Design and Analysis of a New Device for Low-Order Wavefront Aberrations Measurement

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Abstract: For a high energy laser, thermally induced wavefront distortions include a large proportion of low-order aberrations with large peak-valley (PV) value. In this paper we design a Low-Order Wavefront Aberration Detector which can detect the large peak-valley value of low-order phase aberrations. Different from Shack – Hartmann Wavefront Sensor, this device includes one special diaphragm, six sets of optical focusing system and six displacement detectors. The length of Low-Order Wavefront Aberration Detector can be controlled within 200mm. The minimum low-order aberration coefficient of LOWAD is less than 0.5λ, which is determined by the inherent aberration distribution of optical focusing system. And we can choose reasonable position sensitive detector or four-quadrant photo-detector to detect relative displacement of each focal point, and thus the measurement sensitivity of LOWAD is less than 0.1λ and the measurement capability is more than 80λ. The new wavefront measurement device can be used to direct measure low-order aberrations for laser beam with large transverse area and do not need beam contracting system, and the size and cost is greatly below Shack – Hartmann Wavefront Sensor.

1 INTRODUCTION

Thermally induced wavefront distortions is one of the main technical challenges in the development of high power solid laser and the wavefront distortion caused by thermal effect of solid or gas seriously reduces the beam quality in far field (Redmond et al., 2007; McNaught et al., 2009). Shack – Hartmann Wavefront Sensor (SHWS) is an important device in a AO system, and is widely used to measure wavefront distortions. The wavefront of object beam is divided by an array of transmissive lenses, and the focus spot position of each beam can be detected by CCD camera with multiple pixels (Liujing et al., 2011). The wavefront slope is calculated with displace of each focus spots, then the distortions can be reconstructed by implementing zonal methods or modal methods (Southwell, 1980; Tyson, 2011). SHWS can be used for real-time wavefront correction and the spatial resolution is very high, but it is very expensive and complex. And usually it is designed to detect the small phaseshift mainly contains higher-order aberrations. However, for a high energy solid state laser, thermally induced wavefront distortions include a large proportion of low-order aberrations with large peak-valley (PV) value, mainly constituted of defocus and astigmatism.

In this paper we design a wavefront measurement device which can detect the large peak-valley value of low-order phase aberrations the the abbreviation LOWAD (Low-Order Wavefront Aberration Detector) is used in our discussion. This measurement principle of this device still depends on wavefront slope measurements but only need measurements of 6 spots, and the mathematical algorithm involved to wavefront reconstruction is easier than zonal or modal estimation. The new wavefront measurement device can be used to direct measure low-order aberrations for laser beam with large transverse area and the size and weight is greatly less than that of Shack – Hartmann Wavefront Sensor.

2 PRINCIPLE

In Cartesian coordinates the wavefront distortions
only constituted by defocusing and astigmatism can be written as (Born and Wolf, 1999)

\[ W(x, y) = a_1 + a_2 x + a_3 y + a_4 x^2 + a_5 y^2 \]  

(1)

Then the x-slope measurement \( S_x \) and y-slope measurement \( S_y \) in Cartesian coordinates are (Hernández-Gómez et al., 2014)

\[ S_x = \frac{\partial W(x, y)}{\partial x} = a_1 + 2a_2 x + a_4 y \]
\[ S_y = \frac{\partial W(x, y)}{\partial y} = a_2 + a_3 x + 2a_5 y \]  

(2)

Then the \( a_1 \sim a_5 \) can be obtained from following matrix equations

\[
\begin{pmatrix}
S_{x1} \\
S_{y1} \\
S_{x2}
\end{pmatrix} = \begin{pmatrix}
1 & 2x_1 & y_1 \\
1 & 2x_2 & y_2 \\
1 & 2x_3 & y_3
\end{pmatrix} \begin{pmatrix}
a_1 \\
a_2 \\
a_3
\end{pmatrix}
\]  

(3)

And

\[
\begin{pmatrix}
S_{x1} \\
S_{y1} \\
S_{x2}
\end{pmatrix} = \begin{pmatrix}
1 & 2x_1 & y_1 \\
1 & 2x_2 & y_2 \\
1 & 2x_3 & y_3
\end{pmatrix} \begin{pmatrix}
a_4 \\
a_5 \\
a_6
\end{pmatrix}
\]  

(4)

Where, \( x \) and \( y \) are the coordinates of focusing points, the indexes \( i, j, k \) are signed as random three different point, respectively. In Eq. (1) there are 5 unknown parameters \( a_1 \sim a_5 \) which are completely describe the spherical curvature and the astigmatic curvature.

Based on the Zernike circle polynomials \( Z_{2i}^m(r) \cos m\theta \) that are orthogonal and normalized (Born and Wolf, 1999), the relationship between \( a_1 \sim a_5 \) and Zernike circle polynomials coefficients can be obtain by

\[ A_{1,1} = \frac{\rho_0}{4\sqrt{3}} a_1; A_{1,2} = \frac{\rho_0}{4\sqrt{3}} a_2; \]
\[ A_{2,0} = \frac{\rho_0^2}{4\sqrt{3}} (a_1 + a_2); A_{2,2} = \frac{\rho_0^2}{2\sqrt{6}} (a_3 - a_1); A_{3,0} = \frac{\rho_0^2}{4\sqrt{3}} \]  

(5)

Where, \( A_{1,1} \) and \( A_{1,2} \) are tilt aberration coefficients, \( A_{2,0} \) is defocus aberration coefficient, \( A_{2,2} \) and \( A_{3,0} \) are astigmatism aberration coefficients, \( \rho_0 \) is the normalization radius. So for calculating the defocus aberrations coefficient and astigmatism aberrations coefficients, we need at least 3 sets of the x- and y- slopes measurements. In this case LOWAD is designed to detect displaces of six focus for measuring beam, which means there are six sets of x- and y- slopes measurements. From Eq. (3) and Eq. (4), we notice that there are 20 different sets of values for \( a_1, a_2, a_3, \) and \( a_4 \). The final value is taken as the average of the 20 values. We have 40 results for \( a_4 \), two in each combination of three points, so we take the average of these 40 values. Once the values of \( a_1 \sim a_5 \) are calculated, the Zernike aberration coefficients of wavefront distortions can be obtained by Eq. (5).

3 DESIGN AND ANALYSIS

The LOWAD mainly include three parts: one spcical diaphragm (Part A), six sets of optical focusing system (Part B) and six displacement detectors. The design schematic in cross section view is shown in Figure 1. Measuring beam is divided to 6 sub-beams by the spcical diaphragm, each sub-beam is focused by focusing optical system, then the displacement of focal spots can be detected by displacement detectors. The x- and y- slopes of focal spot can be calculated by using the focal length of focusing system and the displacement of each focal spot (Tyson, 2011).

![Figure 1: Structure diagram of LOWAD.](image)

The distribution of spcical diaphragm is shown in Figure 2. In our case, the diameter of incient light \( D=150mm \), the diameter of each separated circular area \( d=25mm \), and the distance of each adjacent points is \( \rho_0=50mm \). This diaphragm can separate the incient light into six sub- lights, and each sub-light contains the phase information of confirmatory portion of incident light. As the same as SHWS, we must focus each sub- lights and measure the relative displacement of focal points, respectively.

In order to reduce the size of this device and increase the measurement accuracy, as shown in Figure 3, we use the focusing optical system rather than convex lens. The whole focusing system include 2 parts: the first part contains one convex lens (L1)
Table 1: Optical element parameters of focusing optical system (unit: mm).

<table>
<thead>
<tr>
<th>Type</th>
<th>Element</th>
<th>Radius of Curvature</th>
<th>Distance to next element</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Incident surface</td>
<td>69.11</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Exit surface</td>
<td>-28.62</td>
<td>0.727</td>
</tr>
<tr>
<td>L2</td>
<td>Incident surface</td>
<td>-27.33</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exit surface</td>
<td>-144.08</td>
<td>77.5</td>
</tr>
<tr>
<td>L3</td>
<td>Incident surface</td>
<td>-7.798</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exit surface</td>
<td>inf</td>
<td>150.7</td>
</tr>
</tbody>
</table>

Figure 2: Distribution of the special diaphragm.

and one concave lens (L2), and the second part is one convex lens (L3). The equivalent focal length of focusing system can achieve about 5 times of the length of whole focusing system. In other words the f/D of this system can increase 5 times compared with the focusing lens which has the same size, which means the optical aberration and chromatic aberration of focusing system can be controlled in reasonable range.

Figure 3: Schematic of optical focusing system.

For detecting the wavefront aberrations of measuring beam accurately, we have optimize the optical parameters to decrease the aberration of focusing optical system. The optimized optical element parameters are listed in Table 1. The actual focusing distance of this system is about 150mm, but the equivalent focal length can be more than 1000mm.

The inherent aberration distribution of system is calculated and shown in Figure 4. The simulation results is obtained in an ideal optical system without off-axis condition. The PV value of wavefront is 0.2117λ and the RMS value is 0.0599λ. The main aberration is defocusing and spherical aberrations, and the Zernike aberration coefficients are 0.011λ and 0.054λ. The results determine the minimum low-order aberration coefficient of LOWAD.

For our detector the measurement accuracy is determined by the accuracy of displacement detectors. Normally for an incident beam with large value low-order aberrations (the PV value is almost greater than 20λ), the acceptable measurement accuracy of aberration is 0.1λ, which means the sensitivity of position detector must be less than 2um. Considering that the largest PV value of defocusing aberration which can be measured is about 80λ, the effective size of detection surface of position detector used in LOWAD must greater than 2.5mm. Above all, while based on the requirement of measurement sensitivity and capability, PSD (position sensitive detector) and four-quadrant photodetector can be chosen to using in LOWAD, which are commercial products and are much cheaper than CCD camera.

4 CONCLUSIONS

In this paper we designen and discussed a new detector to reconstruct the thermally induced wavefront distortions with large peak-valley value depends on x- and y- slope measurements. The Low-Order Wavefront Aberration Detector is constituted of one special diaphragm, six sets of optical focusing system and six displacement detectors. The actual focusing distance of this system is about 150mm, which means the length of Low-Order Wavefront Aberration Detector can be controlled within 200mm. The inherent aberration distribution of system is anaysed. The main aberration is defocusing and
spherical aberrations, and the minimum low-order aberration coefficient of LOWAD is less than 0.5λ. And by choosing reasonable PSD and four-quadrant photo-detector, the measurement sensitivity of LOWAD is less than 0.1λ and the measurement capability is more than 80λ. To sum up, the LOWAD can be used in direct measurement of low-order aberrations for laser beam with large transverse area and do not need beam contracting system.

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