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

Zhou Qiong[1], Liu Wenguang[1], Wang Gang[2], Yan Baozhu[1], Xi Fengjie[1] and Jiang Zongfu[1]
[1] *College of Opto-electronic Science and Engineering, National University of Defense Technology, Changsha, Hunan, China*
[2] *Science and Technology on Solid-State Laser Laboratory, Beijing, China*
zhouqiong0416@gmail.com

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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 sepcial 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 sensitve detector or four-quadrant photo-detector to detect relatiove 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 resliution 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 reconstrution 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)

$$W(x,y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 \quad (1)$$

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

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

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

$$\begin{pmatrix} S_{x_i} \\ S_{x_j} \\ S_{x_k} \end{pmatrix} = \begin{pmatrix} 1 & 2x_i & y_i \\ 1 & 2x_j & y_j \\ 1 & 2x_k & y_k \end{pmatrix} \begin{pmatrix} a_1 \\ a_3 \\ a_4 \end{pmatrix} \quad (3)$$

And

$$\begin{pmatrix} S_{y_i} \\ S_{y_j} \\ S_{y_k} \end{pmatrix} = \begin{pmatrix} 1 & x_i & 2y_i \\ 1 & x_j & 2y_j \\ 1 & x_k & 2y_k \end{pmatrix} \begin{pmatrix} a_2 \\ a_4 \\ a_5 \end{pmatrix} \quad (4)$$

Where, x and y are the coordinates of focusing points, the indexs i,j,k are signed as radom three different point, respectively. In Eq. (1) there are 5 unknown parameters $a_1 \sim a_5$ which are completely discribe the spherical curvature and the astigmatic curvature. Based on the Zernike circle polynomials $Z_n^m(r)\cos m\theta$ 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

$$A_{1,-1} = \frac{\rho_0}{2} a_1; A_{1,1} = \frac{\rho_0}{2} a_2;$$
$$A_{2,0} = \frac{\rho_0^2}{4\sqrt{3}}(a_3 + a_5); A_{2,-2} = \frac{\rho_0^2}{2\sqrt{6}}(a_3 - a_5); A_{2,0} = \frac{\rho_0^2}{4\sqrt{3}} \quad (5)$$

Where, $A_{-1,-1}$ and $A_{1,1}$ are tilt abberation coefficients, $A_{2,0}$ is defocus abberation coefficient, $A_{2,-2}$and $A_{2,2}$ are astigmatism abberation coefficients, ρ_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_5. 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 calaculated, the Zernike abberation coefficients of wavefront distortions can be obtained by Eq. (5).

3 DESIGN AND ANALYSIS

The LOWAD mainly include three parts: one sepcial 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 sepcial 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 dispalcement of each focal spot (Tyson, 2011).

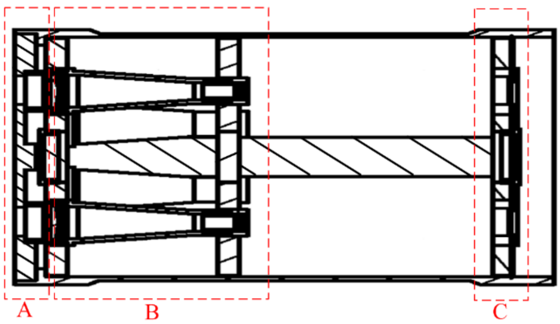

Figure 1: Structure diagram of LOWAD.

The distribution of sepcial 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 ench adjacent points is ρ_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).

Type	Element	Radius of Curvature	Distance to next element
L1	Incident surface	69.11	6
	Exit surface	-28.62	0.727
L2	Incident surface	-27.33	2
	Exit surface	-144.08	77.5
L3	Incident surface	-7.798	2
	Exit surface	*inf*	150.7

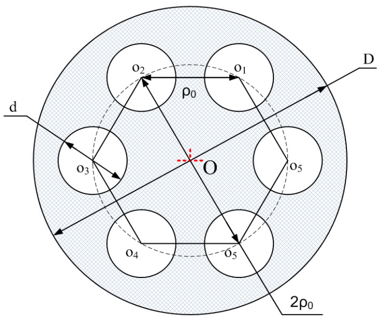

Figure 2: Distribution of the special diaphragm.

and one concave lens (L2), and the second part is one convexlens lens (L3). The eauivalent focal length of focuing system can achieve about 5 times of the length of whole focuing 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

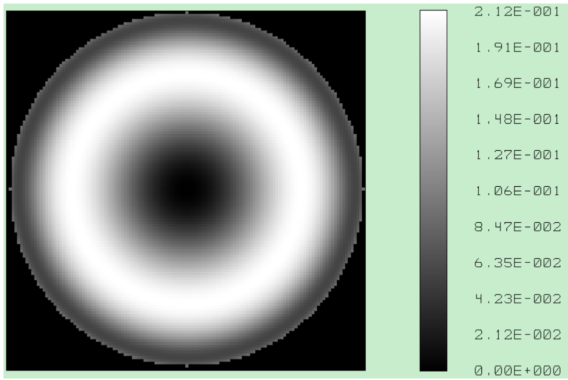

Figure 4: Simulation inherent wavefront distribution of optical focusing system (units: λ).

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 incient 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 sensitve detector) and four-quadrant photo-detector can be choosed 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 reconsruct 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 sepcial 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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REFERENCES

S. Redmond, S. McNaught, J. Zamel, et al, 2007. 15 kW near-diffraction-limited single-frequency Nd:YAG laser, *CLEO.*

Stuart J. McNaught, Charles P. Asman, Hagop Injeyan, et al, 2009. 100-kW Coherently combined Nd: YAG MOPA laser array. *Frontiers in Optics 2009/Laser Science XXV.*

Xu Liujing, Yang Ping, Liang Xinbo, et al, 2011. Application of Hartmann-Shack wavefront detector in testing distorted wavefront of conduction cooled end-pumped slab. *Chin. J. Lasers.*

W. H. Southwell, 1980. Wavefront estimation from wavefront slope measurement. *J. Opt. Soc. Am.*

Robert K. Tyson, 2011. *Principles of adaptive optics*, CRC Press. Boca Raton & London & New York, 3rd edition.

Max Born and Emil Wolf, 1999. *Principles of Optics: Electromagnetic Theory of Propagation, Interferencr and Difftaction of light*, Cambridge University Press. Cambridge, 7th edition.

Geovanni Hernández-Gómez, et al, 2014. Hartmann tests to measure the sphexical and cylidrical curvatures and the axis orientation of astigmatic lenses or optical surfaces, *Applied Optics.*

Zhou Qiong, Liu Wenguang, Jiang Zongfu,2015. A New Method to Measure Low-Order Aberrations Based onWavefront Slope. *Proc. of SPIE/Optical Sensors 2015*