Demonstration of large amplification in multipulse-pumped lithiumlike aluminum soft-x-ray lasers

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We report on a demonstration of a gain-length product greater than five for recombination-pumped Li-like soft-x-ray lasers, using a long plasma length of 3.3 cm. Slab aluminum targets are irradiated by a multipulse Nd:glass laser pump at an intensity of 1 TW/cm^2. A time-integrated small-signal gain coefficient of 1.7 cm^{-1} and a gain-length product of 5.6 are observed for the 154.7 Å Li-like Al laser. Space-resolved observations reveal a gain region width of 200 μm full width at half maximum, which is found to be wide enough for saturated amplification experiments. [S1050-2947(98)09908-9]

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While relatively large gain coefficients have been reported for recombination-pumped soft-x-ray lasers [1–11], only a few have been able to demonstrate gain-length products greater than 5 [12–15]. This is due to a tendency with recombination schemes of gain coefficients diminishing as the length of the active medium is increased, preventing large amplification from being observed [16]. This has led some groups to use pumping methods utilizing picosecond and subpicosecond lasers, which can produce transient high gain coefficients exceeding 10 cm^{-1}, thereby keeping the active medium length short [14,15]. There are, however, some questions as to whether such pumping schemes can be used in experiments with gain lengths longer than 1 cm, due to restrictions in target supporting or pumping configurations. Therefore, while there is no question that the effort to generate high gain with novel methods is important, it is also crucial for the success of the recombination scheme to overcome the gain-length anomaly observed with conventional pumping geometries.

In this paper we report on a demonstration of a large gain-length product of 5.6 for the 154.7 Å $4f$-$3d$ transition of lithiumlike aluminum, observed by extending the plasma length to 3.3 cm and by using a multipulsed pump. This is also a demonstration of a gain-length product exceeding 5 for the Li-like scheme. The multipulse-pump laser used in this work is similar to that used by the RIKEN group [10,11], consisting of several equal intensity 100 ps pulses separated at an equal interval. The main idea of the multipulse irradiation scheme is to assure effective absorption of the pump by the use of a preplasma, while maintaining the fast cutoff in laser energy deposition required for a rapid transition of the plasma from an ionizing to a recombining phase. The present pumping method has several merits over the picosecond pumping schemes mentioned above. First, the low pump intensity of $\sim$ 1 TW/cm^2 required for gain and the simple irradiation configuration allows for the possibility of long gain medium experiments even with moderate sized laser systems. Next the temporal duration of the gain is expected to be on the order of a nanosecond, and together with the transverse pumping configuration makes double-pass amplification experiments possible, which can significantly increase the output.

The experiments were conducted at the multiterawatt neodymium-doped phosphate glass (Nd:glass) laser facility at the Institute for Solid State Physics of the University of Tokyo [17,18]. A single 100 ps duration 1.053 μm wavelength pulse from a Kuizenga-type oscillator is divided into eight equal intensity pulses using a set of nonpolarizing beam splitters and mirrors. A schematic diagram of the pump pulse shape is shown in Fig. 1. The peak-to-peak time interval between each pulse for this work is fixed at 250 ps. The pulse train is then delivered through a cascade of Nd:glass amplifiers, and line focused onto an aluminum slab target using a combination of toric and aspherical lenses. The length of the line focus is 3.3 cm, and the width 100 μm, resulting in a maximum peak intensity of 1 TW/cm^2. The uniformity of the pump intensity along the line focus is checked by observing the off-axis pinhole image of the plasma filtered by a 1500 Å thick aluminum foil. At a position 200 μm from the target surface the nonuniformity in the soft-x-ray intensity is evaluated to be $\pm 10\%$. Soft x rays emitted from the plasma in the on-axis direction are observed by a flat-field Harada-type spectrograph [19,20], employing a 1200 lines/mm varied-pitch grating. A cylindrical mirror is placed after the spectrograph slit to image the plasma emission in a direction perpendicular to the target surface. Since the present spectrograph does not have a premirror before the slit to collect x rays, careful alignment of the line focus and the spectrograph's optical axis is performed using a long-working-distance microscope. The space-resolved time-integrated spectrum is observed using a photocathode x-ray

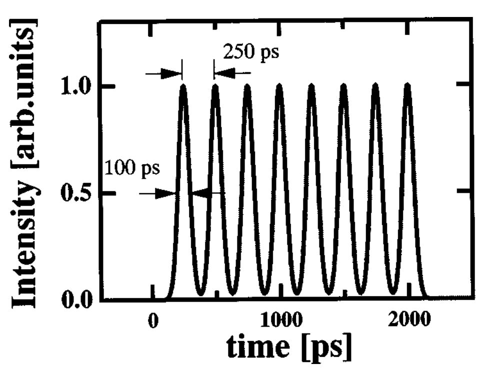

FIG. 1. Typical time history of the multipulse-pump laser intensity at the target surface, for a 3.3-cm-long line focus.

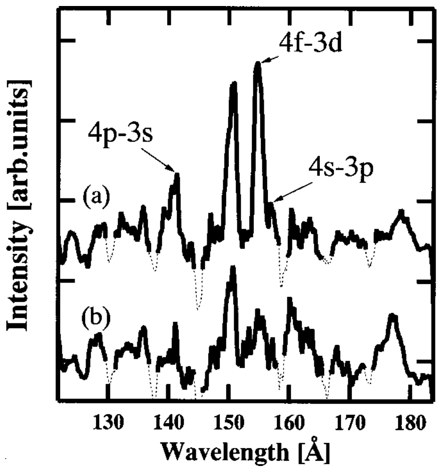

FIG. 2. Time-integrated spectra observed in the on-axis direction, for plasma lengths of (a) 3.3 cm and (b) 2.0 cm. These spectra are observed at 300 μm from the target surface, at a peak pump intensity of 1.04 TW/cm^2.

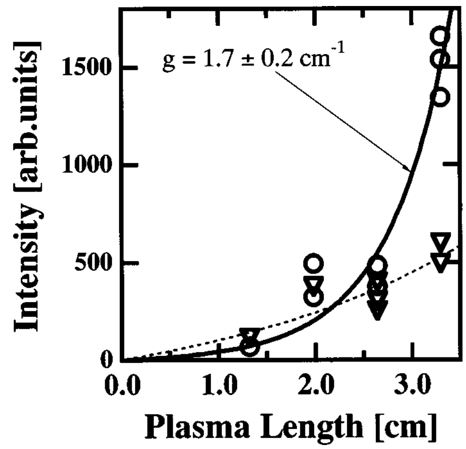

FIG. 3. Intensity of the 154.7-Å Li-like Al laser (○) and the 141.7-Å $4p$-$3s$ line (▽) as a function of plasma length observed at 300 μm from the target surface. The peak intensity of the pump is 1.04 ± 0.04 TW/cm^2. The lines correspond to the least-squares fitting of each data set to the Linford formula [21].

camera placed at the focus plane of the spectrograph. The signal output is coupled to a silicon intensifier target (SIT) camera, and the spectrum image is digitally saved using a Hamamatsu DVS-3000 image processing system. Small-signal gain coefficients of line spectra are evaluated by varying the plasma length and fitting the spectral intensity to the gain formula of Linford *et al.* [21].

In Fig. 2 we show the on-axis spectra observed for aluminum plasmas at wavelengths between 130 and 180 Å, for plasma lengths ℓ of 3.3 and 2.0 cm. These spectra correspond to a position $z=300$ μm normal from the target surface. The peak intensity of the pump for these data is 1.04 TW/cm^2. The wavelength range of the spectrum is limited by the 9 mm visual field of the SIT camera. The portions of the spectrum that are shown as dotted lines are those lost due to the mesh support of the x-ray camera photocathode. Several lines corresponding to Li-like and Be-like aluminum ions can be identified in the figure. The two most prominent are the 150.7 Å $3p\ ^2P-4d\ ^2D$ ($4d$-$3p$) and the 154.7 Å $3d\ ^2D-4f\ ^2F$ ($4f$-$3d$) transitions of Li-like Al. A weaker line corresponding to the Li-like Al $3s\ ^2S-4p\ ^2P$ ($4p$-$3s$) and the $3p\ ^2P-4s\ ^2S$ ($4s$-$3p$) transitions can also be identified at 141.7 Å and 157.5 Å, respectively. There are also several broad lines centered at 160 Å and 177 Å, which can be classified as the $2\ell 3s\ ^{2S+1}S-2\ell 4p\ ^{2S+1}P$ and $2\ell 3d\ ^{2S+1}D-2\ell 4f\ ^{2S+1}F$ multiplets of the Be-like Al ion, respectively [22]. Care must be taken when analyzing the 150.7 Å $4d$-$3p$ line of Li-like Al, which is actually a blend with the 150.1 Å $2s\ ^2S-3p\ ^2P$ line of Li-like O. This can be inferred from the fact that the radiative transition rate of the Li-like Al $4d-3p$ transition is half that of the $4f$-$3d$ transition [23]. Therefore the intensity of the former line should at most be half that of the latter, contrary to that observed in Fig. 2. The presence of the 150.1 Å Li-like O line is also verified from experiments with irradiation intensities of less than 0.7 TW/cm^2. In this case Li-like Al lines disappear due to a lower ionization stage, but the 150.1 Å Li-like O line is still observable due to a smaller ionization potential.

The spectra in Fig. 2 reveal a factor of 5 increase in the 154.7 Å $4f$-$3d$ line intensity for a change in plasma length from 2.0 to 3.3 cm. Compared with the strong $4f$-$3d$ line, the $4p$-$3s$ and $4s$-$3p$ line intensities remain weak, at the same level as the background noise. One can also compare the increase in the intensity of the $4f$-$3d$ line with those of the Be-like line multiplets at 160 Å and 177 Å. These lines show a decrease in intensity with an increase in plasma length, which implies an overall absorption for these transitions. Since these Be-like lines are not resonance lines, they can also be used to verify that errors do not come into the present experiment to induce apparent amplifications of essentially spontaneous emissions.

In Fig. 3 we plot the spectral intensities of the 154.7 Å $4f$-$3d$ and the 141.7 Å $4p-3s$ lines against the plasma length at a position of $z=300$ μm. The length of the plasma is varied to be 1.3, 2.0, 2.6, and 3.3 cm, and several shots are taken for each plasma length. The peak intensity of the multipulse pump is 1.04 ± 0.04 TW/cm^2 for this data set. A strong nonlinear increase in the spectral intensity with plasma length can be observed for the $4f$-$3d$ line, whereas the data for the $4p$-$3s$ line are almost linear. The lines in the figure are the least-squares fitting of the spectral intensities for each transition to Linford's gain formula. As a result, a time-integrated small-signal gain of 1.7 ± 0.2 cm^{-1} is evaluated for the 154.7 Å $4f$-$3d$ line, corresponding to a gain-length product of 5.6 for $\ell=3.3$ cm plasmas. Similar data analysis for the $4p$-$3s$ line reveals a gain coefficient of 0.5 ± 0.4 cm^{-1}. This smaller gain coefficient compared with the $4f$-$3d$ line is a result of the smaller radiative transition rates of both the lasing transition and the transition from the lower laser level to the $2p\ ^2P$ state. The intensity of the 150 Å line is also found to show a weak nonlinear increase with plasma length, in spite of blending of the $4d$-$3p$ and $2s\ ^2S-3p\ ^2P$ Li-like O lines. A simple fit of the 150 Å line intensity to the gain formula, neglecting for a while the effects of line spectrum mixtures, results in a small-signal gain coefficient of 0.8 ± 0.3 cm^{-1}. Since the $2s\ ^2S$ level is the ground state of Li-like ions, the 150.1 Å Li-like O $2s\ ^2S-3p\ ^2P$ transition will not show amplification under the present pumping conditions. Therefore the 0.8 cm^{-1} gain coefficient obtained from our data can be considered to be a

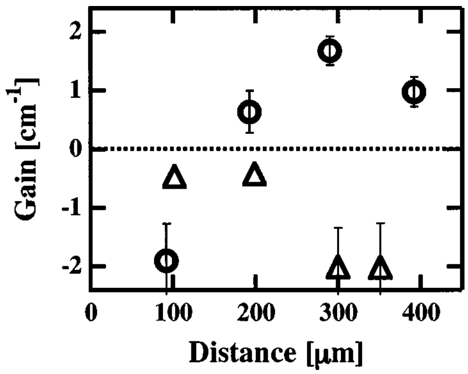

FIG. 4. Small-signal gain coefficient of the 154.7-Å Li-like Al laser as a function of distance from the target surface. The peak intensity of the pump is 1.04 (○) and 0.88 TW/cm^2 (△).

lower limit to the actual gain for the 150.7 Å $4d$-$3p$ line, which is expected to have a larger gain compared with the $4p$-$3s$ transition.

In Fig. 4 we show the spatial distribution of the experimentally evaluated gain coefficients for the $4f$-$3d$ line of Li-like Al. Absorption is observed at $z = 100$ μm, which turns to amplification for $z \geqslant 200$ μm. The gain coefficient is found to peak at $z = 300$ μm, and the spatial extent of the gain region is found to be 200 μm full width at half maximum (FWHM). A concern arising from these results is whether curved targets are necessary to compensate for refraction effects of the x-ray laser beam for the 154.7 Å Li-like Al laser. Recombination-pumped soft-x-ray lasers operate at a lower electron density than collisional systems, and hence refraction is generally considered to have minor effects. However, the maximum gain coefficient observed in this experiment is 1.7 cm^{-1}, which will require the x-ray laser beam to propagate a length of 10 cm in order to obtain saturated output. We therefore performed a ray trace simulation to clarify this point. For the electron density profile, we used simulation results for irradiation conditions similar to those used in our experiments [11]. The data used are for times 2 nsec after the start of irradiation, when gain is expected to be generated. Ray tracing results show that an x-ray laser beam traveling parallel to the target surface at the position of maximum gain is able to propagate 15 cm within the plasma before deflecting into regions with half the peak gain. The deflection angle of this beam after 15 cm propagation through the gain region is 1.16 mrad. This shows that a plain slab target can be used for experiments aimed at saturated operation of the 154.7 Å Li-like Al soft-x-ray laser.

Gain measurements are also performed at lower irradiation intensities. In Fig. 4 we also plot the $4f$-$3d$ gain coefficients evaluated from data sets for pump intensities of 0.88 $\pm$ 0.05 TW/cm^2. The errors for gain at $z = 100$ and 200 μm are ± 5.2 cm^{-1} and ± 9.4 cm^{-1}, respectively, and therefore are omitted from the figure. The $4f$-$3d$ line is found to be absorptive throughout the spatial region for this irradiation condition. This can be qualitatively understood as a result of a lower He-like ion abundance and a higher Li-like ground state population within the initially produced laser plasma. The former results in a lower pumping of the upper laser level, while the latter in the increase in reabsorption effects, both suppressing the formation of gain. A further reduction in the pump intensity below 0.75 TW/cm^2 resulted in a disappearance in the Li-like Al lines, suggesting plasma conditions to be insufficient for producing He-like Al ions. The above set of experiments shows that there is a threshold for gain at pump irradiances between 0.9 and 1.0 TW/cm^2, for pulse train pumps used in this work.

In conclusion we report on an observation of a gain-length product greater than 5 for recombination-pumped Li-like soft-x-ray lasers. A multipulse-pump laser consisting of eight 100 ps duration pulses and a temporal spacing of 250 ps is irradiated onto an aluminum slab target. At a peak pump intensity of 1.0 TW/cm^2, a time-integrated small-signal gain coefficient of 1.7 cm^{-1} is observed at 300 μm from the target surface for the 154.7 Å Li-like Al laser, and a gain-length product of 5.6 is demonstrated for a 3.3-cm-long plasma. The extent of the gain region is evaluated to be 200 μm FWHM, which is shown to be wide enough for performing saturated amplification experiments requiring plasmas longer than 10 cm, without suffering from undesired refraction effects. The above results suggest the possibility of using multilayered mirrors for double-pass amplification experiments, which can significantly increase the x-ray laser output.

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