EFFECT OF THE PUMP POWER ON THE EFFICIENCY OF A Ne PENNING PLASMA LASER

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Experimental data on the pumping of a Penning plasma Ne laser by electron-beams (e-beams) with power densities of 25 W/cm^3 and 25 kW/cm^3 *are presented. The absorption coefficient, small-signal gain, and instantaneous value of the efficiency are discussed as a function of the excitation power.*

The convenient spectral range of radiation, the nonagressive character of the components in the gas mixture, the possibility for quasicontinuous lasing during some milliseconds[1,2] and for repetitive pulsed operation,[1] as well as the low threshold excitation powers and relatively high efficiency[3,4] stimulate researchers' interest in the Penning plasma Ne laser (see a detailed review in Ref. 3). An inverted population in a Penning plasma laser is produced by the following scheme: the population of the upper laser levels (ULL) occurs through electron-ion recombination "from overhead" and the depopulation of the lower laser levels (LLL) results from the Penning reaction of Ne with the admixed atoms (H_2, Ar, Kr, and Xe). The advantages of such a scheme are most completely exhibited for active media excited by "hard ionizers", such as accelerated e–beams, discharges with a hard component,[3] and fragments of nuclear reactions.[2,4] For a Ne laser operating with a high–pressure (p ≥ 1 atm) He–Ne–Ar mixture excited by an e–beam the population of the ULL occurs through the reaction chain (see, e.g., Ref.–5).

$$Ne^+ + 2\,Ne\,(Ne + He) \rightarrow Ne_2^+ + Ne\,(+\,He)\,; \qquad (1)$$

$$Ne^+ + 2\,Ne\,(Ne + He) \rightarrow He\,Ne^+ + He\,(+\,Ne)\,; \qquad (2)$$

$$He\,Ne^+ + Ne \rightarrow Ne_2^+ + He\,; \qquad (3)$$

$$Ne_2^+ + e \rightarrow Ne_2^{**} + Ne^*\,. \qquad (4)$$

In the process of dissociative recombination of Ne_2^+ from the excited states [see reaction (4)] the selectivity of population of the $3p'[1/2]_0$ level, i.e., the ULL, for the transition NeI at λ = 583.3 nm can reach 30% with respect to other $3p$ and $3p'$ multiplet levels.[6] The ULL deactivation at low excitation powers, when collisions of the excited atoms with plasma electrons can be neglected, generally occurs through collisions with neutral Ne and Ar atoms

$$Ne\,(3p'\,[1/2]_0) + Ne \xrightarrow{K_{Ne}} \text{products}, \qquad (5)$$

$$Ne\,(3p'\,[1/2]_0) + Ar \xrightarrow{K_{Ar}} Ne + Ar^+ + e\,, \qquad (6)$$

with respective rate constants $K_{Ne} \approx (8 \pm 2) \cdot 10^{-12}$ cm$^3 \cdot$ s^{-1} (Ref. 6) and $K_{Ar} \approx (1.4 \pm 0.1) \cdot 10^{-10}$ cm$^3 \cdot$ s^{-1} (Ref. 7). The LLL de-excitation occurs through the Penning reaction

$$Ne\,(3\,s'\,[1/2]_1^0\,) + Ar \xrightarrow{K_p} Ne + Ar^+ + e\,, \qquad (7)$$

with a rate constant $K_p = 5 \cdot 10^{-10}$ cm$^3 \cdot$ s^{-1} (Ref. 8). The mechanism of generation of an inverted medium by the $3\,p - 3\,s$ transitions of the Ne atom has been considered in detail, e.g., in Ref. 3 and the kinetic model accounting for about 200 plasma–chemical reactions has been proposed in Ref. 8. The predictions obtained with this model agree satisfactorily with experimental data within a wide range of operating conditions. In this paper we present the experimental results obtained for a Penning plasma Ne laser pumped by an e-beam with pump powers of 25 W/cm^3 and 25 kW/cm^3. On the basis of our experimental results and data obtained by other authors we estimate also the unsaturated absorption coefficients, small-signal gain, and efficiency as functions of excitation power.

The experiments were carried out using setups based on electron accelerators which were designed at the Institute of High–Current Electronics, Siberian Branch of the Russian Academy of Sciences. We used the transverse pumping by radially convergent e–beams in order to make good use of the e-beam energy and to obtain a homogeneously excited medium for the large (up to 20 cm) cross section of the active space. The first accelerator using a plasma cathode[9] provided a 16 mA/cm^2 current density downstream of the foil for an average electron energy of about 180 keV and pulse width of 30 μs. The excited volume of the cylindrical laser chamber was 18 liters with an active length of 60 cm. The maximum pressure of the gas mixture was 1.5 atm and it was limited by the mechanical strength of the unit supporting the separative foil of the vacuum diode. In our experiments the average power density delivered into the active medium estimated from measured and calculated input energies[1,3] was about 25 W/cm^3. With the same excited volume (about 20 liters) and an active length of 1 m, another accelerator with an explosive-emission cathode provided a pump power density of about 25 kW/cm^3 at the pulse maximum for a mixture of He–Ne–Ar = 2.1 : 0.34 : 0.06 at p = 2.5 atm and a full pulse width of 700 ns. Mirrors coated with dielectric were used as a cavity. A FÉK–22 SPU photocathode was used to record the time behavior of the radiation characteristics. The signal from the photocathode was fed to an S8–17 oscillograph. All the measurements were usually carried out for the central part of the active space. The gain and the absorption coefficient for the active medium were calculated by the experimental dependence of the laser output power on the reflectivity of the outcoupling mirror of the cavity. The calculations were performed according to the technique described in detail in Ref. 10.

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Figure 1 shows the temporal dependences of the radiation intensity at λ = 585.3 nm for two different input powers. The delay time of the lasing pulse with respect to the start of the *e*-beam current pulse increases with decreasing the pump power density. Moreover, for low excitation powers, the radiation pulse terminates somewhat earlier than the beam current ceases, what suggests the laser operations in the near-threshold mode. When increasing the excitation power one can observe the typical "overheating" of the active medium, when the "dip" on the curve describing the temporal dependence of the lasing pulse corresponds to the maximum of the excitation power, as well as the release of a substantial portion of radiation energy during the falltime of the excitation pulse (see curves *3* and *4* in Fig. 1). When a coaxial accelerator is used with a plasma emitter, which produced an excitation pulse duration of 30 μs, the threshold current density j_{thr} was about 7 mA/cm^2 that corresponds to about 11 W/cm^3 of power density.

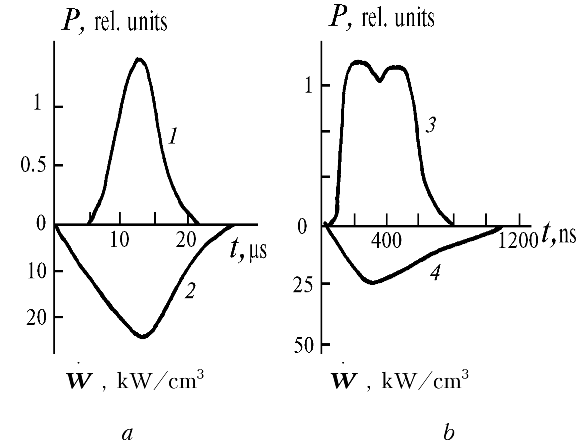

FIG. 1. Losing pulse waveforms at λ = 585.3 nm *(1) and (3) and the temporal dependence of excitation power (2) and (4) for the mixtures* He : Ne : Ar = 1.0 : 0.27 : 0.02 atm *(a) and* He : Ne : Ar = 2.1 : 0.34 : 0.06 atm *(b).*

Experiments on finding optimum concentrations of the gas mixture components were also carried out for the case of near-threshold powers. The typical optimum content of the Penning impurity Ar ~ 2% can be observed as for the large power densities,[3] the optimum ratio Ne : Ar = (5–10) : 1 remaining the same for the beam current density being varied in a wide range of from 0.016 to 0.3 A/cm^2. The optimum concentration of helium was about 70%. However, the laser radiation intensity increased as the gas mixture pressure was increased by adding helium.

Under near–threshold conditions the output energy density increases linearly with input energy as it does at higher excitation powers[13] (~ 10 W/cm^3). This occurs due to the increase of the *e*–beam current from its threshold to maximum value and due to increased pressure in the mixture. The above said suggests that the lasing efficiency is unchanged for the excitation parameters under study. We did not carry out a detailed optimization of the mixture for the excitation intensity 25 kW/cm^3, but we used our data[8] obtained earlier. Our experimental data on the small-signal gains and coefficients of unsaturated intracavity absorption are presented in Table I for different powers as compared with the results of our earlier works and other authors' data.

Let us discuss the obtained results. The maximum lasing efficiency, corresponding to the case when the entire energy contributed to the ULL is emitted, can be given in the form

$$\eta_{las}^{max} \approx \frac{\delta\, q\, \Delta E}{\dot{W}}, \tag{8}$$

where δ is the degree of selectivity of the ULL excitation, q is the rate of formation of electron–ion pairs in the gas due to the beam action, ΔE is the quantum energy of the laser radiation, and $\dot{W} = q\Delta\varepsilon$ is the specific excitation power ($\Delta\varepsilon$ is the energy of formation of the electron–ion pairs). By substituting the expression for $\dot{W}$ into Eq. (8) and taking into account that $\Delta E/\Delta\varepsilon = \eta_q^{eff}$ is the effective quantum efficiency we obtain

$$\eta_{las}^{max} \approx \delta\, \eta_q^{eff}. \tag{9}$$

For a Ne laser pumped in a recombination mode the effective quantum efficiency accounting for the ULL population scheme with ionization of helium as the main component in the mixture is about 5%.

Let us use the relations for the small-signal gain g_0 (whose value can be obtained experimentally) to derive the degree of pumping selectivity δ. These relations were derived in the approximation of the two–level model.[5,11] In the general case we have

$$g_0 = \sigma\,(N_1 - g_1/g_2\, N_2), \tag{10}$$

where g_1 and g_2 are the statistical weights of the upper and lower laser levels, respectively. The cross section of the induced transition is

$$\sigma = \frac{\lambda^2}{4\pi^2}\frac{A}{\Delta\nu}, \tag{11}$$

where $A \approx 7.2 \cdot 10^7\ s^{-1}$ is the probability of the ULL spontaneous decay. The line broadening Дe can be represented as

$$\Delta\nu = \Delta\nu_D + \gamma_{He}[He] + \gamma_{Ne}[Ne], \tag{12}$$

$$\delta\nu_0 \approx 3.4 \cdot 10^{10}\sqrt{T} \approx 8 \cdot 10^9\ s^{-1} \tag{13}$$

is the broadening of the transition frequency as a result of the Doppler effect. The value of $\delta\nu_0$ is given for T = 0.05 eV in Ref. 12. The collisional broadening is described by the constants y_{He} and 7_{Ne} whose values are found experimentally[7]

$$\gamma_{He} = (0.62 \pm 0.06) \cdot 10^{-9}\ cm^3/s;$$

$$\gamma_{Ne} = (2.1 \pm 0.2) \cdot 10^{-9}\ cm^3/s.$$

The inverted populations in the quasi–steady–state approximation can be given in terms of the two–level model.[5,7] It follows that

$$g_0 \approx \delta\, q\, \frac{\sigma}{K_p[Ar]}\, \frac{K_p[Ar] - g_1/g_2\,(A + K_{Ar}[Ar] + K_{Ne}[Ne])}{A + K_{Ar}[Ar] + K_{Ne}[Ne]}. \tag{15}$$

Here it is assumed that in the process of collisional deactivation of the ULL principally the LLL is populated and the excitation power is so much low that the intermultiplet mixing in collisions with plasma electrons can be neglected.[5] For the conditions of our experiments with radially convergent low-density beams the small signal gain was $g_0 = 6 \cdot 10^{-4}$ cm^{-1}. By substituting the values of the constants of the above-considered reactions into relation (15) and using Eqs. (11)–(14) we can obtain the selectivity of the ULL excitation. For the given conditions it is about 10%. By performing similar calculations for conditions of the experiment described in Ref. 13 the same value of *6* can be obtained for $W \sim 25$ kW/cm^3. The values of gains for the transition at $\lambda = 585.3$ nm are shown in Fig. 2. They were experimentally obtained for different excitation powers according to the conditions given in the table (the numbers of close circles in the figure coincide with the line numbers in the table).

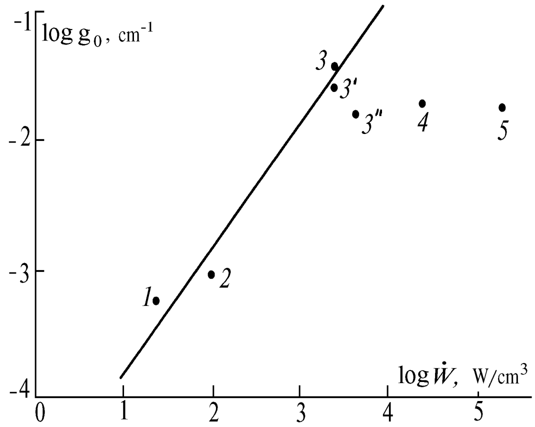

FIG. 2. Small-signal gain at $\lambda = 585.3$ nm *vs the excitation power. The numbers of close circles correspond to the line numbers in the table (see the text of this paper).*

TABLE I.

Item	Mixture, atm	Excitation power, kW/cm^3	Beam width, τ, μs	Gain, g_0, cm^{-1}	Absorption coefficient, β, cm^{-1}	References
1	He : Ne : Ar = 1 : 0.27 : 0.02	0,025	30	$6 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	Our results
2	He : Ne : Ar = 1.9 : 0.06 : 0.04	0,1	100	$9 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	17
3	He : Ne : Ar = 3 : 0.2 : 0.015	2,5	1.5	$3.8 \cdot 10^{-2}$	$2 \cdot 10^{-3}$	13
3′	He : Ne : Ar:H_2=3 : 0.26 : 0.04:0.001	2,1	1.5	$2.7 \cdot 10^{-2}$	$6 \cdot 10^{-4}$	7
3″	He : Ne : Ar = 3 : 0.27 : 0.04	4,0	1.5	$1.7 \cdot 10^{-2}$	$1.1 \cdot 10^{-3}$	15
4	He : Ne : Ar = 2.1 : 0.34 : 0.06	25	0.7	$2 \cdot 10^{-2}$	$1.2 \cdot 10^{-3}$	Our results
5	He : Ne : Ar = 1 : 0.34 : 0.06	200	0.01	$1.8 \cdot 10^{-2}$	$1 \cdot 10^{-6}$	8

Since the variation of the helium concentration in the mixture at $p_{He} \le 3$ atm only slightly affects the cross section of the induced transition and the operating level populations[7] and since the contents of Ne and Ar for conditions numbered as *1*, *2*, and *3* (see Fig. 2) are virtually the same, we can state that the small–signal gain g_0 at $\lambda = 585.3$ nm increases linearly up to $1.5 \cdot 10^{-5}\ \dot{W}$ and the value of $\delta \sim 10\%$ remains the same as the excitation power $\dot{W}$ increases from ~ 11 to $\sim 10^3$ W/cm^3. This conclusion agrees well with theoretical predictions[12] and experimental data[14] obtained within a narrower range of excitation powers. In addition, this agrees with the conclusion that the lasing efficiency does not vary with $\dot{W}$ as was demonstrated experimentally in Ref. 3. According to Eq. (9) and with the assumptions made in the calculation of *6*, the estimate of the lasing efficiency is about 0.5% or somewhat more (~ 1%) for the given pumping selectivity.

Our estimate of the lasing efficiency is close to the values of $\eta \sim 0.3$–0.4% reported in Refs. 2, 3, and 14. The violation of the linearity in the dependence $g_0(\dot{W})$ at $\dot{W} \ge 2 \cdot 10^3$ W/cm^3 can be caused by several reasons.

First, for such pump power densities $n_e \gtrsim 10^{15}$cm^{-3}, as shown in Ref. 5, and the intermultiplet level mixing in collisions with electrons becomes considerable. Such a mixing more strongly influences the transition at $\lambda = 585.3$ nm which shows a great oscillator strength $f = 0.12$.

Second, the concentration of Ne^+ exceeds that of Ne_2^+ at the large pump power densities ($J \ge 10$ A/cm^2, Ref. 12) and it is necessary to increase the content of Ne in the mixture in order to increase the ULL population rate in the process of dissociative recombination (see points *4* and 5 in Fig. 2). This leads to a more intense deactivation of the ULL in collisions with Ne atoms, to a decrease in the cross section of the induced transition, and, finally, to a reduced g_0.

Third, the rate of dissociative recombination and the selectivity of the ULL population decrease with increasing the electron temperature (see Refs. 13 and 15).

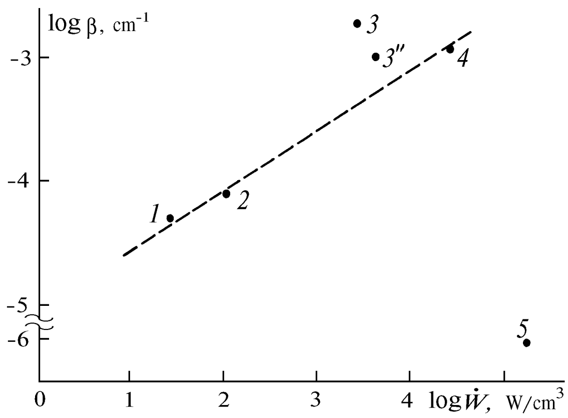

FIG. 3. Absorption coefficient at $\lambda = 585.3$ nm *vs excitation power. The numbers of close circles correspond to the line numbers in Table I (see the text of this paper).*

Figure 3 shows the values of the absorption coefficient for Ne at $\lambda = 585.3$ nm (obtained experimentally as a function of the excitation power for the conditions given in the table) as well as a curve of the function $\beta \sim \dot{W}^{0.5}$. For this case the value of β at the point *3* is taken to correspond to peak of the lasing pulse, the calculated absorption coefficient is an order of magnitude larger than the maximum calculated absorption coefficient,[13] and the lasing at this instant has already ceased. In the experiments[5] the absorption during the afterglow of the nanosecond electron beam was small, since some time was required to generate a sufficient number of absorbing particles.[13] Nevertheless, one can suppose that, since the absorption in the plasma of the Ne laser intensifies with increasing the pump power density almost in the same way as $\sqrt{\dot{W}} \sim n_e$, it mainly occurs due to ions.[15] It is well known[16] that the absorption band of the molecular ions of rare gases in the transition shifts toward the red region of the spectrum as one passes from dimeric ions to trimeric ones R_3^+. Thus, according to calculations,[16] the cross section of the photoabsorption of Ar_3^+ reaches its maximum $\sigma_{ph} \sim 0.2 \cdot 10^{-6}$ cm^3 in the range 550–600 nm. However, to obtain $\beta \sim 5 \cdot 10^{-5}$ cm^{-1} under the conditions of our experiments, the concentration of absorbing particles should be about $2.5 \cdot 10^{12}$, what exceeds the estimate of the Ar_3^+ concentration for the given pump power density and Ar content. The addition of H_2 (~ 0.4 Torr, see Ref. 10) to the Ne laser mixture under the near-threshold conditions of excitation has not resulted, in contrast to Ref. 13, ($\dot{W} \sim 2.5$ kW/cm^3), in a decrease of the absorption coefficient or in a substantial increase of lasing efficiency. Additional experiments are necessary for solving more particularly the problem concerning the cause of the decrease of lasing efficiency and the enhancement of absorption in the Penning plasma Ne laser ($\lambda = 585$ nm) with increasing the pump power density.

Thus, in this paper we discuss the experimental results of the study of the lasing in the Penning plasma Ne laser operating by the transition at $\lambda = 585.3$ nm under the conditions being near-threshold by excitation power. The threshold pump power density was about 11 W/cm^3. The selectivity of the ULL population δ was about 10%, the small–signal gain g_0 was about $6 \cdot 10^{-4}$ cm^{-1}, and the absorption coefficient β was about $5 \cdot 10^{-5}$ cm^{-1}. The performed analysis of the dependences of g_0 and β on the pump power density $\dot{W}$ has shown that g_0 increases linearly with increase of $\dot{W}$ ($11 \le \dot{W} \le 10^3$ W/cm^3) for $\delta \sim 10\%$ being unchanged, and that the absorption coefficient is proportional to the electron density within a wide range of pump power. The instantaneous lasing efficiency is unchanged within the interval $15 \le \dot{W} \le 10^3$ W/cm^3 and does not exceed 0.5%.

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