frontiers | Frontiers in Physics

TYPE Brief Research Report
PUBLISHED 15 July 2025
DOI 10.3389/fphy.2025.1590608

Check for updates

OPEN ACCESS

EDITED BY
Lorenzo Pavesi,
University of Trento, Italy

REVIEWED BY
Patrice Salzenstein,
Centre National de la Recherche Scientifique (CNRS), France
Duo Jin,
Northeast Forestry University, China
Miaojun Guo,
Taiyuan University of Science and Technology, China

*CORRESPONDENCE
Hongli Wang,
wanghl@nuc.edu.cn

RECEIVED 10 March 2025
ACCEPTED 30 June 2025
PUBLISHED 15 July 2025

CITATION
Wang H, Liu C, Jiang T and Li K (2025) Optimization of off-centered lens parameters in high-power stimulated Brillouin-scattering phase-conjugation mirror.
Front. Phys. 13:1590608.
doi: 10.3389/fphy.2025.1590608

Optimization of off-centered lens parameters in high-power stimulated Brillouin-scattering phase-conjugation mirror

Hongli Wang[1,2]*, Chaoshuai Liu[1], Tianrun Jiang[1] and Kaiyang Li[1]

[1]School of Information and Communication Engineering, North University of China, Taiyuan, China, [2]Shanxi Province Key Laboratory of Intelligent Detection Technology and Equipment, North University of China, Taiyuan, China

The rotating off-centered lens method serves as a crucial role for improving the performance of high-power stimulated Brillouin-scattering phase-conjugation mirrors (SBS-PCMs). A practical method based on optimization parameters of off-centered focusing lenses was proposed to mitigate laser spot distortion due to thermal effects. The influence of off-centered lens parameters on the beam intensity pattern at the focal point is simulated and analyzed using the ray tracing method. Experimental results demonstrate that implementing a rotating off-centered lens configuration with optimized parameters (150 mm focal length and 6 mm decentration) achieves significant reduction in coma aberration. This study can provide valuable experimental references for the application of SBS-PCMs in high power and high-repetition rate laser systems.

KEYWORDS

stimulated Brillouin scattering (SBS), parameter optimization, coma aberration, phase conjugation mirror, high power laser

1 Introduction

High-repetition-rate laser systems with sub-nanosecond pulses and excellent beam quality have significant application value in fields such as lidar, medical laser cosmetic, and high-resolution spectroscopy [1, 2]. Stimulated Brillouin scattering (SBS) technology, as a phase conjugation mirror and pulse compressor, can improve the beam quality of high-energy laser systems and compress nanosecond laser pulses to the sub-nanosecond level [3]. It is extensively applied in high-energy and high-power laser systems, mainly to compensate for beam distortion in master oscillator power amplifier (MOPA) laser systems [4–6].

In SBS compression, the liquid medium is most suitable for high-input energy SBS pulse compression due to their advantages over gaseous and solid media, such as the absence of high pressure, high laser damage threshold, and high optical breakdown threshold [7–9]. Consequently, SBS pulse compression based on liquid media emerges as the most promising technological approach for the generation of high-energy hundred-picosecond lasers at high repetition rates in the kilohertz range. However, for high-repetition rate laser, a non-uniform temperature field is formed at the focusing focal point in the generator cell due to heat accumulation [10]. This results in optical breakdown and spot aberration when the temperature reaches the critical threshold. These phenomena have a significant impact on the quality of the beam, which is the primary factor limiting the application of the SBS-PCMs in high-power, high-repetition rate laser systems.

At present, there are three methods to mitigate thermal effects: a purifying medium method, a flowing liquid and moving focal spot method [11–13]. The implementation of circulating liquid media requires maintaining laminar flow conditions in the liquid medium, representing a complex operational process that poses significant engineering challenges. Although the methods to enhance the purity of the SBS gain medium have proven effective in reducing laser energy absorption by impurities and increasing the optical breakdown threshold, it is important to note that laser energy absorption by the liquid medium itself remains a persistent issue [7]. It is evident that the initial two methods are inadequate in mitigating heat accumulation in high-power SBS compression. The method of rotating the focal point utilizes wedge to dynamically relocate the focal point, thereby effectively alleviating the thermal effect caused by laser focusing. The focal point of the beam rotates continuously within the medium cell as the rotation of the wedge plate, thereby reducing the heat accumulated in the media. This approach effectively reduce the probability of optical breakdown and improve the beam quality.

This study utilizes an off-centered lens configuration to achieve precise displacement of the beam's focal spot. Through the rotational motion of the off-centered lens, the focal spot position is dynamically modulated within the medium, generating a near-circular focal trajectory. A comparison of the rotating off-centered lens method and the rotating wedge plate method reveals that the former has a simpler configuration and exhibits a less coma aberration when replacing a wedge and lens combination with a single off-centered lens. In the process of choosing an off-centered lens, it is necessary to consider the impact of several parameters such as the lens decentration, focal length, and the pump beam size on the focal spot of SBS-PCM. To effectively suppress thermal effects, it is essential that the aforementioned parameters should be given full consideration and optimized by design. However, there is limited literature addressing the optimization of SBS compression structure parameters based on rotating off-centered lenses. Consequently, it is meaningful to conduct research on the optimal design of SBS compression structure parameters based on rotating off-centered lenses.

This study aims to improve beam quality by optimizing parameters, including focal length and decentration of the off-centered lens as well as the pump beam size, while analyzing their effects on the focused spot. Section 2 describes the experimental setup. Section 3 presents the basic principle of ray tracing. Section 4 provides parameter optimization of off-centered lenses. Section 5 shows experimental verification, and Section 6 concludes the paper. This work has important reference value for the design of SBS compression structures in high-energy laser systems.

2 Experimental setup

The structures of SBS pulse compression devices include single-cell structures, generation-amplification cascade double-cell structures, and generation-amplification parallel double-cell structures. The configuration of single-cell SBS experimental setup utilized in this study is shown in Figure 1. The pump beam first passes through a half-wave plate (HWP) and then enters a polarizing beam splitter (PBS). After that, it passes through a quarter-wave plate (QWP) and is focused into a 20 cm medium cell by an off-centered lens (L3). Subsequently, the beam passes through the relay imaging system, which consists of lenses L4 and L5, to form a clear image on the image plane. The image is captured by a camera for subsequent analysis. A power meter is also equipped at the end to measure the power of the reflected beam.

3 Theoretical description of ray tracing methods

The ray tracing method is employed to simulate the propagation paths of light rays in various media [14, 15]. By this method, the propagation behavior of light in an optical system can be accurately calculated, encompassing phenomena such as reflection, refraction, and absorption. The imaging characteristics of the optical system can be quantitatively calculated, and the performance of the system can be predicted and evaluated.

The laser beam is a Gaussian beam with variable amplitude and equiphase surface, maintaining a consistent Gaussian intensity distribution. The fundamental mode Gaussian beam expression is as follows:

$$\begin{cases} E_{00}(x,y,z) = \dfrac{A_0}{\omega(z)} \exp\left[-\dfrac{x^2+y^2}{\omega(z)^2}\right] \exp\left\{-ik\left[z+\dfrac{x^2+y^2}{\omega(z)}\right]+i\varphi(z)\right\} \\ \omega(z) = \omega_0\left[1+\left(\dfrac{\lambda z}{\pi\omega_0{}^2}\right)^2\right]^{\frac{1}{2}} \\ R(z) = z+\left(\dfrac{\pi\omega_0{}^2}{\lambda}\right)^2\dfrac{1}{z} \\ \varphi(z) = \arctan\left(\dfrac{\lambda z}{\pi\omega_0{}^2}\right) \end{cases} \tag{1}$$

In Equation 1, the propagation of light is depicted as occurring along the Z-axis. A_0 is a constant factor for the fundamental mode Gaussian beams. λ is the wavelength of the laser. k is the laser wave number. $\omega(z)$ denotes the radius of the circle corresponding to the time when the intensity of the light field at a distance Z from the laser emission plane decreases to $1/e^2$ of the light intensity at the center of the spot. $R(z)$ denotes the radius of curvature of the isophase plane of the Gaussian beam. $\varphi(z)$ denotes the additional phase factor.

4 Parameter optimization

In SBS pulse compression, the parameters of the pump beam size, the focal length and decentration of the off-centered lens are the primary factors influencing the focusing spot. To systematically analyze the parametric effects on focal spot characteristics, comprehensive numerical simulations were conducted. In the design of SBS-PCM, a configuration with improper pump beam size can degrade the quality of the focal spot. Furthermore, an unsuitable choice of focal length may introduce significant coma aberration.

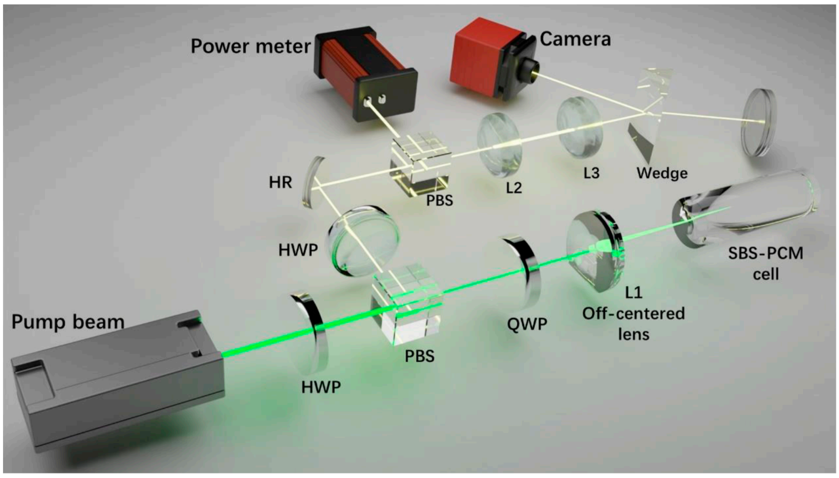

FIGURE 1
Schematic of experimental setups for single-cell SBS-PCM. QWP, quarter wave plate; HWP, half wave plate; L1, off-centered lens; L2~3, focusing lenses.

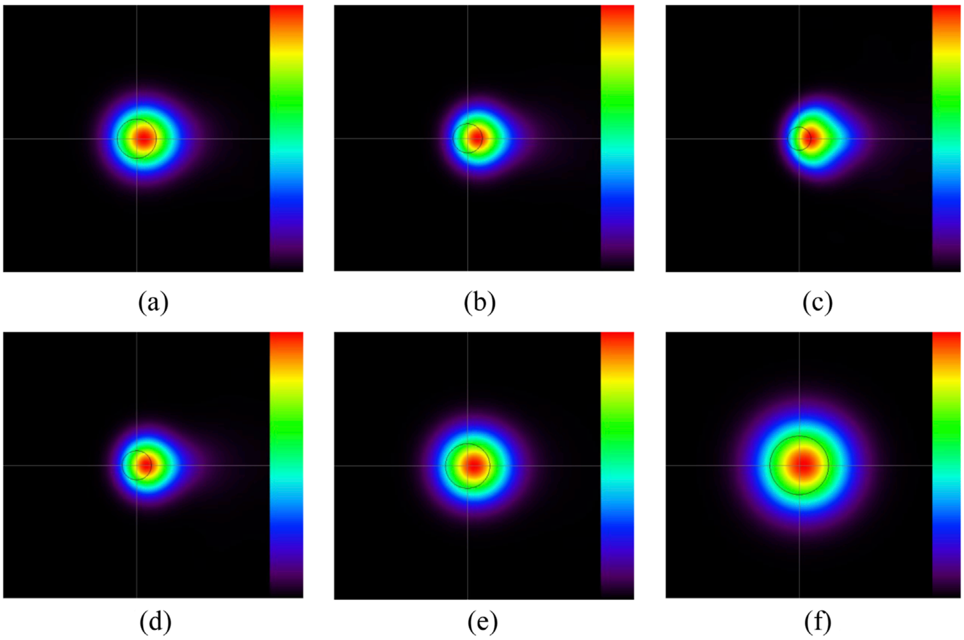

FIGURE 2
(a–c) The focal spot diagrams for different pump beam sizes, and **(d,e)** the focal spot diagrams at different focal lengths of off-centered lenses. **(a)** ω = 3 mm. **(b)** ω = 4 mm. **(c)** ω = 5 mm. **(d)** f = 100 mm. **(e)** f = 150 mm. **(f)** f = 200 mm.

Consequently, it is imperative to conduct a thorough analysis of how the pump beam size and focal length affect the focused spot's morphology and intensity distribution, as shown in Figure 2.

Figures 2a–c presents the simulation results of the focal spot under three different pump beam cross-sectional sizes of 3 mm, 4 mm, and 5 mm, respectively. For the focal spot with a pump size of 3 mm, no significant distortion is observed; but the spot profile is relatively larger. As the pump size increases, the coma aberration becomes more evident, accompanied by an increase in the degree of beam center displacement. This phenomenon is caused by the significant phase differences generated at the focal plane by rays traveling along different paths as the pump beam size increases, exacerbating coma aberration. Furthermore, the increased pump beam size causes more rays to enter at larger angles, leading to marginal rays focusing farther from the optical axis than the central rays. Consequently, the focal spot exhibits a displaced center. Figures 2d–f displays the simulated focal spot images obtained with off-centered lenses of focal lengths 100 mm, 150 mm, and 200 mm, respectively. For a lens with 100-mm focal length, significant coma aberration was observed. Increasing the lens

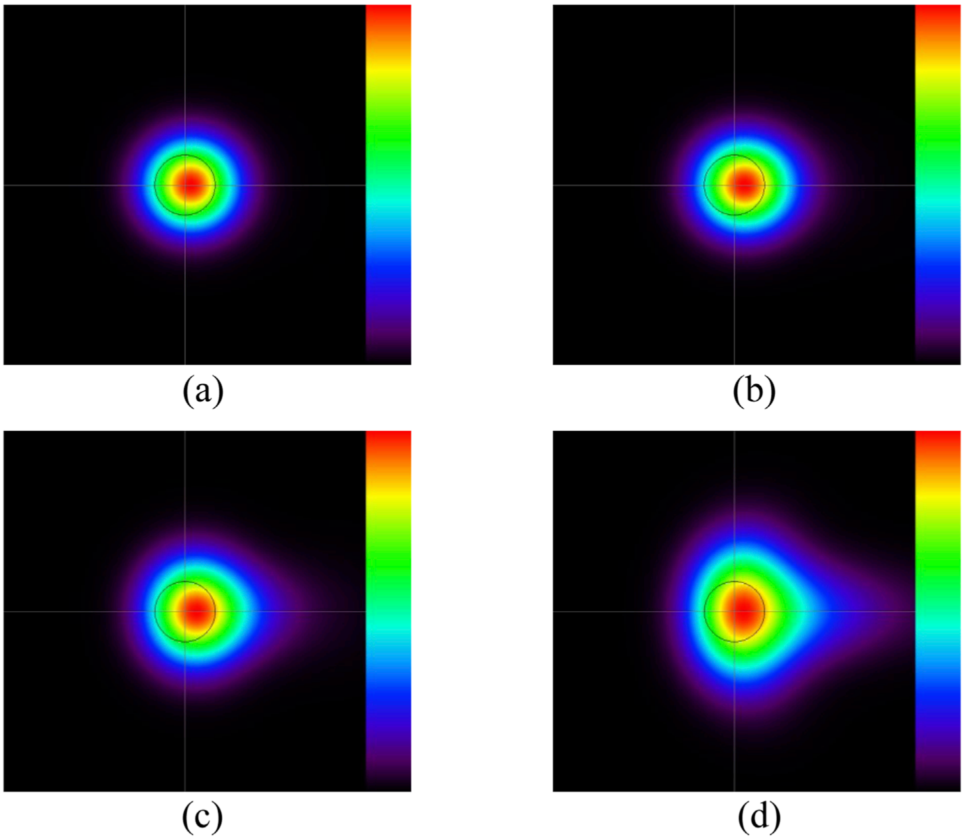

FIGURE 3
Simulated focal spot beam patterns with different decentration lenses. **(a)** d = 3 mm. **(b)** d = 6 mm. **(c)** d = 9 mm. **(d)** d = 12 mm.

focal length to 200 mm demonstrates a trade-off between aberration reduction and spot size, effectively mitigating coma aberration while simultaneously increasing the focal spot radius. This occurs because a longer focal length reduces the focusing differences of rays at the lens edges, thereby alleviating coma aberration. The beam's focal point becomes more dispersed, leading to a larger spot radius and a reduction in the energy density of the focused beam.

Therefore, optimal selection of lens focal length requires careful consideration of the trade-off between coma aberration minimization and preservation of beam energy density. Through comparative analysis, a pump beam size of 4 mm and a lens with 150-mm focal length are selected for subsequent simulations, considering the trade-off between higher energy density and less coma aberration.

Employing the rotating off-centered lens method can effectively mitigate thermal accumulation in the SBS-PCM medium cell, thereby minimizing focal spot distortion. Nevertheless, although the implementation of off-centered lenses enhances focused beam quality, their inherent decentration introduces asymmetric perturbations that generate coma aberration. To analyze the influence of the decentration of lens on the characteristics of focal spot density distribution, the decentration is set to 3 mm, 6 mm, 9 mm, and 12 mm, respectively, for numerical simulations in Figure 3 [16].

Figure 3 presents the simulated focal spot beam patterns for different lens decentrations. With a 3-mm decentration lens, the focal spot is concentrated without significant distortion. When the decentration of lens is increased to 6 mm, the beam center exhibits a slight displacement, while the spot still follows the Gaussian distribution well. At 9 mm decentration, the focal spot exhibits obvious coma aberration, and the spot center position is displaced. Increasing the decentration distance to 12 mm significantly amplifies coma aberration at the focal plane. The reason is that as the lens decentration increases, the travel paths of the edge beams and the core beams are significantly different, leading to a displacement of the focal point for the edge beams. This displacement finally exhibits as coma aberration, degrading the beam's uniformity and symmetry. Therefore, it is necessary to set the appropriate decentration of lens to consider the trade-off between the dynamic movement range of the focal spot and the coma aberration. Based on a comprehensive comparison, a decentration of 6 mm was chosen.

5 Experimental verification

To verify that the parameter optimization of off-centered lens can improve the quality of the SBS reflected beam, a 50-W laser with a repetition rate of 1 kHz was used. A comparative analysis

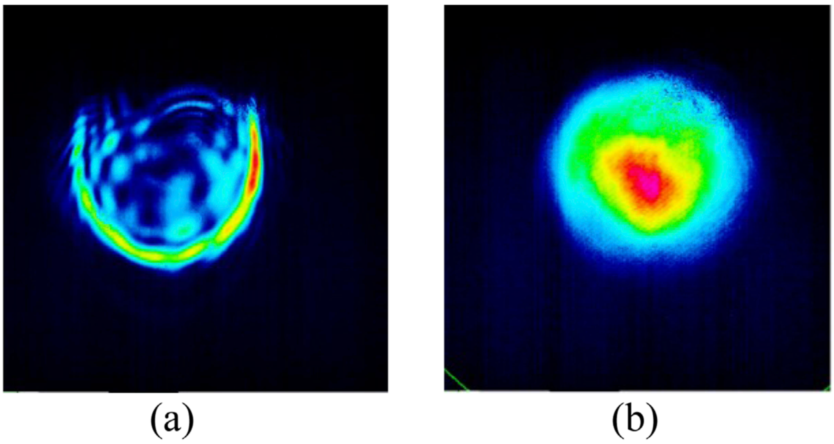

FIGURE 4
Comparison of SBS reflected beam patterns between normal and off-centered lenses. **(a)** Normal lens. **(b)** Off-centered lens.

of SBS reflected beam patterns is conducted between normal and off-centered lenses, both with a focal length of 150 mm. The experimental results, presented in Figure 4, were obtained using HT110 liquid medium with a phonon lifetime of 0.6 ns and a Brillouin gain coefficient of 4.7 cm/GW. For normal lens, beam quality is significantly degraded with larger aberrations. And with the off-centered lens, the beam profile is well-maintained. The results show that the optimization of the off-centered lens parameters can effectively compensate for the beam distortion caused by thermal and other nonlinear effects, maintaining satisfactory beam quality for high repetition rate operation. For this method, the pump power may be increased beyond current levels, but the absorption of the liquid will increase the temperature and decrease its reflectivity if the input power increases.

6 Conclusion

This study proposes a method for optimizing the parameters of off-centered lens to address the influence of thermal effects in SBS-PCMs. The effect of pump beam size, focal length, and lens decentration on the focal spot are simulated and analyzed using the ray tracing method. The results indicate that the larger pump beam size leads to more obvious coma aberration and lager beam center displacement. Increasing the focal length of off-centered lens can mitigate coma aberration, increase the focal spot radius, and decrease the beam energy density. The larger the lens decentration, the wider dynamic moving range of the focal spot and more less the thermal accumulation, but this also leads to more obvious coma aberration. Therefore, it is necessary to select appropriate off-centered lens parameters to achieve a high energy density beam while maintaining minimal coma aberration. Based on comparative analysis, the following parameters are determined: a pump beam diameter of 4 mm, off-centered lens with a 150-mm focal length and a decentration of 6 mm. These results could provide an experimental reference for optimizing SBS compression parameters in subsequent research endeavors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HW: Writing – original draft, Writing – review and editing. CL: Writing – original draft. TJ: Writing – review and editing. KL: Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. National Natural Science Foundation of China (No: 62105303); Open Subject of Hebei Key Laboratory of Advanced Laser Technology and Equipment (HBKL-ALTE2025002).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

1. Wang H, Shan SM, Wang G. Experimental optimization of compact double-cell stimulated Brillouin scattering pulse compressor. *Front Phys* (2023) 10:1115557. doi:10.3389/fphy.2022.1115557

2. Kong HJ, Park S, Cha S, Ahn H, Lee H, Oh J, et al. Conceptual design of the Kumgang laser: a high-power coherent beam combination laser using SC-SBS-PCMs towards a Dream laser. *High Power Laser Sci Eng* (2015) 3:e1. doi:10.1017/hpl.2014.49

3. Cao C, Wang Y, Bai Z, Li Y, Yu Y, Lu Z. Developments of picosecond lasers based on stimulated Brillouin scattering pulse compression. *Front Phys* (2021) 9:524. doi:10.3389/fphy.2021.747272

4. Sheng L, Ba D, Lu Z. Imaging enhancement based on stimulated Brillouin amplification in optical fiber. *Opt Express* (2019) 27:10974–80. doi:10.1364/OE.27.010974

5. Wang J, Zhao K, Feng T, Zhu X, Chen W. 1.5 J high-beam-quality Nd:LuAG ceramic active mirror laser amplifier. *Chin Opt Lett* (2020) 18:021401. doi:10.3788/COL202018.021401

6. Liu F, Wang Y, Cao C, Meng Z, Man Z, Bai Z, et al. Characterization of sub-nanosecond pulse compression based on frequency-detuning SBS. *Opt Express* (2024) 32(2):2281–92. doi:10.1364/OE.514562

7. Kang Z, Fan Z, Huang Y, Zhang H, Ge W, Li M, et al. High-repetition-rate, high-pulse-energy, and high-beam-quality laser system using an ultraclean closed-type SBS-PCM. *Opt Express* (2018) 26:6560. doi:10.1364/OE.26.006560

8. Fan R, Liu Z, Jin D, Luo T, Li N, Li S, et al. High temporal waveform fidelity stimulated Brillouin scattering phase conjugate mirror using Novec-7500. *Opt Express* (2023) 31:1878–87. doi:10.1364/OE.470032

9. Chen B, Bai Z, Chen Y, Deng Y, Ma T, Wang K, et al. Enhanced beam quality of high-energy lasers utilizing fused silica as an all-solid-state SBS-PCM. *Opt Laser Technol* (2025) 181:111850. doi:10.1016/j.optlastec.2024.111850

10. Wang H, Cha S, Kong H, Wang Y, Lu Z. Thermal suppression of high-repetition rate SBS pulse compression in liquid media. *Opt Express* (2022) 30(21):38995–9013. doi:10.1364/OE.469481

11. Tang X, Qiu J, Fan Z, Wang H, Liu H, Liu Y, et al. Experimental study on SBS-PCM at 200 Hz repetition rate pumped with joule-level energy. *Opt Mater* (2017) 67:64–9. doi:10.1016/j.optmat.2017.03.044

12. Park S, Cha S, Oh J, Lee H, Ahn H, Churn KS, et al. Coherent beam combination using self-phase locked stimulated Brillouin scattering phase conjugate mirrors with a rotating wedge for high power laser generation. *Opt Express* (2016) 24:8641–6. doi:10.1364/OE.24.008641

13. Chen Y, Tan B, Jin D, Chen B, Bai Z, Wang K, et al. Characteristics and suppression of beam distortion in a high repetition rate nanosecond stimulated Brillouin scattering phase conjugation mirror. *High Pow Laser Sci Eng* (2024) 12:e20. doi:10.1017/hpl.2024.4

14. Navarro R, Moreno-Barriuso E. Laser ray-tracing method for optical testing. *Opt Lett* (1999) 24:951–3. doi:10.1364/OL.24.000951

15. Chang Y, Liu C, Cheng C. Design and characterisation of a fast steering mirror compensation system based on double porro prisms by a screw-ray tracing method. *Sensors* (2018) 18:4046. doi:10.3390/s18114046

16. Leach R. Abbe error/offset. In: *CIRP encyclopedia of production engineering*. Springer (2015). p. 1–4. doi:10.1007/978-3-642-35950-7_16793-1