High-aspect-ratio line focus for an x-ray laser by a deformable mirror

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A high-aspect-ratio line focus is required on a plane target in x-ray laser experiments for obtaining a high gain-length product. Inherent wave-front aberrations in line-focusing optics, which consist of a cylindrical lens and a spherical lens, are discussed with respect to beam diameter. The nonuniformity of the linewidth that is due to the aberrations is also calculated by the $ABCD$ matrix method. A deformable mirror of a continuous plate type with a diameter of 185 mm provides an adequate wave-front distribution for compensating for the wave-front aberration. The wave-front control by the deformable mirror realizes a fine linewidth of 25 μm and 18.2 mm long, corresponding to the aspect ratio of 728. The linewidth is three times the diffraction limit. The intensity distribution along the line focus is also improved. © 1997 Optical Society of America

Key words: Line focus, x-ray laser, deformable mirror, wave-front control, aberration compensation.

1. Introduction

In x-ray laser experiments, a high-power laser beam must be illuminated onto the plane target to produce a long narrow plasma. Line-focusing optics generally consist of a positive or negative cylindrical lens and a spherical lens. However, it is difficult to obtain the line focus with a high aspect ratio and uniform intensity distribution by use of only conventional line-focusing optics. This is because the focus difference between the $x$ and the $y$ direction is generated by a cylindrical lens. The nonuniformity of the width and the intensity distribution of a line focus generate the fluctuation of the density distribution of plasma. The fluctuation results in the gain reduction of an x-ray laser that is due to the degradation of the uniformity of the refractive index of plasma.

In recent years, many schemes have been proposed to realize a high-quality line focus with a uniform intensity distribution, such as beam-smoothing techniques that use a random phase plate, $^1$ off-axis line-focus geometry with a spherical mirror, $^2$ a segmented wedge array $^3$ with a limiting aperture, and a cylindrical lens array. $^4$ However, the smoothing technique of the beam, for which a random phase plate is used, has an energy loss of ~15% by large-angle diffraction at the phase boundaries. The off-axis line-focus geometry requires severe alignment tolerances. For line-focusing optics by the segmented wedge array and the cylindrical lens array, it is difficult to focus into near-diffraction-limited line focus, even if the intensity distribution along a line focus is uniform.

We have proposed and tested a simple line-focusing system. The system provides not only a high-aspect-ratio line focus but also uniform intensity distribution along a line without energy loss. The basic idea is to control the wave front of an incident laser beam to compensate for the inherent aberrations in conventional line-focusing optics. The wave-front control is done by a deformable mirror.

We adopted a discrete actuator deformable mirror of a continuous faceplate type $^5$ for reducing the energy loss. Many kinds of deformable mirrors $^6-11$ have been suggested for compensating for the wave-front distortion induced by atmospheric turbulence, and the usefulness has been demonstrated in adaptive optical systems. The deformable mirror provides an appropriate wave-front distribution to obtain a high-quality line focus. The inherent wave-front aberrations in conventional line-focusing optics, almost a defocus and an astigmatism, can be simply compensated for by the deformable mirror.

In Section 2, the inherent wave-front aberrations in conventional line-focus optics are discussed, and several results of the calculation and the measurement of nonstraight line-focus width with respect to
beam diameter are presented. In Section 3, we describe the fabrication of a large-aperture deformable mirror of a large aperture and the evaluation of the surface deformation. Experimental results on the improvement of the line-focus pattern with our line-focusing optics are described in Section 4. Section 5 contains our conclusions.

2. Wave-Front Aberration in Line-Focus Optics

A. Geometric Optics Consideration

Conventional line-focusing optics consist of a cylindrical lens and a spherical lens, the combination of which has a defocus and an astigmatism on axis at a certain object plane, as shown in Fig. 1(a). These wave-front aberrations come about because a cylindrical surface has power in one direction and behaves like a plane surface in the orthogonal direction. This property is also demonstrated by the spot diagram at the in focus and out focus by use of the ray-tracing technique, as shown in Fig. 1(b). An elliptic shape between each spot diagram at the in focus and the out focus has an orthogonal relation. This means that the line-focusing optics have an astigmatism. From the spot diagram at the best focus [see magnified part in Fig. 1(b)], the width of the line focus differs at a distance from the optical axis. This also means that the wave-front aberration in the optics is a defocus. Therefore the best focal plane is not a flat surface but a curved surface; a long and uniformly narrow line focus cannot be obtained on a plane target for x-ray laser experiments, as shown in Fig. 1(a). As a result, the wave-front aberration in conventional line-focusing optics is the combination of a defocus and an astigmatism, that is, a cylindrical shape.

B. Calculation of Width Nonuniformity

We have calculated the change of the line-focus width with respect to the beam diameter by the geometric optics. Line-focusing optics for the calculation consist of a negative cylindrical lens that has a curvature in the y direction and a spherical lens. The width of the line focus at the center has been calculated when both sides of the line focus have the minimum width, which means that both sides of the wave front of a defocused laser beam have reached the plane that generates the line focus.

In the formulas below [see Fig. 1(a)], \(D\) is the beam diameter, \(l\) is the distance between a cylindrical lens \(L_c\) and a spherical lens \(L_s\), \(f_{cy}\) is the focal length of a cylindrical lens that has a curvature in the \(y\) direction, \(f_s\) is the focal length of a spherical lens, \(\Delta f\) is the difference between focal lengths in the \(x\) and \(y\) directions, \(d_c\) is the defocused distance at the center of a line focus by the propagation of a spherical wave, and \(W_c\) is the width of a line focus at the center of the plane target.

Basically the width nonuniformity of a line focus is generated by the difference of focal lengths, \(f_c\) \((=f_s)\) and \(f_s\) in the \(x\) and \(y\) directions, respectively, of line-focusing optics. The difference can be calculated by the \(ABCD\) matrix method:

\[
\Delta f = f_y - f_x = -\frac{f_{cy}^2}{f_{cy} + f_y - l} . \tag{1}
\]

\(W_c\) is proportional to the defocused distance at the center of a line focus generated by the propagation of a spherical wave front. \(d_c\) can be calculated from a geometric relation:

\[
d_c = \Delta f \left[ \left( 1 + \frac{1}{4} \frac{D^2}{f_s^2} \right)^{1/2} - 1 \right]. \tag{2}
\]

The prolonged focal length \(d_c\) is derived by the matrix method used in the calculation of Eq. (1). Only the propagation distance of the translation matrix after a spherical lens must be substituted for \(f_c + \Delta f + d_c\). To obtain the central width of the line focus, the focal length of a cylindrical lens and the propagation distance of the translation matrix after a spherical lens must be also substituted for the prolonged focal length and \(f_c + \Delta f\), respectively. After these calculations, the width of line focus is given by

\[
W_c = \frac{f_d D}{f_s^2 + (\Delta f + d_c)f_s - l\Delta f - ld_c} . \tag{3}
\]

Figure 2 shows the calculation and measurement results of the central width of the line focus with
respect to a beam diameter when the edges are in the best focus. The parameters used in the calculation are \( l = 30 \text{ cm} \), \( f_{c1} = -10 \text{ m} \), and \( f_s = 1 \text{ m} \). The distance \( l \) hardly influences the result because the cylindrical lens has a long focal length of \(-10 \text{ m}\) compared with \( l \). The inserted images in Fig. 2 show a 5-mm-long line pattern in the central part of the total line focus of 18.2 mm when the edges were in the best focus of 20 \( \mu \text{m} \) wide. The beam diameter has been changed to 180, 230, 280, and 320 mm. For a smaller beam diameter (180 mm), the experimental result shows a good agreement with the calculated one. For the larger beam diameter, however, the measured width is smaller than the calculated one. This should be because an aspherical lens has been used in the experiment instead of a spherical lens for the calculation.

The width nonuniformity of line-focus pattern can be improved by a cylindrical wave-front control with a deformable mirror or an additional cylindrical lens. The curvature of the second cylindrical lens must have the same direction and the opposite sign of the main cylindrical lens. For our line-focusing optics, the cylindrical wave front to be controlled has \( y \) direction and minus curvature. A curvature radius to compensate for the aberration can be simply calculated with the matrix method. The peak-to-valley value of the required wave front \( W_{pv} \) by a deformable mirror is provided by

\[
W_{pv} = 2R_y - (4R_y^2 - D^2)^{1/2},
\]

where \( R_y \) is the curvature radius of a deformable mirror.

Figure 3 shows peak-to-valley values of a deformable mirror shape to be controlled with respect to several beam diameters.

A high-quality line focus can be obtained by the cylindrical wave-front control mentioned above. For the practical experiments, however, the various wave-front aberrations generated because of thermal effects, misalignment, and optical fabrication error in a laser system must be simultaneously compensated for. The spherical aberration in a spherical lens used in line-focusing optics must also be compensated for because the peripheral component of the beam is influenced by the strong power from a spherical surface of the optic. From these facts, the adoption of a deformable mirror for x-ray laser experiments is more effective than the insertion of an additional cylindrical lens or mirror.

3. Large-Aperture Deformable Mirror

A. Fabrication

For arbitrary wave-front control of a laser beam, a deformable mirror with discrete actuators has been designed. The deformable mirror is the continuous faceplate type, which is suitable for applications to high-power lasers because energy loss is smaller than that of segmented mirror types. The circular faceplate was aluminum-coated BK 7 glass with a diameter of 185 mm and a thickness of 5 mm. Nine actuators were adhered onto the back surface of the faceplate in a \( 3 \times 3 \) square arrangement in the 60-mm spacing. The rectangular arrangement is suitable for deforming a cylindrical surface in only a perpendicular or lateral direction. The actuator was an electrostrictive device with a multilayer structure consisting of alternate ceramic and metallic layers made of lead, magnesium, and niobate. It has a stroke of 15 \( \mu \text{m} \) for a relatively low-voltage application (100 V).

Figure 4 shows the interferograms of the faceplate during each process of the fabrication of the deformable mirror. The surface accuracy of the deformable mirror becomes worse just after gluing, 0.64\( \lambda \) (\( \lambda \) is 633 nm) in rms value. It could be improved to 0.08\( \lambda \) in rms value by driving the actuators. Higher-order wave-front aberrations, however, remained near points at the actuators, which were caused by the mirror deformation because of stress generated during the hardening process of the glue.

B. Surface Deformation

The deforming characteristic of the deformable mirror surface is an important parameter for the precise control of the wavefront, which is called an influence function. We have compared the measured influence function by using an interferometer and the cal-

![Fig. 2. Relation between the central width of the line focus and the laser beam diameter by the calculation (solid curve) and the measurement (circles) when both sides of the line focus have the minimum width. The inserted images are the central line-focus pattern 5 mm in length of a 18.2-mm line focus in the case of several beam diameters.](image1)

![Fig. 3. Required wave-front compensation of peak-to-valley (P-V) values by a deformable mirror with respect to the beam diameter for generating a uniform line focus.](image2)
culated one by the finite-element method. Figure 5 shows the mirror deformation when only the central actuator is driven to push. The influence function $F_i$ calculated by the finite-element method can be fitted to the Gaussian function:

$$F_i = A \exp(Br_i^2),$$

where $A$ and $B$ are constants determined by the displacement of the mirror surface and the actuator spacing, respectively, and $r_i$ is the radial distance from the $i$th actuator to the adjacent actuator.

The good agreement between the measurement and the calculation results can be achieved by the severe adjustment of the tip height of actuators and the thickness of the glue, which should be as thin as possible. This adjustment is effective in reducing the deformation of the glue caused by the push–pull process. The height of actuators is adjusted to within ±5 μm by the polishing of the top pieces of the actuators. The glue thickness is controlled at less than 10 μm.

The small difference of the influence function between the calculation and the measurement is caused by the glue deformation in the measurement. The glue deformation by stress has not been considered in the calculation. For a large deformation, the stress effect on the glue must be investigated more because that gives a severe error of the driving condition of a deformable mirror.

The maximum mirror deformation is 10 μm, which is sufficient for the cylindrical wave-front control of 1.5 μm in the peak-to-valley value to be required in the case of the 180-mm diameter shown in Fig. 3. In this case the error of the influence function that is due to the glue deformation is also negligible.

4. Improvement of the Line-Focus Pattern

Figure 6 shows an optical setup for improving the line-focus pattern. A He–Ne laser 633 nm in wavelength was used as a light source with a plane wave front as a reference. The diameter of the incident laser beam was 180 mm. The wave front of the laser beam was controlled by the deformable mirror located obliquely at 10°. The laser beam reflected by the fold mirror was incident upon the negative cylindrical lens and the aspherical lens whose focal lengths were −10 and 1 m, respectively. The width and the intensity distribution of line focus were measured by a CCD camera and analyzed by an image processor.

Before the wave-front control, the shape of the line focus had a width of 70 μm at the center when both edges of the line were adjusted to the minimum width of 20 μm, as shown in Fig. 7(a). This width nonuniformity was caused by the focal-length difference between the $x$ and the $y$ directions, as mentioned in Section 2. The width and the intensity distribution of the line focus are not uniform on a plane for conventional line-focus optics. The pattern of line focus could be uniformly produced by wave-front control of the incident laser beam, as shown in Fig. 7(b). After the wave-front control, the width for the whole line focus was 25 μm and the intensity distribution along the line focus was uniform. This value is three times the diffraction limit. The aspect ratio of the line focus has been improved to 728 after the wave-front control versus 260 before the control. The intensity distribution scanned across the line after the wave-
front control is also uniform compared with it before the wave-front control, as shown in Fig. 8. Several profiles in the middle of the line focus before the wave-front control have double peaks. This indicates that the laser beam in the central part of the line focus is defocused into the outer focus.

The surface shape of the deformable mirror after adjustment for the best focus was measured by a Fizeau-type interferometer after reorientation of the mirror to the interferometer. The beam diameter on the surface of the deformable mirror for an oblique set became slightly larger than that for normal incidence, which may be negligible because the oblique degree of the deformable mirror is small. The measured surface shape of the deformable mirror was expanded by Zernike circle polynomials. The controlled wave front had a cylindrical curvature in the $y$ direction of 1.96 waves in the peak-to-valley value shown in Fig. 9. This cylindrical wave front consisted of the combination of a defocus and an astigmatism oriented along the $x$ axis of the Zernike coefficients, which are summarized in Table 1. The wavefront formed by a defocus and an astigmatism oriented along $x$-axis is 1.8 waves in peak-to-valley value, which are 90% of the totally controlled wave-front of 1.96 waves.

5. Conclusion

A cylindrical wave-front aberration in conventional line-focusing optics, which originated from the focal-length difference between the $x$ and the $y$ directions, even if the amount of aberration differed in the beam diameter, was discussed. A deformable mirror can compensate for the wave-front aberrations. The deformable mirror with a large aperture of 185 mm has been developed with a good initial surface accuracy of 0.08 waves in the rms value. The deformable mirror with a small number of actuators has simply provided a high-aspect-ratio line focus over 700 with uniform width and intensity distribution without energy loss. Our line-focusing optics have a wide controllability. An arbitrary linewidth and intensity distribution can be simply provided without changing the optical devices, and the uniform line focus on a curved target as well as a plane target for an x-ray laser experiment can be generated.

In practical application to x-ray laser experiments, a larger-aperture deformable mirror with more actuators may be required for compensating for the wave-front aberrations in a high-power laser system in addition to the cylindrical wave-front control. If an incident laser beam has spatially higher-order wave-front aberrations, the deformable mirror becomes expensive to fabricate because of the number of actuators that are required. It costs more to develop a larger-aperture deformable mirror because of the technical problem of polishing and gluing a thin substrate. The larger-aperture deformable mirror 400 mm in diameter with 37 actuators has been developed for applications to the x-ray laser experiments in the GEKKO XII laser system. This deformable mirror will be used to improve the line-focus pattern.

Table 1. Lower-Order Zernike Coefficients by the Expansion of the Wave Front by Zernike Circle Polynomials

<table>
<thead>
<tr>
<th>Zernike Coefficient</th>
<th>Amount (in Units of Waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defocus</td>
<td>0.52</td>
</tr>
<tr>
<td>Astigmatism $x$</td>
<td>-0.748</td>
</tr>
<tr>
<td>Astigmatism $y$</td>
<td>0.101</td>
</tr>
<tr>
<td>Coma $x$</td>
<td>-0.028</td>
</tr>
<tr>
<td>Coma $y$</td>
<td>-0.156</td>
</tr>
<tr>
<td>Spherical aberration</td>
<td>-0.023</td>
</tr>
</tbody>
</table>
and to compensate for wave-front aberrations included in the laser system in the near future.

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References