Low Order Aberrations Compensation by Direct Adjustment of the Reflective Beam Shaper in Slab Laser

Liu Wenguang[1], Zhou Qiong[1], Wang Gang[2], Xie Kun[1], Yan Baozhu[1] and Xi Fengjie[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*

Keywords: Slab Laser, Low Order Aberrations, Compensation, Beam Shaper.

Abstract: A direct method for compensation of low order aberrations with large PV value was presented in this paper. In which, the relationship between the optical layout parameters and the output aberration coefficients were derived by ray matrix method. Then, the adjustment parameters calculated by the equations were used to change the optical layout parameters to compensate the low order aberrations with defocus and astigmatism. The effectiveness of this method was verified by simulations based on the optical models built in a optical design software. It shows that the low order aberrations can be accurately compensated to a level below 0.5λ by the direct method.

1 INTRODUCTION

In the development of high power slab lasers, both output power and beam quality are crucial parameters to be considered. Although power scaling of slab laser can be realized by MOPA (Master Oscillator and Power Amplification) configuration, preserving high beam quality in high power slab laser is a real challenge (Redmond et al, 2007). In high power slab lasers, the Peak-Valley (PV) value of thermally induced wave-front distortion can be dozens of micrometers (Ganija et al., 2013), and it's difficult to be corrected by a deformable mirror with limited correction range (typically in the range of 6 μm). Multiple deformable mirrors are proposed to correct the wave-front distortions in high power lasers (Xiang et al., 2012; Conan et al., 2007). However, this solution is both expensive and complex. Some experiments have been done to analysis the characteristics of the wave-front in the high power slab laser (Liujing et al., 2011). It shows that in the distortions, low order aberrations, mainly consist of defocus and astigmatism, are the main contributors. So the two-steps beam cleanup concept is proposed as a cost-effective approach to get high beam quality. That is, low order aberrations are compensated by one compensator firstly. And next, the high order aberrations are corrected by one deformable mirror. Static phase corrector (W Qiao, et al, 2014) can be used to compensate some low order aberrations, but it doesn't work well when the operational conditions were changed, and it can also be thermally distorted under high power flux. A reflective beam shaper with two cylindrical mirrors and one spherical mirror was proposed to compensate the low order aberrations by active adjustment of the optical parameters with PID algorithm (Wenguang et al., 2014). Due to the respond speed of the motorized linear stage used, the convergence of PID controller may take about 20s.

In this paper, for the purpose of speeding the compensation process of low order aberrations in slab laser, a direct method was proposed, in which the relationships between the low order aberrations and adjusting parameters were derived from ray matrix equations. Simulations were done to verify the correctness of the method.

2 THEORITICAL DERIVATION

2.1 Layout of the Reflective Beam Shaper

A reflective beam shaper is often used to transform a narrow beam to a square one in slab laser system. The beam shaper can also be used to compensate the low

Wenguang, L., Qiong, Z., Gang, W., Kun, X., Baozhu, Y. and Fengjie, X.
Low Order Aberrations Compensation by Direct Adjustment of the Reflective Beam Shaper in Slab Laser.
DOI: 10.5220/0005736501130118
In *Proceedings of the 4th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2016)*, pages 115-120
ISBN: 978-989-758-174-8

order aberrations, As shown in Fig.1, where the beam shaper mainly consists of two cylindrical mirrors(y-oriented mirror M_y, x-oriented mirror M_x), one spherical mirror (M_R). The distance between M_y and M_R is L_1, and the distance between M_R and M_x is L_2. Four plane mirrors (M_1, M_2, M_3, M_4) are used to fold the optical path, for the purpose of keeping the output beam position unchangeable while L_1 and L_2 are adjusted to compensate the defocus and 0 degree astigmatism, and M_x can be rotated a angle of κ about z-axis to compensate the 45 degree astigmatism. The PID algorithm was used to adjust L_1 and L_2,and κ to slowly compensate the low order aberrations.

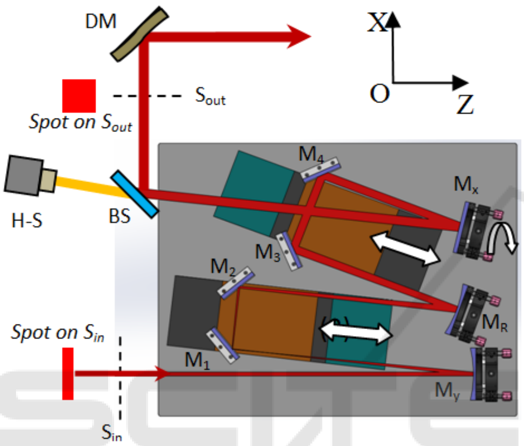

Figure 1: The optical layout of a reflective beam shaper and adjustment parameters for compensation of low order aberrations.

2.2 Matrix Analysis of the Low Order Aberration Compensator

In this paper, matrix methods are used to analyze the relationship between low order aberrations and the adjustment of L_1 and L_2,and κ, to compensate the aberrations directly and quickly without PID algorithm.

Ray tracing are taken from M_y to the output plane S_{out}, as shown in Fig.1. Using a Cartesian-azimuth representation, an incident ray on M_y can be written as:

$$V_{in} = \begin{bmatrix} x \\ \alpha \\ y \\ \beta \end{bmatrix} \tag{1}$$

For a reflective y-oriented cylindrical mirror of curvature R_1 the matrix is:

$$M_{cy} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\frac{2}{R_1} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The propagation matrix between M_x and M_R is :

$$M_{L1} = \begin{bmatrix} 1 & L_1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The reflective matrix of spherical mirror M_R of curvature R_2 is:

$$M_R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\frac{2}{R_2} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{2}{R_2} & 1 \end{bmatrix} \tag{4}$$

The propagation matrix between M_R and M_x is :

$$M_{L2} = \begin{bmatrix} 1 & L_2 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The coordinate transform matrix with rotation angle of κ about z-axis is:

$$R_z = \begin{bmatrix} \cos\kappa & 0 & -\sin\kappa & 0 \\ 0 & \cos\kappa & 0 & -\sin\kappa \\ \sin\kappa & 0 & \cos\kappa & 0 \\ 0 & \sin\kappa & 0 & \cos\kappa \end{bmatrix} \tag{6}$$

For a reflective x-oriented cylindrical mirror of curvature R_3 the matrix is:

$$M_{cx} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{2}{R_3} & 1 \end{bmatrix} \tag{7}$$

And the coordinate transform matrix with rotation angle of -κ about z-axis is:

$$R_{zp} = \begin{bmatrix} \cos\kappa & 0 & \sin\kappa & 0 \\ 0 & \cos\kappa & 0 & \sin\kappa \\ -\sin\kappa & 0 & \cos\kappa & 0 \\ 0 & -\sin\kappa & 0 & \cos\kappa \end{bmatrix} \tag{8}$$

The propagation matrix between M_y and S_{out} is :

$$M_{L3} = \begin{bmatrix} 1 & L_3 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

Matrix of reflective beam shaper in this paper can be calculated by the matrix product of the component matrixes:

$$M = M_{L3} \cdot R_{zp} \cdot M_{cx} \cdot R_z \cdot M_{L2} \cdot M_R \cdot M_{L1} \cdot M_{cy} \tag{10}$$

2.2.1 Functions for Compensating the Defocus and 90^O Astigmatism

In Cartesian coordinates, the combination of defocus and 90° astigmatism can be written as:

$$w(x, y) = \frac{x^2}{2R_x} + \frac{y^2}{2R_y} \tag{11}$$

where R_x is the curvature of beam divergence in XOZ plane, and R_y is the curvature in YOZ plane (Geovanni et al., 2014). So the ray incident M_y with defocus and 90° astigmatism in matrix form is:

$$V_{in} = \begin{bmatrix} x \\ \frac{\partial w}{\partial x} \\ y \\ \frac{\partial w}{\partial y} \end{bmatrix} = \begin{bmatrix} x \\ \frac{x}{R_x} \\ y \\ \frac{y}{R_y} \end{bmatrix} \tag{12}$$

Rewrite the distance as

$$L_1 = (\mathrm{R}_1 + R_2)/2 + \Delta L_1$$
$$L_2 = (\mathrm{R}_2 + R_3)/2 + \Delta L_2$$

where ΔL_1 and ΔL_2 are the adjustment of distance desired to compensate the defocus and 90° astigmatism. Set rotation angle κ=0 for the simplification of derivation, The rays leaving M_x is calculate by

$$V_{out} = \begin{bmatrix} x' \\ \alpha' \\ y' \\ \beta' \end{bmatrix} = M \cdot V_{in} =$$

$$\begin{bmatrix} \frac{R_1R_2^2 - 2R_xR_2^2 - R_1^2R_3 - 2R_1^2L_3}{2R_1R_2R_x}x + \frac{\left[(2R_x - R_1)R_3 + (4R_x - 2R_1)\Delta \mathrm{L}_2 - 2(R_1 - 2R_x)L_3\right]\Delta L_1 - R_1^2\Delta \mathrm{L}_2}{R_1R_2R_x}x \\ -\frac{R_1^2 + 2(R_1 - 2R_x)\Delta L_1}{R_1R_2R_x}x \\ \frac{R_3R_2^2 - R_1R_3^2 - 2R_3^2R_y - 2R_2^2L_3}{2R_2R_yR_3}y + \frac{\left[(2R_y - R_1 - 2R_3\Delta L_1)R_3 + 2(R_1 + 2R_y + 2\Delta L_1)L_3\right]\Delta L_2 - R_3^2\Delta L_1}{R_2R_3R_y}y \\ \frac{-R_2^2 + 2(R_1 + 2R_y)\Delta L_2 + 4\Delta L_1\Delta L_2}{R_2R_3R_y}y \end{bmatrix} \tag{13}$$

From Eq. (13) the adjustment of distance ΔL_1 and ΔL_2 are obtained when $\alpha' = 0, \beta' = 0$:

$$\Delta L_1 = \frac{R_1^2}{2(2R_x - R_1)} \tag{14}$$

$$\Delta L_2 = \frac{R_2^2}{2\left[2R_y + R_1 + 2\Delta L_1\right]} \tag{15}$$

It means that defocus and 90° astigmatism can be compensated by proper adjustment of ΔL_1 and ΔL_2. However, in the practical compensation process, Wave-front aberrations on S_{out} are often expressed as Zernike coefficients in most wave-front sensor, such as Hartman-Shack sensors. So it is convenience to express ΔL_1 and ΔL_2 as the functions of Zernike coefficients detected by H-S sensor on output plane S_{out}.

Before adjustment, ΔL_1=0, $\Delta L_2=0$. From Eq. (13), the relationship of x-curvature of divergence beam on the output plane R_x' and the curvature on the input plane R_x is:

$$R_x' = \frac{x'}{\alpha'} = -\frac{R_1R_2^2 - 2R_xR_2^2 - R_1^2R_3 - 2R_1^2L_3}{2R_1^2} \tag{16}$$

We can rewrite Eq. (16) as:

$$R_x = \frac{2R_1^2R_x' + R_1R_2^2 - R_1^2R_3 - 2R_1^2L_3}{2R_2^2} \tag{17}$$

In the same manner, the relationship of y-curvature of divergence beam on the output plane R_y' and the curvature on the input plane R_y is:

$$R_y = \frac{2R_2^2R_y' + R_3R_2^2 - R_3^2R_1 - 2R_2^2L_3}{2R_3^2} \tag{18}$$

The relationship between Zernike coefficients and beam divergence curvature on the output plane S_{out} is:

$$R_x' = \frac{r_0^2}{2\lambda\left(2\sqrt{3}Z_4 - \sqrt{6}Z_6\right)} = \frac{\eta k_x}{2} \tag{19}$$

$$R_y' = \frac{r_0^2}{2\lambda\left(2\sqrt{3}Z_4 + \sqrt{6}Z_6\right)} = \frac{\eta k_y}{2} \tag{20}$$

Where

$$\eta = r_0^2/\lambda, k_x = 1/\left(2\sqrt{3}Z_4 - \sqrt{6}Z_6\right)$$

$$k_y = 1/\left(2\sqrt{3}Z_4 + \sqrt{6}Z_6\right)$$

r_0 is the normalized aperture on the output plane, and λ is the wavelength used in the beam shaper, Z_4 is the

Zernike coefficient of defocus term, and Z_6 is the coefficients of 90° astigmatism defined in the wave-front sensor. Insert Eq. (17)~(20) into Eq. (14) and Eq. (15), adjustment of distance ΔL_1 and ΔL_2 can be determined according to the Zernike coefficients from wave-front sensor on output plane:

$$\Delta L_1 = \frac{R_2{}^2}{2\left(\eta k_x - R_3 - 2L_3\right)} \tag{21}$$

$$\Delta L_2 = \frac{R_3{}^2}{2\left[\eta k_y + \left(R_3 - 2L_3 + 2\Delta L_1 R_3{}^2 / R_2{}^2\right)\right]} \tag{22}$$

2.2.2 Functions for Compensating the 45^O Astigmatism

In Cartesian coordinates, the 45° astigmatism can be written as:

$$w(x,y) = \frac{2}{R_c} xy \tag{23}$$

where R_c is the curvature parameter of 45° astigmatism[9].

So the ray incident M_y with 45° astigmatism in matrix form is:

$$V_{in45} = \begin{bmatrix} x \\ \alpha \\ y \\ \beta \end{bmatrix} = \begin{bmatrix} x \\ \dfrac{2}{R_c} y \\ y \\ \dfrac{2}{R_c} x \end{bmatrix} \tag{24}$$

The rays leaving S_{out} can be calculate by

$$V_{out45} = M \cdot V_{in45}$$

In the derivation of V_{out45}, both ΔL_1 and ΔL_2 is set to zeros for the simplicity of derivation, and the terms of $\sin^2\kappa$ are omitted for it's a high order quantity in the functions. The rays leaving S_{out} can be written as:

$$V_{out45} = \begin{bmatrix} x' \\ \alpha' \\ y' \\ \beta' \end{bmatrix} = \begin{bmatrix} -\dfrac{R_2}{R_1} x - \dfrac{R_1 R_3 - R_2{}^2}{R_2 R_c} y + \alpha' L_3 \\ \dfrac{R_1 R_3 \sin(2\kappa) \text{-} R_2{}^2 \sin(2\kappa)}{R_2 R_3 R_c} x + \dfrac{R_c \sin(2\kappa) - 2R_1 \cos^2\kappa}{R_2 R_c} y \\ -\dfrac{R_3}{R_2} y - \dfrac{R_1 R_3 - R_2{}^2}{R_2 R_c} x + \beta' L_3 \\ \dfrac{R_2 R_c \sin 2\kappa - 2R_1 R_2 \cos^2\kappa}{R_1 R_3 R_c} x + \dfrac{R_1 R_3 \sin 2\kappa - R_2{}^2 \sin 2\kappa}{R_2 R_3 R_c} y \end{bmatrix} \tag{25}$$

The rotation of M_x with an angle of κ is to eliminate the 45° astigmatism, that is, the terms about y in α' become zeros, and the terms about x in β' also become zeros by proper rotating of M_y with an angle of κ. From Eq. (25), we can derive the relationship between rotation angle κ and the input 45° astigmatism parameter R_c:

$$\tan\kappa = \frac{R_1}{R_c} \tag{26}$$

When κ is a small angle

$$\sin\kappa = \tan\kappa = R_1 / R_c \tag{27}$$

Insert Eq. (26) into Eq. (25), we can found that after the 45° astigmatism is compensated, there still are some small defocus:

$$\alpha' = 2\frac{R_1\left(R_1 R_3 \text{-} R_2{}^2\right)}{R_2 R_3 R_c{}^2} x \tag{28}$$

$$\beta' = 2\frac{R_1\left(R_1 R_3 - R_2{}^2\right)}{R_2 R_3 R_c{}^2} y \tag{29}$$

In most situations, the defocus introduced is small enough that could be omitted, and also it can be compensated by adjusting of L_1 and L_2 later if it is necessary.

The relationship between the coefficient of 45° astigmatism on the input plane and output plane can be derived when we let κ=0:

$$R_c = \frac{R_1}{R_3} R_c' \tag{30}$$

The relationship between the Zernike coefficient Z_5 and R_c' is:

$$R_c' = \frac{r_0^2}{\lambda} \frac{1}{\sqrt{6} Z_5} = \eta k_{xy} \tag{31}$$

Where

$$k_{xy} = 1 / \left(\sqrt{6} Z_5\right)$$

Insert Eq. (30) and Eq. (31) into Eq. (26), the equation between the rotation angle κ and the Zernike coefficient of 45° astigmatism on the output plane can be derived as:

$$\tan\kappa = R_3 / \eta k_{xy} \tag{32}$$

From Eq. (32), we can find that the rotation angle κ have a very simple linear relationship with the Zernike coefficient Z_5 on the output plane.

3 VERIFICATION OF THE METHOD

In the derivation of the relationships between the compensating parameters (ΔL_1, ΔL_2, κ) and the Zernike coefficients (Z_4,Z_5,Z_6) on the output plane, some higher order quantities have been omitted. To verify the correctness of the theoretical derivation, the optical model of the reflective beam shaper designed in Sec.2 was built in commercial optical design software, where $R_1=516mm$, $R_2=800mm$, $R_3=206mm$, $L_1=(R_1+R_2)/2$, $L_2=(R_2+R_3)/2$. In the model, the input aberrations were generated by adding a phase plate with different combination of Zernike coefficients. And the Zernike coefficients of aberrations on the output plane and normalized radius r_0 can be generated by the commercial software, to serve as the H-S sensor in Fig.1, which is needed in Eq. (21), (22) and (31). In the calculations of the adjusting parameters, the rotational angle κ was the first parameter to be calculated, then the adjustment of distance ΔL_1 was calculated, at last, ΔL_2 was calculated. After κ, ΔL_1 *and* ΔL_2 were calculated, these value were sent to the optical model, then the wave-front parameters, such as Zernike coefficients and Peak-to valley (PV) of the wave-front can be generated by the software. The comparison before and after compensation by adjusting of κ, ΔL_1 *and* ΔL_2 for four cases of input low order aberrations are listed in Table.1.

It shows that the adjusting parameters calculated in case1~case3 are very well to compensate the low order aberrations in the input plane, and the PV value after compensation is below 1λ, which is suitable for later wave-front corrections by a higher order deformable mirror, as shown in Fig. 1.

When the aberrations consists of both defocus and 45-Deg astigmatism, the first step of adjusting values of ΔL_1 and ΔL_2 are less effective, and the PV value after compensation is still larger than 1λ, as shown in Fig.2(h). It is because the adjusting of 45-Deg astigmatism can introduce small defocus, as illuminated in Eq. (27) and Eq. (28). So two steps compensation are necessary to solve this problem. That is, after the first step compensation, the normalized radius and Zernike coefficients are renewed to serve as the calculating parameters for second step compensation, as listed in case 4b in Table.1. Then the second adjusting parameters are obtained, and the final compensation result is satisfactory with a wave-front PV of 0.31λ.

Table 1: Compensation results for 4 cases.

	Optical parameters on S_{out} before compensation					Adjusting parameter and PtV after compensation			
	r_0 /mm	Z_4	Z_5	Z_6	PV_i /λ	ΔL_1 /mm	ΔL_2 /mm	κ Deg	PV /λ
1	*6.15*	*1.14*	*0*	*1.60*	*4.18*	0.27	***5.08***	0	0.31
2	*9.85*	*2.37*	*0*	*-3.33*	*8.53*	***67.0***	0	0	0.24
3	*5.70*	*0.02*	*0.52*	*0.01*	*2.53*	-0.14	0.06	0.47	***0.47***
4a	*7.30*	*3.25*	*0.79*	*3.35*	*13.3*	22.3	9.6	0.45	1.13
4b	*6.45*	*0.25*	*0*	*0.16*	*1.13*	3.9	0.68	0	0.31
4	Total adjusting parameters for case 4					***26.2***	***10.3***	***0.45***	

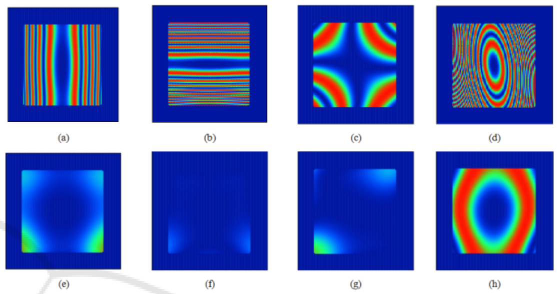

Figure 2: Wave-front distribution before compensation (a) PV=4.18λ, in case 1, (b) PV=8.53λ, in case2, (c) PV=2.53λ, in case3, (d) PV=13. 3λ, in case4 and after low order aberration compensation (e) PV=0.31λ, (f) PV=0.24λ, (g) PV=0.43λ, (h) PV=1.13λ (0.31λ after two steps compensation).

4 CONCLUSIONS

Based on the relationships between the optical layout parameters of a reflective beam shaper and Zernike coefficients on the output plane, the low order aberrations can be well compensated by directly adjusting the parameters. And the PV value after compensation is below 1λ, which can be further corrected by deformable mirrors. With this direct compensation method, low order aberration with large PV value in slab laser could be compensated both efficiently and quickly.

ACKNOWLEDGEMENTS

This work was supported by Science and Technology on Solid-State Laser Laboratory Foudation (No.9140C040101140C04016) and National Natural Science Foundation of China (NSFC, No.61379065 and No.11504423).

REFERENCES

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

M. Ganija, D. Ottaway, P. Veitch, et al, 2013. *High power, near diffraction limited, Yb: YAG slab laser*, Opt. Express.

L Xiang, W Shuai, H Yang, et al, 2012. *Double-deformable-mirror adaptive optics system for laser beam cleanup using blind optimization*, Opt. Express.

R. Conan. C. Bradley, P. Hampton, O. Keskin, et al. 2007. *Distributed modal command for a two deformable-mirror adaptive optics system,* Appl. Opt.

X Liujing, Y Ping, L Xinbo, et al, 2011. *Application of Hartmann-Shack wavefront detector in testing distorted wavefront of conduction cooled end-pumped slab laser*, Chin. J. Lasers.

W Qiao, Zh Xiaojun, W Yonggang, S Liqun, et al, 2014. *A simple method for astigmatic compensation of folded resonator without Brewster window*, Opt. Express.

L Wenguang, Zh Qiong, F Fei, et al, 2014. *Active compensation of low-order aberrations with reflective beam shaper*, Opt. Engineering.

H. J. Geovanni, M. J. Zacarías and M. H. Daniel, 2014. *Hartmann tests to measure the spherical and cylindrical curvatures and the axis orientation of astigmatic lenses or optical surfaces*, App. Optics.