Astigmatic Aberration Correction of Slab Laser

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Abstract
Aiming at the problem that the astigmatism component of the slab laser is dominated mainly by large-scale astigmatic aberrations, a method for simultaneously correcting defocus, 0° and 45° astigmatism is proposed. The spherical lens, cylindrical lens and adjustment system are employed. Using the theory of ray tracing, the beam divergence angle is used as the intermediate variable to construct a relationship between defocus, 0° astigmatic aberrations and spacing of the two lenses. Further, a mathematical analysis relationship between the 45° astigmatic aberration and the cylindrical lens rotation angle is established, and the correcting rotation angle for 45° astigmatic aberration is directly calculated according to the parameters detected by the wavefront sensor. Then, the experimental results show that the PV value of the incident beam wavefront can be reduced from 30.51μm to 1.5μm, and the beam quality is obviously improved.

Keywords: Slab Laser, Astigmatic Aberration, Aberration Correction, Wavefront Sensor

1. Introduction

The slab laser has the advantages of compact structure and full electric operation, and has extremely broad application prospects. By adopting the zigzag propagation path, the aberration components in the narrow direction are suppressed, which is advantageous for obtaining high power with high beam quality laser output, and thus has become a research hotspot at present [1-3]. However, as the output power of the laser continues to rise, the components of low-order aberrations (defocus, astigmatism) caused by the thermal effect increase remarkably, and it is difficult to satisfy the demand for high beam quality by suppressing only the aberration components in the narrow direction. Eventually, the wavefront PV value of the output beam changes from tens of microns to hundreds of microns, which severely limits the improvement of beam quality [4, 5].

Although the adaptive optical correction system can effectively solve the problem of aberration correction, it is limited by the stroke of the driver, making it difficult to solve the correction problem of large-value aberration and limiting the correction ability. At present, geometric geometry-based correction techniques are mainly used to solve the correction problem of large-value low-order aberrations. In 2014, Liu et al. [6] proposed a method of adjusting the spacing of three mirrors and rotating the cylindrical lens with Zernike coefficient as feedback to compensate for the defocus and astigmatism in the high-power slab laser (0° and 45°) aberration. With a reflective structure, the energy utilization rate is high, but the volume is relatively large. In 2015, Xue et al. [7] proposed a transmissive correction system based on learning algorithm. The Zernike coefficient is also used as an evaluation index to adjust the lens spacing to achieve the correction of defocus and astigmatism (0°) aberration. However, characterizing the aberration information of the rectangular aperture only with the Zernike coefficient will introduce a certain error, which limits the correction effect of the above scheme [8]. In addition, it is difficult to characterize the aberration characteristics of the slab laser using a low-order aberration simulator. In 2017, Yu et al. [9, 10] used the mathematical analysis relationship between low-order aberration and lens distance to achieve the correction of defocus and 0° astigmatic aberration, and obtained a certain value in the slab laser. Applications.

However, the correction of the 45° astigmatic aberration is not achieved. In order to solve the above problems, this paper proposes a correction method for simultaneously correcting defocus, 0° astigmatism and 45° astigmatism. The correction system consists of two lenses with an adjustment system, one of which is a cylindrical lens and a spherical lens. Using the ray tracing method, the beam divergence angle is taken as the intermediate variable, and the mathematical analysis relationship between the defocus, 0° astigmatic aberration and the lens position is established, so that the position adjustment is directly solved according to the parameters detected by wavefront sensor. Further, a mathematical analysis relationship between the 45° astigmatic aberration and the cylindrical lens rotation angle is established, and the rotation angle is directly calculated according to the parameters detected by the wavefront sensor to realize the correction of the 45° astigmatic aberration. Finally, with the parameters detected by the wavefront sensor, according to the established mathematical analytical relationship, the adjustment of the distance and angle is solved to achieve the correction of defocus, 0° astigmatism and 45° astigmatism. Finally, in order to verify the correctness of the proposed method, a related experimental device was built to verify the effect of aberration correction in the slab laser.
2. Low Order Aberration Correction Principle

Since the beam size of the output beam has a high aspect ratio, the orthogonal information of the Legendre polynomial in the rectangular domain is used to characterize the aberration information. The aberrations of slab lasers are mainly low-order aberrations such as defocus, 0° astigmatism and 45° astigmatism [11], so the wavefront function can be expressed as:

\[
\omega(x, y) = \frac{2\pi}{\lambda} (P + T_x x + T_y y + \alpha x^2 + \beta y^2 + \gamma xy)
\]  \hspace{1cm} (1)

Where \( P \) is a constant, \( T_x \) and \( T_y \) are primary term coefficients, and \( \alpha, \beta \), and \( \gamma \) are quadratic terms coefficients, respectively. The wave front can be expressed by using the Legendre polynomial as:

\[
w(x, y) = a_0 + a_1 x + a_2 y + a_3 [L_{02}(x, y) + L_{20}(x, y)] + a_4 [L_{02}(x, y) - L_{20}(x, y)] + \frac{1}{2} a_5 L_1(x, y)
\]  \hspace{1cm} (2)

Where \( x_i = 2x/l_x \) and \( y_i = 2y/l_y \). \( l_x \) and \( l_y \) represent the geometric dimensions of the spot to be measured, respectively. \( L_{02}(x, y), L_{20}(x, y), \) and \( L_1(x, y) \) are Legendre polynomials, and \( a_0, a_1, a_2, a_3, a_4, \) and \( a_5 \) are coefficients of respective aberrations. Further finishing can be obtained:

\[
w(x, y) = a_0 + a_1 x_i + a_2 y_i + (a_3 + a_4) \left( \frac{1}{2} (3x_i^2 - 1) \right) + (a_3 - a_4) \left( (3y_i^2 - 1) \right) + a_5 x_i y_i
\]  \hspace{1cm} (3)

According to formula (1) and (3), \( \alpha, \beta, \) and \( \gamma \) can be obtained as follows:

\[
\begin{align*}
\alpha &= \frac{3a_3 + a_4}{2} & \frac{L_x}{l_x} \\
\beta &= \frac{3a_3 - a_4}{2} & \frac{L_y}{l_y} \\
\gamma &= \frac{a_5}{L_x L_y}
\end{align*}
\]  \hspace{1cm} (4)

When there are defocus and astigmatic aberrations, the radius of curvature of the wave front has the following expression:

\[
\begin{align*}
R_x &= \frac{1}{2\alpha} = \frac{L_x^2}{3(a_3 + a_4)} \\
R_y &= \frac{1}{2\beta} = \frac{L_y^2}{3(a_3 - a_4)}
\end{align*}
\]  \hspace{1cm} (5)

Where \( R_x \) and \( R_y \) are the radius of curvature of the wave front in the \( X \) and \( Y \) directions, respectively.

When there is only defocus aberration, and in the square area, \( a_3 = 0, L_x = L_y \). At this time, \( R_x \) is equal to \( R_y \), and the wave front has a rotationally symmetric characteristic along the beam propagation direction (\( Z \)-axis), and the radius of curvature of the wave front gradually decreases as \( a_1 \) increases. On the other hand, the spherical lens has the same radius of curvature in the \( X \) and \( Y \) directions, and therefore, by changing the position of the spherical lens having the rotational symmetry characteristic, the correction of the out-of-focus aberration can be realized.

However, when there is 0° astigmatic aberration at the same time \( a_4 \neq 0 \), even if \( L_x = L_y \), at this time, \( R_x \neq R_y \). It is shown that the 0° astigmatic aberration destroys the characteristics of this rotational symmetry, so that the difference in the radius of curvature of the wave front at the \( XOZ \) and \( YOZ \) planes is elliptical, and the major and minor axes are in the \( XOZ \) and \( YOZ \) planes respectively. It also has axisymmetric properties. The cylindrical lens has a radius of curvature only in a single plane. Therefore, by introducing a cylindrical lens and changing the radius of curvature of the wave front in a single direction, so that \( R_x = R_y \), the correction of 0° astigmatic aberration can be realized.

The 45° astigmatic aberration not only destroys the rotational symmetry, but also destroys the axisymmetric property. The radius of curvature of the wave front changes regularly around the \( Z \) axis, and its expression is as shown in formula (6):
Where $\theta$ represents the angle of rotation. When only $45^\circ$ astigmatic aberration is contained, $a_3 = a_4 = 0$, and $\alpha = \beta = 0$. It can be seen from the formula (5) that the radius of curvature of the wave front is not only related to the aberration coefficient, but also decreases as the angle of rotation increases, and the angle between the major axis and the minor axis of the elliptical isophase plane about the $Z$ axis is $\theta$. At this time, it is difficult to compensate the rotation angle only by adjusting the distance of the lens. The spherical lens has a rotationally symmetrical characteristic, and the cylindrical lens has a radius of curvature only in a single plane. Therefore, by rotating the cylindrical lens, the wave front is rotated, and $45^\circ$ astigmatic aberration compensation can be realized.

The cylindrical lens rotation angle and the aberration coefficient have the expression of formula (7):

$$\tan 2\theta = \frac{2a_s}{\alpha - \beta}$$

(7)

Bring the formula (4) into the formula (7), and sort out:

$$\tan 2\theta = \frac{2a_s}{3[(a_1 + a_4)L_y - (a_1 - a_4)L_x]}$$

(8)

When $a_3 = a_4 = 0$ or $(a_1 + a_4)L_y = (a_1 - a_4)L_x$, it is difficult to calculate the $45^\circ$ astigmatism compensation angle $\theta_{45^\circ}$ of the cylindrical lens from the measured aberration coefficient.

Based on the above compensation principle, this paper takes the centroid offset detected by the wavefront sensor as the intermediate variable, and realizes the $45^\circ$ astigmatism aberration by establishing the mathematical analytical relationship between the $45^\circ$ astigmatic aberration and the cylindrical lens angle adjustment. Using the correction principle based on geometric optics, the divergence angle is used as the intermediate variable, and the mathematical analysis relationship between the low-order aberration and the lens position is established to realize the correction of the defocus and $0^\circ$ astigmatic aberration.

The working principle of the low-order aberration correction system is shown in Figure 1. It consists mainly of a spherical lens, a cylindrical lens, an adjustment system.

**Figure 1. Schematic diagram**

By adjusting the distance of the spherical lens, the radius of curvature of the wave front in the $X$ direction is adjusted to correct the low-order aberration in the $X$ direction; by adjusting the position of the cylindrical lens $L_y$ in the $Y$ direction, the defocusing and $0^\circ$ astigmatic aberration are realized; and by rotating cylindrical lens $L_y$ in $Y$ direction, the correction of $45^\circ$ astigmatism can be realized. Finally, the goal of automatic correction of low-order aberrations is achieved. Where $K_1$ represents the distance from the laser exit opening to the spherical lens $L_x$, and $K_2$ represents the air separation of the spherical lens $L_x$ and the cylindrical lens $L_y$.

The distance parameter $K_1$ of spherical lens $L_R$ can be obtained by formula (9):

$$K_1 = f_s \frac{h_s}{\tan(\theta_s)}$$

(9)

Where $f_s$ represents the radius of curvature of the spherical surface of the spherical lens $L_x$, $h_s$ represents the size of the outgoing beam of the slab laser in the $X$ direction, and $\theta_s$ is the divergence angle in the $X$ direction. Both $h_s$ and $\theta_s$ are laser self-parameters and can be directly measured. Therefore, the position of the spherical lens can be directly calculated, so that the radius of curvature of the wave front of the outgoing beam in the $X$
direction is approximately infinite, and the divergence angle $\theta_x$ is approximately zero, thereby compensating for the low-order aberration in the X direction.

Further, the position of the cylindrical lens $L_y$ is adjusted according to the formula (10) such that the wave surface curvature radius of the Y-direction outgoing beam is approximately infinite, and the divergence angle $\theta_y$ is approximately zero, thereby compensating for the low-order aberration in the Y direction.

$$
K_2 = \frac{f_y}{R_y} - \left( \frac{h_y \cdot \sin \theta_y}{R_y} \right) \cdot \sin \left( \arctan \left( \frac{\sin(A - \theta_y)}{h_y \cdot \cos(A - \theta_y)} \right) \right) \frac{\tan A}{\tan \arcsin(\sin(A))}
$$

$$
A = \theta_y + \arcsin\left( \frac{h_y \cdot \cos \theta_y}{R_y} - \left( \frac{R_y + K_y}{R_y} \right) \cdot \sin \theta_y \right) - \arcsin\left( \frac{h_y \cdot \cos \theta_y}{R_y \cdot n_y} - \left( \frac{R_y + K_y}{R_y} \right) \cdot \sin \theta_y \right)
$$

(10)

Where: $\theta_y$ is the divergence angle of the beam in the Y direction at the incident plane, $h_y$ is the dimension parameter of the incident beam in the Y direction, $R_y$ is the radius of curvature of the cylindrical lens $L_y$, and $f_y$ is the focal length of the cylindrical lens $L_y$, and there is a radius of curvature in the Y direction only. Both $h_y$ and $\theta_y$ are the property parameters of the laser itself. Therefore, the position that satisfies the aberration correction can be directly solved according to the parameters of the incident beam.

Finally, the 45° astigmatic aberration correction is achieved by rotating the cylindrical lens, and the rotation angle can be directly solved according to the formula (11):

$$
\theta_{45} = \arctan\left( \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \right)
$$

(11)

Where $(x_i, y_i)$, $(x_{i+1}, y_{i+1})$ respectively represent the centroid coordinates of any two adjacent spots in the same array of spots in the Y direction.

According to the size of the beam emitted by the slab laser, $h_x$, $h_y$, The divergence angles $\theta_x$, $\theta_y$, and the centroid coordinates of the array spot, bring them into the formula (9)–(11), the position of the spherical mirror $L_z$ and the cylindrical lens $L_y$, and the angular compensation amount $\theta_{45}$ of the cylindrical lens can be directly calculated. Finally, the lens attitude is adjusted according to the calculation result to realize automatic compensation of low-order aberrations.

3. Experimental Verification

In order to verify the feasibility of the above low-order correction method, an experimental device as shown in Figure 2. was constructed.

![Figure 2. Experimental device diagram](image)

It is mainly composed of a slab laser, a low-order aberration automatic compensation system, and a detection system. Among them, the slab laser adopts the technical scheme of main oscillation power amplification. Its maximum output power is 1.2kW, and the output beam size is $h_i = 1.5$ mm, $h_y = 12$ mm. When the full power output, the divergence angle variation is $\theta_x = 1.5$ mrad–1.8 mrad, $\theta_y = 6$ mrad–6.5 mrad. The low-order aberration compensation system mainly consists of a cylindrical lens $L_y$, a spherical lens $L_z$, and a spacing and deflection angle adjusting unit. The structural parameters of the optical system are shown in Table 1. The detection system uses a Hartmann wavefront sensor to measure the parameters of the incident beam.
Table 1. Optical system structure parameters

<table>
<thead>
<tr>
<th>Unit</th>
<th>Face type</th>
<th>Radius of curvature (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_y$</td>
<td>Y-direction flat concave cylindrical mirror</td>
<td>$R_x = -91.25$</td>
<td>$a_i = 4.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_y = \infty$</td>
<td></td>
</tr>
<tr>
<td>$L_x$</td>
<td>Spherical mirror</td>
<td>$R_x = 729.784$</td>
<td>$a_i = 8.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_y = \infty$</td>
<td></td>
</tr>
</tbody>
</table>

Three sets of experiments were performed under full power output conditions. The wavefront information of the incident beam is measured as shown in Figure 3. The output power of the CCEPS laser gradually reaches about 1.2 kW, and its wavefront PV value increases to 31.84 μm, and the beam quality deteriorates rapidly.

![Figure 3. Wavefront information of the incident beam at different pump currents (μm).](image)

(a) PV=31.84μm, RMS=6.53μm; (b) PV=30.91μm, RMS=5.80μm; (c) PV=31.28μm, RMS=6.02μm

According to the coefficients of the Legendre polynomials in Figure 4, the wavefront aberration of the incident beam at this time is mainly defocus, 0° astigmatism, 45° astigmatic aberration, and contains high-order components.

![Figure 4. Legendre polynomial coefficients](image)

Before and after calibration, the variation of the beam parameters is shown in Table 2. The beam parameters measured in Table 2, are brought into the formula (9) ~ (11), and the adjustment amount of the lens can be obtained. The adjusted wavefront is shown in Figure 5. The corrected wavefront PV value can be due to 1.2 μm.

Table 2. Beam parameters before and after calibration

<table>
<thead>
<tr>
<th>No.</th>
<th>Incident beam parameter</th>
<th>Lens spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimension (mm)</td>
<td>Divergence angle (mrad)</td>
</tr>
<tr>
<td>1</td>
<td>$x=0.75$</td>
<td>$y=6.00$</td>
</tr>
<tr>
<td>2</td>
<td>$x=0.75$</td>
<td>$y=6.00$</td>
</tr>
<tr>
<td>No.</td>
<td>Simulation results</td>
<td>Experimental results</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>PV(μm)</td>
<td>RMS(μm)</td>
</tr>
<tr>
<td>1</td>
<td>1.03</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**Figure 5.** Wavefront information of the emitted beam after correction (μm). (a) PV=1.19μm, RMS=0.35μm; (b) PV=1.17μm, RMS=0.34μm; (c) PV=1.18μm, RMS=0.35μm

To further analyze the components of its residual aberrations, the coefficients of the modified Legendre polynomials are given in Figure 6.

**Figure 6.** Adjusted Legendre polynomial coefficients

Except for the fourth, sixth, eleventh, thirteenth, and fifteenth factors, the coefficients of the 21st and 28th items are relatively large, but the two coefficients are slightly smaller than the low-order aberration and the spherical aberration coefficient. This indicates that in the residual aberration, the high-order aberration component is contained, and the high-order aberration component has already exceeded the low-order aberration component, which is also the limitation of the low-order aberration automatic correction system. To further improve the correction effect, the adaptive optical system can be used to correct the high-order aberration components. The variation of the beam quality β factor before and after calibration is shown in Figure 7. After the low-order aberration compensation, the beam quality β factor is increased from 21.14×DL to 2.64×DL, and the beam quality is obviously improved.
4. Conclusions

In this paper, we aim to correct the large-scale astigmatic aberration of slab lasers. We propose a correction method based on the establishment of analytical relations. The mathematical analysis relationship between defocus, 0° astigmatism, 45° astigmatic aberration and lens parameters is established. According to the established mathematical analysis relationship, the distance and angle parameters satisfying the demand are directly solved. The lens position and angle are adjusted according to the parameters of the solution, and the slab laser defocus, 0° astigmatism, and 45° astigmatic aberration correction are realized. The experimental results show that the corrected wave front PV value decreases from 31.84μm to 1.19μm, the beam quality β factor is improved from 21×DL to 2.4×DL, and the beam quality is effectively improved through this method.

References