Generation of Small-Divergence Soft X-Ray Laser by Plasma Waveguiding with a Curved Target

R. Kodama,[1] D. Neely,[2]* Y. Kato,[1] H. Daido,[1] K. Murai,[1] G. Yuan,[1] A. MacPhee,[2] and C. L. S. Lewis[2]
[1]*Institute of Laser Engineering, Osaka University, 2-6 Suita Yamada-oka, 565 Osaka, Japan*
[2]*Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland*
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We have studied plasma waveguiding in soft x-ray laser experiments. A curved-slab target was used in order to compensate for x-ray refraction in a gradient-density plasma. In addition to significant increase in the x-ray laser intensity in single-pass amplification, a small beam divergence of less than 1 mrad has been stably generated in double-pass amplification with the curved target. The angular intensity distribution of the double-passed beam indicates that the x-ray laser has been amplified in a plasma waveguide.

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X-ray lasers with high coherent power are required for various applications such as holography [1,2], plasma diagnostics [3], holographic nanolithography [4], and nonlinear x-ray optics [5]. Most of the x-ray laser schemes now operating, especially the collisional excitation x-ray lasers [6], use laser-produced plasmas with high electron density. The major difficulty in improving the spatial coherence of the x-ray lasers lies in controlling the propagation of the x rays through nonstationary and nonuniform x-ray-refracting plasmas [7]. It has been proposed that x-ray lasers with a fundamental Gaussian mode could be generated by gain guiding in a spatially symmetric expanding amplifying plasma [8]. This concept, however, has not been experimentally demonstrated since gain guiding is strongly affected by the asymmetry of the plasma expansion [9]. In the case of massive slab targets, it was proposed that refraction of the x ray in a steep gradient plasma could be compensated by using opposite-gradient plasmas generated with separate slab targets irradiated from opposite directions [10]. This target configuration was tested [11], providing near-diffraction-limited operation inferred from the transient generation of a small (3.6 mrad) divergence soft x-ray laser beam [12]. As an alternative approach for refraction compensation, it was proposed that x rays could be waveguided in a toroidal-shape plasma which was produced by bending a concave cylindrical target [13]. In this Letter, we present the first experimental evidence for the plasma waveguiding of the x-ray laser beam propagating in a gradient-density plasma where x-ray refraction is one-dimensionally compensated by applying a curvature to the plasma.

The target configuration we have studied in this work is a slab target curved along the x-ray propagation direction as shown in Fig. 1. The refractive index profile of an expanding plasma of a slab target is compensated by bending the target, resulting in the effective index profile which has a maximum value at a distance from the target surface which is determined by the density profile and the target curvature. Presence of gain in such a plasma may result in soft x-ray amplification in a plasma waveguide, resulting in stable pointing and small beam divergence. When an x-ray laser beam is incident to the waveguide even at a mismatched angle, the x-ray laser beam will be stably amplified and propagated along the waveguide overcoming the refractive escape of the beam from the plasma [9]. We have examined this concept with single- and double-pass soft x-ray amplification in an Ne-like Ge laser using a curved slab target. The slab target bent at a proper angle has resulted in a decrease in the beam divergence accompanied with an increase in the peak intensity of the soft x-ray laser. In the double-pass amplification, the beam divergence of less than 1 mrad

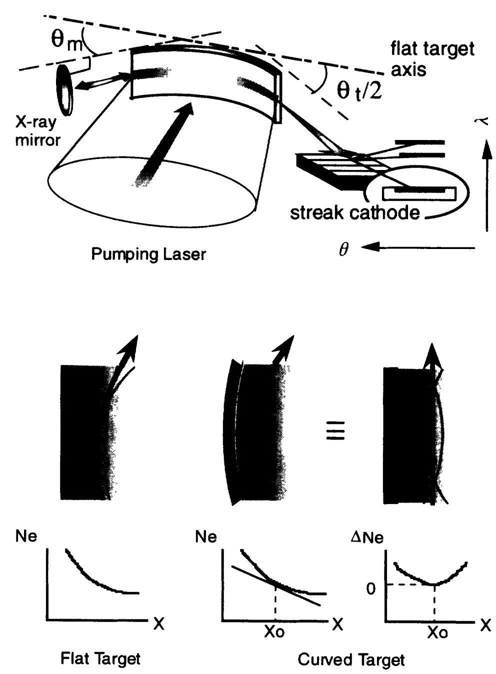

FIG. 1. Schematic of the curved target, x-ray mirror setting in the double-pass amplification, and the diagnostic of the time-resolved angular distribution. θ_t is the target bending angle and θ_m the angle of the mirror normal to the flat-target axis. Schematic of x-ray laser propagation is also shown in a flat and a curved target.

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has been stably obtained, indicating realization of soft x-ray amplification in a plasma waveguide.

Ne-like Ge plasmas were created with the GEKKO XII laser at the Institute of Laser Engineering, Osaka University. A single laser beam of 1.053 μm wavelength was focused with a cylindrical and an aspheric lens combination to a line of 100 μm average width on a Ge slab target. The average peak intensity on the target was 1.7×10^{13} W/cm^2 with a 1 ns FWHM Gaussian pulse. The target was a Ge stripe of 200 μm width and 1 μm thickness evaporated on a quartz plate of 1.5 mm thickness. The maximum target length was limited to 4 cm to avoid edge effects due to lower irradiance above this length. The irradiance distribution was monitored with a crossed-slit x-ray camera and with a space-resolved crystal x-ray spectrograph providing the ionization balance along the plasma length.

The angular intensity distributions of the Ge lasing lines along the horizontal direction, i.e., perpendicular to the target surface, were measured with an on-axis flat-field grazing-incidence extreme ultraviolet spectrometer as shown in Fig. 1. An x-ray streak camera was coupled to the spectrometer for the time-resolved measurements of the angular distributions [14]. The streak slit cathode was aligned on one of the lasing lines, i.e., the J = 0-1 line at 19.6 nm or the J = 2-1 line at 23.6 nm. The temporal resolution of the whole system was 100 ps. Relative time of the signal to the pumping laser pulse was determined within ± 100 ps accuracy using a time fiducial laser pulse introduced to the streak cathode. Details of the experimental conditions are described in Ref. [15] except for the use of the curved targets.

The target was curved along its length at a variable curvature up to 2 m radius by bending the quartz substrate with mechanical pressures. The maximum target curvature was limited by the rigidity of the substrate. The target structure and curvature were measured with the deflection of a He-Ne laser beam reflected from the target [16]. The target bending angle (θ_t) and the corresponding radius of curvature are used for describing the target curvature in this paper (Fig. 1). In double-pass amplification, a flat x-ray mirror was placed at 5.9 cm from the center of the target. The mirror was made of a multilayer Mo-Si coated on a quartz substrate of less than 1 nm surface roughness, which provided the measured reflectivity of either 10% for the 19.6 nm amplification or 35% for the 23.6 nm. The slab target and the mirror were prealigned prior to installation with an optical alignment jig. The target bending angle and the mirror angle were adjusted to within 1 mrad accuracies.

In single-pass amplification, bending a 4 cm flat target from 0 (flat) to 20 mrad (2 m radius) resulted in significant changes in the temporal pulse shape, the beam divergence, and the peak intensity of the x-ray laser pulse. Figure 2 shows the angular intensity distributions of the J = 0-1 line and the temporal pulse shapes of the J = 0-1 and J = 2-1 lines for a flat and 15 mrad (2.7 m radius) curved targets. The beam divergence with the curved target was about half the value with the flat target. The peak intensity of the J = 0-1 line with the curved target was enhanced by a factor of 10, as compared with a flat target. The intensity enhancement is stronger before the peak of the pumping laser pulse.

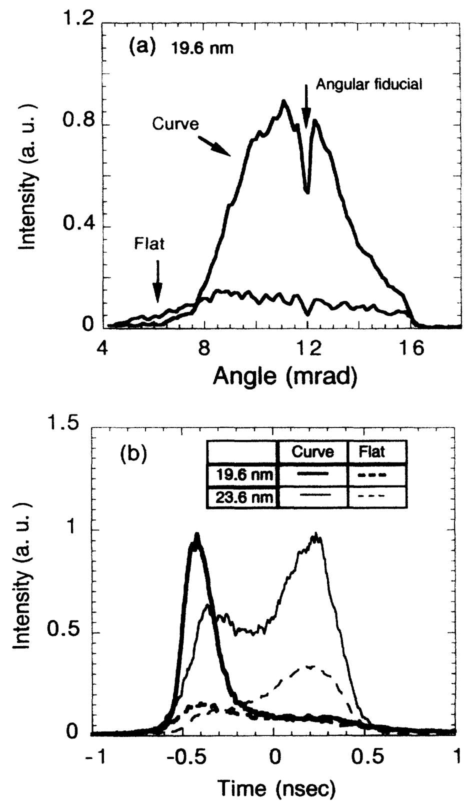

FIG. 2. (a) Angular intensity distributions of the J = 0-1 line (19.6 nm) using a 15 mrad (2.7 m radius) curved target and a flat target at the peak of the x-ray laser pulse. (b) Temporal pulse shapes of the J = 0-1 line and J = 2-1 line (23.6 nm) using a 15-mrad (2.7 m radius) curved target and a flat target at the angular peak. The peak intensities of the two lasing lines for the curved target are normalized to compare the temporal shapes.

The dependences of the beam divergences and the peak intensities of the J = 0-1 and J = 2-1 lines on the target curvature are shown in Fig. 3. The divergences decrease with the target curvature accompanied with increases in the peak intensity for both of the lasing lines. These results are consistent with the refraction compensation of the x-ray laser beam in the plasma with the curved target. It is expected that the highest intensity is obtained when the x-ray laser beam propagates along a curved path which matches to the highest gain region. Referring to the density and gain profiles from the hydrodynamic simulation [15], the optimum curvature for a 4 cm target is estimated to be ~60 mrad (0.7 m radius) for the J = 0-1 line and ~30 mrad (1.2 m radius) for the J = 2-1 line. The experimental data in Fig. 3 suggest that the optimum curvature has not been reached up to 20 mrad (2 m radius) bending angle for 4 cm target.

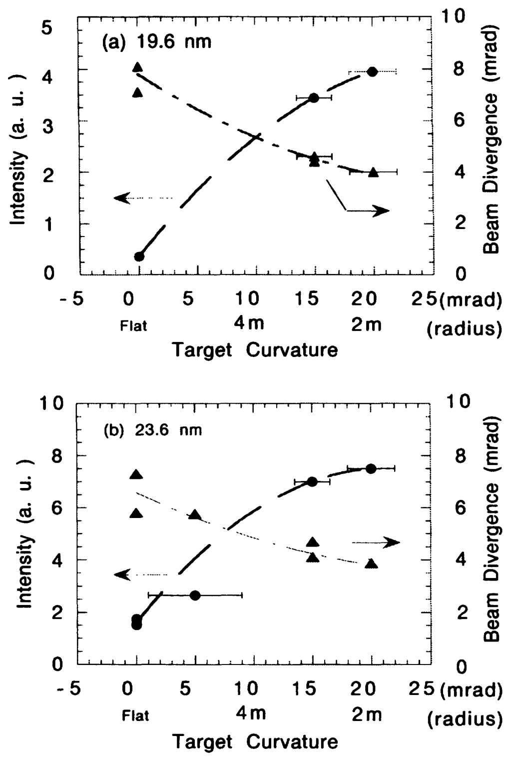

FIG. 3. Beam divergences (FWHM) and angular peak intensities at the temporal peaks of (a) the J = 0-1 and (b) the J = 2-1 lines as a function of the target curvature. 0 mrad corresponds to the flat slab target.

The divergences of both lasing lines decrease by bending the target, providing the similar divergences (4 mrad) for the J = 0-1 and J = 2-1 lines. The peak intensity enhancement of the J = 0-1 line is more pronounced, making its intensity comparable (50%) to that of the J = 2-1 line, whereas the peak intensity of the J = 0-1 was 10% of the J = 2-1 with a flat target. We note that the intensity enhancement was also obtained with the double slab target, especially for the J = 0-1 line whose intensity reached to 40% of the J = 2-1 line [15]. The small divergence is obtained over the whole duration of the laser pulse with a curved target, whereas the small divergence was obtained over a short period with a double-slab target [12], indicating that refraction compensation is more stable with a curved target.

The gain coefficient of the J = 0-1 line, estimated by changing the target length of the curved target, was 2.5 cm^{-1} and comparable to that (2.5 cm^{-1}) of the J = 2-1 line, while the coefficients were 2.0 cm^{-1} for the J = 0-1 line and 2.5 cm^{-1} for the J = 2-1 with the flat target [15]. Ray trace calculations in the flat target, as reported in Ref. [15], predict that the effective propagation length in a planar target is limited by beam refraction, giving 2–3 cm for the J = 0-1 line and 3–4 cm for the J = 2-1 in the 4 cm flat target. The J = 0-1 line is more deflected outward from the plasma with a flat target due to the higher electron density accompanied with a larger density gradient at the gain region for this line in comparison to the J = 2-1 line [15]. Refraction of the x-ray laser beam is compensated with the curved target more effectively for the J = 0-1 line, resulting in narrowing of the beam divergence accompanied with more enhancement of the peak intensity.

Double-pass amplification of the J = 0-1 and J = 2-1 lines was studied with a curved target to look into waveguided propagation of the x-ray laser beam. In double-pass amplification, the x-ray laser beam reflected from a flat mirror acts as a probe beam for the amplifying plasma produced with a 15 mrad (2.7 m radius) curved target. The most remarkable result in the double-pass amplification was the reproducible generation of an x-ray laser beam with a small beam divergence of less than 1 mrad for both lasing lines. The intensity peak having a small beam divergence was always pointing at 6.5 ± 1 mrad, which was close to the angle tangential to the target end (7.5 mrad). The temporal intensity peaks in both lines indicated no feedback reduction due to mirror damage during the pulse duration, indicating the second pass beam could work as a probe beam of the amplifying plasma. The temporal pulse shapes with double-pass amplification were different for the J = 0-1 and J = 2-1 lines because of the difference in the pulse shapes with single-pass amplification. Clear temporal separation of the double-pass pulse from the single-pass pulse was obtained in the J = 0-1 amplification. This temporal behavior of the J = 0-1 line is useful for the second-pass beam to probe into the amplifying plasma for the time-resolved measurements.

We have measured the time-resolved angular intensity distribution of the J = 0-1 line with 15 mrad curved (2.7 m radius) targets by changing the incidence angle of the mirror. Figure 4 shows the angular intensity distributions at the peak of the x-ray laser pulse as a function of the mirror angle. The mirror angles in Fig. 4 are measured from the axial direction of a flat target (see Fig. 1). Starting from 10 mrad, the peak intensity increased with a decrease in the mirror angle up to 8 mrad which is close to normal to the target end. However, no amplification of the double-pass pulse was observed at a mirror angle of 6 mrad. The observed angular intensity distributions are composed of two components. The one, named SD (small divergence) component, had a small beam divergence of less than 1 mrad and had a pointing direction, independent of the mirror angle, at 6 to 7 mrad which is close to the axial direction of the curved target end. The other, called BD (broad divergence) component, had a broad beam divergence with its pointing influenced by the mirror angle.

Dotted lines in Fig. 4 represent the angular profiles of the double-passed beam according to the geometrical optic calculation, where the single-pass amplified beam of 4 mrad divergence reflected from the mirror was ray traced, assuming the curved plasma to be a specular curved reflector. The peak intensity in the calculation was normalized to the experimental peak. The angular profiles

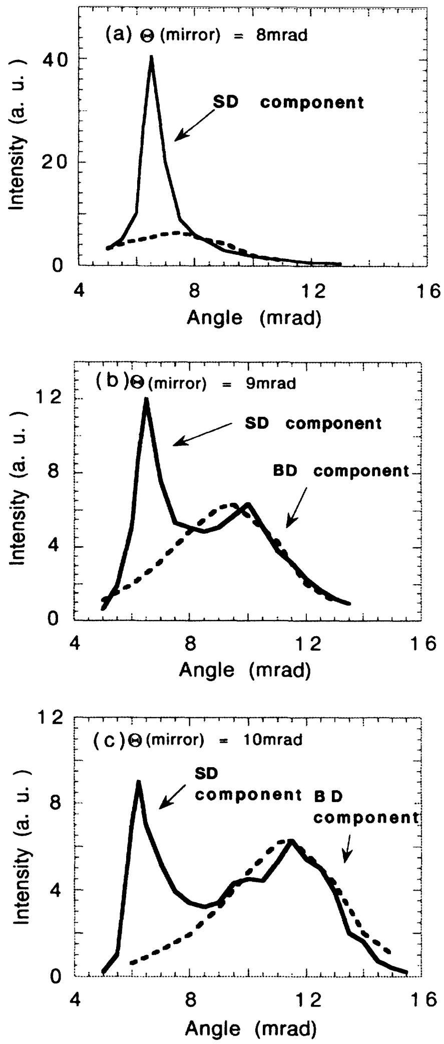

FIG. 4. (a)–(c) Angular intensity distributions of the $J = 0\text{-}1$ line at the peak of the x-ray laser pulse as a function of the angle of the mirror in double-pass amplification. SD small divergence component and BD broad divergence component. Dotted lines represent simple calculations of the double-passed beam profile, taking account of the single-pass amplified beam of 4 mrad divergence. The peak intensity in the calculation was normalized to the experimental peak of the BD component.

as well as the pointing angles of the BD component are in good agreement with these simple calculations. On the other hand, the beam pointing and divergence of the SD component had no dependence on the mirror angle, and its peak intensity increased significantly when the mirror angle approached to an optimum angle of 7.5 mrad. This indicates that the SD component corresponds to the guided mode in the curved plasma.

We have analyzed propagation of a soft x-ray laser beam in the curved Ge plasma by applying the formulation developed for Gaussian beam propagation through inhomogeneous media [9,17]. The spatial profiles of refractive index and gain were determined from 2D simulation applicable to our experimental condition [18]. The input beam is a circular Gaussian beam of 160 μm radius with a wave-front curvature of 8 cm, corresponding appropriately to the x-ray laser beam incident to the plasma in double-pass amplification with a plane mirror. Because of positive lensing effect of the waveguide along the horizontal direction, the radius decreases and the beam divergence (full angle) is calculated to be 2 mrad along the horizontal directions [19]. This calculational result is consistent with the experimental results, supporting the assumption that the SD component corresponds to the guided propagation of the x-ray laser beam.

In conclusion, we have demonstrated stable generation of a narrow divergence x-ray laser beam in double-pass amplification with a curved-slab target. This result may imply that plasma waveguiding has been achieved in the 1D expanding plasma where refraction is compensated for the target curvature.

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*Present address: Rutherford Appleton Laboratory, Chilton Didcot Oxon, OX11 0QX, United Kingdom.

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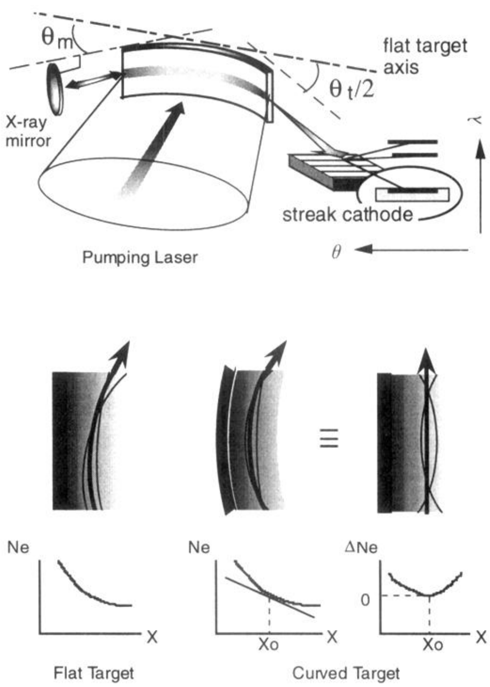

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