STIMULATED EMISSION EVOKED BY PUMPING WITH A PULSED ELECTRON BEAM PRODUCED IN A LINEAR DISCHARGE

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It is demonstrated experimentally that argon ion stimulated emission arises during the collective interaction of a ~100-MW high-power electron beam produced in a high-current linear discharge with an already prepared argon plasma of $n_0 = (3-5) \times 10^{13}$ cm^{-3}. The generation occurs in the visible (Ar II, λλ4764 and 4880 Å) and the ultraviolet (Ar III, λλ3511 and 3638 Å) spectral regions, the generation power for the Ar-II transitions being ~1 kW.

1. INTRODUCTION

DIFFERENT methods exist at present for obtaining an inverted population of levels in gas lasers. A promising method is to use the collective processes that develop in a plasma and are responsible for the formation of nonequilibrium states and the level population inversion. We attain then in the plasma a high electron temperature at which ionic transitions in the ultraviolet spectral region are excited. One of the first investigations in this direction was the application of the pinch discharge, in which argon-ion laser generation is obtained at an electron temperature of ~ 20 eV[1]. Another example of the utilization of collective processes in a plasma is the plasma-beam discharge, in which an electron temperature of ~ 90 eV has been achieved, and a ~ 100-W laser generation in ionized argon has been realized[2]. In[2] the electron beam was produced outside the plasma.

It is well-known that under certain conditions charged-particle beams can be produced inside a plasma[3-5]. It has been demonstrated experimentally[6] that a ~ 100-MW electron beam is produced in a high-current linear discharge of plasma density $10^{13}-7 \times 10^{13}$ cm^{-3} in electric fields exceeding the critical Dreicer field. The total beam current is 10–15 kA, the electron density in the beam ~ 10^{11} cm^{-3}, and the beam length ~ 0.6 μsec. The interaction of such a beam with an already prepared plasma leads to an intense beam heating of the plasma electrons up to nT ~ 10^{16} eV/cm^3.

Theory based on the concepts of collective interactions indicates that an increase in the density of the electron beam should correspond to greater effectiveness of the interaction in the plasma-beam system[7-9]. It is natural to suppose that when a high-density electron beam is used for laser pumping, the intensity of the excitation processes increases, and this facilitates a higher generation power.

The method of sudden perturbations[10] is used to estimate the excitation probability of the ionic laser levels. The method shows that, depending on the nature of the excitation (direct or step-by-step), different gains are obtained for the same transitions. The assumption of LS-coupling and sudden perturbation for argon gives a preferential excitation of the $4p^2P_{3/2}-4s^2P_{1/2}$, λ 4765 Å laser transition, and this was experimentally observed in[11] (direct excitation). The rest of the transitions belonging to the same configuration can be excited if the LS-coupling is broken, or there exist deviations from sudden perturbation[10]. Thus, for example, in[12] maximum gain was obtained in a pulsed discharge in argon in the $4p^2D_{5/2}-4s^2P_{3/2}$, λ4880 Å transition (step-by-step excitation). It is apparently necessary, in explaining this fact, to take into account the role of the collective interactions that occur in a plasma and complicate the laser level excitation process[9,11]. The time delay of the laser radiation is connected with the development of collective phenomena in the plasma, and this points to the existence of a threshold in the appearance of the collective interactions[11].

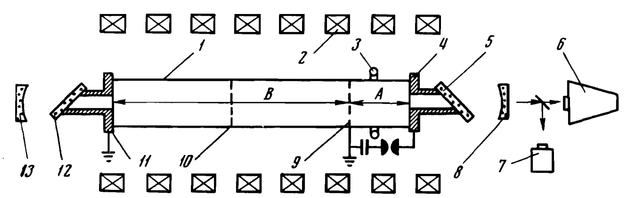

FIG. 1. Diagram of the apparatus: 1) chamber; 2) solenoid; 3) Rogowski loop; 4), 9), 10), and 11) electrodes; 5) and 12) Brewster windows; 6) and 7) radiation indicators; 8) and 13) resonator mirrors.

The purpose of the present work is the experimental investigation of the possibility of obtaining laser radiation in an argon plasma by pumping with a high-power pulsed electron beam produced in a linear discharge.

2. SCHEME OF THE EXPERIMENT

All the experiments were conducted on the apparatus schematically shown in Fig. 1.

The glass vacuum chamber 1 of diameter 10 and 4 cm and length 1.5 m was evacuated by an oil-vapor pump. The initial vacuum was 5×10^{-6} Torr. The chamber was filled with the working gas up to a pressure of $P_0 = 10^{-2}-10^{-4}$ Torr. Continuous admission of the gas (flow-through) as well as steady filling of the chamber were used. Argon was used as the working gas. The whole chamber was placed in a solenoid 2, which provided a quasi-stationary magnetic field $H_0 \leq 800$ Oe. Metallic electrodes 4 (high-voltage) and 11 (grounded) were located at the ends of the chamber, and two reticular electrodes 9 (grounded) and 10 were mounted at distances of 35 cm and 1 m, respectively from the electrode 4. A Penning discharge, which produced an initial cold plasma with an adjustable density ($n_0 = 1 \times 10^{12} - 5 \times 10^{13}$ cm^{-3}), was induced in the chamber with the aid of the electrode 10. A capacitor rated $C_0 = 0.1 - 0.2\ \mu$F was connected to the electrodes 4 and 9 through a discharge gap, and a high-current linear discharge (period $\sim 2\ \mu$sec, current amplitude in the first half-period $I_0 = 6 - 12$ kA at an initial voltage $U_0 \approx 20$ kV across the capacitor) was excited in this circuit. The current of the linear discharge was measured with a Rogowski loop 3.

Thus, the whole chamber was divided into a region A, where a high-power electron beam was produced and which served as an electron gun, and a region B filled with an initial cold plasma (Fig. 1). The density of the initial plasma was measured with a double electrostatic probe which had been calibrated with the aid of an ultrahigh-frequency interferometer.

Upon excitation of the high-current discharge between the electrodes 4 and 9 and the onset of conditions for current instability[6], a high-power electron beam was produced in the gas-discharge region A (Fig. 1). This beam passed through the reticular anode 9, propagated along the magnetic field, and could be detected by a bolometer in the entire region B of interaction of the beam with the plasma. Passage of the beam through the region B (Fig. 1) filled with the initial cold plasma heated the electronic component of the plasma, with subsequent excitation of the ionic component and formation of conditions for stimulated emission. The radiation escaped through holes in the electrodes and the Brewster windows into an optical resonator consisting of mirrors (diameter 35 mm, radius of curvature ~ 3 m, and reflection coefficients 100 and 98% in the generation region) positioned at a distance of 1.7 m from each other (Fig. 1). An STÉ-1 spectrograph was employed for the indication of the radiation; detection of radiation in the lines was performed with the aid of a ZMR-3 monochromator with an FÉU-18A photomultiplier. The total light radiation was received by an FÉK-11 photocell. The signals from the photocell (radiation) and the Rogowski loop (current of the linear discharge) were fed to an OK-17 double oscillograph with a photo-attachment.

3. GENERATION OF STIMULATED EMISSION IN SINGLY IONIZED ARGON (Ar II)

A. Experiment with the Discharge Chamber of Diameter 10 cm.

The linear discharge in the region A of the chamber (Fig. 1) occurred at an initial potential difference $U_0 = 20$ kV across a 0.2-μF capacitor; the current amplitude in the first half-period reached $I_0 = 12$ kA. The electron beam energy density distribution over the cross section of the discharge chamber in region B (Fig. 1) is shown in Fig. 2. The composition of the radiation was investigated in the 4500–5640 Å band;

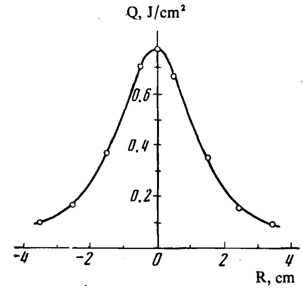

FIG. 2. Electron beam energy density distribution over the cross section of the discharge chamber (diameter 10 cm).

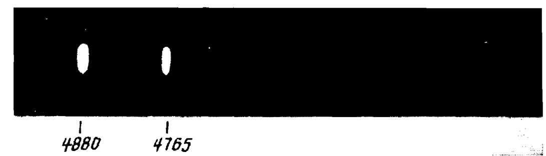

FIG. 3. Radiation spectrum (visible part; chamber of diameter 10 cm).

the resonator mirrors were constructed for the 4200–5500 Å range. Figure 3 shows the radiation spectrum (line 1, order V, dispersion 7.6 Å/mm). Generation of stimulated radiation occurs in the Ar-II ion transitions λ4765 Å ($4p^2P_{3/2} - 4s^2P_{4/2}$) and λ4880 Å ($4p^2D_{5/2} - 4s^2P_{3/2}$).

Figure 4 shows the oscillograms of the discharge current and generation pulse. In the case a), when generation is observed, the high-voltage electrode 4 serves as the cathode in the first half-period of the discharge, the electron beam produced in the region A (Fig. 1) is directed towards the region B filled with an initial plasma and, as a result of the beam-plasma interaction, the whole chamber becomes optically active. In the case b), when there is no generation, the electrode 4 is the anode in the first half-period of the discharge, and an electron beam of the same power as in the case a) is directed towards the high-voltage electrode 4 (Fig. 1). If by chance the pulsed electron beam interacts in the region B with the neutral gas (there is no initial ionization by the Penning discharge), there is no generation of stimulated radiation.

Figure 5 shows a section of the radiation spectrum. In case a), when there is generation, the electron beam is directed towards the region B filled with an initial plasma, while in the case when generation is absent, the beam is directed towards the high-voltage electrode 4.

The generation is formed in the first half-period of the discharge; the generation pulse starts later than the current discharge, and this is connected with the moment of onset of the current instability and the formation of the electron beam[6]. It was observed in the experiment in[6] that the optimum conditions for the development of the high-power electron beam are created, in the main, in the first half-period of a linear discharge. It is reasonable to assume that during the development of the beam instability in the first half-period of the discharge, the parameters of the plasma (density, temperature) change, and this leads to a cutoff of the current instability and the absence of an electron beam in the subsequent half-periods of the discharge[6].

An estimate of the generation power from the bolometric measurements yields a value of ~ 1 kW. The

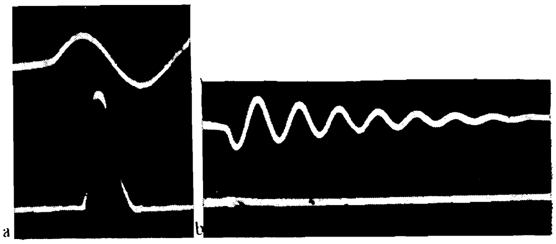

FIG. 4. Oscillograms of current discharge with period of ~2 μsec—upper trace—and generation pulse—lower trace (visible region; chamber of diameter 10 cm): a) electron beam was directed towards the region B (Fig. 1) filled with an initial plasma; b) electron beam was directed towards the high-voltage electrode 4.

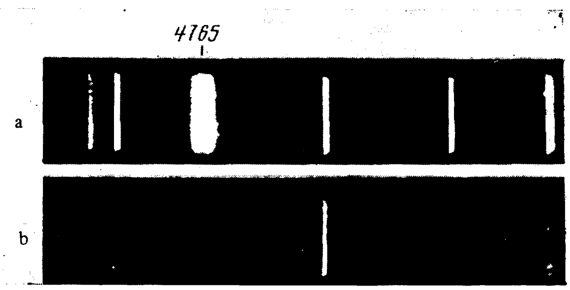

FIG. 5. Section of radiation spectrum (visible region; chamber of diameter 10 cm): a) electron beam directed towards the region B; b) electron beam directed towards the electrode 4 (Fig. 1). The exposure (number of discharges) was the same in both cases.

width of the λ4765-Å generation line, measured with the aid of a Fabry-Perot interferometer and an STÉ-1 spectrograph, is $\Delta\lambda \approx 2 \times 10^{-3}$ Å. Generation is observed in the argon pressure region $P_0 = (6-8) \times 10^{-4}$ Torr, which corresponds to a density $n_0 \approx 5 \times 10^{13}$ cm^{-3} of the initial cold plasma.

Figure 6 shows the dependence of the intensity of the λ4765- and λ4880-Å generation lines on the pressure of the argon. It can be seen that the maximum intensity is reached at different values of the pressure (or density of the plasma). It was shown experimentally in[12] that there exist for the passage of an external electron beam through an initial cold plasma resonance conditions, upon fulfillment of which the interaction of the beam with the plasma is most effective. If we try to relate this result to the appearance of generation in the plasma-beam system realized in the present work, then we must take into account the fact that the mechanism underlying the formation of a dense electron beam in such a system[6] and the subsequent interaction of the beam with the plasma are more complicated than in the case of a low-density monoenergetic external beam[13]. The complexity lies in the fact that the nature of the development of the current instability and the energy spectrum of the electron beam which develops during the

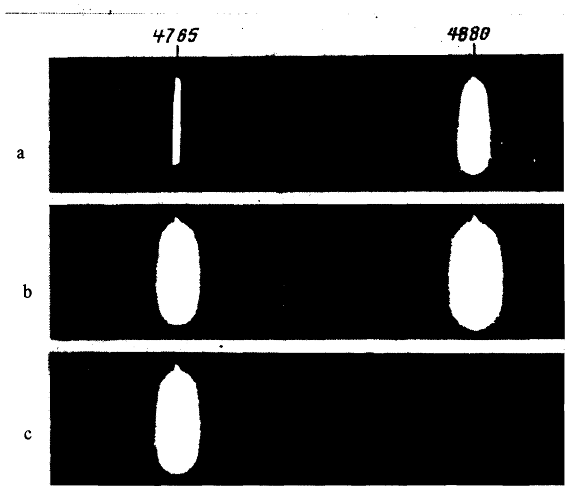

FIG. 6. Dependence of the intensity of the generation lines on the argon pressure P_0 visible region; chamber of diameter 10 cm): a) $P_0 = 6 \times 10^{-4}$ Torr; b) $P_0 = 7 \times 10^{-4}$ Torr; c) $P_0 = 8 \times 10^{-4}$ Torr.

instability, as well as the effectiveness of the beam-plasma interaction, are largely determined by the parameters of the initial plasma (density and temperature), in which the observed phenomena develop.

B. Experiments with the Discharge Chamber of Diameter 4 cm.

The linear discharge was produced at an initial potential difference $U_0 = 20$ kV across a 0.1-μF capacitor; the current amplitude in the first half-period attained the value $I_0 = 6$ kA. Generation occurred in the λ4765-Å Ar-II transition. The argon pressure range in which generation exists is contained in the interval $P_0 = (1-4) \times 10^{-3}$ Torr (plasma density $n_0 \approx 3 \times 10^{13}$ cm^{-3}). Generation is formed in the first half-period of the discharge current, and as in the case of the discharge chamber of diameter 10 cm, the commencement of the generation pulse lags behind the onset of the current discharge.

4. GENERATION OF STIMULATED RADIATION IN DOUBLY IONIZED ARGON (Ar III)

The experiments were conducted on a discharge chamber of diameter 4 cm (Fig. 1). The linear discharge in the region A of the chamber was realized at an initial potential difference $U_0 = 25$ kV across a 0.1-μF capacitor; the current amplitude in the first half-period was $I_0 = 7$ kA. The composition of the radiation was investigated in the 3165—4500 Å band; the resonator mirrors were constructed for the 3200—4000 Å range.

Figure 7 shows the spectrum of the radiation (line 3, order III, dispersion 6.4 Å/mm). Generation of the stimulated radiation occurs in the λ3511-Å

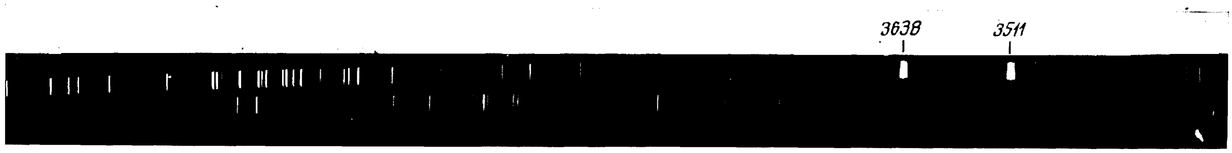

FIG. 7. Radiation spectrum (ultraviolet region; discharge chamber of diameter 4 cm.).

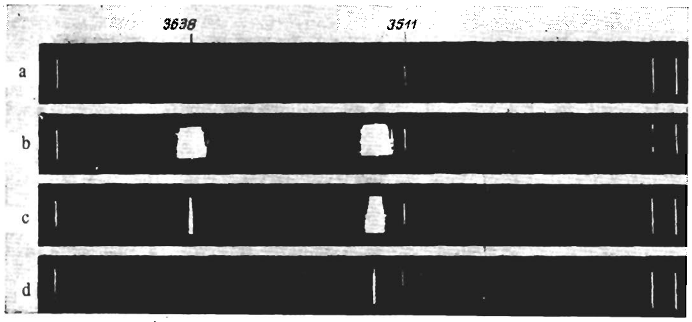

FIG. 8. Dependence of the intensity of the generation lines on the pressure P_0 of the argon (ultraviolet region; chamber of diameter 4 cm). In a) $P_0 = 10^{-3}$ Torr, b) $P_0 = 2 \times 10^{-3}$ Torr, c) $P_0 = 3 \times 10^{-3}$ Torr, d) $P_0 = 4 \times 10^{-3}$ Torr.

($4p^3P_2 - 4s^2S_1$) and λ3638-Å ($4p^1F_3 - 4s^1D_2$), Ar-II transitions[14]. Generation is observed in the argon pressure range $P_0 = (1-4) \times 10^{-3}$ Torr (density of the initial plasma $n_0 \approx 3 \times 10^{13}$ cm^{-3}). We must note that as the pressure is varied from 10^{-3} to 4×10^{-3} Torr the intensity of the generation lines behave differently: the intensity of the λ3638-Å line decreases relatively more rapidly (Fig. 8). Generation occurs in the first half-period of the discharge current and, as in the case of the Ar-II generation, the onset of the generation pulse lags behind the onset of the current.

5. CONCLUSION

As a result of the experiments performed we can draw the following conclusions:

1. The creation of conditions responsible for the appearance of generation begins from the moment of formation of the electron beam in the linear discharge and its subsequent collective interaction with the argon plasma[6]; the observed delay of the generation pulse with respect to the onset of the linear-discharge current is apparently connected with this.

2. Generation occurs in a definite range of argon pressure (range of initial plasma density). This is apparently connected with the effectiveness of the beam-plasma interaction, which is determined in turn by the energy spectrum of the electron beam produced in the linear discharge[6,13].

3. Interaction of a high-power electron beam produced in a linear discharge with an initial argon plasma creates conditions created for the excitation of laser levels through direct (Ar II, λ4765 Å) as well as step-by-step (Ar II, λ4880 Å) processes.

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