Design of a Slab Laser Beam Shaping System with Astigmatism

Fu Xiaoying[1,2,3] Yang Ping[1,2] He Xing[1,2,3] ChenXiaojun[1,2,3]
Dong Lizhi[1,2] Xu Bing[1,2]

[1] *Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, Sichuan* 610209, *China*

[2] *Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu, Sichuan* 610209, *China*

[3] *University of Chinese Academy of Sciences, Beijing* 100049, *China*

Abstract The output beam of a slab laser is rectangular with high aspect ratio, and its divergence angles in horizontal and vertical directions are quite different. It contains large phase aberrations which greatly limit the beam qualities of slab lasers. A beam shaping and aberration compensation system is designed for a slab laser with the wavelength of 1064 nm in this paper. This system consists of 3 cylindrical and 1 spherical lenses. Cylindrical lenses are able to change the propagation of light in a particular direction, and the combination of two cylindrical lenses with different focal directions can achieve beam shaping in two dimensions. By changing the distance between the lenses, the rectangular beam can be shaped into square collimated beam, whose size varied in the range from 15 mm×15 mm to 19 mm×19 mm with low phase aberrations, while the size of the input beam is 15 mm×1.5 mm.

Key words optical design; aberration compensation; beam shaping; slab laser

OCIS codes 220.4830; 140.3300; 140.3480; 140.3580; 140.3460

板条激光像散整形系统设计

傅筱莹[1,2,3] 杨 平[1,2] 何 星[1,2,3] 陈小君[1,2,3] 董理治[1,2] 许 冰[1,2]

[1]中国科学院光电技术研究所自适应光学实验室,四川 成都 610209

[2]中国科学院自适应光学国家重点实验室,四川 成都 610209

[3]中国科学院大学,北京 100049

摘要 板条激光器的输出光束是具有大长宽比的矩形光束,其光束发散角在水平方向与竖直方向有较大差异。板条激光器输出光束含有的大量波前像差,极大地影响了其输出光束的光束质量。设计了一套针对板条激光器输出的 1064 nm 的矩形像散光束的整形与像差补偿系统,该系统由 3 个球面柱面透镜与 1 个球面透镜组成,其中不同方向光焦度的柱面镜组合可以实现矩形光束在 2 个维度的整形扩束。从仿真中可以得到,通过改变光束整形与补偿系统内部的透镜间距,可以将入射的大小为 15 mm×1.5 mm 的矩形像散光束整形成为大小可在 15 mm×15 mm~19 mm×19 mm 之间变化的方形准直光束,且整形后的光束具有较高的光束质量。

关键词 光学设计;像差补偿;光束整形;板条激光

中图分类号 O439 **文献标识码** A

doi: 10.3788/AOS201535.s222003

1 Introduction

Slab laser with zigzag beam propagation is a prominent approach to achieve high power output with good

收稿日期: 2015-01-13; **收到修改稿日期**: 2015-03-04

基金项目: 国家重点科研装备研制项目(ZDYZ2013-2)、国家自然科学基金(11173008)、四川省杰出青年基金(2012JQ0012)

作者简介: 傅筱莹(1989—),女,硕士研究生,主要从事固体激光器像差校正补偿方面的研究。E-mail:momo_xy0512@163.com

导师简介: 杨 平(1980—),男,博士,研究员,主要从事自适应光学光束净化方面的研究。
E-mail:pingyang2516@hotmail.com(通信联系人)

beam quality[1-3]. However, the aspect ratio of the output beam is very high, which brings great difficulties in many applications. At the same time, the divergence angles in horizontal and vertical directions are different, showing typical astigmatic beam characteristics, which result in significantly reduce of beam qualities.

Multiple deformable mirrors are proposed as a solution to compensate for the aberrations of slab laser beam, but they cannot effectively change its aspect ratio[4-6]. Roffin-Sinar company uses two spherical mirrors and a cylindrical mirror with a small aperture to turn the rectangular beam into square or circular beam, but it cannot modify the beam size on demand[7]. Binary optical elements can be made to shape the slab laser beam, but the quality of the element and laser damage threshold level are still restricted by the development of the manufacturing process[8-9].

This paper presents a method of designing and optimizing a beam shaping and aberration compensation system for slab laser based on Zemax. The system consists of two x-oriented cylindrical lenses, one y-oriented cylindrical lens and one spherical lens. All lenses are plano-convex or plano-concave for easier manufacturing. By adjusting the distance between the lenses, the input astigmatism beam with large aspect ratio can be shaped to square collimated beam, whose size varies in the range from 15 mm×15 mm to 19 mm×19 mm when the input beam size is 15 mm ×1.5 mm.

2 Calculation of initial structure parameters

The input beam of our beam shaping and aberration compensation system is a rectangular beam, whose size is 15 mm×1.5 mm, with 8 mrad divergence angle in X direction and 18 mrad divergence angle in Y direction. After beam shaping and aberration compensation, the targeted output beam is a square collimated spot whose size can vary from 15 mm×15 mm to 19 mm×19 mm. The quality of the output beam is assessed by its wavefront, and is intended for diffraction limit [the peak-to-valley (PV) wavefront error is less than $1/4\lambda$]. A laser beam shaping system is usually composed of a plurality of spherical lenses and cylindrical lenses. Cylindrical lens will change the propagation of light in a particular direction. Thus combination of two cylindrical lenses with different focal directions can achieve beam shaping in two dimensions.

In matrix optics, the light ray vector of center symmetric optical system can be represented by a 2×2 matrix, a 2×2 transmission matrix can be used to describe the transmission characteristics of light in the symmetry optical system[10]. The light propagation and transformation of non-symmetric optical system can be described by an extended 4×4 matrix[11].

Assume the vector expression of the input beam for the beam shaper is $\boldsymbol{X}_0=[\omega_{x0};\omega_{y0};\theta_{x0};\theta_{y0}]$, and the vector expression of the output beam is $\boldsymbol{X}_1=[\omega_{x1};\omega_{y1};\theta_{x1};\theta_{y1}]$, where ω_x, ω_y are the widths in X and Y directions, θ_x, θ_y are the divergence angles of X and Y directions. The transformation matrix of beam is $\boldsymbol{M}_L$ when the transmission distance is L in the free space. The transformation matrix of cylindrical lens is $\boldsymbol{M}_{fx}$ and $\boldsymbol{M}_{fy}$. The transformation matrix of spherical lens is $\boldsymbol{M}_f$. The total transformation matrix of the optical system is a product of each transformation matrix. The input beam and output beam were in a relationship of $\boldsymbol{X}_1=\boldsymbol{M}\times\boldsymbol{X}_0$.

Through calculation, a proper result is got when the optical system is composed of four optical elements (two x-oriented cylindrical lens, one y-oriented cylindrical lens and one spherical lens) and all lenses are plano-convex or plano-concave lens. Under this circumstance, the total transformation matrix can be given by

$$\boldsymbol{M}=\boldsymbol{M}_f\times\boldsymbol{M}_{L_4}\times\boldsymbol{M}_{fy_1}\times\boldsymbol{M}_{L_3}\times\boldsymbol{M}_{fx_2}\times\boldsymbol{M}_{L_2}\times\boldsymbol{M}_{fx_1}\times\boldsymbol{M}_{L_1}, \tag{1}$$

when $\boldsymbol{X}_0=[15;1.5;\theta_{x0};\theta_{y0}]$, $\boldsymbol{X}_1=[19;19;0;0]$, the initial structure parameters are listed in Table 1. The initial structure of the optical system is shown in Fig. 1.

Table 1　Optical element parameters of beamshaper system

Element	Type	Focus length/mm	Curvature/mm	Distance to next element/mm
Input	15 mm×1.5 mm	—	infinity	208.283
$\boldsymbol{M}_{fx_1}$	x-oriented cylindrical lens	−63.1	R_{x_1}=28.435	101.266
$\boldsymbol{M}_{fx_2}$	x-oriented cylindrical lens	182.5	R_{x_2}=−82.208	50.451
$\boldsymbol{M}_{fy_1}$	y-oriented cylindrical lens	−4257.1	R_{y_1}=1917.195	15.000
$\boldsymbol{M}_y$	Spherical lens	1319.7	R_1=−594.335	0
Output	19 mm×19 mm	—	Infinity	—

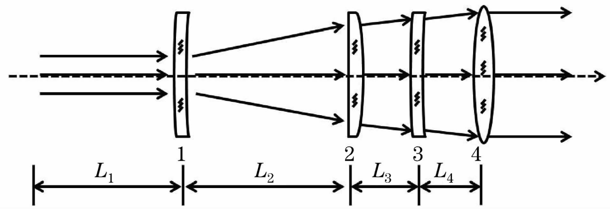

Fig. 1　Optical layout of the beam shaping system

3　Initial system design in Zemax

Zemax was used to optimize the initial structure of the system. In sequence mode, the entrance pupil diameter was set to 15 mm, and a 15 mm×1.5 mm rectangular aperture was added behind the source. The lens unit was millimeters, and thickness was chosen to be 5 mm for both lenses. Through setting a paraxial XY lens, which the optical power could be specified in the X and Y directions separately, it can provide different divergent angles in X and Y directions of the input beam. The Field of view was set to 0° because the output beam was collimated. At 100 mm front of the image plane, adding a paraxial lens whose focal length was 100 mm, when the spot in image plane can get close to the diffraction limit, it is believed the laser beam has been collimated before the paraxial lens. All lenses were made of fused silica (n_d = 1.458467, V_d = 67.7950).

Figure 2 is the layout of the beam shaping system. It is shown from Fig. 3 (a) that the collimation effect is not good enough. The root mean square (RMS) radius is 12.435 μm and the GEO radius is 17.411 μm, while the Airy disk is only 3.77 μm. Fig. 3 (b) is the wavefront map of the output beam with PV value of 27.7758λ and RMS value of 7.6686λ. The wavefront aberration is so large that the modulation transfer function (MTF) curves cannot be calculated, as well as the Strehl ratio.

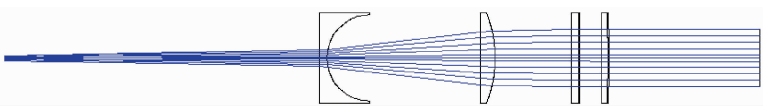

Fig. 2　Layout of the beam shaping system in Zemax

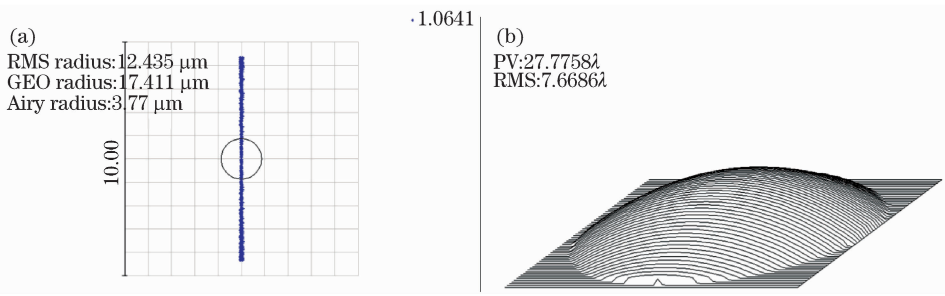

Fig. 3　(a) Comparison of focusing spot and Airy disk; (b) wavefront of the output beam

The above calculations are based on the assumption of thin lens, but lenses in Zemax has an actual thickness, which does not meet the assumptions required. The image quality still needs to be optimized by optical design software.

4 Optimization

The optimization feature provided by Zemax is quite powerful, it uses an actively damped least squares algorithm, the algorithm is capable of optimizing a merit function composed of weighted target values to find the local minimum of the specified merit function.

In the process of 1064 nm slab laser beam shaping system design, due to the high requirements of PV, RMS and Strehl Ratio, the default merit function should be modified by adding new operands or building our own operands to the merit function list.

4.1 Default merit function

Several different types of merit functions are available in Zemax. A general rule of the thumb to use is that if the system is close to diffraction limited then using wavefront error, otherwise, using spot radius. So, when selecting optimization function and reference, choose a combination of RMS-spot-centroid at the very beginning. After a few preliminary optimization, choosing RMS-wavefront-centroid for the beam shaping system is more focused on the high requirements of wavefront.

Here (rectangular array RA) is chosen because the entrance pupil is non-elliptical. Select appropriate grid value based on the ability of computer and ray tracing accuracy considerations. Zemax will automatically generate boundary operands in the default merit function. Taking the practical application of the system into account, the total length should be limited under 500 mm by adding operands to the merit function list.

The default merit function is easy to set up, efficient for numerical calculation, and suitable for a number of optimization problems. However, most of the optical designs require modification or extension during the design process, if the field, weights or wavelength values are changed, we must re-construct the default merit function.

4.2 Multi-configuration

To achieve the goal that the input rectangular beam with different divergence angles can be shaped to square collimated beam whose size variation is within 15 mm×15 mm to 19 mm×19 mm through the system, multi-configurations can be used. It put′s different values to the same parameters to distinguish different configurations.

In multi-configuration data editor, adding multi-configuration operands to change the X or Y direction optical power of paraxial lens so that the input beam′s divergence angle can be controlled. Set the thickness between each lens variable, adding REAX operand and REAY operand to cooperate with other multi-configuration operands to constraints on the final output beam of the system. After constructing an appropriate merit function, optimization can be performed by using the CONF operand. The entered operands, whose respective targets or weights can be different in each configuration.

5 Analysis

In the process of optimization, it′s necessary to pay attention to low-order aberration such as astigmatism, defocus, spherical, coma, as well as some senior aberrations. Modifying some operands, change weights or values in merit function during the process of optimization is necessary for aberration correction and balance. While constructing merit functions, using damped least squares (DLS) optimization came surprisingly close to the final solution in some situations. It is useful in tracking the progress of the optimization through the observation of system data such as fast Fourier transformation (FFT) MTF, Zernike coefficients. Increasing more rays can help bring out some under-sampling problems.

Table 2 shows the system parameters of the designed beam shaping and aberration compensation system for slab laser using the beam shaping merit function and optimization procedures described here.

Table 2 Optical element parameters of beam shaper system

Element	Type	Focus length/mm	Curvature/mm	Distance to next element/mm
Input	15 mm×1.5 mm	—	Infinity	30.76
$\boldsymbol{M}_{fx_1}$	x-oriented cylindrical lens	−18.35	$R_{x_1}=8.26$	75.45
$\boldsymbol{M}_{fx_2}$	x-oriented cylindrical lens	117.19	$R_{x_2}=-51.78$	132.98
$\boldsymbol{M}_{fy_1}$	y-oriented cylindrical lens	−977.91	$R_{y_1}=440.41$	29.18
$\boldsymbol{M}_y$	Spherical lens	660.18	$R_1=-297.32$	0
Output	19 mm×19 mm	—	Infinity	—

Figure 4 is the shaded mode layout of the beam shaping system in Zemax, and the total length is less than 500 mm.

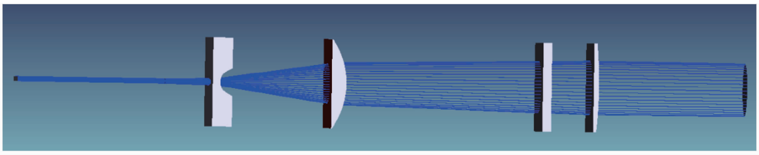

Fig. 4 Shaded mode layout of the beam shaping system in Zemax

The size of input beam is 1.5 mm×15 mm as shown in Fig. 5(a), and from Fig. 5(b) we can see, after shaping, its size became 19 mm×19 mm. As shown in Fig. 6, the focusing spot is very close to the Airy disk, PV value is 0.1582λ, RMS value is 0.0278λ, Strehl ratio is 0.9696, i.e., the system is close to diffraction limited.

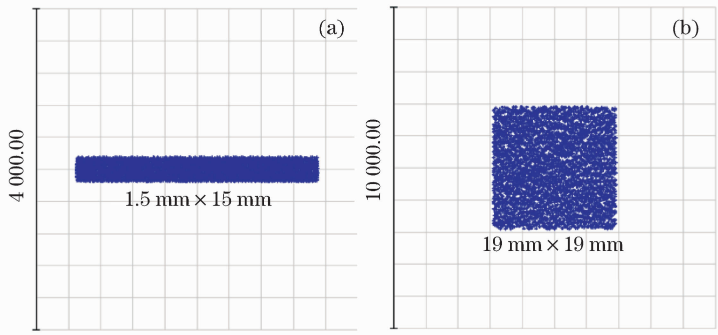

Fig. 5 Spot diagram of the beam shaping system. (a) Input beam; (b) output beam

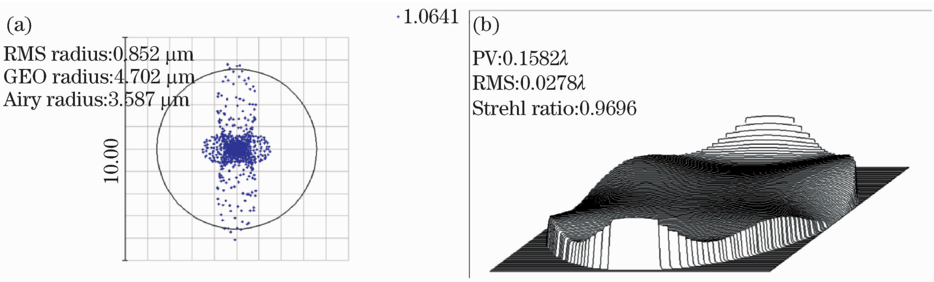

Fig. 6 (a) Comparison of focusing spot and Airy disk; (b) wavefront of the output beam

In Zemax, encircled energy diagram shows the percentage of total energy enclosed as a function of distance from either the chief ray or the image centroid at the image of a point object. From Fig. 7(a), it is easy to find that there is more than 80% energy at 5 μm from the image centroid, and more than 95%

energy at 10 μm from the image centroid. The encircle energy curve is close to the diffraction limited curve. Fig. 7(b) shows the MTF curve of the system. The MTF curves in sagittal plane and meridian plane are both close to the diffraction limited. System achieves high quality in both low and high frequencies. Considering all factors above, the beam in front of the last paraxial lens can be regarded as a collimated beam, and the aberration has been compensated in a proper range.

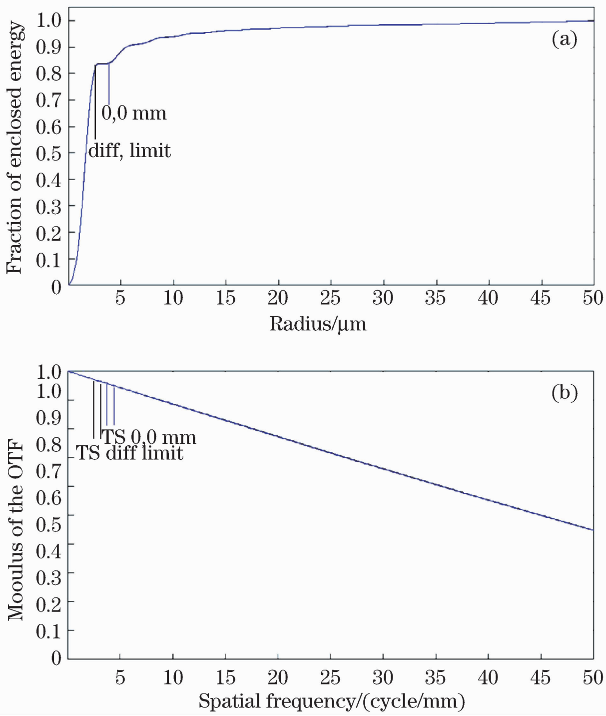

Fig. 7　(a) Diffraction encircled energy of the output beam; (b) MTF of the system

The size of output beam can be adjusted by controlling the distance between lenses. Fig. 8 showes the variation curves of the distance between lenses, PV, RMS and Strehl ratio, when beam size changes from

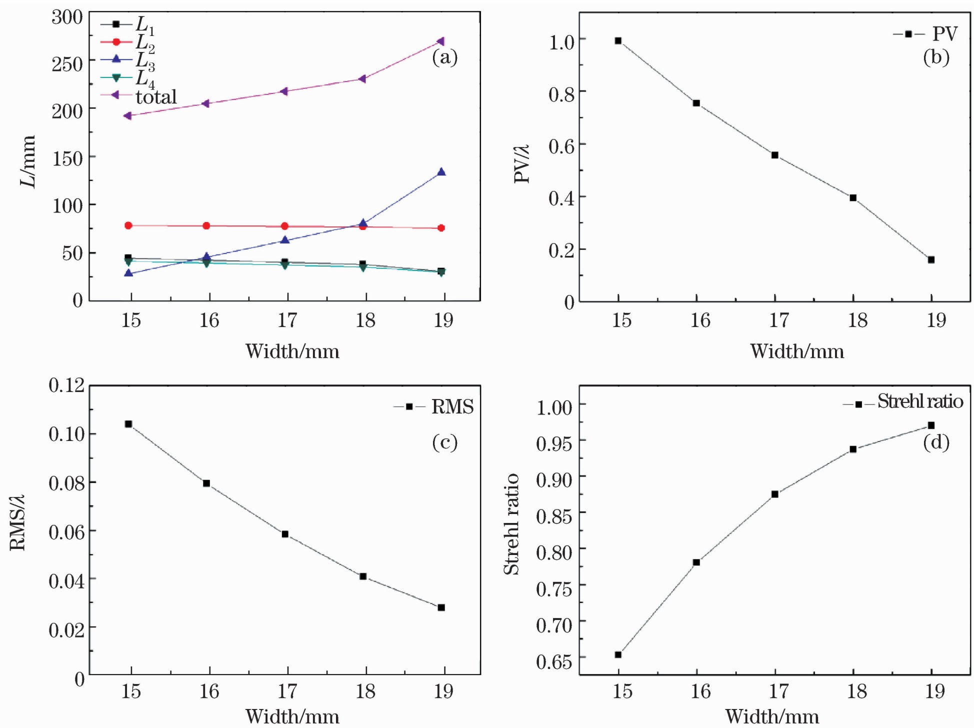

Fig. 8　(a) Distance versus width; (b) PV value versus width; (c) RMS value versus width; (d) Strehl ratio versus width

15 mm×15 mm to 19 mm×19 mm. With the increasing of the beam size, PV and RMS decrease, Strehl ratio increases. The PV value and RMS value reach the minimum (PV: 0.1582λ, RMS: 0.0278λ) when beam size equals to 19 mm×19 mm, and Strehl ratio is 0.9696.

6 Conclusion

A method of designing a beam shaping and aberration compensation system for slab laser based on Zemax is presented. By calculating parameters by matrix optics, constructing different configurations and merit functions in Zemax, these parameters can be optimized. The optimized system can realize the beam shaping and collimating when the divergence angles of X and Y directions ranged form 7 mrad to 9 mrad and 17 mrad to 19 mrad, respectively, where the output beam size varies from 15 mm×15 mm to 19 mm×19 mm. Lenses in this design are all cylindrical lenses or spherical lenses, and manufacturing processes are mature. The total length is controlled within 500 mm, which can be a reference on slab laser beam aberration compensation.

7 Acknowledgements

We would like to thank Guo Yading from Technical Institute for Physics and Chemistry, Chinese Academy of Sciences for constructive discussions.

References

1 Liu Wenguang, Zhou Qiong, Feng Fei, *et al*.. Active compensation of low-order aberration with reflective beam shaper[J]. Opt Eng, 2014, 53(9):096103.

2 H Injeyan,G Goodno. High-Power Laser Handbook[M]. Chicago: McGraw-Hill Professional, 2011:163－164.

3 Zhou Shouheng, Zhao Hong, Tang Xiaojun. High average power laser diode pumped solid-state laser[J]. Chinese J Lasers,2009,36(7):1605－1618.

周寿桓,赵 鸿,唐小军. 高平均功率全固态激光器[J]. 中国激光,2009,36(7):1605－1618

4 Lei X, Wang Si, Yan H, *et al*.. Double-deformable-mirror adaptive optics system for laser beam cleanup using blind optimization[J]. Opt Express, 2012, 20(20): 22143－22157.

5 Lei Xiang. Research on Beam Cleanup of Slab Lasers[D]. Chengdu: Insitute of Optics and Electronics, Chinese Academy of Science,2013.

雷 翔. 板条固体激光器光束净化控制技术研究[D]. 成都:中国科学院光电技术研究所,2013.

6 R Conan,C Bradley, P Hampton, *et al*.. Distributed modal command for a two deformable-mirror adaptive optics system[J]. Appl Opt, 2007, 46(20):4329－4340.

7 BeiJing BoDeHeng Laser Science and Technology Limited Company. Changing and Shaping Method for Plate Strip Wave Guide Laser Output Laser Beam: China, 200610001327.6[P/OL]. 2006-08-23[2015-03-04]. http://patview.drugfuture.com/cnpat/fulltext.aspx? patentno＝200610001327.6&filetype＝A.

北京礴德恒激光科技有限公司. 一种板条波导激光器输出激光束的变换整形方法:中国,200610001327.6[P/OL]. 2006-08-23[2015-03-04]. http://patview.drugfuture.com/cnpat/fulltext.aspx? patentno＝200610001327.6&filetype＝A.

8 Jin Guofan, Yan Yingbai, Wu Minxian, *et al*.. Binary Optics[M]. Beijing: National Defense Industry Press, 1998:3－9.

金国藩,严瑛白,邬敏贤,等. 二元光学[M]. 北京:国防工业出版社,1998:3－9.

9 Gong Huaping, Lv Zhiwei, Lin Dianyang. Present status of laser beam spatial Shaping[J]. Laser & Optoelectronics Progress,2005,42(9):2－5.

龚华平,吕志伟,林殿阳. 激光束空间整形的研究现状[J],激光与光电子学进展,2005,42(9):2－5.

10 Shi Shunxiang, Wang Xueen, Liu Jinsong. Physical Optics and Applied Optics[M]. 2nd edition. Xi'an: Xidian University Press, 2008:380－381.

石顺祥,王学恩,刘劲松. 物理光学与应用光学[M]. 第2版. 西安:西安电子科技大学出版社,2008:380－381.

11 Lv Baida. Optical of Laser Beam Propagation and Transformation-Description, Resonator Technology and Physics[M]. 3rd edition. Beijing: Higher Education Press,2003:33－34.

吕百达. 激光光学:光束描述、传输变换与光腔技术物理[M]. 第3版. 北京:高等教育出版社,2003:33－34.

栏目编辑: 史 敏