SOVIET PHYSICS JETP VOLUME 35, NUMBER 5 NOVEMBER, 1972

A Plasma-Beam Discharge Laser

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Submitted July 8, 1971
Zh. Eksp. Teor. Fiz. 62, 1702–1716 (May, 1972)

The possibility of employing collective interactions between electron beams and the plasma for pumping gas lasers is studied experimentally. By means of this method of producing inversion states one can obtain stimulated emission in a rather broad range of wavelengths and for a large variety of substances. Generation is attained in ionized argon, krypton, xenon, nitrogen, and chlorine. The generation mechanism in a plasma-beam discharge laser is considered.

INTRODUCTION

To increase the intensity of laser radiation in the visible and ultraviolet regions of the spectrum and to develop lasers operating at even shorter wavelengths it is not necessary to have effective inversion methods that result in higher pump intensities. Such methods can be based, in particular, on the use of a non-equilibrium high-temperature plasma.

The idea of using non-equilibrium processes in a high-temperature plasma to obtain induced radiation was proposed by Rabinovich in the Physics Institute of the U.S.S.R. Academy of Sciences (pinch discharge)[1] and by Fainberg and Tkach at the Physico-technical Institute of the Ukrainian Academy of Sciences (plasma-beam discharge)[2]. The possibility of pumping lasers with the aid of the high-frequency fields that accompany the development of instabilities was pointed out also in[3]. The generation of induced radiation in a straight pinch discharge was investigated in[1] using a plasma with density 4×10^{15} cm^{-3} and an approximate electron temperature 3–5 eV. The generation was observed at the instant of pinch cumulation with increasing plasma temperature and density, on the transitions of singly-ionized argon. Inversion is produced in a discharge of this type because of the direct excitation of the ionic levels from the free state of the neutral atom or from the ground state of an ion of lower multiplicity. Similar investigations were subsequently reported in[4].

The method of obtaining intense pumping and stimulated emission, based on the use of a collective interaction of electron beams with a plasma, was proposed and developed in our earlier papers.[2,5] This interaction produces a plasma-beam discharge characterized by a high electron temperature, reaching tens and hundreds of of keV at a considerable plasma density produced in large volumes, and by a high density of multiply-charged ions. Owing to the Doppler effect produced by the intense motion of ions whose temperature and velocity can vary in a wide range, the self-absorption processes become weaker. All these features of the plasma-beam discharge make its use quite promising for the development of new gas lasers. An important distinguishing feature of a plasma-beam discharge is that the excitation and ionization of the atoms of the gas and the heating of the plasma electrons and ions are produced in it not as a result of pair collisions of beam electrons with atoms, but as a result of collective processes, during the development of which the plasma electrons acquire the energy required for excitation, ionization, and heating in the electric field of the oscillations excited by the electron beams moving in the plasma. The plasma density is higher in this case by three or four orders of magnitude than the beam electron density, and the plasma volume greatly exceeds the volume occupied by the electron beam. The mechanism whereby the plasma-discharge is produced can be very briefly explained in the following manner[6,7]. When an electron beam passes through a neutral gas, the pair collisions of the beam electrons with the gas atoms produce a plasma whose density is comparable with the beam density. The collective interaction with the beam with this plasma excites oscillations at the cyclotron frequency ω_H, if this frequency is lower than the plasma Langmuir frequency ω_p. The electrons acquire energy in the electric fields of the excited oscillations and produce additional ionization. The plasma density is then rapidly increased, ω_p becomes larger than the cyclotron frequency ω_H and intense oscillations with frequencies close to ω_p are excited. The elementary excitation mechanism of these oscillations is the Cerenkov effect. In addition, oscillations can be excited at frequencies $\omega - k_z v_z = \pm l\omega_c$, due to the normal and anomalous Doppler effects. As the result of the reaction of the excited oscillations on the beam electrons, the frequency and phase-velocity spectra become broader, and the excited oscillations become stochastic. The plasma electrons and ions become intensively heated in the electric field of the stochastic oscillations[8,9].

Since the plasma electron density exceeds the electron-beam density by three or four orders of magnitude, and since the electron energy corresponds to the maximum values of the atom and ion inversion cross-sections, high pump intensities are easily realized in a plasma-beam discharge. Simultaneously with the excitation of high-frequency oscillations, the decay excites in the discharge low-frequency oscillations that lead to diffusion and heating of the ions. The volume occupied by the plasma then increases strongly. Thus, it becomes possible to generate stimulated emission in large volumes. The distribution function in such a discharge can differ strongly from Maxwellian. The time needed to obtain the maximum temperature and density of the plasma is determined only by the reciprocal increment of instability development and can reach 10^{-10}–10^{-11} sec. External high-frequency fields can be used to control instabilities in a plasma-beam discharge, and this uncovers a possibility of controlling the

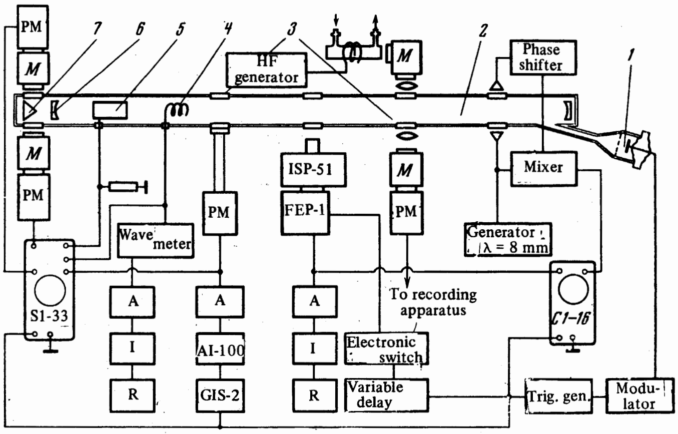

FIG. 1. Experimental setup and block diagram of experiment: 1—electron gun, 2—discharge chamber, 3—windows for plasma diagnostics, 4—high-frequency receiver, 5—collector, 6—mirror, 7—prism, M-monochromator, A—amplifier, I—integrator, R—automatic recorder, PM—photomultiplier.

discharge temperature. This circumstance is very important, since modulation of the beam by external high-frequency fields makes it possible to control the generation spectrum and to modulate the coherent radiation up to frequencies 10^{10}–10^{11} Hz.

We report in this paper the result of an investigation of generation of stimulated emission in the visible region of the spectrum, using for the laser pumping the collective processes that develop in a high-temperature plasma.

EXPERIMENTAL SETUP AND ITS PARAMETERS

The experimental investigations of the onset of stimulated emission and the measurement of its parameters were performed with the setup illustrated in Fig. 1. The electron gun operated in a pulsed regime with a pulsed duration 90 μsec, and produced an electron beam with a current up to 35 A and an energy up to 40 keV. The beam was injected through a pressure-drop tube into a stainless steel plasma chamber of 110 mm diameter and 3m length. At the end of the chamber was a water-cooled collector to dissipate the beam power, the average value of which could reach 1.5 kW. Mirrors in adjustable mounts were placed at the two ends inside the discharge chamber. By using differential pumping, the pressure in the gun chamber did not exceed 2×10^{-5} Torr when the pressure in the plasma chamber was raised to 2×10^{-3} Torr. The latter was adjusted with the aid of a system of leak valves.

The electron gun and the plasma chamber were placed in a homogeneous magnetic field whose intensity could be varied from 0.4 to 1.7 kOe, the longitudinal inhomogeneity not exceeding 3%. The electron beam was injected into the plasma chamber at an angle 80° to its axis and was adjusted with the aid of a magnetic field in such a way that, without damaging the mirrors, it could pass along the axis of the optical resonator. A magnetic screen was used to protect the mirrors against strong ion bombardment. The resonator consisted of dielectric-coated mirrors having curvature radii 5 and 10 meters. The side walls of the discharge chamber had windows for optical, x-ray, and microwave diagnostics of the discharge.

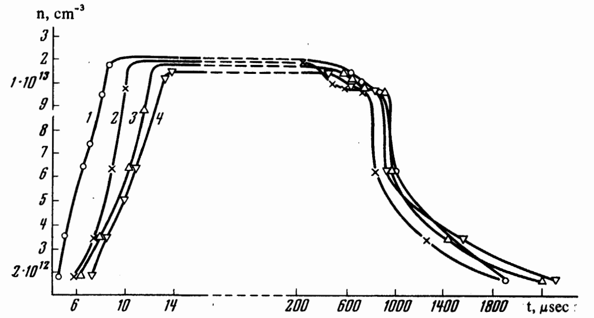

FIG. 2. Time variation of plasma density at different argon pressures: 1–3.5 × 10^{-3} Torr, 2–2.0 × 10^{-3} Torr, 3–1.4 × 10^{-3} Torr, 4–6.0 × 10^{-4} Torr (J_{beam} = 9 A, U_{beam} = 22 kV).

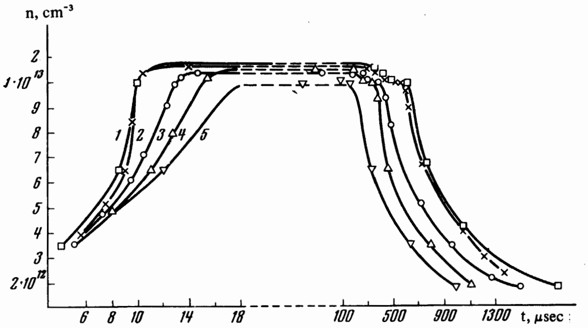

FIG. 3. Time variation of plasma density at different beam currents: 1–17 A, 2–20 A, 3–9 A, 4–4 A, 5–1.5 A (P_{Ar} = 5 × 10^{-4} Torr, U_{beam} = 34 kV).

The plasma density reached in the discharge and its time variation were measured with the aid of a millimeter-band interferometer, in one arm of which the investigated plasma was placed. Analysis of the interference pattern yielded the absolute values of the plasma density and its time variation at different pressures P in the discharge chamber and at the different beam currents J_{beam}. The results of these measurements are shown in Figs. 2 and 3. It is seen from them that the rate of density growth increases, and the time required for it to reach the maximum value of 2×10^{13} cm^{-3} decreases accordingly with increasing beam current and with increasing pressure. This is connected with the increase of the growth increment of the high-frequency oscillations in the plasma.

It should be noted that at the pressures below 5×10^{-4} Torr the plasma density can exceed somewhat the density of the admitted neutral gas. The reason for this effect is that during the time of the pulse the pressure in the chamber can greatly exceed the registered value, owing to the gas released from the metallic walls of the chamber when they are bombarded with hot plasma particles.

The plasma electron temperature was measured with the aid of a device whose block diagram is shown in Fig. 1. The device consisted of an ISP-51 spectrograph with an FÉP-1 attachment, the photomultiplier of which was kept in the blocked position with the aid of an electronic switch and was unblocked by a rectangular pulse of variable duration from 0.1 to 10 μsec. The start of this pulse could be delayed from 0 to 110 μsec relative to the start of the current pulse with the aid of a varia-

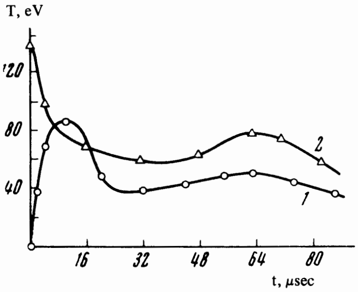

FIG. 4. Variation of plasma electron temperature during the current pulse at different argon pressures: 1—3.0 × 10^{-4} Torr, 2—3.0 × 10^{-3} Torr (J_{beam} = 5 A, U_{beam} = 16 kV).

ble delay line. The signal from the photomultiplier was then amplified, integrated, and fed to the input of an ÉPP-09 automatic recorder. The use of such a setup made it possible to obtain the absolute values of the electron temperature of the plasma and its variation during the current pulse with sufficiently high time resolution. The temperature was determined by measuring the relative intensity of the He I lines. Although at our maximum plasma densities this procedure leads to errors, the use of correction coefficients[10] results in a correct picture of the time variation and the absolute value of the temperature.

The measured time variation of the electron temperature at different pressures is illustrated in Fig. 4. Comparison of Fig. 4 with Fig. 2 shows that the maximum temperature (curve 1) is attained at the 8-th—10-th microsecond and exceeds 80 eV. It then decreases to 40 eV, since the plasma density is sharply increased and accordingly the energy per particle is decreased. With increasing plasma density, the growth rate of the temperature (curve 2) increases, since the instability-development time is decreased: $\tau \approx \omega_0^{-1}(n_0/n)^{1/3}$.

The plasma ion temperature was determined from the broadening of the ion lines with the aid of an ISP-51 spectrograph crossed an ID-51/30 interferometer. It increased linearly with increasing electron-beam power and reached 0.4 eV at a beam power 800 kW in an argon plasma.

LASING AND INVESTIGATION OF STIMULATED EMISSION PARAMETERS IN A PLASMA-BEAM DISCHARGE

Using the apparatus described above, we obtained stimulated emission in the blue-green and yellow regions of the spectrum on the lines of singly-ionized argon, krypton, xenon, nitrogen, and chlorine. The data on the generated wavelengths and the systematics of the transitions are given in the table. In the present paper we consider the mechanism of generation on argon, krypton, xenon, nitrogen, and chlorine ions. Since the inverted population is produced for all these ions and for all the lasing transitions as a result of the large rate of radiative decay of the lower level in comparison with the rate of decay of the upper level, one should expect the lasing mechanism not to vary in principle on going from one gas to another. We present therefore the experimental results and their analysis only for lasing on the transitions of singly-ionized argon. The interpretation of the results is facilitated by the fact that the lifetimes, excitation cross-sections, and the oscillator strengths are known for these transitions.

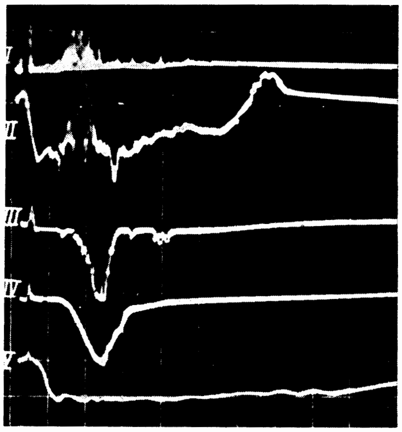

FIG. 5. Oscillograms in pulsed generation regime at P_{Ar} = 3.0 × 10^{-4} Torr: I—HF signal, II—collector-current signal, III—x-ray signal, IV—coherent-radiation signal, V—signal characterizing the time variation of the plasma density (sweep rate 10 μsec/cm).

Generation of coherent radiation was observed in two regimes, the first of which we shall arbitrarily call pulsed. This regime is observed in the pressure range 3 × 10^{-4}—9 × 10^{-4} Torr with a maximum coherent-emission intensity at 4—5 × 10^{-4} Torr. It is characterized by a low laser-pulse duration in comparison with the current-pulse duration. In the same pressure region, collective processes developed effectively in the plasma-beam discharge, with intense development of two-stream instability accompanied by powerful high-frequency bremsstrahlung x-radiation from the plasma. In the pulsed lasing regime one observes not only temporal but also amplitude correlation of the generation and of the high-frequency and bremsstrahlung x-radiation, i.e., the generation intensity increases with increasing intensity of the high-frequency radiation and of the bremsstrahlung from the plasma. From the oscillogram of Fig. 5 we see that the stimulated emission appears stimultaneously with the high-frequency and x-radiation. The dip on the current pulse, which occurs at the same time, is due to the slowing down of the electron beam by the collective interaction with the plasma. The same oscillogram shows the variation of the plasma density with time. It should be noted that when the instability stops the generation also stops. All this allows us to state that in the pulsed regime the necessary density of the inverted states is produced by a group of plasma electrons heated to high temperature during the development of the two-stream instability. Thus, the lasing levels are pumped in this regime by collective processes in the plasma-beam discharge.

We have determined the parameters of the group of plasma electrons responsible for the lasing in the pulsed regime. The electron temperature was determined from the spectral distribution of the bremsstrahlung x-rays, measured with the gamma spectrometer[11] whose block diagram of which is shown in Fig. 1. The x-radiation passed through a lead collimator (ratio of inside diameter to length 1 : 22) and was incident on an NaI(Tl) crystal placed on the cathode of an FÉU-29 photomultiplier. The crystal area was 1 cm^2 and the thickness 0.2 cm. The crystal was coated with a beryllium film less than 20 μ thick. The photomultiplier operated in the spectrometric mode and was shielded against magnetic fields by a double screen. To check on the operation of the setup, we plotted the spectral distribution of the gamma radiation from Cs^{137}. The signal from the photomultiplier was fed through an AI-100 multichannel pulse-height analyzer, operating in the external-control mode. A control pulse of adjustable duration was fed to the analyzer from a GIS-2 generator synchronized with the start of the current pulse, and could be delayed relative to the latter by the required time interval.

The histograms were processed under the assumption that in our case the distribution function of this group of plasma electrons does not differ strongly from Maxwellian. Therefore, by measuring the energy distribution of the bremsstrahlung x-rays, we could determine the temperature from the slope of the line lnI = f(E), where I is the intensity of the x-radiation and E is its energy. From the absolute measurements of the bremsstrahlung x-radiation energy we found the density of the hot particles to be 10^{-2}—10^{-3} of the plasma density. The temperature of the hot group of particles and its time variation at different pressures in the plasma chamber are shown in Fig. 6.

Wave-length, Å	Ion and multiplicity	Transition classification
4764.83	ArII	$4p^2P^0_{3/2} - 4s^2P_{1/2}$
4879.90	ArII	$4p^2D^0_{5/2} - 4s^2P_{3/2}$
5145,34	ArII	$4p^4D^0_{5/2} - 4s^2P_{3/2}$
4765,74	KrII	$5p^4D^0_{5/2} - 5s^4P_{3/2}$
5681.89	KrII	$5p^4D^0_{5/2} - 5s^2P_{3/2}$
5419.15	XeII	$6p^4D^0_{5/2} - 6s^4P_{3/2}$
4896.86	ClII	$(^2D^0)\,4p^3F_4 - (^2D^0)\,4s^3D_3{}^0$
5217.92	ClII	$4p^3P_2 - 4s^3S_1{}^0$
5392.16	ClII	$(^2D^0)\,4p^1F_3 - (^2D^0)\,4s^1D_2{}^0$
5679.59	NII	$(^2P^0)3p^3D_3 - (^2P^0)\,3s^3P^0{}_2$

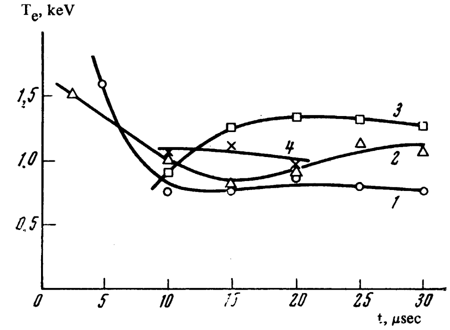

FIG. 6. Time variation of plasma electron temperature at different argon pressures: 1–4.0 × 10^{-4} Torr, 2–6.5 × 10^{-4} Torr, 3–9.5 × 10^{-4} Torr, 4–2.3 × 10^{-3} Torr (J_{beam} = 18 A, U_{beam} = 26 kV).

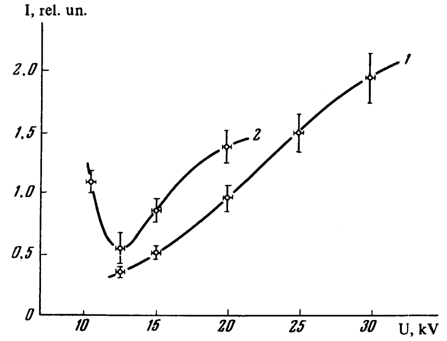

FIG. 7. Coherent-radiation density vs. electron energy: 1–pulsed generation regime (J_{beam} = 10 A, P_{Ar} = 3.0 × 10^{-4} Torr), 2–quasi-stationary generation regime (J_{beam} = 8 A, P_{Ar} = 9.0 × 10^{-4} Torr).

In the pulsed regime, only a fraction of the lines listed in the table generate. The lasing-pulse duration ranges from 6 to 10 μsec when the pressure is varied from 3 to 9 × 10^{-4} Torr. The generation power in this regime is 100 W for argon. Plots of the radiation intensity against the energy and the beam current are shown in Figs. 7 (curve 1) and Fig. 8 (curve 1), respectively. It is seen from these figures that in the pulsed regime the intensity of the coherent radiation first increases with increasing beam current at a fixed plasma density, and then reaches saturation at a beam current higher than 18—20 A. The saturation is due to the strong increase of the temperature of the fast-electron group with increasing beam current, whereas the pump intensity ceases to increase, since the inversion cross section decreases. In the pulsed regime, the start of the lasing can be delayed by 10—20 μsec relative to the start of the current pulse, depending on the variation of the beam power and the pressure in the discharge chamber. This variation is caused by the dependences of the growth rates of the temperature and of the plasma density on the gas pressure and on the beam power.

The temperatures of the electronic and ionic components are determined by the intensity and by the spectrum of the excited oscillations. We have therefore investigated the intensity and the spectra of the high-frequency oscillations as functions of different parameters of the apparatus. A block diagram of the measurements is shown in Fig. 1. The signal from the receiving element (coil or loop) placed inside the plasma chamber was fed to a resonant wavemeter with automatic scanning of the spectrum. This signal was then amplified, integrated, and fed to an automatic recorder. The typical frequencies for our case were $\omega_0 = 10^{11}$ Hz and $\omega_c = 3 \times 10^{10}$ Hz, and the Langmuir frequency of the electron beam was $\omega_b = 4 \times 10^9$ Hz. The spectrum of the oscillations observed in the plasma at different pressures is shown in Fig. 9. A comparison has shown it to differ somewhat from the theoretically-calculated spectrum. The apparent reason is the instability due to "slipping"[12,13]. Since in our case the electron beam was injected into the interaction chamber along a curved trajectory, a radial velocity gradient exists in the beam and causes instabilities connected with the slipping of individual parts of the beam relative to one another. Various nonlinear effects in the plasma lead to a broadening of the spectrum. Out of the entire spectrum, the observed frequencies correlating in time with the coherent radiation, are those with $\omega < \omega_c$, and also the oscillations with frequencies in the interval 1—20 MHz. The latter, as shown in[14], are connected with the ionic oscillations.

When the pressure in the plasma chamber is increased from 6 × 10^{-4} Torr to 6 × 10^{-3} Torr, the pulsed regime goes over into a quasistationary one. In the

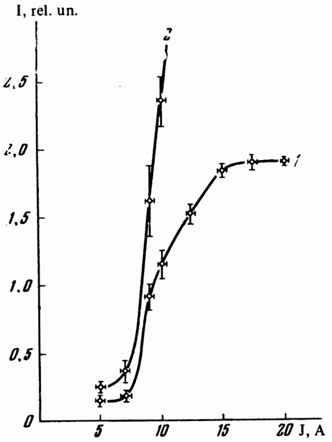

FIG. 8. Coherent-radiation intensity vs. electron-beam current: 1—pulsed generation regime (U_{beam} = 45 kV, $P_{Ar} = 3.0 \times 10^{-4}$ Torr), 2—quasistationary generation regime (U_{beam} = 35 kV, $P_{Ar} = 9.0 \times 10^{-4}$ Torr).

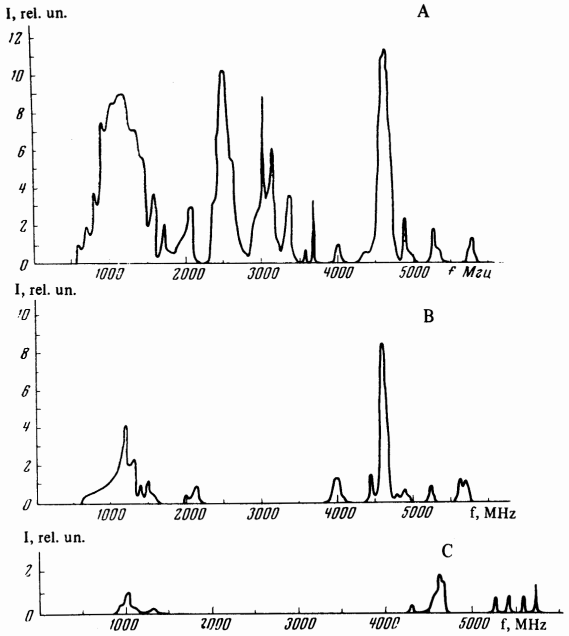

FIG. 9. Spectral composition of HF oscillations vs. argon pressure: 1–3.5 × 10^{-4} Torr, 2–6.5 × 10^{-4} Torr, 3–9 × 10^{-4} Torr (J_{beam} = 13 A, U_{beam} = 20 kV).

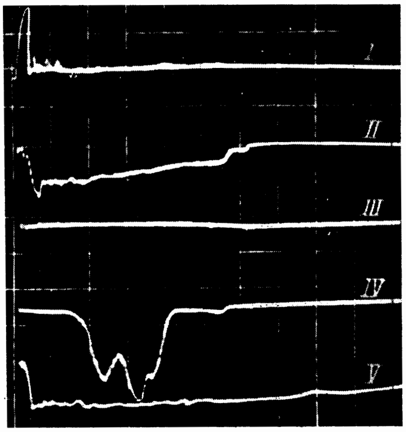

FIG. 10. Oscillograms in the quasistationary regime at $P_{Ar} = 9.0 \times 10^{-4}$ Torr: I—HF signal, II—collector-current signal, III—x-ray signal, IV—coherent-radiation signal, V—signal characterizing the time variation of the plasma density (sweep rate 10 μsec/cm).

pressure range 6×10^{-4}—9×10^{-4} Torr, there exists a regime intermediate between the pulsed and the quasi-stationary ones. Starting with 9×10^{-4} Torr, only the quasi-stationary regime is observed. In this regime, the laser pulse begins at the 15—25-th microsecond and continues until the termination of the current pulse. With increasing current duration, the laser pulse duration increases and a transition to the stationary regime becomes possible. At pressures corresponding to the quasistationary regime, the intensity of the high-frequency oscillations in the plasma decreases sharply, and the electron temperature decreases accordingly. These processes are due to the elimination of the instability when the plasma density is increased above 2×10^{13} cm^{-3}. Figure 10 shows oscillograms of the high-frequency oscillations excited in the plasma, of the beam current, of the bremsstrahlung x-rays from the plasma, of the coherent radiation, and of a signal proportional to the plasma density. It is seen from this figure that in the quasistationary regime that there are no dips on the current and x-ray oscillograms, thus indicating a lowering of the plasma temperature.

Obviously, the character of variation of the electron temperature of the plasma with increasing pressure is determined by the change of the intensity of the high-frequency oscillations. A curve illustrating how the high-frequency power in different frequency intervals depends on the pressure in the plasma chamber is shown in Fig. 11. At pressures optimal for lasing in the quasistationary regime, the electron temperature does not exceed 10—15 eV. The spectral composition and the variation of the generation intensity as a function of the parameters of the apparatus differs significantly in the quasistationary and pulsed regimes (Figs. 7 and 8). The reason is that the inversion mechanism in the quasi-stationary regime differs from that in the pulsed regime. The difference between the dependences of the lasing intensity and the beam energy for the different generation regimes is due to plasma processes. The dip on curve 2 of Fig. 7 at beam energies 12—20 keV is due to the fact that beam energy is consumed by plasma oscillations that are not connected with inversion. This increases the threshold value of the beam current in the same energy band. Plots of the threshold values of the beam current against the energy are shown for the two generation regimes in Fig. 12.

GENERATION MECHANISM

We consider now the generation mechanism in a laser based on a plasma-beam discharge for transitions of singly-ionized argon, krypton, xenon, nitrogen, and chlorine. As already noted the generation mechanisms are similar for all these gases. The level schemes of these gases are such that population inversion cannot be obtained by electron collisions alone. Since the energy difference between the generating levels is $\Delta E \ll kT_e$, these levels will have comparable pump intensities. Inversion is the result of a high rate of radiative decay of the lower level, which is coupled to the ground state

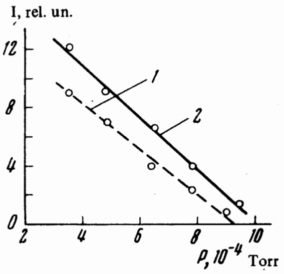

FIG. 11

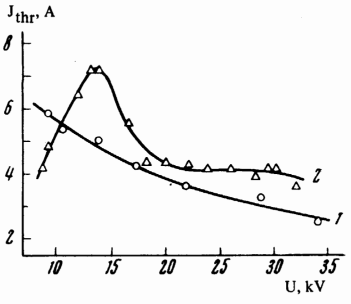

FIG. 12

FIG. 11. HF oscillation intensity vs. pressure for different frequency bands: 1—600—2000 MHz, 2—3000—6000 MHz.

FIG. 12. Threshold value of beam current vs. beam energy for two generation regimes: 1—pulsed regeneration regime, 2—quasistationary generation regime.

of the ion by a strong transition lying in the region of the vacuum ultraviolet. The level scheme for these gases is similar to the scheme of the Ar II levels. We shall therefore analyze the generation mechanism in greater detail, using argon as the example.

In the pulsed regime, there exists a group of hot electrons whose temperature can be varied. In our case its maximum value reaches 0.7—0.8 keV. The generation is due to the appearance of this group and ceases when this group vanishes once the instability disappears. Since the electron energy greatly exceeds the level-excitation energy, it is natural to assume that the pumping is described by a reaction of the type[15]

$$A + e \to (A^+)^* + 2e.$$

If the change of energy ΔE of the system occurs within a time $t \ll \hbar/\Delta E$, then such processes can be described by using the "sudden perturbation" approximation[15,16]. The calculations of[15,16] have shown that in the "sudden perturbation" approximation the bulk of the excited states will lie in configurations similar to the configurations of the electronic core after the atom loses one electron. In our case, this imposes a limitation on the spectrum of the generated wavelengths. In the pulsed regime, the only levels excited are those whose parity coincides with the parity of the ionic ground state. Thus, the upper levels of the observed strong transitions of Ar II, Kr II, and Xe II pertain to p-configurations. After excitation by fast electrons, the argon ion is thus in the upper laser configuration $3p^4 4p$. A contribution is made to the pump not only by the population from the ground state of the neutral atom, is made also by 4d—4p cascade transitions. Since inversion is produced in our case by radiative decay of the lower laser configuration, which is coupled by a strong transition with the ground state $3p^5$ of the ion, one should expect the inversion to decrease at our densities, owing to the resonant capture by this transition. In the pulsed regime, however, the plasma ions become heated upon development of the instability, and their temperature can reach 0.4 eV. At the same time, intense ion streams are produced in the plasma, and their energy can reach 100—1000 eV. The heating of the ions leads to an appreciable lowering of the resonant capture. This heating is due to excitation of oscillations in the 1—30 MHz band.

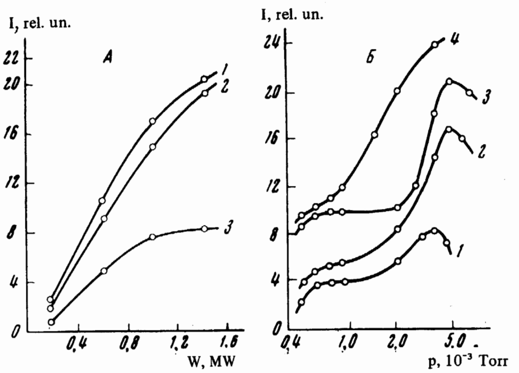

FIG. 13. Intensities of the stimulated emission and of the spontaneous emission for the generating and cascade transitions: A) as functions of the beam power at $P_{Ar} = 2.3 \times 10^{-3}$ Torr; B) as functions of the pressure at $J_{beam} = 20$ A and $U_{beam} = 30$ kV: Curves: 1—spontaneous transition with $\lambda = 4880$ Å, 2—cascade transition with $\lambda = 4372$ Å, 3—stimulated transition with $\lambda = 4880$ Å, 4—cascade transition with $\lambda = 4379$ Å.

Thus it is possible to control the density of the inverted states by controlling the power of the oscillations in this band.

The conditions for exciting the generating levels are quite different in the quasistationary regime. In this regime the electron temperature, as shown by measurements, decreases to 10—15 eV, and the electron density exceeds 2×10^{13} cm^{-3}. The electron energies are insufficient for direct excitation of the levels, and the pumping is by stepwise processes that proceed, in the case of argon, in accordance with the reactions[15,18]

$$e + \mathrm{Ar}(3p^6) \to \mathrm{Ar}^+(3p^5) + 2e,$$
$$e + \mathrm{Ar}^+(3p^5) \to \mathrm{Ar}^+(3p^4 4p) + e.$$

In the case of a stepwise population process, the inversion mechanism differs somewhat from the direct-excitation case that occurs in the pulsed regime. In the pulsed regime, inasmuch as the cross section varies smoothly with changing energy, the upper and lower levels are equally populated. Therefore the inversion is the result of the rates of radiative decays of the upper and lower levels. When the electron energy is close to the level excitation energy, resonance effects can alter significantly the cross section for excitation by electron impact. In this case, selective population of the upper laser levels, having a parity opposite that of the ionic ground state, is possible. This indeed determines the change of the spectral composition of the radiation on going from one regime to the other.

In addition to the principal process 3p—4p of population from the ground state of the ion, a definite contribution is made also by the cascade processes 3p—4p—4p. Figure 13 shows the intensities of the generation and spontaneous emission on the generating and cascade transitions as functions of the beam power and the pressure in the plasma chamber for the quasistationary regime. It is seen from the plots that, starting with a pressure 4×10^{-3} and a beam power exceeding 1.1 MW, the intensity of the spontaneous emission on the generating transition and the intensity of the cascade transitions still increase, whereas the generation power decreases. This indicates a decrease of the density of the inverted states as a result of resonant capture. At high densities ($n_i \sim 10^{14}$ cm^{-3} for Ar II) the lifetime of the lower state increases G times. According to[19,20], the expression for G can be written in the form

$$G = \frac{1,6}{k_0 R}[\pi \ln(k_0 R)]^{1/2}.$$

Here k_0 is the absorption coefficient at the center of the Doppler-broadened line and R is the radius of the plasma column. Estimates show that in the quasistationary regime the lifetime of the 4s state for argon increases by 8—9 times as a result of capture on the 4s—4p transition. Since the intensity of the ion oscillations is very small, disruption of the resonant capture in this regime is impossible.

In a stepwise-inversion mechanism proposed in[15,18], the employed intermediate level is the metastable state of the neutral atom. In this case the reaction follows the scheme

$$e + \mathrm{Ar}(3p^6) \rightarrow \mathrm{Ar}^*(3p^5 4s) + e,$$
$$e + \mathrm{Ar}^*(3p^5 4s) \rightarrow \mathrm{Ar}^+(3p^4 np) + 2e$$

We have investigated the role of the metastable states in inversion. To this end we used the procedure of[21]. A block diagram of the setup is shown in Fig. 1. A high-frequency generator with a continuous output power 2 kW produced in the discharge tube a plasma in an atmosphere of the gas employed as the active medium. A monochromator was used to separate the radiation line corresponding to a transition between levels, of which the lower was metastable. This radiation, modulated at the generator frequency, subsequently passed through a system of lenses to the plasma of the investigated laser. After passing through the plasma column, the radiation proceeded through a monochromator to a photomultiplier. The signal from the photomultiplier was applied to the input of an oscilloscope through special electronic circuitry. The density of the metastable states in the plasma and its time variation could be determined from the absorption of the radiation. The investigations have shown that in the quasistationary regime the density of the metastable states does not exceed 10^{-4}—10^{-5} of the plasma density. It can therefore be stated that inversion into the 4p configuration of singly-ionized argon proceeds from the ground state of the ion, and not from a metastable state of the atom. The inversion mechanism in a plasma-beam discharge is perfectly analogous for the other gases in which lasing was observed.

Inasmuch as in our case the discharge-chamber diameter was 110 mm and the plasma was in a strong magnetic field, the recombination on the walls was negligible. In the main, three-body recombination takes place.

CONCLUSION

We have demonstrated the feasibility of pumping gas lasers by using collective processes in a high-temperature plasma. The use of the collective processes makes it possible to broaden considerably the spectrum of the generated wavelengths and to increase the generation power. Particularly promising in this respect is the plasma-beam discharge. Its promise lies in the fact that relativistic beams with pulse powers of 10^{12} W have already been produced and that work in this direction is progressing rapidly. We can therefore state that pumping with the aid of collective processes in a plasma-beam discharge is apparently the most suitable for obtaining generation in the short-wave region of the optical band.

In conclusion the authors consider it their duty to thank V. P. Tychinskiĭ, V. V. Slezov, V. D. Shapiro, and V. I. Sevchenko for numerous and useful discussions.

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Translated by J. G. Adashko
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