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Ne-like ion lasers in the extreme ultraviolet region

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We report strong $J=0-1$, $3p$-$3s$ lasing in Ne-like scandium, calcium, potassium, and chlorine at wavelengths ranging from 35.3 nm in scandium to 52.9 nm in chlorine. The experiments were carried out with the ASTERIX IV iodine laser using a 15% prepulse 5.2 ns before the main pulse. These results extend the range of laser plasma x-ray lasers into the extreme ultraviolet region. Gain lengths between 7 and 11 were measured for the different lines. The 38.3-nm laser in calcium lased at an intensity as low as 5×10^{12} W/cm^{-2}.

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The initial prediction of Ne-like lasing was predominantly for low-Z elements with atomic numbers around 20 [1,2]. Since the demonstration of high-gain lasing in Ne-like selenium [3], Ne-like soft-x-ray (SXR) lasers in laser plasmas have been made to operate in a great number of elements ranging from silver ($Z=47$) down to titanium ($Z=22$) [4,5]. For even lower-Z materials, a successful demonstration of gains has so far been missing.

Recently, there has been an increasing interest in lasers in these low-Z materials [6,7], mainly due to the reduced drive power requirements and a number of applications anticipated for the coherent extreme ultraviolet (XUV) radiation generated. Progress has been made by demonstrating the gain on the $J=0-1$, $3p$-$3s$ transition in Ne-like Ar ($Z=18$) at a wavelength of 46.9 nm in a capillary discharge [6].

For laser-plasma lasers in low-Z Ne-like ions, a plasma with a relatively low electron density must be generated, while keeping a small density gradient to allow the laser beam to propagate down the gain region. The electron density scaling of Elton [8], for example, predicts the optimum electron density for chlorine ($Z=17$) to be 9.7×10^{18} cm^{-3}, about two orders of magnitude lower than the critical density of a drive laser operating at around 1 μm, and lasing therefore is normally not achieved.

A solution to this problem is provided by the prepulse technique [9,10], in which a low-intensity prepulse is used to generate the laser medium, which is heated several nanoseconds later by the main pulse. Simulations by Nilsen *et al.* [9] indicated that the prepulse is very efficient in making a larger and more uniform plasma that allows a better propagation of laser beam along the gain region. This method has been proven to be successful for producing strong $J=0-1$, $3p$-$3s$ lasing in many low-Z Ne-like ions down to titanium [9–12]. In this work we apply this technique to scandium, calcium, potassium, and chlorine ($Z=21$, 20, 19, and 17), thus generating a number of strong $J=0-1$, $3p$-$3s$ lasers in Ne-like ions with wavelengths extending from 35.3 nm in scandium to 52.9 nm in chlorine. The 52.9-nm chlorine laser is the longest-wavelength Ne-like laser demonstrated to date. We also demonstrate the 38.3-nm, $J=0-1$ laser in Ne-like calcium at an intensity as low as 5×10^{12} W cm^{-2}, which could be an important step towards a laser-plasma SXR or XUV laser operating with high output but low pump intensity.

450-ps [full width at half maximum (FWHM)] pump pulses at 1.315 μm from the ASTERIX IV iodine laser [13] were used in these experiments. The spurious prepulse of the system was measured below 10^{-6} of the main pulse energy. A line focus, 3 cm long and 150 μm wide, was produced by a cylindrical lens array [14], yielding an irradiation intensity on the target surface of about 2×10^{13} W cm^{-2} with 450 J. To produce a defined prepulse, a setup similar to our previous experiments was used [11,12], with a prepulse–main pulse delay of 5.23 ns and an energy ratio of the prepulse to the main pulse of 15%.

For scandium targets, 100-μm-thick foils were glued on flat Al substrates. Calcium fluoride (CaF_2) and potassium chloride (KCl) crystals with polished surfaces were used for the calcium, potassium, and chlorine lasers. Slabs of germanium were used for comparison and wavelength calibration. The target lengths ranged from 1.4 to 3 cm.

The principal diagnostics was a time-integrated, space-resolved transmission grating spectrometer coupled to a thinned, backside-illuminated charge-coupled device (CCD) [15]. It looked axially onto one end of the plasma column, with spatial resolution in the direction perpendicular to the target surface. The spatial resolution of about 50 μm with a magnification of 3 was provided by a spherical mirror 500 cm in radius. A 5000 lines per millimeter free-standing transmission grating with a 50-μm-wide slit dispersed the incident radiation perpendicularly to the spatially resolved direction. The CCD could be translated along the dispersion direction to scan a wavelength range of up to 60 nm with a coverage of 7.2 nm and a spectral resolution of about 0.05 nm. The grating has a supporting structure perpendicular to the grating bars with a period of 4 μm that disperses the incident emission along the spatial direction. This diffraction pattern provides a wavelength scale in regions where calibration lines are not available. Furthermore, these higher orders are used for intensity measurements when the nondispersed image is saturated.

As an example of the spatially resolved spectra, a record for a 3-cm-long CaF_2 target is displayed in Fig. 1. A bright laser emission at 38.3 nm, accompanied by the diffraction

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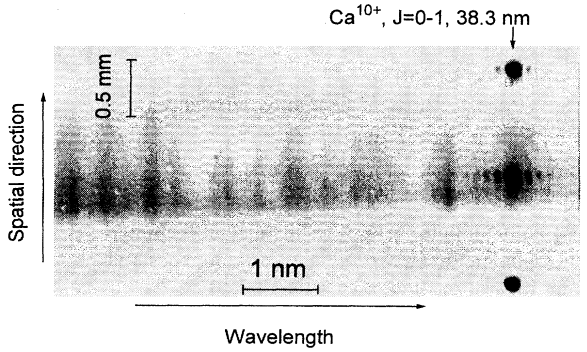

FIG. 1. Spatially resolved spectrum for a 3-cm CaF$_2$ target with 444 J total drive energy and a 15% prepulse. The laser at 38.3 nm, accompanied by diffraction due to the 4-μm support structure of the transmission grating (in spatial direction) and the 50-μm slit on top of the grating (in wavelength direction), is clearly seen. The scaling of the display is chosen to show the weak surrounding emission, so the lasing spot is saturated.

due to the grating support and the slit on top of the grating, is clearly seen. An energy of 444 J with a 15% prepulse was used for this shot. It is obvious from Fig. 1 that the lasing region is detached from the target surface. An accurate measurement of the distance of the lasing position from the target surface was not possible due to the short depth of focus of the imaging optics, which made it difficult to determine the exact position of the target surface.

In Fig. 2, we show the spectra obtained from scandium, CaF$_2$, and KCl targets. All spectra were obtained with drive energies of 450±20 J and a 15% prepulse. The laser lines dominate the spectra for all these elements. Beside the laser on the normal $3p\ {}^1S_0 - 3s\ {}^1P_1$ [termed $E(0-1)$] transition, we also observed the $3p\ {}^1S_0 - 3s\ {}^3P_1$ [termed $G(0-1)$] transition to lase weakly in scandium, with the $E(0-1)$ line saturating the detector, as shown in Fig. 2. By measuring the intensity of the diffraction from the grating support, the intensity of the $E(0-1)$ laser in scandium was deduced to have 42 000 counts on the scale of Fig. 2.

TABLE I. Transitions, wavelengths (λ), gain coefficients (g), and gain lengths (GL) of the lasers observed in this work. The wavelengths are taken from Ref. [15]. The gain coefficients have an error bar of $\pm 0.8\ \mathrm{cm}^{-1}$.

Ions	Transitions	λ (nm)	g (cm^{-1})	GL
Sc^{11+}	$E(0-1)^{a}$	35.2	3.8	9.8
	$G(0-1)^{b}$	31.2		
Ca^{10+}	$E(0-1)$	38.3	3.8	11.4
K^{9+}	$E(0-1)$	42.1	3.4	10.2
Cl^{7+}	$E(0-1)$	52.9	2.5	7.5

[a] $3p\ {}^1S_0 - 3s\ {}^1P_1$ transition.

[b] $3p\ {}^1S_0 - 3s\ {}^3P_1$ transition.

The wavelengths of all the observed lasing lines, as taken from Ref. [16], are listed in Table I. The $E(0-1)$ laser at 52.9 nm in chlorine is the longest-wavelength Ne-like ion laser to date. Table I also summarizes the measured gain coefficients, which were determined by comparing the lasing output from two target lengths (2.6 and 1.4 cm for scandium, 3.0 and 2.1 for calcium, 3.0 and 2.1 cm for potassium, and 3.0 and 2.2 cm for chlorine) with the standard formula [17]. Since our gain coefficients are obtained from one shot for each target length, a large error bar of $\pm 0.8\ \mathrm{cm}^{-1}$ is quoted, derived from the worst shot-to-shot irreproducibility observed in our previous experiments. The value serves as an upper limit for the error bar. The gain lengths obtained are also listed. The $G(0-1)$ line in scandium was too weak in the shorter target to allow a gain measurement to be made.

We made a series of shots with 3-cm-long CaF$_2$ targets, successively reducing the pump energy while keeping a constant prepulse–to–main pulse energy ratio. The result is shown in Fig. 3, where the spectra at total energies of 444, 202, and 115 J (which correspond approximately to intensities of 2, 1, and $0.5\times10^{13}\ \mathrm{W\,cm^{-2}}$) are shown. A reduction of the drive energy from 444 to 202 J reduces the output of

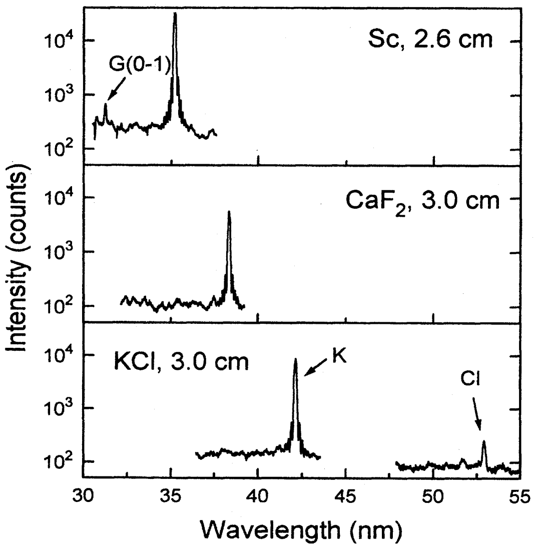

FIG. 2. Spectra for scandium, CaF$_2$, and KCl with lasing on the $J=0-1$, $3p$-$3s$ transitions. The weak $G(0-1)$ line in scandium is indicated by an arrow, and the other lines are $E(0-1)$ transitions. The total drive energy was 450±20 J with a 15% prepulse.

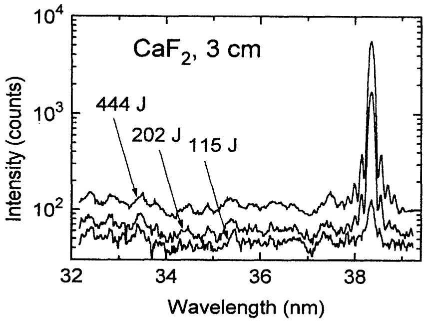

FIG. 3. Spectra from 3-cm CaF$_2$ targets at different drive energies. The 38.3-nm $E(0-1)$ laser lased even with an energy of 115 J ($5\times10^{12}\ \mathrm{W\,cm^{-2}}$). Again, one notes the diffraction of the SXR laser beam due to the 50-μm slit on top of the grating.

the 38.3-nm $E(0-1)$ laser by a factor of 3. Further reducing the drive energy by a factor of 2 reduces the output by another factor of 10. With an optimized prepulse–to–main pulse intensity ratio, lasing with a further reduction of the pump energy might be possible.

It is interesting to compare our results with the recent result of Rocca *et al.* In that work [6], capillaries as long as 12 cm have been used to achieved a gain-length of 7.2 on the 46.9-nm, $J=0-1$, $3p$-$3s$ transition in Ne-like argon. (The same group reported a gain length of 14 in a more recent experiment under optimized conditions [18].) In our experiment with potassium and chlorine, which are, respectively, one number higher and lower in Z compared to argon, we obtained a similar gain length (11.4 for potassium and 7.5 for chlorine) on the analogous Ne-like transition, with shorter target length and higher gain coefficients, however.

In summary, we have demonstrated lasing in a number of low-Z Ne-like ions with wavelengths ranging from 35.3 to 52.9 nm. These results extend the available wavelength range of laser-plasma lasers into the XUV region, and more importantly, verify the original theoretical prediction for Ne-like lasing [1,2]. For one of these, i.e., the 38.3-nm laser in calcium, we have shown that lasing can be achieved at a significantly lower drive power than for previous Ne-like lasers. These findings may be an important step towards the realization of a high gain length, table-top soft-x-ray laser operating with laser plasmas.

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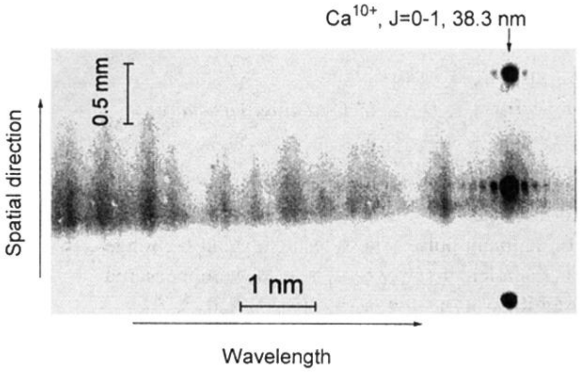

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