Enhancement of x-ray lasing due to wavefront correction of line-focusing optics with a large-aperture deformable mirror

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(Received 12 January 1998; accepted for publication 27 March 1998)

Intense x-ray laser radiation at 7.92 nm in nickel-like neodymium has been achieved by improving the line-focusing pattern using a large-aperture deformable mirror. A deformable mirror of 40 cm diameter with hexagonally arranged 37 mechanical actuators has been developed. The wavefront aberration due to a cylindrical lens used for line focusing has been corrected with the deformable mirror to produce a line-focusing pattern of uniform narrow width and uniform intensity distribution. The intensity of the x-ray laser beam has increased six times due to the improvement of the line-focusing pattern. © 1998 American Institute of Physics. [S0003-6951(98)01822-1]

Extremely short-wavelength lasers have wide and new applications such as x-ray holography, biological microscopy, and high-density plasma diagnostics. The electron-collisional excitation x-ray laser has been most successful in terms of short wavelength, small divergence, and saturated amplification. The electron collisional excitation x-ray laser in the nickel-like ions have been demonstrated over broad spectral range.

For transverse excitation of the laser medium, it is necessary to focus a high power laser beam to a line of narrow width and long length. It is, however, difficult to achieve the line-focus pattern with a high aspect ratio and uniform intensity distribution using a conventional line-focusing optics composed of a cylindrical lens and an aspherical lens due to the change in the focusing position along the length of the line focus. This is because the bow tie shaped line pattern resulted in the different focal position for the x and the y direction generated by a cylindrical lens. The wavefront aberration included in this optical system is mainly consisted by a defocus and astigmatism, and nonuniformity of the line focus largely depends on an incident beam diameter for pumping. Several line-focusing optical systems have been proposed to produce a plasma with uniform density distribution such as off-axis line-focus geometry with a spherical mirror, beam smoothing using a one-dimensional random phase plate, and a cylindrical lens array. We have previously proposed a new line-focusing optics and tested the concept using a small-aperture deformable mirror. It has been shown that both the uniformity of the intensity profile and the width of the line-focusing pattern are improved due to the continuous control of the wavefront for correction of aberration of the cylindrical lens. This scheme is useful for the line-focusing optics to pump x-ray laser because the required wavefront control is a lower order and is not time dependent. This means that the deformable mirror mainly corrects a static distortion in the lenses. But the deformable mirror is also useful for correction of a thermally induced wavefront distortion in a laser system.

In this letter, we describe the development of a large-aperture deformable mirror with 40 cm in diameter for application to an x-ray laser experiment using the Gekko XII laser. The line-focus patterns produced with a conventional line-focusing optics and a deformable mirror based line-focusing optics are compared. The enhancement of the x-ray laser radiation at 7.92 nm with the Ni-like Nd ions due to wavefront control using a deformable mirror is presented.

A deformable mirror with a large aperture is required for application to high power laser systems in order to control the wavefront of the laser beam before target irradiation. A mirror diameter of at least 40 cm is required at oblique incidence in this experiment because the final beam size of Gekko XII laser is 32 cm. Although the installation of a smaller-aperture deformable mirror before an amplification chain is useful for cost reduction and easy controllability, it is not desirable in the present case because the controlled wavefront with a deformable mirror for improving line-focusing pattern increases wavefront aberration during the amplification chain.

We have used a 7-mm-thick and 40-cm-diam quartz plate as a substrate of the deformable mirror. Thirty-seven mechanical actuators were hexagonally located and glued at the back surface of the mirror. Figures 1(a) and 1(b) show the photographs of the deformable mirror showing the actuator positions and the flatness of the reflective wavefront of the deformable mirror, respectively. The surface flatness was improved to 0.2λ (λ = 633 nm) in rms value after correcting

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the mirror surface with the actuators from the initial reflective wavefront of $4\lambda$ in rms before gluing.

Figure 2 shows the schematic optical setup for the x-ray laser experiment using the Gekko XII glass laser. For the wavefront control of the laser beam with a deformable mirror (DM in Fig. 2), the laser beam was directed to the deformable mirror by the final folding mirror (M1 in Fig. 2). First, the reflected beam from the deformable mirror was sent with the folding mirror M2 to the monitoring optics composed of the same optics as those for irradiating the target. We have equalized the position of a CCD camera and a target from each line focusing optics which is precisely aligned by the same method using the reflective beam from the front surface of a cylindrical lens. This is to prove that the duplicate lens is identical to the ones in the chamber. This process is to generate the optimized wavefront distribution with a deformable mirror to obtain a uniform line-focusing pattern on the target. The surface of the deformable mirror was changed while monitoring the line-focusing pattern by a CCD camera. A cw-YAG laser (wavelength is 1.06 $\mu$m) which has propagated through the amplification chain from the front end was used for this alignment. When the line-focusing pattern with a desired width and intensity distribution was achieved, the laser beam was directed with M2 to the line-focusing optics to irradiate the target. The deformable mirror after the adjustment of the optimized wavefront distribution was sufficiently stable until the actual laser shot. By using this optical setup, the controlled wavefront distribution when adjusting the deformable mirror and irradiating the target is exactly same because the direction of the deformable mirror with respect to the incident beam is fixed. This indicates that the same line-focusing pattern with uniform width and intensity distribution can also be achieved on the target.

An x-ray slit camera of 2.13 $\times$ magnification with 10 $\mu$m spatial resolution along the vertical direction and 0.49 $\times$ magnification with 100 $\mu$m spatial resolution along the horizontal direction was used for the measurement of the line-focusing pattern. An x-ray CCD camera was used for recording the x-ray image. A grazing incidence spectrometer with a 1200 lines/mm varied-space toroidal grating with back-thinned CCD detector was used for recording the x-ray laser beam.

A curved-slab target used in this experiment was a 20-mm-long and 1-mm-wide stripe of neodymium coated on a 1.5-mm-thick quartz plate with a surface roughness of within 2 $\mu$m. The target was bent to the radius of curvature of 2.5 m corresponding to refractive compensation angle of 4 mrad/cm. The laser pulse consisted of four Gaussian pulses with 100 ps duration as shown in Fig. 2. The first three pulses were separated by 400 ps, whereas the fourth pulse was 1.6 ns apart from the third pulse. The intensity ratio of the four pulses was 1:1.4:1.1:1.2 in turn. The energy and the intensity of the laser beam were 540 J and $5 \times 10^{13}$ W/cm$^2$, respectively. These values were evaluated by considering the reflectance of the deformable mirror and folding mirrors. The total reflectance of the mirrors was 94% for wavelength of 1.06 $\mu$m.

Figures 3(a) and 3(b) show the line-focusing patterns measured with the x-ray slit camera before and after the wavefront control, respectively. The solid and dotted curves show the vertical linewidth and the irradiation intensity distribution along the horizontal direction, respectively. Figure 3(a) shows the typical “bow tie” shaped line pattern generated...
ated with a conventional line-focusing optics. The linewidth varies from 100 to 200 $\mu$m along the line. The intensity distribution is inversely proportional to the width distribution. A uniform line pattern with the width of 100 to 130 $\mu$m has been achieved by the wavefront control using the deformable mirror as shown in Fig. 3(b). Also the intensity distribution has been significantly improved. We have analyzed the slit camera images in terms of the two-dimensional intensity distribution. The standard deviation of the normalized intensity distribution, $\sigma$, with respect to the flat-topped pattern having perfect uniformity of $\sigma=0$ was calculated. The values of $\sigma$ with and without the wavefront control are 0.21 and 0.61, respectively. When the line-focusing pattern was improved as described above, the controlled wavefront by the deformable mirror mainly consisted of astigmatism and spherical aberration and was measured to be $20\lambda$ ($\lambda=633$ nm) in the peak-to-valley whose value has a good agreement with our previous calculation result (see Fig. 3 in Ref. 10). In this experiment, we have optimized the deformable mirror for the line focus on a plane target, whereas the actual target irradiation shown in Fig. 3 was done using curved targets which causes a shift of the surface position of approximately 40 $\mu$m at both ends of the target relative to the central position. The width of less than 65 $\mu$m over the full length should be achievable by optimizing the mirror shape for the curved target.

The improved line focusing pattern resulted in a higher intensity x-ray lasing in Ni-like Nd ions. Figure 4 shows the angle-resolved spectrum of the x-ray laser at 7.92 nm. The two traces in this figure show the intensity distributions along the horizontal angle and the wavelength at the maximum intensity, respectively. The divergence angle is about 1.3 mrad in FWHM. The intensity of the x-ray laser was six times higher than that when a conventional line focusing optics was used under the same pumping energy condition and the target parameters. The average irradiance on the target with and without the deformable mirror was almost same as $5.0 \times 10^{13}$ and $4.4 \times 10^{13}$ W/cm$^2$, respectively. These results show that improvement in the line-focusing width and the intensity uniformity achieved by wavefront control are very effective for improving the x-ray lasing. Output energy of the Nd x-ray laser at 7.92 nm was around 10 $\mu$J which corresponds to 1/10 times of saturated operation because gain-length product of $\sim 3$ is not sufficient for saturated operation. However, if we consider double target irradiation scheme with the deformable mirror, the x-ray laser may be achieved near laser saturated output energy demonstrated by Zhang et al.\textsuperscript{5}

In conclusion, a 40-cm-diam deformable mirror has been developed and a narrow-width line-focusing pattern with uniform intensity distribution has been generated by the wavefront control using the deformable mirror. Using this improved line focusing, the x-ray laser intensity increased six times in comparison to the intensity using the conventional line-focusing optics. This line-focusing scheme using a deformable mirror can simultaneously correct the wavefront aberration in the laser system. For more effective x-ray lasing, an optimized line-focusing pattern adjusted on a curved target may be required, which can be performed with measuring the line-focusing pattern formed by partial incident cw laser beam passed through an aperture. A conventional CCD camera is moved to the direction of optical axis and along the line focus with the distance corresponding curvature of a curved target and the position of an aperture. Considering the complex refraction problem in laser-induced plasma, dependence of the line-focus pattern in an aspect of whole shape and intensity distribution must be investigated. Deformable mirror is also possible to generate an arbitrary line-focusing pattern with the spatially varying width and intensity distribution by wavefront control up to a higher spatial frequencies with a larger number of actuators.

This work was partially supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists and by the Grant-in-Aid for Scientific Researches of the Ministry of Education, Science and Culture (Nos. 07555016 and 08680505).

FIG. 4. Intense x-ray laser radiation at 7.9 nm in nickel-like neodymium measured by an x-ray CCD camera.