Sensors and Materials, Vol. 36, No. 11 (2024) 4939–4950
MYU Tokyo

S & M 3841

Innovative Optical Axis Adjustment Method for Reflective Beam Expander

Feng-Ming Yeh,[1] Chun-Yu Chiang,[2*] Chi-Hung Lee,[3]
Chuen-Lin Tien,[2,3] and Der-Chin Chen[1]

[1]Department of Optometry, Yuanpei University of Medical Technology Hsinchu, Taiwan (R.O.C.)
[2]Ph.D. Program of Electrical and Communications Engineering, Feng Chia University, Taichung, Taiwan (R.O.C.)
[3]Department of Electrical Engineering, Feng Chia University, Taichung, Taiwan (R.O.C.)

(Received April 30, 2024; accepted November 7, 2024)

Keywords: parabolic mirror, alignment, beam expander

In this study, a rapid and accurate optical axis alignment technique of a reflective beam expander composed of convex and concave off-axis parabolic mirrors was established by using (a) five parallel lasers and (b) shear interferometry. The five parallel lasers are placed on the top, bottom, left, and right sides, and center of the disc fixture, forming a circular symmetrical distribution and parallel to each other. Since the convex and concave off-axis parabolic mirrors are both confocal systems, the central laser of the five parallel laser beams is incident along the optical axis of the reflective beam expander, and the surrounding four beams diverge outward after the first reflection of the convex off-axis parabolic mirror, and these diverging laser beams converge inward after the second reflection of the concave off-axis parabolic mirror, so that the four output beams are parallel to each other, maintaining a circular distribution and a large diameter, but the divergence angle is relatively small relative to the incidence. The optical plate with excellent parallelism is placed in front of the collimated beam at an angle of 45°. The reflected beams on both sides of the optical plate are expected to interfere. In this study, this shear interferometry method was used to measure the collimation of a parallel beam after passing through a reflective beam expander. In this experiment, a HeNe laser was used as the light source, and its wavelength and beam diameter were 0.6328 μm and 3 mm, respectively. The test sample is a beam expander with a magnification of 2× and an incident beam diameter of 3 mm. After 30 repeated tests, the experimental results showed that the beam diameter increased to 5.78 mm and that the magnification accuracy was 96.3%.

1. Introduction

For simple electrooptical and optical systems with few components, optical alignment methods are often simple and alignment problems can be solved using a commercial laser tracker, retroreflector prism, autocollimator, and optical interferometer.[1–3] However, as systems become more complex and smaller, it can be difficult to decide where to start and which

*Corresponding author: e-mail: hank4681898@gmail.com
https://doi.org/10.18494/SAM5116

ISSN 0914-4935 © MYU K.K.
https://myukk.org/

approach to use.[4–7] For example, multiple paths with folding, multiple light sources with multiple wavelengths, off-axis mirrors, tight tolerances, and special optical components such as holographic elements, cylindrical, aspherical, free-form surfaces, optical sensors, and fiber optic components can all cause alignment problems. However, even if a system is complex, alignment does not have to be complex. In the vast majority of cases, optical alignment methods are deliberately combined with the mechanics and consideration of the necessary alignments based on feedback from the optical instrument.[8–11] The assembly and optical alignment of many optical devices and systems can be accomplished using many common strategies, as well as well-known tools and optical instruments available for a wide range of applications.[12–14] When the optical alignment and tilt tolerances are between 25 and 50 μm and 6 arc minutes, the simple plug-in assembly method relative to the reference machined surface is one of the most efficient and inexpensive optical alignment techniques for most commercial applications, sufficient for system alignment in many applications. This type of installation can become very complex when the system has multiple paths and folds. In addition, in modern computer numerical control (CNC) optical machines, complex geometries only need to be programmed and verified once, eliminating the need to recalibrate subsequent parts, which is ideal for commercial optical component machining. The reflective beam expander in this study is used as the input and output of collimated light, and its eyepiece and objective lens are composed of off-axis parabolic mirrors. Considering the difficulty in three-dimensional spatial adjustment, a five-parallel-laser alignment device is used to align the optical axis, and then shearing interference is used to measure the collimation of parallel light. In this innovative approach, an optical alignment method that is not very complex and has a simple device but is practical is proposed to ensure that the optical alignment method is not only suitable for laboratories but also for mass production applications.[15–17]

Reflective beam expanders are used for laser beam expansion or image magnification, which has the advantages of reducing the beam divergence angle, enlarging the beam diameter, and allowing the beam to travel farther, and this optical system is suitable for both imaging and non-imaging systems. Since the optical system is reflective and has a wide spectral band range, it can be used for ultraviolet, visible, infrared wavelengths and so forth, but when used at short wavelengths, its mirror qualities such as roughness and flatness require special requirements. The reflective system has high requirements for the alignment sensitivity of the optical axis. Hence, the accuracy of the central laser receiver four-quadrant detector in the five-parallel-laser alignment device is high, and signal processing is also very important.

2. Principle

If the two converging lenses are confocal systems and are separated by a distance (t), as shown in Fig. 1, the system requirements are as follows: (a) When a collimated beam is fed, the two converging lenses must be kept at a distance so that the output beam is far from the second lens while still maintaining the collimated beam. (b) After leaving the second lens, the beam magnification (M) is larger and the divergence angle is smaller. (c) The distance t between the two convex lenses is the sum of their focal lengths. According to Fig. 1, the magnification M can be obtained as

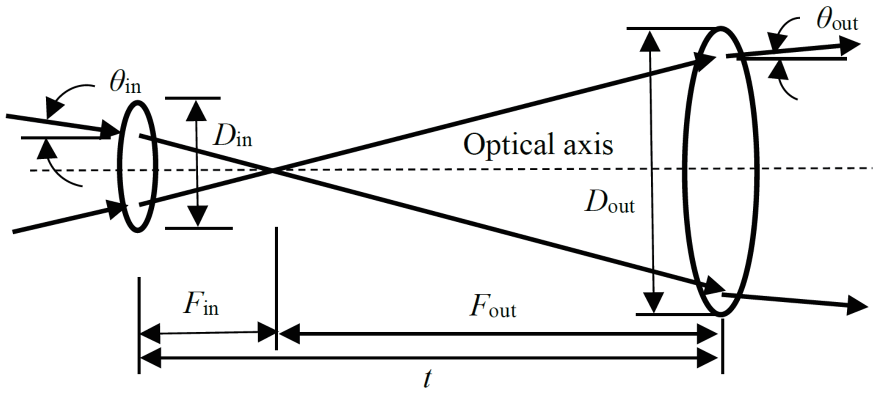

Fig. 1. Two converging lenses form a beam expander.

$$M = (\theta_{in})/(\theta_{out}) = (D_{out})/(D_{in}) = (F_{out})/(F_{in}), \tag{1}$$

where θ_{in}, θ_{out}, D_{in}, D_{out}, F_{in}, and F_{out} are the divergence angle of the input beam, the divergence angle of the output beam, the diameter of the input beam, the diameter of the output beam, the focal length of the input lens, and the focal length of the output lens, respectively.

The calculation of the beam divergence angle can be obtained from Fig. 2 as

$$D_{out} = D_{in} + \left[L * \tan\left(\theta_{in}\right)\right],$$

$$D_{out} = \left[MP * D_{in}\right] + \left[L * \tan\left(\theta_{out}\right)\right]. \tag{2}$$

Laser beam expanders can expand the collimated beam and compress the divergence. They are widely used in laser ranging, LiDAR, interferometry, atmospheric detection, and other fields. To compress the external mechanical dimensions of the laser beam expander and reduce the space distance between the output beam and the input beam, a multi-stage reflective laser beam expander composed of multiple confocal off-axis parabolic mirrors is used. Therefore, in this study, we used a reflective beam expander consisting of convex and concave off-axis parabolic mirrors to reduce size and weight. Off-axis parabolic mirrors have more optical parameters, which also increases the difficulty in assembly and optical axis adjustment. The collimation accuracy of the collimated light after the beam expansion of the laser beam expander should be confirmed, and the collimation degree should be tested by shear interferometry.

Shear interference is generated by placing an optical plate with two extremely flat optical surfaces and excellent parallelism at an angle of 45° in front of the collimated beam. The reflected beams on both sides of the optical plate overlap to produce interference fringes, as shown in Fig. 3. The distribution of the interference fringe on the screen can be obtained by using the geometric relationship, so the fringe spacing is $\Delta = \lambda/(2*n*\theta)$, where Δ is the spacing of

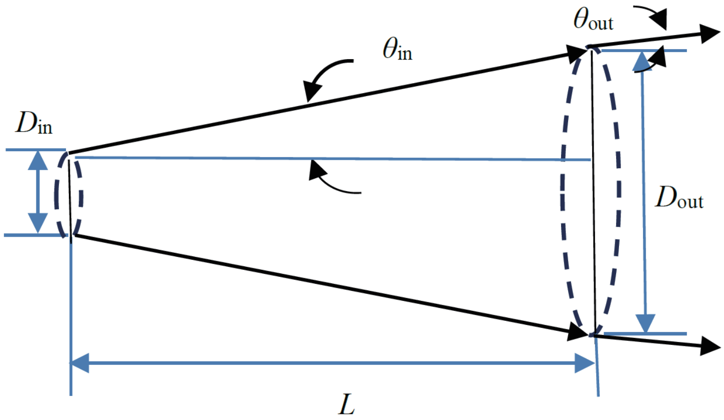

Fig. 2. (Color online) Schematic of magnified divergence angle of collimated beam.

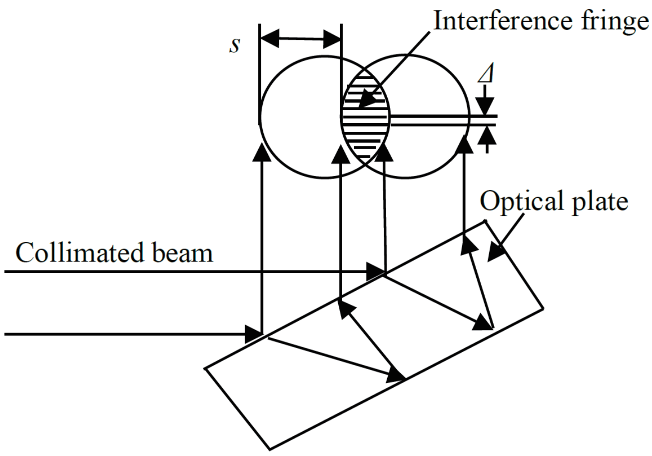

Fig. 3. Schematic of collimated beam shear interferometer.

the interference fringe perpendicular to the shear force and λ is the wavelength of the laser beam. n and θ are the refractive index and wedge angle of the optical plate, respectively. This formula assumes that the distance from the optical plate to the observation plane is smaller than the wavefront curvature radius at the observation plane. When a non-collimated beam is incident on an optical plate, the optical path difference between the reflected wavefronts on both sides of the beam will cause the radius of curvature of the wavefront on the observation plane to change. Its magnitude will increase or decrease with the degree of deviation from the collimation of the collimated beam, and the direction of the interference fringes will also change. The pattern is then rotated, and the beam's wavefront radius of curvature can be calculated as $R = (s*\Delta)/(\lambda*\tan\beta)$, where s, Δ, λ, and β are the shearing distance, fringe distance, laser wavelength, and fringe angle with respect to the shear force, respectively. β is the rotation angle of the shear interference fringe relative to the shear force due to the non-collimated beam, as shown in Fig. 4.

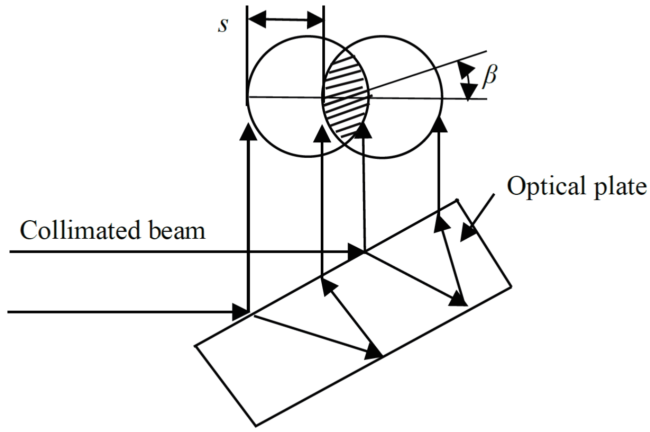

Fig. 4. Schematic of non-collimated beam shear interferometer.

The design of the reflective beam expander is completed and enters the assembly and optical axis adjustment stages. A five-parallel-laser alignment device was used to align the optical axis of the system, and then shearing interferometry was used to confirm the collimation of the collimated beam. The main optical requirements of the reflective beam expander are to increase the collimation of the input collimated beam and expand the diameter of the input beam. After the optical axis of the reflective beam expander is aligned, these two parameters need to be tested to confirm its optical quality. The general test of the collimated beam diameter method is briefly described as follows: relative to the diameter of the collimated beam, a single slit suitable for the width is selected, this experiment uses a width of 90 microns, the single slit is placed on the beam path, and perpendicular to the collimated beam, the single slit is used to scan the beam horizontally and vertically, and the light intensity distribution curve is obtained from the moving position of the single slit, so as to obtain the collimated beam diameter.

3. System and Experimental Results

The optical axis adjustment system consists of a reflective beam expander, a laser diode, and a five-parallel-laser alignment device; the system architecture is shown in Fig. 5. The reflective beam expander is a confocal system consisting of concave and convex off-axis parabolic mirrors with base radii of curvature, R_1 and R_2, respectively. The distance between the two mirrors is t, as shown in Fig. 6. CA_i and CA_o are the clear apertures of input and output beams, respectively. The design results at R_1, R_2, D, and t are 2455, 1219, 10, and 619 mm, respectively. Figure 7 shows the reflective beam expander's appearance and internal structure diagram. Since the optical axes of the two off-axis parabolic mirrors of the reflective beam expander are not axial, the technical difficulty in use is higher than that of the refractive beam expander. Therefore, the support of the off-axis parabolic mirror is equipped with a precise mechanical reference plane so that the user can rapidly and accurately align the laser beam to be amplified into the optical axis of the system. The five lasers are symmetrically distributed in the upper (#5), lower (#4), left (#3), right (#1), and center (#2) positions of the disc fixture with a diameter of d and are parallel

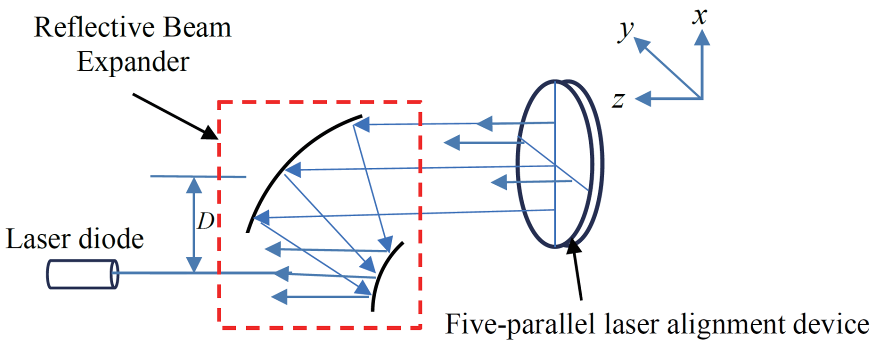

Fig. 5. (Color online) Schematic of optical axis alignment of reflective beam expander.

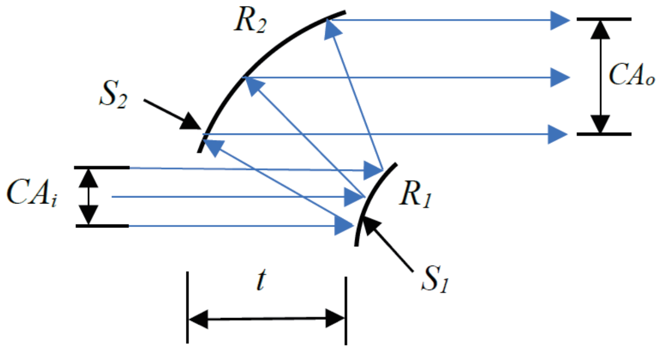

Fig. 6. (Color online) 2D diagram of reflective beam expander.

to each other. To match the reflective beam expander clear aperture, *d* is 23 mm. To cooperate with the beam expander's optical axis adjustment, the bottom of the device is set as a reference plane perpendicular to the five parallel laser beams. Figure 8 shows the five-parallel-laser alignment device.[18] Each semiconductor laser has a fine-adjustable holder and is fixed on the disc fixture. The five lasers are aligned using the fine-adjustable holder and confirmed that they are parallel to each other. The wavelength and power of the semiconductor laser and laser diode are 645 nm and 1.8 W, respectively.[19]

The five-parallel-laser alignment device is located on the right side of the reflective beam expander, and the laser diode is on the left. The vertical distance (*D*) between the central laser of the five-parallel-laser alignment device and the light of the laser diode is the height of the off-axis optical axis of the two off-axis parabolic mirrors, which are parallel to each other. After the optical axis alignment of the reflective beam expander is completed, the central laser of the five-parallel-laser alignment device must be coaxial with the laser of the left laser diode after passing through the reflective beam expander.

To improve the efficiency and accuracy of optical alignment, the system uses optoelectric sensing and digital signal processing, and in addition to visual inspection, it can also be judged by data to reduce the calibration error in the calibration process, as shown in Fig. 8(b). The five-

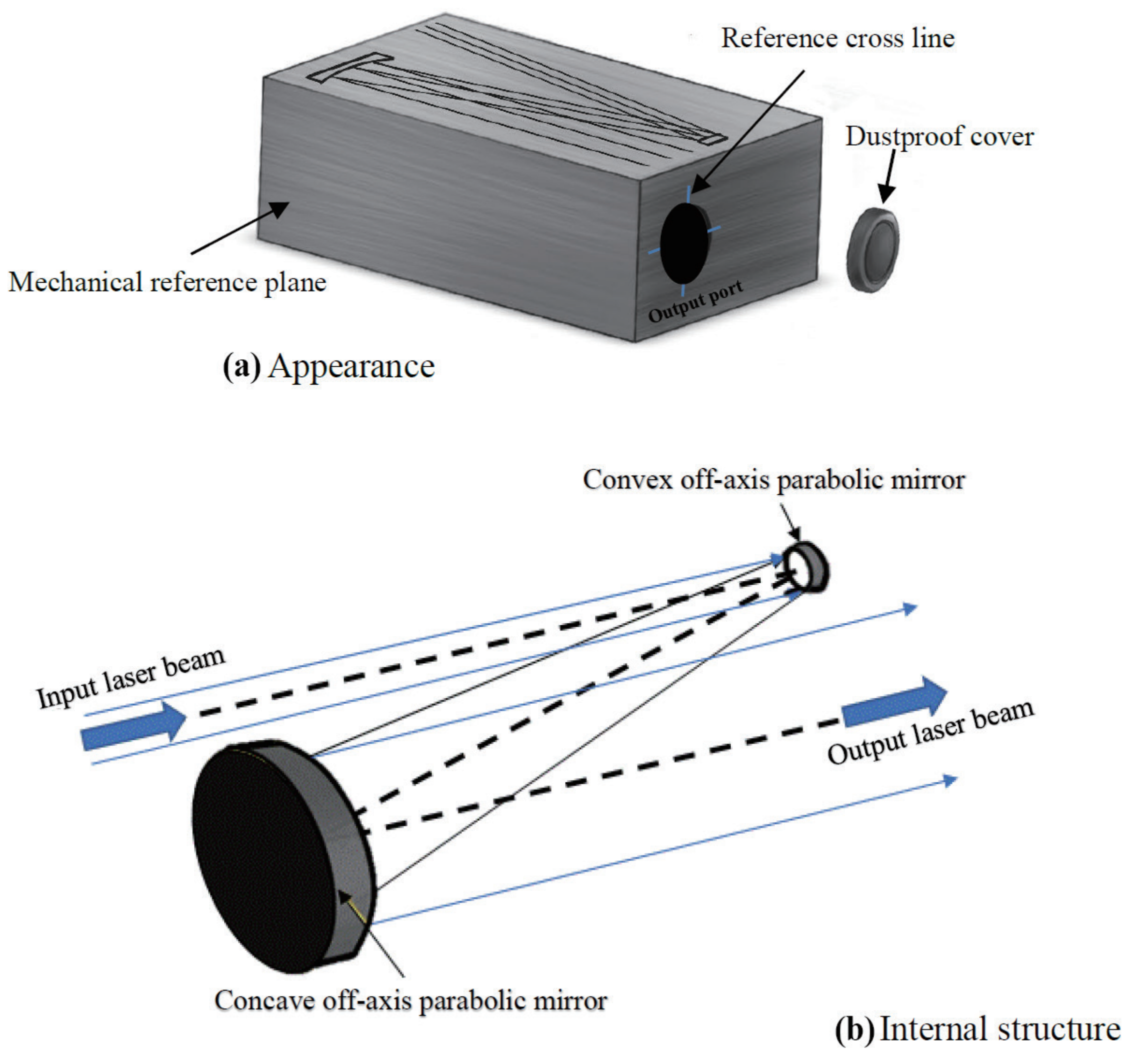

Fig. 7. (Color online) Appearance and internal structure of reflective beam expander. (a) Appearance and (b) internal structure.

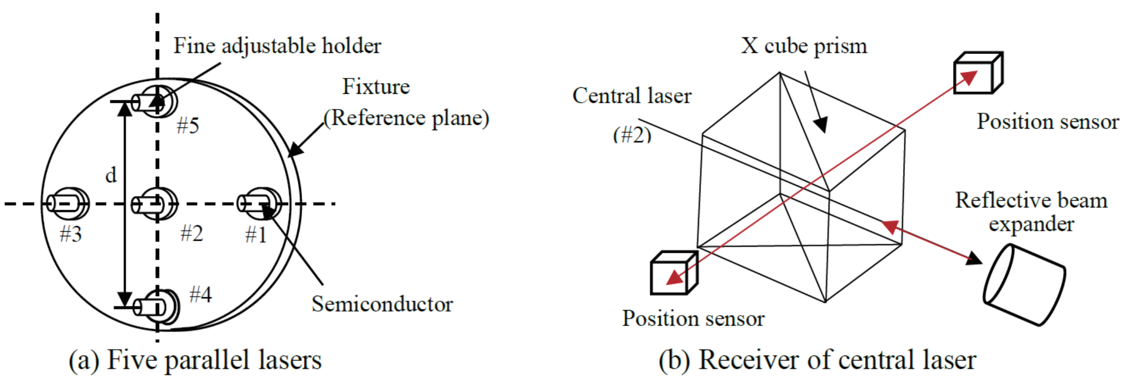

Fig. 8. (Color online) Schematic of five-parallel-laser alignment device.

parallel-laser alignment device has five lasers parallel to each other, and a sub-receiver module is added to the central laser (#2), including an X cube prism and two position sensors, so that the position of the reflected light spot of the central laser of the reflective beam expander can be accurately detected and fed back to align accurately, as shown in Fig. 8(b). The position sensor of the receiving sub-module detects the signal and transmits it to the rear signal processor for processing. The output beam of the central laser (#2) of the reflective beam expander is placed in front of the plane mirror, which is perpendicular to the central laser (#2), causing the central laser (#2) to be reflected. The sub-receiver module and the central laser are integrated into one module. The receiver module can be rotated 90° relative to the central laser, and the reflective beam expander can be aligned correctly in both the horizontal and vertical directions.(20)

The entire study is divided into two parts: the optical design and optical axis alignment of the reflective beam expander. When the optical system aligns the optical axis, the central laser of the five-parallel-laser alignment device is incident parallelly along the optical axis of the reflective beam expander and then five laser beams converge to a point after being reflected by the concave off-axis parabolic mirror (*S*2). Since the concave and convex off-axis parabolic mirrors are confocal systems, the four convergent laser beams diverge after being reflected by the convex off-axis parabolic mirror (*S*1), as shown in Fig. 6. After such convergence and divergence, the five output laser beams remain parallel to each other. The arrangement maintains the circular distribution of the input, and the diameter of the circle is smaller than that at the time of incidence.

The optical axis alignment process of the system consists of the following six steps, as shown in Fig. 9, which is briefly described below.

1. According to the system design, each module's relative position and spatial posture are initially set. First, we place the laser diode and the five-parallel-laser alignment device on the optical table. The five parallel laser beams and the light of the laser diode are opposite to each other, and the central laser of the five-parallel-laser alignment device and the light of the laser diode are aligned coaxially because the reflective beam expander is not placed, and *D* in Fig. 5 is zero.
2. According to the system planning, the concave off-axis parabolic mirror (*S*2) of the reflective beam expander is initially set up, and the attitude of *x* and *y* directions of the concave off-axis parabolic mirror is adjusted to keep the #2 central laser parallel to the optical platform by using the five-parallel-laser alignment device. The five incident parallel laser beams converge at the focus after being reflected by the concave mirror, and then the concave mirror is fine-tuned to make the focus smaller.
3. According to the system planning, a convex off-axis parabolic mirror (*S*1) is set at a horizontal distance *t* and a vertical distance *D* from the concave axis of the off-axis parabolic mirror (*S*2), and the attitude of *S*1 in the *x* and *y* directions is adjusted, so that the converging light in step 2 is reflected by the surface *S*1 to form a divergence, and the central laser of the five-parallel-laser alignment device is parallel to the optical platform, as shown in Fig. 6.
4. According to the design distance of the dual off-axis optical axes of the two off-axis parabolic mirrors of the reflective beam expander, the laser diode is translated vertically downward by a distance *D*. At this time, the light from the laser diode incident on the surface *S*1 will be

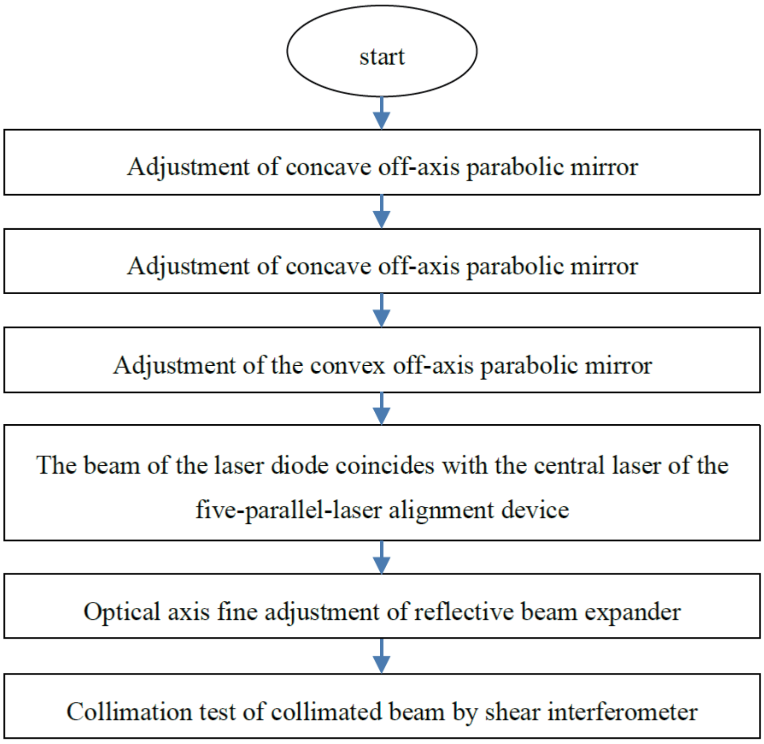

Fig. 9. (Color online) Flow chart of optical axis fine adjustment of reflective beam expander.

reflected and directed to the surface *S*2. We fine-tune the surface *S*1 so that the light from the laser diode coincides with the central laser of the five-parallel-laser alignment device. We place a double-sided plane mirror between the surface *S*2 and the five-parallel-laser alignment device at the exit pupil CA_o of the reflective beam expander, and confirm that it is perpendicular to the five lasers, and adjust the laser diode's beam to overlap with the central laser of the five-parallel-laser alignment device. Similarly, we place a double-sided plane mirror between the surface *S*1 and the laser diode at the entrance pupil CA_i of the reflective beam expander and ensure that it is perpendicular to the laser diode beam to determine whether the signal error of the receiving module is minimized.

5. After precise optical axis adjustment, the five parallel laser beams pass through the surfaces *S*2 and *S*1, and the outputs of the five parallel laser beams are arranged in a circular manner, but the diameter of the circle becomes smaller than that at the time of incidence or the outputs intersect at infinity.
6. When a single laser collimated beam has been expanded by a reflective beam expander, the collimation of the collimated beam after the expanded beam can be further accurately confirmed using a shear interferometer. According to the measurement structure in Fig. 3, the collimation of the expanded single laser collimating beam is measured through the shear interference fringes of the reflected beam on both sides of the optical plate.

To confirm the alignment efficiency and accuracy of this innovative optical axis alignment technology for actual verification, this experimental test light source uses a HeNe laser with a beam expander, and its wavelength, divergence angle, and beam diameter are 0.6328 μm, 1.3

mrad, and 3 mm, respectively. A reflective beam expander with test data provided by the manufacturer is used as the test sample. Its magnification and input aperture are 6× and 6 mm, respectively, which is suitable for an incident beam diameter of 3 mm. This test sample has been tested repeatedly 30 times, and the test data is shown in Table 1. The average output beam diameter is 5.78 mm and the beam amplification accuracy reaches 96.3%. The collimation of the collimated beam is further tested, and the divergence angles of the collimated beam obtained before and after passing through the reflective beam expander are tested individually. The test was performed with shear interference, configured with fixed test conditions, and using the same optical plate with a thickness of 2 mm and a parallelism of 10 arc seconds. The test results were a shear distance of 1.6 mm before incidence and a calculated divergence angle of 1.3 mrad, which are consistent with the data provided by the manufacturer. The shear distance after the reflective beam expander is 1.35 mm and the calculated divergence angle is 1.1 mrad. Therefore, after the collimated light passes through the reflective beam expander, the divergence angle decreases.

The collimated beam diameter of the HeNe laser used in the experiment is only 3 mm. It is too small that the diameter of the beam is difficult to manually identify and quantify. If a single slit is used to scan the collimated beam cross section, the precision of the moving platform is very high. To reduce the complexity and time of testing, in the experiment, we use a CCD camera to capture the cross section of the collimated beam and then image recognition software to determine and calculate the collimated beam diameter on the basis of the cross-sectional distribution of light intensity. The advantages are high measurement speed, no need for a high-precision moving platform, and reduced costs. After the above improvements, the measurement process is simplified. Finally, the experimental results are analyzed, and we find that the light intensity distribution of the collimated beam output by the reflective beam expander is not completely symmetrical, which is expected to affect the accuracy of the beam diameter measurement. To improve the uneven symmetry of the light spot, one can add more than two existing eyepieces and objective lenses from a single piece of off-axis parabolic mirrors. On the basis of the results obtained in this study, the design and production capabilities of the reflective beam expanders can be improved by using this optical axis alignment technology and measurement of the collimated beam diameter.

The method in this study can be applied to the optical axis alignment and testing of reflective beam expanders. At present, the same set of devices is used for optical axis alignment and testing during the experiment. Since the test and alignment are carried out on the same device, the data may not be objective enough, such that to obtain more rigorous and reliable test data, it

Table 1
Test data (unit: mm).

5.8	5.6	5.8	5.8	5.7
5.9	5.7	5.7	5.9	5.9
5.8	5.8	5.8	5.7	5.8
5.8	5.9	5.8	5.6	5.8
5.7	5.9	5.9	5.7	5.7
5.7	5.8	5.8	5.8	5.8

Table 2
Comparison of characteristics between traditional and innovative methods.

Method	Characteristic		
	Ease of operation	Alignment principle	Instrument precision
Traditional method	The instrument is expensive, requires professional personnel to operate, and takes time to align, such as interferometers.	Interference, reflection	High precision
This research method	Portable and simple, easy to operate, and does not require specialized personnel.	Auto-collimating method, reflection	Average precision and suitable for optical alignment using this object

is recommended to use more than two sets of devices for optical axis alignment and testing separately in the future. This can reduce systematic errors and improve the objectivity and accuracy of measurement. Because only one sample is used to perform multiple experiments, it is impossible to cover all types of error. If the reflective beam expander goes to the pilot run, more test data can be obtained. Through big data analysis, this method can be further optimized and refined. For example, the five-parallel-laser alignment device adds a new receiver, uses a CCD camera to capture test images, and cooperates with edge computing processing, coupled with AI technology, which can accelerate the commercialization of this method.

4. Conclusions

The reflective beam expander uses an off-axis optical system, which is complex and has many related optical parameters. There are many factors to consider when adjusting the optical axis, and the alignment process is also cumbersome. In addition, the reflection system also has a double-angle problem during reflection and is particularly sensitive to optical axis alignment. Therefore, tolerance analysis is required before optical axis alignment to determine the key parameters for adjustment. The beam diameter is usually defined as twice the beam radius, and for a Gaussian beam, the half-maximum beam diameter is approximately 1.18 times the Gaussian beam radius ($1/e^2$ value). This device is portable and the system is simple and easy to operate. Although the accuracy is average, it can be used by personnel without relevant professional experience, and the alignment efficiency is high and the cost is low. Table 2 shows a comparison of characteristics between the traditional and innovative methods.

References

1 P. C. D. Hobbs: Building Electro-optical Systems: Making It All Work (John Wiley & Sons, 2022) p. 441.
2 L. Yang, Y. Pan, J. Lin, Y. Liu, Y. Shang, S. Yang, and H. Cao: Sensors **20** (2020) 4168. https://doi.org/10.3390/s20154168
3 X. Wang, J. Yang, M. Chen, L. Miao, and T. Huang: Sensors **21** (2021) 6295. https://doi.org/10.3390/s21186295
4 S. M. Kamali, E. Arbabi, A. Arbabi, and A. Faraon: Nanophotonics **11** (2017) 415. https://doi.org/10.1038/nphoton.2017.96
5 K. Igor, R. P. Li, M. Zhou, D. D. Duan, N. Mikhail, G. F. Huang, J. W. Yang, and X. Tan: Optoelectron. Lett. **17** (2021) 468. https://doi.org/10.1007/s11801-021-0141-3
6 R. Li, I. Konyakhin, Q. Zhang, W. Cui, D. Wen, X. Zou, J. Guo, and Y. Liu: Opt. Eng. **58** (2019) 104112. https://doi.org/10.1117/1.OE.58.10.104112

7 R. Li, L. Xie, Y. Zhen, H. Xiao, W. Wang, J. Guo, I. Konyakhin, M. Nikitin, and X. Yu: Opt. Express **30** (2022) 7147. https://doi.org/10.1364/OE.453979
8 Y. Isomae, Y. Shibata, T. Ishinabe, and H. Fujikake: IEEE Consum. Electron. Mag. **8** (IEEE, 2019) 99.
9 T. Zhan, J. Xiong, J. Zou, and S. T. Wu: PhotoniX **1** (2020) 1. https://doi.org/10.1186/s43074-020-00010-0
10 S. L.Wei, Z. C. Fan, Z. B. Zhu, and D. L. Ma: Appl. Opt. **58** (2019) 1675.
11 L. Gu, D. W. Cheng, Y. Liu, J. H. Ni, and Y. T. Wang: Appl. Opt. **59** (2020) 4893. https://doi.org/10.1364/AO.392602
12 W. Dong and V. Isler: IEEE Sens. J. **18** (2018) 4200. https://doi.org/10.1109/JSEN.2018.2819082
13 K. M. Hampson, D. Gooding, R. Cole, and M. J. Booth: Appl Opt. **58** (2019) 7388. https://doi.org/10.1364/AO.58.007388
14 K. M. Hinrichs and J. J. Piotrowski: Opt. Eng. **59** (2020) 074107. https://doi.org/10.1117/1.OE.59.7.074107
15 J. Sasián: Lens Tolerancing: Introduction to Lens Design (Cambridge University Press, 2019) pp. 110–125.
16 B. J. Bauman and M. D. Schneider: Opt. Express **26** (2018) 13819. https://doi.org/10.1364/OE.26.013819
17 M. Grenier, N. Desnoyers, F. Lamontagne, B. Leduc, M. Legros, and S. Paradis: Opt. Eng. **60** (2021) 051213. https://doi.org/10.1117/1.OE.60.5.051213
18 Q. Li, Z. Bin, R. Fan, B. Qi, D. Guo, and C. Wang: Microwave Opt. Technol. Lett. **63** (2021) 2548. https://doi.org/10.1002/mop.32998
19 F. Zheng, Q. Feng, B. Zhang, J. Li, and Y. Zhao: Int. J. Adv. Manuf. Technol. **109** (2020) 1285. https://doi.org/10.1007/s00170-020-05716-w
20 R. A. Boudreau and S. M. Boudreau: Passive Micro-optical Alignment Methods (CRC Press, 2018).