and 3.0 kW/cm^3 (with H_2). In this case, laser efficiency is $\eta \le 0.4\%$ without H_2 and $\eta \le 0.5\%$ with H_2. Under conditions of nuclear pumping (pulse duration is 8 ms), the best performance is observed at a helium pressure of 1.5 atm, a neon pressure of 30 Torr, an argon pressure of 15 Torr, T = 15%, L = 2 m, and $\dot{w}$ = 150 W/cm^3 with efficiency $\eta \le 0.3\%$. When a small amount of hydrogen (≤ 1 Torr) is added to this mixture, a slight increase in the efficiency can be observed at pump power density in excess of 100 W/cm^3. Optimal conditions for He-Ne-H_2 laser are as follows: p_{He} = 0.5–1 atm, p_{Ne} = 300 Torr, p_{H_2} = 30–40 Torr, and $\dot{w}$ = 250–300 W/cm^3. The efficiency of this laser can reach 0.2%.

3. Threshold characteristics of nuclear pumped He-Ne-Ar-H_2 laser have been calculated. Under near-ideal conditions in He-Ne-Ar mixture, the laser threshold pump power density was about 3 W/cm^3. However, under real experimental conditions the threshold pump power density is no less than 10 W/cm^3. The lowest laser threshold pump power density in He-Ne-H_2 mixture is about 8 W/cm^3, but its real value is no less than 100 W/cm^3.

4. The model developed enables us to optimize the performance of the Penning neon plasma laser (λ = 585.3 nm) with high degree of reliability and to answer a number of questions concerning kinetics of the processes in its active medium.

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