Lasing at 60.8 nm in Ne-like sulfur ions in ablated material excited by a capillary discharge

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We report the observation of discharge-pumped extreme ultraviolet lasing in collisionally excited ions of a material ablated from a solid target. Excitation of sulfur plasmas by a capillary discharge resulted in amplification of the $J=0-1$ line of Ne-like sulfur at 60.8 nm, with a gain coefficient of 0.45 cm^{-1} and a gain-length product of 7.5. Overheating of the electron temperature and transient population effects are computed to make a significant contribution to the measured gain. [S1050-2947(97)01702-2]

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Since their first realization in 1984 [1], soft x-ray and extreme ultraviolet lasers based on the collisional excitation of Ne-like ions have been pumped by laser drivers. Laser action in this isoelectronic series has been achieved in elements from a wide range of atomic numbers, from silver [2] down to silicon [3]. Alternatively, a recent experiment demonstrated large amplification at 46.9 nm in a discharge-pumped argon plasma [4], opening a new route to the development of simpler and more compact ultrashort wavelength lasers based on excitation by capillary discharges. That argon capillary discharge experiment also constituted the first observation of soft x-ray amplification on the Ne-like sequence utilizing a gaseous target. However, only a few elements are available in gaseous form under normal laboratory conditions. Therefore, the observation of lasing in materials produced from solid targets is important to extend the spectral range of discharge-pumped soft-x-ray lasers. In this paper we report the demonstration of lasing action in Ne-like sulfur ions by capillary discharge excitation of sulfur vapor produced by discharge ablation of a solid target.

The production of plasmas from solid materials in capillary discharges in a repetitive way can be done either by ablation of the material from the capillary wall or by injection of the material into the capillary. Previous attempts of producing discharge-pumped plasmas for soft-x-ray amplifiers from solid elements have utilized direct ablation of the material from the capillary wall [5–9]. In the case of plasmas for collisionally excited lasers, we have previously used excitation of ablated material from 1.5 mm diam capillary channels up to 3 cm in length for the identification of line emission at wavelengths corresponding to the $J=0-1$ transition in Ne-like calcium and titanium [10]. In this case, the capillary channels were drilled on cylinders made either by pressing CaH_2 powder to high pressures or by binding TiH_2 and CaH_2 with epoxy resin. For longer channels, however, it is difficult to ensure the uniformity and homogeneity of the capillary material along the axis.

Alternatively, as in the case of gaseous targets, the lasing material can be injected into the capillary channel of the laser. In the scheme demonstrated in the present study the lasing material is produced by ablating with a slow current pulse the wall of a separate capillary discharge channel drilled on the selected material. The vapor produced by this secondary discharge is injected into the main capillary channel and is subsequently excited by a fast current pulse to generate a narrow plasma column with the necessary conditions for amplification. In this scheme, the choice of the solid material used to produce the laser medium in vapor form largely depends on its electrical properties. For the experiments described herein, sulfur was chosen as the closest element to argon which is an insulator on its pure form. Lasing in Ne-like sulfur at 60.8 nm has been recently observed in laser-created plasmas generated using the Asterix iodine laser facility at the Max Planck Institute for Quantum Optics [3].

The fast capillary discharge setup used to excite the gain medium has been already described in a previous publication [11]. In this setup, the capillary channel is placed on the axis of a 3 nF, circular parallel-plate capacitor which is pulse charged by a Marx generator. The capacitor is then discharged through a series circuit which includes the capillary channel and a pressurized SF_6 spark-gap switch. The radiation exits the capillary through an axial hole in the ground electrode. In the experiments discussed herein, polyacetal capillaries 4 mm in diameter and up to 16.8 cm long were excited with current pulses having a first half cycle duration of approximately 72 ns. This short current pulse was preceded by a discharge prepulse several microseconds long, used to obtain a uniform preionization of the plasma. This original configuration was modified as schematically shown in Fig. 1 to allow injection of sulfur vapor into the capillary through the axial hole of the ground electrode. The vapor was produced by ablating the wall of a 5 mm in diam, 2 cm long sulfur channel with a current pulse delivering 200 J in about 50 μs. The channel was drilled on a sulfur cylinder formed by pressing sulfur powder to 0.2 GPa. The pressure of the sulfur vapor in the laser capillary channel was selected by varying the timing of the fast current pulse with respect to the firing of the secondary ablative discharge through the evacuated sulfur channel. The pressure was measured with a capacitive manometer.

The main diagnostics consisted of a 2.2-m grazing incidence spectrograph provided with a 1200 lines/mm gold-coated diffraction grating mounted at 4.2° with respect to the incoming radiation. The emission from the plasma was collected and focused onto the slit of the spectrograph by a 13 cm radius cylindrical aluminum mirror placed at grazing incidence. The radiation dispersed by the grating was recorded

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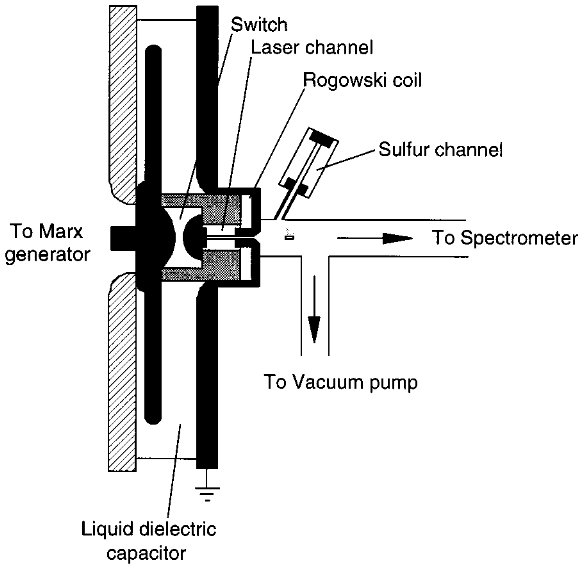

FIG. 1. Schematic diagram of the discharge showing the relative position of the sulfur discharge channel respect to the laser channel.

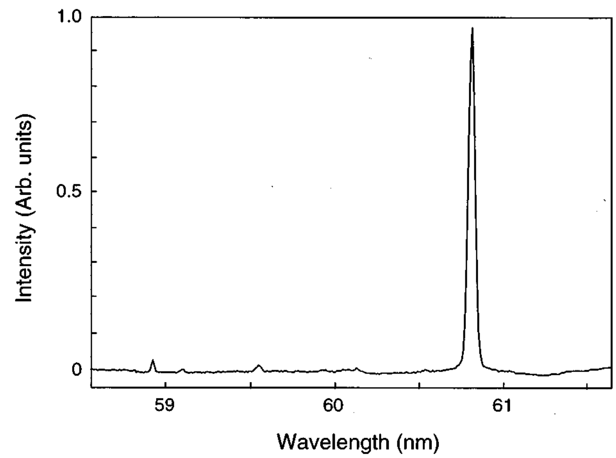

FIG. 2. Spectrum of the axial emission of the sulfur plasma column showing the region between 58.8 and 61.2 nm. The spectrum corresponds to a 37 kA discharge through a 4 mm diam, 16.8 cm long capillary filled with 460 mTorr of ablated sulfur vapor. The $3s\,^1P_1^o$–$3p\,^1S_o$ laser line of Ne-like sulfur completely dominates the spectrum, while the 60.1 nm $3p\,^1P_1$–$3d\,^1P_1^o$ of the same ion is not observed.

by a detector consisting of a microchannel plate intensifier, a phosphorus screen, and a charge-coupled device (CCD) array detector. Gating of the gain of the microchannel plates allowed for the acquisition of spectra with a temporal resolution of approximately 5 ns.

Under optimized conditions, strong lasing in Ne-like sulfur was expected to occur in the $3s\,^1P_1^o-3p\,^1S_o$ line, as is the case in the discharge-pumped Ne-like argon laser [4]. This $J=0-1$ line had been accurately identified at 60.84 nm in spectra obtained from laser-created sulfur plasmas [12]. To identify this line in the capillary discharge plasma, series of spectra were taken in the vicinity of 60 nm. The spectrograph was calibrated in this spectral region by using He I, Ar II, and Ar III line radiation emitted by a low-pressure dc capillary discharge.

It was observed in preliminary shots that the spectra obtained from sulfur plasmas in the region close to the $J=0-1$ transition showed the third diffraction order of strong lines from S VIII (F-like sulfur) and S IX (O-like sulfur) in the proximity of 20 nm. One of the strongest spectral features, a blend of the third order of the $2s\,^22p^5-2s\,^12p^6$ transition of S VIII and the $2s\,^22p^4-2s\,^12p^5$ transition of S IX, was observed to appear at 60.78 nm, 0.06 nm away from the measured wavelength of the $J=0-1$ line. To eliminate the radiation from these short-wavelength transitions, that can complicate the detection of gain for low amplification, a tin filter was interposed in the path of the incoming radiation. Tin foil acts as bandpass filters in the range from approximately 50 to 80 nm.

Figure 2 shows a spectrum obtained under optimized lasing conditions in the spectral region spanning from 58.8 to 61.2 nm using the tin filter. The spectrum corresponds to a 37 kA discharge through a 4 mm in diam, 16.8 cm long channel filled with 460 mTorr of sulfur. The spectrum on this region is completely dominated by the $J=0-1$ transition of Ne-like sulfur, which appears at 60.84 ± 0.015 nm. Another line of Ne-like sulfur (the $3p\,^1P_1-3d\,^1P_1^o$ transition at 60.12 nm [12]), that in absence of amplification should have similar intensity, also falls in the spectral range of Fig. 2. The fact that in our plasma column the intensity ratio of these two lines is observed to be at least 100 is clear evidence of amplification.

The gain was determined by measuring the variation of the intensity of the 60.84 nm line as a function of the plasma column length for capillary lengths between 10.5 and 16.8 cm. For the gain measurements, the amplitude and period of the current pulse were maintained at 37 ± 1 kA and 70 ± 2 ns for all capillary channel lengths by changing discharge voltage and the inductance of the discharge circuit. The sulfur vapor pressure was approximately 470 mTorr in all the shots. As the only tin filter available had an attenuation at 60.84 nm that was excessive ($\approx140\times$) to make a reliable measurement of the intensity for the shorter capillaries, aluminum filters were used to attenuate the intensity of the radiation emitted by the plasma. The intensity of the $J=0-1$ line of Ne-like sulfur was determined by fitting the line profiles at 60.84 nm to subtract the contribution of the above mentioned lines of S VIII and S IX. Figure 3 shows the measured variation of the integrated intensity of the $J=0-1$ line of Ne-like sulfur as a function of plasma column length. An increase of about 1.6 in the plasma length is observed to increase by a factor of 13 the integrated intensity of the laser line. A fit of the Linford formula [13] to the experimental data results in a gain coefficient of 0.45 ± 0.01 cm^{-1}, corresponding a gain-length product of 7.55 ± 0.15 for the 16.8 cm long capillaries.

The lasing occurs shortly before the stagnation of the plasma, as is the case for Ne-like argon [14]. The region of gain is a narrow plasma column of about 0.03 cm in diameter surrounded by a lower-density plasma containing sulfur ions of a lower degree of ionization, which is in turn surrounded by material ablated from the capillary wall. The deceleration of the plasma near the axis prior to stagnation results in a velocity gradient that, due to motional Doppler broadening, considerably facilitates the radial escape of the lower laser level radiation. At the time of lasing, which for our discharge conditions is observed to occur near the time of maximum current, the electron density and temperature in the gain re-

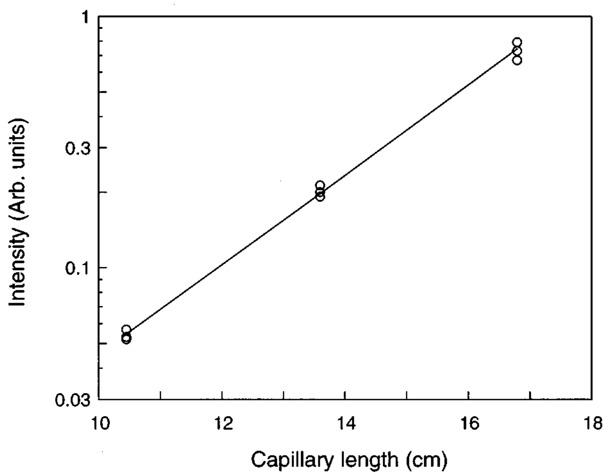

FIG. 3. Variation of the integrated intensity of the $J=0-1$ line of Ne-like sulfur as a function of plasma column length. The line is a fit to the Linford formula [13], which results in a gain coefficient of $0.45\pm0.01\ \mathrm{cm}^{-1}$ and to a gl product of 7.55 ± 0.15 for the longest plasma column.

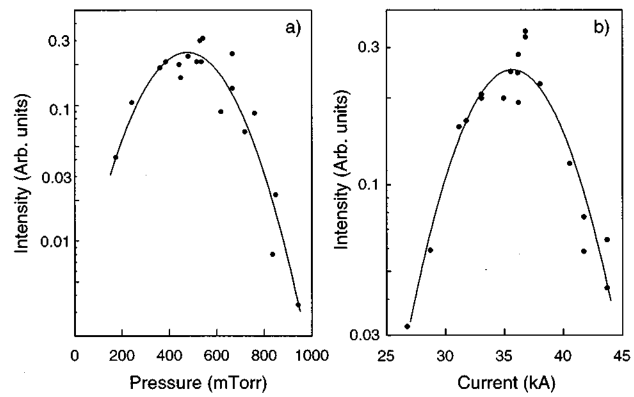

FIG. 4. (a) Integrated intensity of the 60.84 nm lasing line as a function of the filling sulfur vapor pressure. The data correspond to 37 ± 1 kA discharges through 4 mm in diam, 16.8 cm long capillary channels. (b) Variation of the integrated intensity of the $J=0-1$ line of Ne-like sulfur as a function of the discharge current on the same capillaries. The pressure was maintained constant at about 470 mTorr in all the shots.

gion are computed to be about $(2–3)\times10^{18}\ \mathrm{cm}^{-3}$ and 60–80 eV, respectively. As described below, this electron temperature corresponds to a plasma which is overheated with respect to the conditions for maximum Ne-like sulfur abundance in a steady-state plasma.

The change in the integrated laser line intensity was also measured as a function of the amplitude of the fast current pulse and the sulfur filling pressure. Figure 4(a) shows the dependence of the intensity of the lasing line as a function of filling pressure for discharge shots with a peak current of 37 ± 1 kA. The $J=0-1$ line was observed to lase strongly for a broad pressure range, from 300 to 700 mTorr. Figure 4(b) shows the variation of the integrated intensity as a function of peak current, for a filling pressure of 470 ± 10 mTorr. It is observed that large amplification occurs in discharge shots driven by peak currents between 33 and 38 kA.

According to the approximate scaling laws of atomic kinetics valid for lasing in Ne-like ions in steady-state conditions, the gain scales for ions of charge Z approximately as $G\propto Z^{4.5}$ [15]. Consequently, for sulfur, a gain ≈3 times smaller than that observed in Ne-like argon could be estimated. In the case of the $J=0-1$ line of argon, the effective gain was measured to reach $1.16\ \mathrm{cm}^{-1}$ [14], a value that is smaller than the maximum computed plasma gain of about $1.5–1.8\ \mathrm{cm}^{-1}$ due to refraction losses. According to the above mentioned scaling, the effective gain in Ne-like sulfur would be expected to be rather small, less than $0.3\ \mathrm{cm}^{-1}$. However, computations performed with the code RADEX [16] show substantial differences with respect to a steady-state scenario. The calculations indicate important contributions to the generation of the population inversion by plasma overheating and transient population effects. Due to the exponential dependence of the excitation rates on the electron temperature, a larger population inversion and, consequently, a larger gain, arises from the overheating. Such overheating of the plasma with respect to steady-state ionization conditions can be more easily achieved in low-Z elements like sulfur, due to a decrease of the ionization time with ion charge. Lasing in the $J=0-1$ line of Ne-like sulfur in our experiment is computed to occur in a substantially overheated plasma with $T_e\approx60–80$ eV. For comparison, in steady-state conditions, the Ne-like sulfur ions reach a maximum abundance at $T_e\approx20–40$ eV [15]. In addition, in the sulfur laser transient population effects are found to play a more important role than in the argon laser. A transient increase in the population inversion can arise when the characteristic time of the rise of the excitation is of the order of the effective lifetime of the laser upper level [17]. While in these relatively long-lived discharge plasmas transient effects are not nearly as dramatic as in plasmas produced by subpicosecond lasers [18], their contribution to the gain can be noticeable. The computations indicate that, in the case of sulfur, transient population effects can increase the gain by 20–40%. As a result of plasma overheating and transient population effects the maximum gain in the $J=0-1$ line of Ne-like sulfur is computed to approach $1\ \mathrm{cm}^{-1}$, a value which taking into account refraction losses is in satisfactory agreement with the measured effective gain of $0.45\ \mathrm{cm}^{-1}$.

In summary, we have demonstrated for the first time extreme-ultraviolet lasing in the Ne-like sequence in a discharge-pumped plasma produced by excitation of vapor produced by ablation from a solid target. A gain-length product of 7.5 was measured at 60.84 nm in the $J=0-1$ line of Ne-like sulfur. The contributions of plasma overheating and transient population effects result in a gain that is substantially higher than that for steady-state conditions. The combination of the capillary discharge excitation and the discharge ablation technique demonstrated herein is likely also to result in the successful excitation of ultrashort wavelength laser transitions in other materials, extending the range of discharge-pumped lasers.

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