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高亮度半导体激光尾纤模块中光学补偿方法

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摘要　高亮度、高功率半导体激光尾纤模块中的光束准直是保证高亮度输出的关键因素，光束准直的实现除了需要准直发散角小，还需要极好的光轴指向性，从而保证光束的精密耦合。在半导体激光直接应用中，依靠机械对准保证光轴的指向是有限的，并需要进一步采用光学校正的方法来保证光轴可调。基于光在介质中的折射原理，研究了异形慢轴准直镜对快轴方向激光光轴指向性的校正作用，当慢轴准直镜的倾斜角约为 0.23°时，原有的快轴指向偏差约为 2.1 mrad，校正后的光轴偏差降低到约 290 μrad，这使得光纤前的光能够精密对准，极大地提高了耦合进光纤的功率，提高了光纤耦合的效率，从而为高效率、高亮度光纤耦合半导体激光模块的研制提供了新的思路。

关键词　激光光学；高亮度半导体激光；异形慢轴准直镜；快轴指向误差；高效率

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1　引　　言

高亮度半导体激光(LD)尾纤模块是高功率光纤激光器的有效泵浦源，以其轻量化、小型紧凑化的优点，在高功率光纤激光高效泵浦中具有不可替代的作用[1-3]，此外，其在激光打印、激光雷达、工业加工等领域有很大的应用价值和市场需求[4-11]。高亮度芯片在很大程度上决定了模块的功率、效率。同时，光学设计和装调是保证模块高效、高功率输出的重要因素[12-14]。模块输出光束的发散角和指向性受快轴准直镜(FAC)、慢轴准直镜(SAC)和反射镜约束。其中，激光测距、激光雷达、激光照明等激光应用对激光的指向性有很高的要求，一般在亚 mrad 量级，因此，需要精密的光束整形来保证高精度光轴指向性。

激光器的光轴指向性可以通过设计多维调节架、机械件来校正，但是这些方法难以完全保证光轴的指向性，且存在牢固性差、体积大、成本高的缺点。基于现有的机械对准难以保证激光光轴指向性问题，本文提出了一种新颖的光学方法来实现光轴的校准，从而保证指向性偏差在亚 mrad 量级。通过对慢轴准直镜(SAC)沿快轴方向引入特定角度偏差可以实现对 LD 快轴光束指向性的精密调节。该方法在单模光纤耦合、半导体激光窄脊形波导耦合系统中有重要的应用前景。

2　原理及分析

半导体激光的发光机理决定了半导体激光的发光特性，如表 1 所示，表中 I_{th} 为阈值电流，V_{on} 为开启电压，SE 为斜效率，SE_Max 为最大斜效率，WPE 为电光效率，WPE_Max 为最大电光效率，I_{op} 为工作电流，P_{op} 为工作功率。采用的 915 nm 波段的 cos 芯片的快轴发散角约为 50°，波导厚度约为 1 μm，慢轴发散角约为 10°，条宽约为 100 μm。单个 cos 芯片的结构如图 1 所示，其光学特性直接影响后续光纤耦合的效果。单个cos芯片的功率与效

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表 1 单个 cos 芯片的参数列表

Table 1 Parameter list of single cos chip

Parameter of PIV	Value
I_{th}/A	0.58
V_{on}/V	1.4
SE /(W·A^{-1})	1.1
SE_Max /(W·A^{-1})	1.08
WPE_Max /%	65.26
I at WPE_Max /A	5.5
P at WPE_Max /W	5.48
I_{op}/A	11
P_{op}/W	11.13
V at I_{op}/V	1.64
WPE at I_{op}/%	61.62

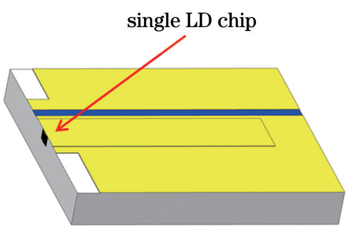

图 1 单管 LD 芯片封装示意图

Fig. 1 Diagram of single LD chip package

率曲线如图 2 所示，可以看出，电流为 10 A、功率约为 10.13 W、工作电压约为 1.6 V、工作电流约为 5 A 时，最高的电光效率约为 65.26%。

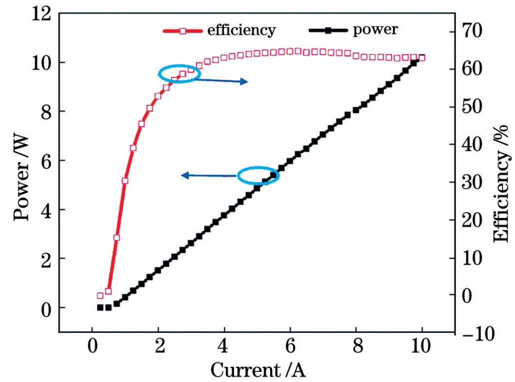

图 2 单个 cos 芯片的功率与电压曲线

Fig. 2 Curves of power and voltage of single cos chip

采用 cos 测试仪测量了单个 cos 芯片的快慢轴发散角分布和光谱曲线，图 3 给出了单个 cos 芯片的快慢轴发散角分布和波长分布曲线，如图 3(a)和图 3(b)所示。可以看出快轴发散角约为 50°，慢轴发散角约为 10°，中心波长为 917 nm，谱宽约为 5 nm。单管芯片的发散角较大，需要进行快慢轴准直。准直后的快轴、慢轴剩余发散角分别约为 9 mrad、5 mrad。快轴准直镜采用 900 μm 短焦距非球面透镜，慢轴采用 6 mm 焦距准直镜。

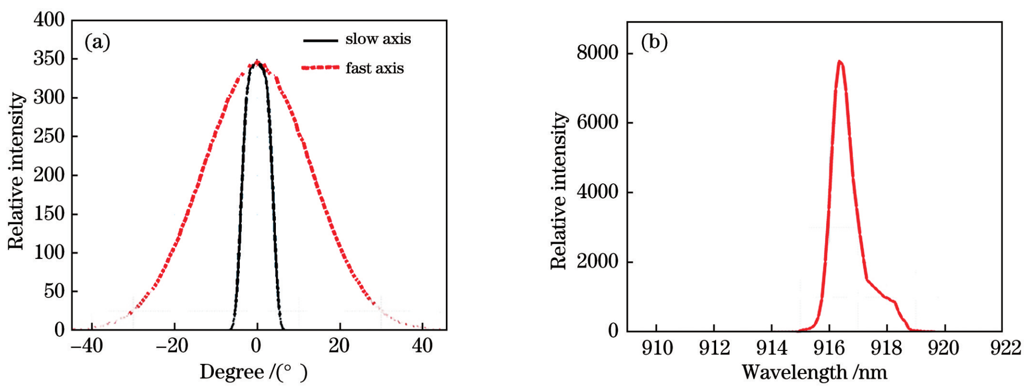

图 3 单个 cos 芯片的发散角曲线和波长分布曲线。(a)发散角曲线；(b)波长分布曲线

Fig. 3 Curves of divergence angle and wavelength distribution of single cos chip. (a) Curve of divergence angle; (b) wavelength distribution curve

在实际工程实践中，受快轴准直镜粘接固定工艺的限制，胶的固化存在固有的收缩应力，难以保证快轴的指向性，这已成为制约 LD 光纤耦合效率提升的一个因素。本文利用慢轴准直镜沿快轴方向的厚度差异来弥补快轴的指向性偏差。

理想情况下，慢轴准直镜沿着快轴方向具有良好的平行度，垂直入射与斜入射时，出射方向与入射方向一致，快轴方向的光可等效于经过一个平行平板，如图 4(a)所示，如果慢轴准直镜沿快轴方向有一定的倾斜，当光束沿快轴方向有指向偏差且入射到慢轴准直镜时，光束方向将会发生改变，如图 4(b)所示，设入射角为 θ_1、折射角为 θ_2，再次入射到慢轴准直镜斜面的角度为 θ_3，假设激光在快轴方向完全水平出射，则理论上光从慢轴镜的出射角度为 θ，慢轴准直镜的折射率为 n，根据折射率公式得出

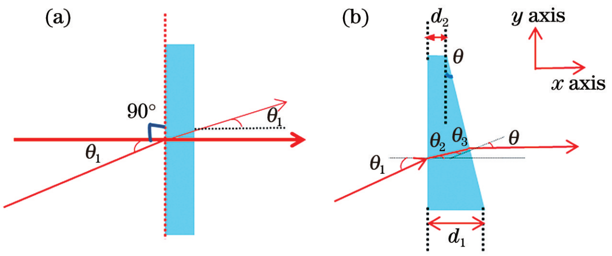

图 4　慢轴准直镜示意图。(a)理想准直镜；(b)倾斜的准直镜

Fig. 4　Diagrams of slow axis collimation mirrors. (a) Ideal collimation mirror; (b) tilt collimation mirror

$$\begin{cases} \dfrac{\sin\theta_1}{\sin\theta_2}=n \\ \dfrac{\sin(\theta-\theta_2)}{\sin\theta}=\dfrac{1}{n} \end{cases}。\tag{1}$$

由于 θ_1、θ_2、θ_3 和 θ 较小，在 mrad 量级，因此 $\sin\theta\approx\theta$，此外，可由(1)式推出慢轴准直镜的倾斜角和快轴指向性偏差的关系为

$$\theta\approx\frac{\theta_1}{n-1}。\tag{2}$$

(2)式给出设计并加工异形慢轴准直镜的理论依据，可以根据快轴指向性偏差设计合适倾角的慢轴准直镜，以对快轴指向偏差进行有效校正。

本文选用 6 mm 焦距的慢轴准直镜来校正快轴的指向偏差，其材料为 BK7 冕玻璃，折射率 n 约为 1.46，厚度为 0.8 mm，高度 d 为 2 mm，宽度为 4 mm，厚度差异约为 0.009，在高度方向上的倾斜角约为 0.23°。依据该理论设计了 4 组异形慢轴准直镜，设计的倾斜角可以表示为

$$\theta=\arctan\left(\frac{d_1-d_2}{d}\right)=\arctan\left(\frac{\Delta d}{d}\right),\tag{3}$$

式中：Δd 为慢轴准直镜的厚度差；d 为慢轴准直镜的宽度。该倾斜角的大小直接决定了快轴指向偏离角度的校正程度。设计的异形慢轴准直镜采用 OLYMPUS 大视场体式测量显微镜，测试数据如表 2 所示。

表 2　慢轴准直镜厚度差异测量值

Table 2　Measured thickness difference of slow axis collimation mirror

Experiment No.	Thickness of one edge /mm	Thickness of the other edge /mm
1	0.7010	0.7100
2	0.7012	0.7103
3	0.6998	0.7091
4	0.7011	0.7101

3　实验结果

在实验室调试了基于 7 台阶空间合束的 915 nm 波段的半导体激光模块，在快轴方向进行单管光束的空间拼接，模块结构如图 5 所示。

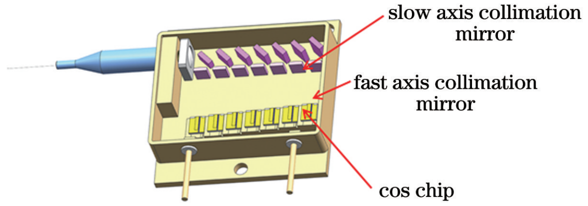

图 5　基于 7 台阶的尾纤模块示意图

Fig. 5　Diagram of pigtail module based on 7 steps

模块中采用的异形慢轴准直镜如图 6 所示，采用 OLYMPUS 大视场体式测量显微镜精确测量慢轴准直镜的厚度(可以精确到 0.1 μm)。采用基于表 2 参数设计的慢轴准直镜进行 7 台阶模块光学装调，装调的模块实物图如图 7 所示。

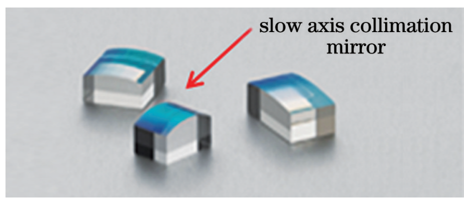

图 6　慢轴准直镜实物图

Fig. 6　Physical picture of slow axis collimation mirror

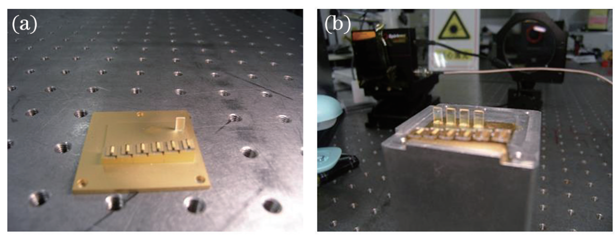

图 7　模块实物图。(a)单管调试图；(b)多单管调试图

Fig. 7　Physical pictures of module. (a) Debug diagram of single chip; (b) debug diagram of multiple single chip

基于该模块分别测量了在无异形慢轴准直镜下的快轴指向偏差和有异形慢轴准直镜下的快轴指向偏差，测量结果如图 8 所示。

无慢轴准直镜时，如图 8(a)、(b)所示，快轴方向的中心坐标从 1.96 mm 变到了 3.03 mm；有慢轴准直镜时，校正后快轴方向中心坐标从 2.18 mm 变到了 2.33 mm，如图 8(c)、(d)所示。远场傅里叶变换透镜的焦距为 510 mm，指向性偏差可表示为

$$\Delta\theta_1=\frac{\Delta y}{f},\tag{4}$$

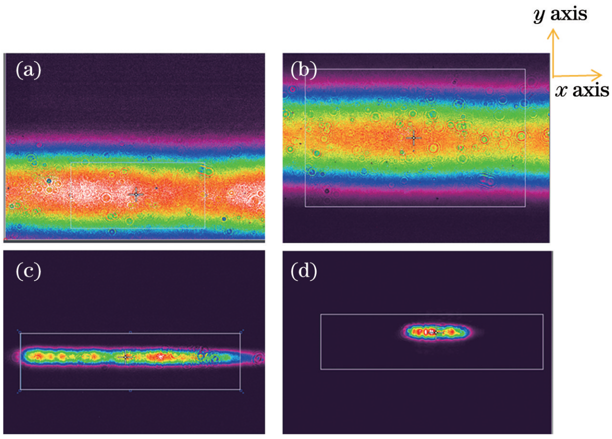

图 8　近场与远场光斑测量图。无慢轴准直镜时的(a)近场和(b)远场光斑分布;有慢轴准直镜时的(c)近场和(d)远场光斑分布图

Fig. 8　Measured spots of near and far fields. Spot distributions of (a) near field and (b) far field without slow axis collimation mirror; Spot distributions of (c) near field and (d) far field with slow axis collimation mirror

式中:Δy 为近场和远场光斑的快轴方向中心偏移量;f 为傅里叶变换透镜焦距。按照以上方法,对每个 cos 芯片的指向性进行校正,并进行了测量,测量结果如图 9 所示。可以发现,快轴指向偏差的平均值由 2.1 mrad 降低为 0.29 mrad,指向性误差降低了 1 个数量级。

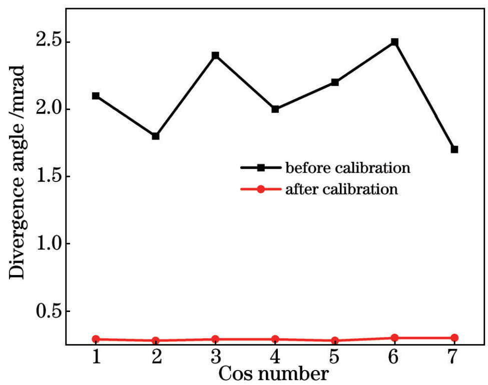

图 9　指向性误差校正前后测量结果

Fig. 9　Measured results of pointing error before and after correlation

经过模块内每一个 LD 单元的光轴校准,模块的光纤耦合效率提高了约 3%,设计图如图 10(a)所示,当在快轴方向存在指向偏差时,溢出光纤的光功率将会增多,如图 10(b)和(c)所示,因此校正光轴后可以使得模块整体效率从 53%提高到约 55%。模块整体的功率、效率测试结果如图 11 所示。对于芯径为 100 μm、NA 为 0.22、光纤输出功率为 60 W

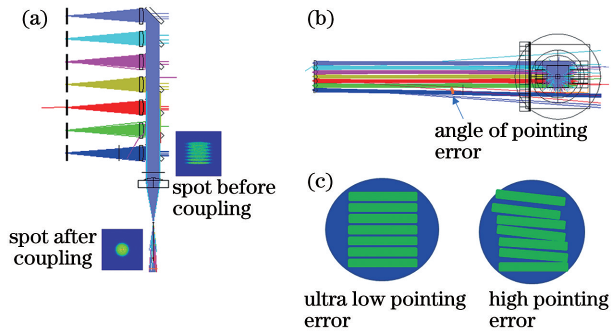

图 10　LD 模块光学设计图。(a)光线追迹;(b)存在较大指向误差时的光纤耦合;(c)存在小指向误差和大指向误差时的光斑填充光纤情况

Fig. 10　Optical designs of LD module. (a) Ray tracing; (b) fiber coupling with large pointing error; (c) spot filled fibers for small and large pointing errors

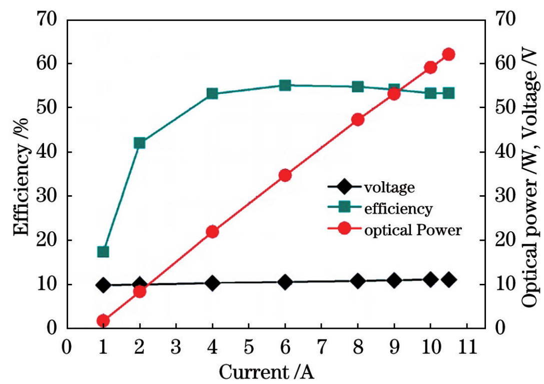

图 11　尾纤输出半导体激光模块的功率、效率测试曲线

Fig. 11　Measured curves of power and efficiency of LD module with tail fiber output

的半导体激光器,国内优势单位研制的同规格的光纤耦合半导体激光模块的效率为 50%~53%,国外 nlight 公司研制的同规格的光纤耦合半导体激光模块的电光效率约为 51%。可以发现,本课题组研制的模块在效率指标方面处于国际领先水平。

4　结　　论

研究了高亮度半导体激光尾纤模块中快轴及慢轴准直中的光学补偿问题,提出了一种利用 SAC 的加工误差精确补偿快轴准直后指向误差的方法。所提方法在高亮度 LD 尾纤模块产品研制中获得应用,具有如下优点:1)无需额外器件,可精确补偿快轴指向误差,从而进一步提高模块的耦合效率;2)降低了对 SAC 的加工要求,降低了产品的材料成本。该方法在激光雷达、激光引信、激光照明等应用中发挥了重要作用。

参 考 文 献

[1] Chen L H, Yang G W, Liu Y X, et al. Development of semiconductor lasers[J]. Chinese Journal of Lasers, 2020, 47(5): 0500001.
陈良惠, 杨国文, 刘育衔. 半导体激光器研究进展[J]. 中国激光, 2020, 47(5): 0500001.

[2] Yuan Q H, Jing H Q, Zhang Q Y, et al. Development and applications of GaAs-based near-infrared high power semiconductor lasers[J]. Laser & Optoelectronics Progress, 2019, 56(4): 040003.
袁庆贺, 井红旗, 张秋月, 等. 砷化镓基近红外大功率半导体激光器的发展及应用[J]. 激光与光电子学进展, 2019, 56(4): 040003.

[3] Huang Y Z, Guo X, Song Q H, et al. Preface to the topic of semiconductor laser[J]. Chinese Journal of Lasers, 2020, 47(7): 0701000.
黄永箴, 郭霞, 宋清海, 等. "半导体激光器"专题前言[J]. 中国激光, 2020, 47(7): 0701000.

[4] Ma X H, Shi Q L, Xu L, et al. High power semiconductor laser fiber coupling module[C]//Proceedings of the 2008 symposium on laser detection guidance and countermeasure technology development and application, November 9, 2008, Nanjing, China. Beijing: Chinese Society of Astronautics, 2008: 13-16.
马晓辉, 史全林, 徐莉, 等. 高功率半导体激光器光纤耦合模块[C]//二〇〇八年激光探测、制导与对抗技术发展与应用研讨会论文集, 南京, 中国. 北京: 中国宇航学会, 2008: 13-16.

[5] Wu H L, Zhang L P, Jiang Q W, et al. Design of a fiber coupled diode laser based on a novel beam shaping component which is provided with beam collimating and re-orienting[J]. Proceedings of SPIE, 2020, 11437: 114370W.

[6] Wang X P, Liang X M, Li Z J, et al. 880 nm semiconductor laser diode arrays and fiber coupling module[J]. Optics and Precision Engineering, 2010, 18(5): 1021-1027.
王祥鹏, 梁雪梅, 李再金, 等. 880 nm 半导体激光器列阵及光纤耦合模块[J]. 光学 精密工程, 2010, 18(5): 1021-1027.

[7] Liu C C, Wang X, Jing H Q, et al. Design of fiber coupling module for three wavelength combined beam single tube laser[J]. Acta Luminescence Sinica, 2018, 39(3): 337-342.
刘翠翠, 王鑫, 井红旗, 等. 三波长合束单管激光器光纤耦合模块设计[J]. 发光学报, 2018, 39(3): 337-342.

[8] Treusch H-G, Du K, Baumann M, et al. Fiber-coupling technique for high-power diode laser arrays[J]. Proceedings of SPIE, 1998, 3267: 98-106.

[9] Wang Q M. Break throughs and developments of semiconductor laser in China[J]. Chinese Journal of Lasers, 2010, 37(9): 2190-2197.
王启明. 中国半导体激光器的历次突破与发展[J]. 中国激光, 2010, 37(9): 2190-2197.

[10] Zhou C X, Liu Y H, Xie W M, et al. Analysis and design of fiber coupled high power laser diode array[J]. Chinese Journal of Lasers, 2004, 31(11): 1296-1300.
周崇喜, 刘银辉, 谢伟民, 等. 大功率半导体激光器阵列光束光纤耦合研究[J]. 中国激光, 2004, 31(11): 1296-1300.

[11] Meng H C, Wu D Y, Tan H, et al. Experimental study on high brightness and narrow band of diode laser by spectral beam combining of grating-external cavity[J]. Chinese Journal of Lasers, 2015, 42(3): 0302003.
孟慧成, 武德勇, 谭昊, 等. 窄光谱高亮度半导体激光器光栅-外腔光谱合束实验研究[J]. 中国激光, 2015, 42(3): 0302003.

[12] Horimatsu T, Sasaki M, Aoyama K. Stabilization of diode laser output by beveled-end fiber coupling[J]. Applied Optics, 1980, 19(12): 1984-1986.

[13] Grasso D M, Shou N, Chen H, et al. Wavelength-stabilized fiber-coupled diode laser with 500-W output and 20-mm · mrad beam quality[J]. Proceedings of SPIE, 2012, 8241: 82410K.

[14] Morris P J, Lüthy W, Weber H P. High-intensity rectangular fiber-coupled diode laser array for solid-state laser pumping[J]. Applied Optics, 1993, 32(27): 5274-5279.

Optical Compensation Method for Pigtail Module in High-Brightness Laser Diodes

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Abstract

Objective The laser diode(LD) coupled with the fiber is an effective and high-quality pump source of fiber and solid lasers. Although this technology is relatively mature, its efficiency, structure, and optical design need to be optimized. The optical alignment and adjustment directly influence the efficiency of the LD module, which has become a restriction in the development of high-efficiency and high-brightness LDs. To improve the efficiency of the LD module, without improving the LD chip itself and electric to optical (e-o) efficiency, reducing the optical loss by the maximum possible extent is a research key. In the optical assembly and adjustment engineering practice, beam collimation has an important impact on LD modules to achieve high brightness, high power, and pigtail output. Furthermore, to ensure smaller divergence, the directivity of the optical axis should also be improved, so as to realize precise beam coupling. In direct LD applications, controlling the direction of the laser beam based only on mechanical alignment is limited by high volume, high cost, and poor stability. Thus, the optical axis should be optically controlled.

Methods The pointing error of the fast axis is mainly influenced by the ultraviolet glum solidification technology; however, in practice, we cannot ensure the pointing error accuracy because there exists inherent shrinkage stress when the UV (ultraviolet) glue solidifies. Through an optical method based on the principle of laser refraction propagation in a medium, calibration of fast-axis directivity via a bizarre slow-axis collimation mirror was studied. When light is normally incident upon a medium, the directions of the transmitted light and source light are the same, but at oblique incidence, the directions of the two light beams differ. We employed this basic principle to design a slow-axis collimation mirror with a certain inclination angle according to the relationship, based on Eqs. (1)-(3), between the inclination angle and pointing error of the fast axis to correct the pointing error.

Results and Discussions We designed four kinds of slow-axis collimation mirrors with a tilt angle of 0.23°, a lens height of approximately 2 mm, and an edge-thickness difference of approximately 0.009 mm (Table 2). We also measured the central offset along the fast axis with and without the bizarre slow-axis collimation mirror (Fig. 8). The central point coordinate decreased from 1.07 mm to 0.15 mm when the focal length of the Fourier transformation lens was 510 mm. After measurement, the original average deviation of fast-axis directivity was approximately 2.1 mrad; after calibration by our designed slow axis collimation mirror matched with the pointing error of the fast axis, the directivity of the fast axis was maintained at 290 μrad. In this way, the power entering the fiber was maximized, and the efficiency of the coupled fiber was increased. We found that the average pointing error was reduced by an order of magnitude based on the seven-step LD module with pigtail output (Fig. 9). The laser spot was not completely filled with the coupled fiber when the pointing error was high, and some of the laser spot overflowed to the fiber outside (Fig. 10). The fiber would be filled with the laser spot only when the pointing error was lower. Thus, the efficiency of the 60-W fiber-output LD module increased from about 53% to 55%. The power and e-o efficiency of the LD module after calibration were measured (Fig. 11).

Conclusions In this research, we proposed a novel method to correct the pointing error of the fast axis by employing a bizarre slow-axis collimation mirror (SAC). This method has applications in high-brightness and high-efficiency LDs with pigtail outputs, and its advantages include not requiring extra devices to compensate for the pointing error of fast axis in existing conditions, so precise compensation can be achieved. The material and machining costs of the SAC are reduced because complex processing is not needed. Globally, domestic advantageous units have reported e-o efficiencies of approximately 51%–53%, whereas the efficiency is approximately 51% overseas. Our technical specifications contribute to the domestic leading efficiency. Our research provides a novel method for high-efficiency LDs with fiber output. In terms of the LD's direct application, this study has numerous potential applications in laser fuse, radar, ranging, and illumination. We have achieved the goal of applying tens of thousands produced LD modules to a pump source.

Key words laser optics; high brightness laser diode; bizarre slow axis collimation mirror; pointing error of fast axis; high efficiency

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