Concerning the problem of lasers for the far ultraviolet $\lambda \sim 500$–700 Å

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Results are reported of experimental investigations aimed at obtaining lasing in the far ultraviolet region of the spectrum ($\lambda \sim 600$ Å on the transitions $2p^53p$–$2p^53s$ of the neon-like ion Ca XI) in a plasma produced by laser heating of a calcium target.

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The possibility of developing lasers for the far ultraviolet region of the spectrum, $\lambda = 300$—700 Å, on transitions of multiply charged ions in a plasma was considered in[1]. It was shown that in a plasma with an electron density $N_e \sim 3 \times 10^{19}$ cm^{-3} and temperature $T_e \sim 150$ eV, one can expect sufficiently large gains $g \gtrsim 10$—20 cm^{-1} on the transitions $2p^53p - 2p^53s$ of the neon-like ions Ca XI, Ti XIII etc. The level scheme of Ca XI is shown in Fig. 1. A whole series of transitions with $\lambda \sim 350$—850 Å is possible between the two groups of levels $2p^53p$ and $2p^53s$. The probabilities of the radiative transitions $2p^53s - 2p^6$, $2p^53d - 2p^6$ and $2p^53p - 2p^53s$ are respectively $\sim 10^{11}$, $\sim 10^{12}$, $\sim 10^9$—10^{10} sec^{-1}. The electric dipole transition $2p^53p - 2p^6$ is forbidden, but the rate of excitation of the $2p^53p$ levels in electron collisions at $T_e \sim 150$ eV is far from small and is even somewhat larger than for the $2p^53s$ levels. It is this ratio of the radiative and collision transitions which gives rise to quasistationary population inversion. According to the estimates of[1], the relative population of the levels $2p^53p$ and $2p^53s$ depends strongly on the dragging of the radiation on the resonant transitions $2p^53s - 2p^6$ and $2p^53d - 2p^6$. For inversion to take place it is necessary that the transverse dimension of the plasma not exceed a certain

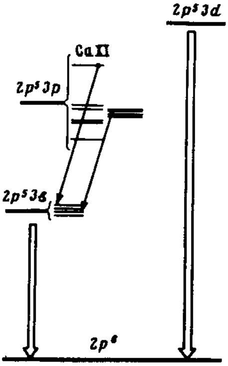

FIG. 1. Level scheme of Ca XI ion.

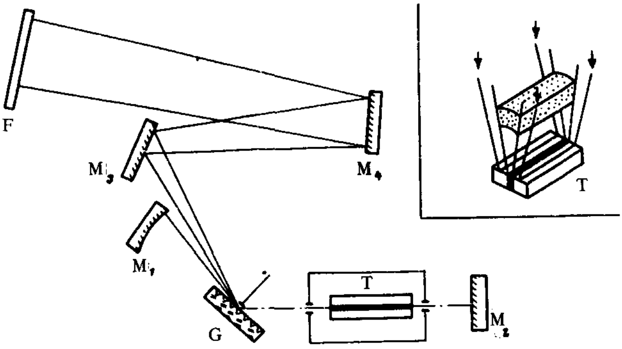

FIG. 2. Diagram of resonator, of registration system, and of target. M_1, M_2—resonator mirrors; M_1—gold, $R = 200$ mm; M_2—ruthenium, flat; M_3, M_4—mirrors of registration system, which attenuate the short-wave radiation (material—gold or tungsten); G—diffraction grating; T—target, the calcium is shown black, the titanium is shown hatched, and the plasma-heating laser radiation is indicated by the arrows; the points mark the active region of the calcium plasma; F—photographic film.

critical value ~150—200 μm, when the resonant radiation still emerges from the plasma with sufficient efficiency.

In our experiments the plasma was produced by laser evaporation of calcium. We used a neodymium laser with a pulse energy up to 30 J. The pulse duration

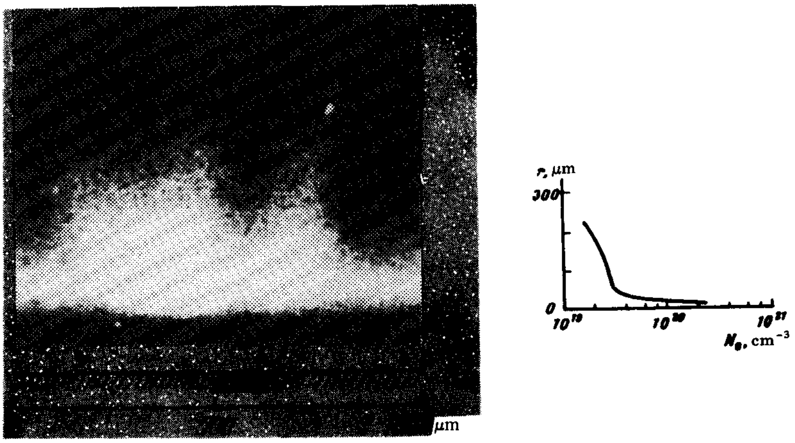

FIG. 3. Photograph of laser flare from a composition target in monochromatic radiation of the 182.17 Å line of the ion C VI (left). The carbon is shown shaded and the beryllium is shown black. The absence of emission in the line of the C VI ion of the plasma layer means that this layer is filled with the beryllium plasma. Right—dependence of the electron density N_e on the distance to the target in a carbon plasma. The vertical scale for the left and right figures is the same.

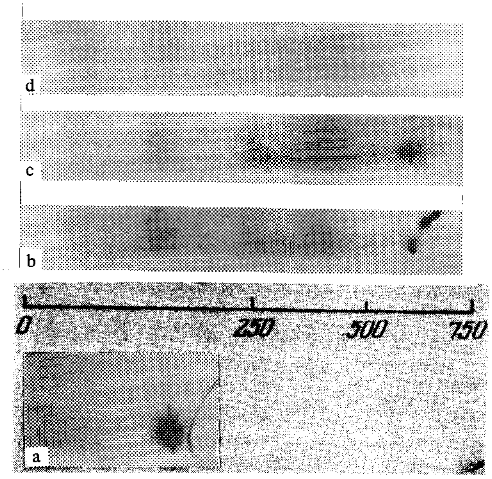

FIG. 4. a, b, c, —Photographic-density spots in the region $\lambda = 600\text{—}660$ Å, d—continuous-background strip under the same irradiation conditions as a, b, and c. The wavelengths are given for the first order of diffraction.

was in the range 2.5—5 nsec. According to estimates and preliminary experiments, a temperature $T_e \sim 150$ eV corresponds to fluxes $q \sim 5\times10^{10}$ W/cm^2. Therefore the fluxes was varied in the range $2\times10^{10}\text{—}7.5\times10^{10}$ W/cm^2. The focusing was by a cylindrical lens; the focusing spot was 0.4—0.8 mm wide and 10—40 mm long. The target (Fig. 2) consisted of a calcium strip whose width ranged from 0.03 to 0.125 mm. Its length was 20—40 mm. This strip was clamped in a steel block between titanium liners 0.3 mm wide, followed by grinding of the target.

As shown in preliminary investigations,[2] evaporation of the target of the type described above should result in a directional spreading of the calcium. This gave grounds for hoping that the transverse dimension of the calcium plasma in the working region would not exceed 150 μm. An approximate idea of the profile of the electron density at fluxes $q \sim 5\times10^{10}$ W/cm^2 was obtained in experiments on laser heating of a carbon plasma. The profile N_e was determined from the Stark broadening of the lines of the hydrogen ions C VI. Values $N_e \sim 3\times10^{19}$ cm^{-3} are realized at distances ~100 μm from the target (see Fig. 3). An approximate estimate of the temperature T_e was obtained from the following experiments. A DFS-6 spectrograph (grating with 600 lines/mm) was used to register the spectrum of a calcium and titanium plasma in the range 80—200 Å. At fluxes 10^{11} W/cm^2 the spectrum revealed lines of hydrogen-like and fluorine-like ions Ca XII, Ca XIII, Ti XIV, and Ti XV, which followed the neon-like ions. Within the framework of the corona model, these conditions correspond to an ionization temperature ~200 eV.

We used in the experiment a resonator[3] made up of a flat mirror, a spherical mirror with radius 200 mm, and a zero-order diffraction grating—see Fig. 2. The radiation was extracted from the resonator as a result of diffraction of first and succeeding orders. The glass grating without a coating had 600 lines/

mm; the angle of incidence of the radiation on the grating was 0.045 rad. The flat mirror had a ruthenium coating, and the spherical mirror was gold coated. The reflection coefficient for freshly sputtered coatings in the region $\lambda \sim 600$ Å were, according to[4,5], $R \approx 0.25$ and $R \approx 0.13$, respectively. The target plane was located 100—150 μm away from the resonator axis. The orientation of the calcium strip relative to the resonator axis was set with accuracy not worse than 3×10^{-4} rad, and its position was set accurately to ~10 μm. Two additional tungsten or gold-coated mirrors were placed in the path from the resonator to the film. This attenuated the background of the short-wave spontaneous emission. We used UF-4 photographic film. All together we performed approximately 20 experiments with very careful adjustment of the resonator and with visual monitoring of the mirror quality. In most experiments only a weak exposure strip produced by the plasma spontaneous-emission spectrum, was observed on the film. Only in some cases were spots registered with large photographic density, of the type that might be expected when lasing sets in—see Fig. 4. The forms of these spots and their positions (in the spontaneous-background strip) distinguishes them strongly from the occasionally occuring film defects. Figure 4 shows a very weak background of spontaneous emission, bounded from below by the edge of the target, and a dense spot with dimension 0.5 mm. Since the distance from the resonator to the film is 20 cm, this dimension corresponds to an angle divergence 2×10^{-3}. Knowing the absolute sensitivity of the film in the $\lambda \sim 600$ Å region, we can estimate the total energy incident on the film. It amounted to $\sim 10^{-8}$ J. The two mirrors between the resonator and the film attenuated the beam by a factor of approximately 100 times. Consequently, the amount extracted from the resonator in one (first) diffraction order is $\sim 10^{-6}$ J ($\sim 10^{12}$ photons). Comparison with the blackbody radiation energy in the same spectrum and angle interval yields the following results. If the black body has a temperature ~150 eV and the illumination lasts 10 nsec, while the area is equal to that of the opening in the diaphragm covering the plasma, then the energy, with allowance for the identical attenuation by two mirrors, turns out to be 10^4 times smaller than that registered in the film.

Figure 4(b) shows several dense spots. The total energy corresponding to them is approximately 30 times smaller than in the first case.

In these first experiments it was impossible to determine exactly the wavelength λ, since the radiation diffracted by the resonator grating was registered directly on the film without an additional spectral instrument. By starting from the relative positions of the resonator grating and of the film, one could only obtain an approximate estimate of λ. The observed photographic-density spots correspond to an interval $\lambda = 600$—660 Å.

No provision was made for monitoring the plasma parameters and the ion composition directly in the experiments with the resonator. The target-irradiation regime was chosen on the basis of the results of the preliminary experiments. At the same time, as shown by calculations, the concentration of the neon-like ions and the populations of the levels $2p^5 3p$ and $2p^5 3s$ depend very strongly on the plasma parameters. In the subsequent experiment we therefore plan to carry out, first of all, a detailed diagnostics of the plasma, including a simultaneous determination of the density profile and of the temperature, control of the ion composition, determination of the dependence on the target irradiation conditions and on the character of the plasma expansion. Only under these conditions can we hope to obtain reproducible results and interpret them reliably. The resonator employed was likewise not optimized. The total length of the resonator was 140 mm. At a pulse duration 2.5—5 nsec this corresponds to 5—10 passes, but in view of the small width of the amplification regime in the calcium plasma (~0.15 mm), at such a length the resonator is sensitive to small misalignments of the mirrors, and also to deviation of the radiation from the resonator axis as a result of refraction in the plasma. We propose in the future also to use a slit resonator.[3]

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[1] A. V. Vinogradov, I. I. Sobel'man, and E. A. Yukov, Kvantovaya Elektron. (Moscow) 4, 63 (1977) [Sov. J. Quantum Electron. 7, 32 (1977)].

[2] A. A. Ilyukhin, G. V. Peregudov, and E. N. Ragozin, Pis'ma Zh. Tekh. Fiz. 2, 681 (1976) [Sov. Tech. Phys. Lett. 2, 266 (1976)].

[3] A. A. Ilyukhin, G. V. Peregudov, E. N. Ragozin, and V. A. Chirkov, Kvantovaya Elektron. (Moscow) 4, 919 (1977) [Sov. J. Quantum Electron. 7, 519 (1977)].

[4] J. T. Cox, G. Hass, J. B. Ramsay, and W. R. Hunter, J. Opt. Soc. Am. 64, 423 (1974).

[5] R. P. Madden, transl. in: Fizika tonkikh plenok (Physics of Thin Films), Mir, 1967, p. 152.