Design and application of a laser beam alignment system based on the imaging properties of a multi-pass amplifier

Daizhong Liu (刘代中)[1], Fengnian Lü (吕凤年)[1], Jinzhou Cao (曹金洲)[1], Renfang Xu (徐仁芳)[1], Jianqiang Zhu (朱健强)[1], Dianyuan Fan (范滇元)[1], Jianbo Xiao (肖剑波)[2], and Xiaojun Zhou (周晓军)[3]

[1]*National Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*Guangdong Ronghui Information Engineering Co.,Ltd, Guangzhou 510665*

[3]*State Intellectual Property Office of China, Beijing 100088*

Received November 21, 2005

Image relaying is presented as a technique for aligning beams onto mm-sized target of high power laser. On the basis of summarizing the preceeding work on the near-field image relaying of multiple spatial filters, the far-filed image relaying is suggested firstly. The near-field and far-field image relaying properties of multiple spatial filters in laser beams automatic alignment system are analyzed. A geometrical optics approach and an *ABCD* ray matrix theory are used throughout. The reasonable and optimum scheme for automatically aligning multi-pass beam paths is presented and demonstrated on the multi-pass amplifier system of the SG-III prototype.

OCIS codes: 220.1140, 110.2970, 330.6110.

The inertial confinement fusion facility is the largest and most complex one of high power lasers, such as the Nova laser, the National Ignition Facility, the GEKKO-XII laser of Japan, the LMJ project of France, and the SG-III facility of China. These lasers, propagating from the master oscillator driver to the target, interact with more than 100 near-field (NF) optical elements and pass through several spatial filter pinholes over a distance exceeding 100 m. To ensure the accuracy of these laser systems, the beam automatic alignment system has been installed on all of them. It has become an important and absolute necessary part of this kind of laser.

It is well known that the multiple spatial filters can sharply minimize nonlinear effects in high power laser amplifiers[1,2], which is accomplished by employing both the normal filtering properties and the imaging properties of a spatial filter. This phenomenon may be called as NF image relaying. On basis of summarizing the preceeding work on the NF image relaying of multiple spatial filters, the far-field (FF) image relaying is suggested firstly. The application of NF and FF image relaying properties of multiple spatial filters in laser beam automatic alignment system is analyzed. A geometrical optics approach and an *ABCD* ray matrix theory are used throughout. An automated, closed-loop, image relaying, laser beam alignment system is described here. Its function is to sense beam alignment errors in the laser beam system and automatically steer mirrors to maintain beam alignment. A reasonable and optimized scheme for automatically aligning multi-pass beam paths is presented. It is demonstrated experimently on the multi-pass amplifier system of the SG-III prototype[3].

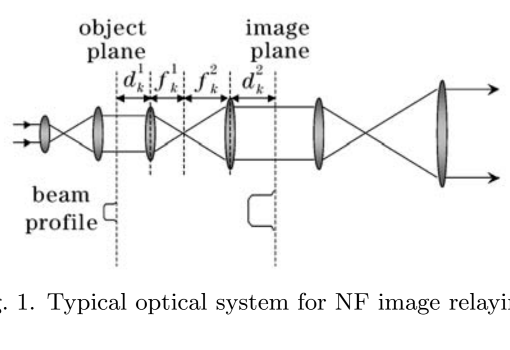

Fig. 1. Typical optical system for NF image relaying.

A typical NF image relaying optical system is depicted in Fig. 1, in which confocal lens pairs are used to meet these imaging properties. The optical transfer matrix for the kth pairs element of this system is

$$t_k^{\mathrm{NF}} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -m_k & -m_k d_k^1 - (m_k)^{-1} d_k^2 + f_k^1 + f_k^2 \\ 0 & -1/m_k \end{pmatrix}, \quad (1)$$

where $m_k = (f_k^2)/(f_k^1)$ is the magnification of the lens pair. For a system requiring N lens pairs, the system transfer matrix is

$$T_N^{\mathrm{NF}} = \prod_{k=1}^{N} t_k^{\mathrm{NF}}. \quad (2)$$

In terms of geometrical optics, if

$$B = m_k d_k^1 + (m_k)^{-1} d_k^2 - f_k^1 - f_k^2 = 0, \quad (3)$$

the beam profile in the plane d_k^1 will be imaged on the plane d_{k+1}^1 with magnification m_k. When Eq. (3) satisfies all k, the beam will be repeatedly imaged or relayed throughout the optical train[1,2,4,5].

Based on the research of NF image relaying, we find that multiple spatial filters have properties of FF image relaying as well. This means that the transverse intensity profile in one spatial filter's focal plane would be reimaged onto the next spatial filter's focal plane. Figure 2

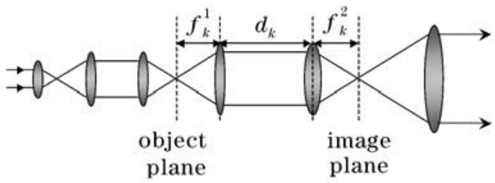

Fig. 2. Typical optical system for FF image relaying.

depicts an optical system of FF image relaying in multiple spatial filters. We can obtain the optical transfer matrix for the kth element of this system

$$t_k^{\mathrm{FF}} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

$$= \begin{pmatrix} -m_k & 0 \\ (f_k^1 f_k^2)^{-1} d_k - (f_k^1)^{-1} - (f_k^2)^{-1} & -1/m_k \end{pmatrix}, \quad (4)$$

where $m_k = (f_k^2)/(f_k^1)$ is the magnification of the lens pair. For a system requiring N lens pairs, we get the system transfer matrix

$$T_N^{\mathrm{FF}} = \prod_{k=1}^{N} t_k^{\mathrm{FF}}. \quad (5)$$

Since $B \equiv 0$, the beam profile in the objective plane will be imaged on the image plane with magnification m_k.

The objective of the beam automatic alignment system is to sense an alignment error in a high power laser system and automatically steer mirrors preceeding the detection point in a closed-loop control system to return the beam alignment to its reference location. Figure 3 is the close-loop of a typical beam automatic alignment system. The alignment errors can be introduced by the temperature changing, the mechanical frame's distortion of mirrors, the excursion of the oscillator's output beam or any other random factors. Thus it is needed to readjust the beam paths before the new shot of the laser facility[6−10].

The alignment errors include centering errors and pointing errors of the beams. In terms of these errors, the beams can be removed to the old location by adjusting motorized mirrors. The beam path is adjusted from head to foot until it reaches the target. The centering and pointing errors can be detected by a NF imaging detection system and a FF imaging detection system, respectively. The NF and FF imaging detection systems are established according the image relaying properties.

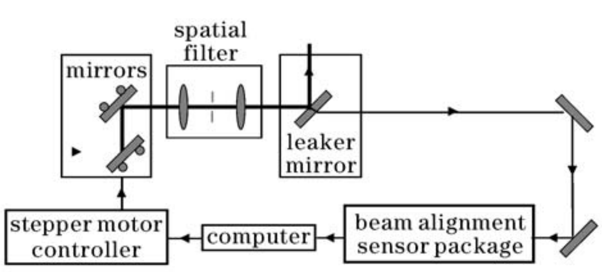

Fig. 3. Alignment closed-loop system.

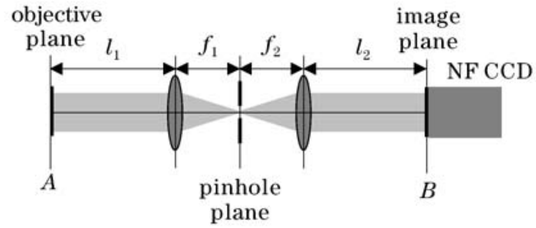

Fig. 4. NF imaging detection system.

A single spatial filter, as shown in Fig. 4, is an example for explaining applications of NF image relaying in NF imaging detection system. The collimated beam propagates from plane A to plane B. The plane A is an objective plane, and plane B is the image plane of the plane A and an observational plane as well, which is the detection plane of a charge coupled device (CCD).

In terms of geometrical optics, using Eq. (1), the optical transfer matrix of this system from plane A to plane B is

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -M & -Ml_1 - \frac{l_2}{M} + f_1 + f_2 \\ 0 & -1/M \end{pmatrix}, \quad (6)$$

where $M = f_2/f_1$ is the magnification of the lens pair. Since plane B is the image of the plane A,

$$-Ml_1 - \frac{l_2}{M} + f_1 + f_2 = 0. \quad (7)$$

Thus

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -M & 0 \\ 0 & -1/M \end{pmatrix}. \quad (8)$$

An arbitrary ray at plane A can be described as $\begin{pmatrix} r_A \\ \theta_A \end{pmatrix}$, where r is the beam position at the entrance to the system, θ is the beam incident angle. Thus the beam trace at plane B is

$$\begin{pmatrix} r_B \\ \theta_B \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_A \\ \theta_A \end{pmatrix} = \begin{pmatrix} -Mr_A \\ -\theta_A/M \end{pmatrix}. \quad (9)$$

It is obvious that the beam position at plane B is linear to that of plane A. The NF CCD can detect the beam position at plane B. So centering errors can be obtained from the NF imaging detection system in laser beam automatic alignment system.

Figure 5 is a sketch of FF imaging detection system, where the pinhole plane is imaged onto the plane B. The detection plane of the FF CCD is the image plane as well as plane B. The second lens focal length is f_2. In the same way for the NF imaging detection system, an

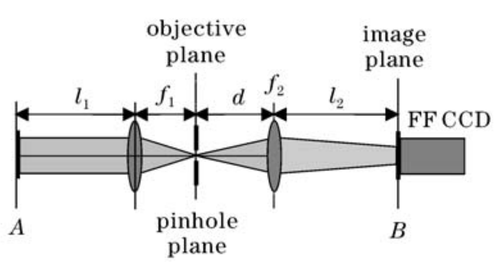

Fig. 5. FF imaging detection system.

arbitrary ray trace of plane A can be depicted in plane B as

$$\begin{pmatrix} r_B \\ \theta_B \end{pmatrix} = \begin{pmatrix} -\frac{f_1 l_2}{d}\theta_A \\ \frac{d}{f_1 l_2} r_A - \frac{f_1}{f_2}\theta_A - \frac{d}{l_2}\left(1 - \frac{l_1}{f_1}\right)\theta_A \end{pmatrix}. \quad (10)$$

It can be seen from that the beam position at plane B is linear to the ray angle of plane A. Thus pointing errors can be detected from the FF imaging detection system in laser beams automatic alignment system also.

The cavity mirror (CM) is a key optical element of multi-pass amplifiers in aligning high-power laser facility. When the beams pass back and forth several times through a multi-pass amplifier, they must be reflected by the same reflector (the cavity mirror). A four-pass amplifier is shown in Fig. 6 as an example, in which beams are reflected by the CM two times. So the CM position is fixed, and if it is not accurate, the whole beam paths cannot be correctly aligned, whatever other reflector mirrors are adjusted.

Generally, four pinholes P1, P2, P3, and P4 have the same size. In terms of the aforementioned FF image relaying, the four-pass amplifier contains several pairs of relay images. First, the CM images itself in the four-pass beam path. Second, pinholes P1 and P2 are located in the pinhole plane symmetrically; pinholes P3 and P4 form another pair of conjugate images as well. Third, the pinhole plane and the CM plane are located at the two focal planes of lens L, respectively.

To adjust the CM, a camera FF CCD of a FF imaging detection system is set behind imaging lens. The center of pinhole P2 is set as the FF CCD detector reference. The beam light passes through pinhole P2 and is focused in the CCD photosensitive plane. At the same time, this focal plane must be the conjugate imaging plane of pinhole P2. Since pinholes P1 and P2 are conjugate and have the same size, pinhole P1 image must be relayed to the CCD photosensitive area of FF CCD. Thus the CM can be adjusted conveniently. A negative lens OM was inserted in front of pinhole P1 in order to make the light illuminate it. It can be examined to determine whether the image of pinhole P1 is located exactly inside pinhole P2. Figure 7(a) shows that the image of pinhole P1 was intercepted by the pinhole P2 while the CM was not correctly aligned. But the motors on CM can be driven to make the pinhole P1 image to move exactly on the center of pinhole P2. Then there was a symmetric and circular image on FF CCD, as shown in Fig. 7(b). The results indicate that the cavity mirror was correctly adjusted[11−13].

Figure 8 depicts an experimental system of the four-pass amplifier in the SG-III prototype facility, which has half a size of the prototype facility. Based on the techniques and principles above mentioned, aimed at the multi-pass beam paths on the SG-III prototype laser facility, a unique scheme for automatically aligning the multipass beams was conceived. The alignment process includes 3 main steps. The cavity mirror is adjusted first. Then the first-pass and the second-pass beams are aligned. Finally, the third-pass and the fourth-pass beams are corrected. The detailed methods are as follows.

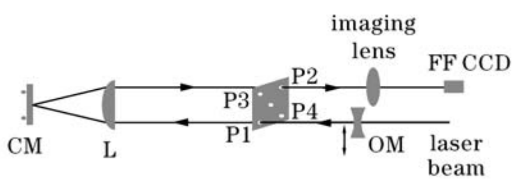

Fig. 6. Alignment of the cavity mirror.

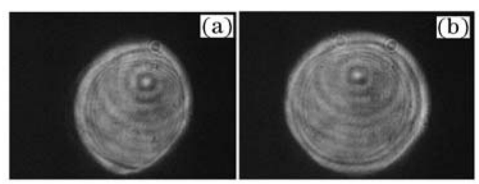

Fig. 7. Images before (a) and after (b) adjusting the cavity mirror.

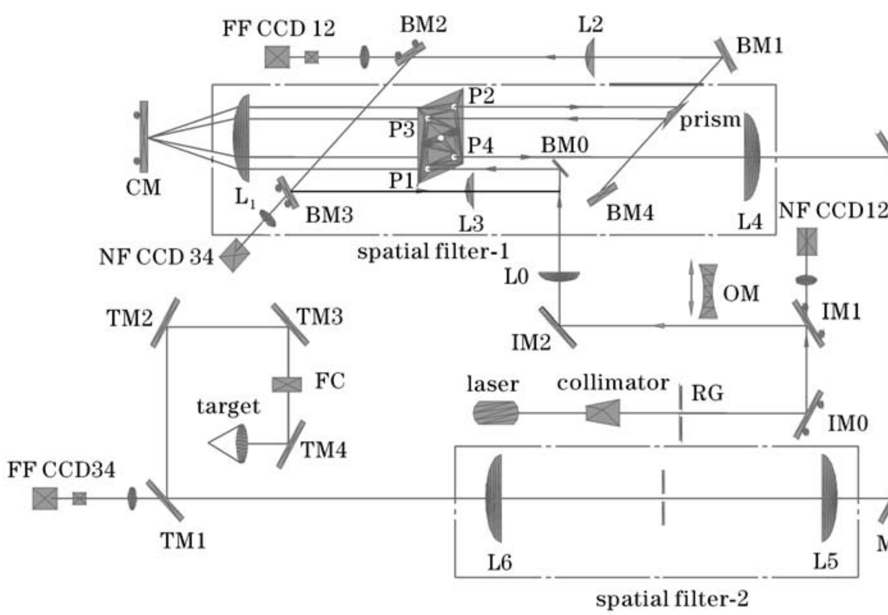

Fig. 8. Alignment experimental system of the SG-III prototype facility.

The methods above mentioned were used to adjust the CM with the help of the FF CCD 12, which was set behind back reverse mirror BM2. To align the first and second passes, the NF CCD 12 was placed behind injection mirror IM1, and IM1 is located at the NF image relayed plane. The NF and FF error information was obtained through the imaging detection systems of NF CCD 12 and FF CCD 12. Then a computer caused the mirrors IM0 and IM1 to move to steer the injected beam passing through the pinholes P1 and P2. For adjusting the third and fourth passes, the NF CCD 34 imaging detection system was set behind the reflector BM3, and the NF image-relayed plane was set at the middle of mirrors BM2 and BM3. The FF CCD 34 was located behind the target mirror TM1, and its reference (objective plane) was set at the pinhole plane of spatial filter-2. Thus the mirrors BM2 and BM3 were adjusted so that the beam could pass through the pinholes P3, P4 and the pinhole of the spatial filter-2 accurately.

In the experiments, the beam adjustment of the four-pass amplifier system can be accomplished in 20 minutes. The precision of the NF adjustment was less than 0.5% of the spot. The accuracy of the FF adjustment was 14.3 μrad. To verify the repeatability of the beam alignment, the beam adjustment was repeated every half an hour. The results were shown in Fig. 9. For these measurements, the beam was just controlled to the same CCD pixel address only 10 times. The triangle points are positions of the FF beam before alignment. The rectangular points are positions of FF reference. The circular points are result positions of the FF beam after alignment. In experiments, the far field spot has a less than ideal intensity profile with its details changing in time due to gas motion in the propagation path or other factors.

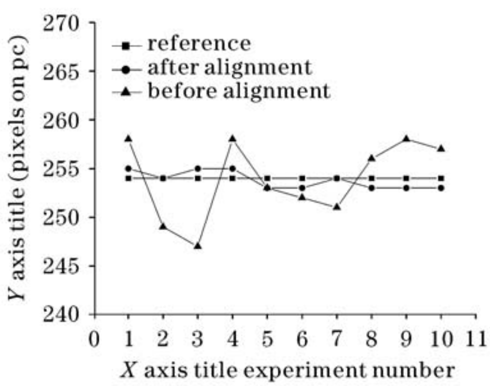

Fig. 9. Experimental results of the FF beam alignment.

On the basis of summarizing the preceeding work on the NF image relaying of multiple spatial filters, the FF image relaying is suggested firstly. The application of NF and FF image relaying properties of multiple spatial filters in laser beam automatic alignment system is analyzed. A geometrical optics approach and an $ABCD$ ray matrix theory are used throughout. A reasonable and optimized scheme for automatically aligning the four-pass amplifier is presented. It is demonstrated on the four-pass amplifier experimental system of the SG-III prototype. The beam adjustment of the four-pass amplifier system can be accomplished in 20 minutes. The precision of the NF adjustment was less than 0.5% of the spot. The accuracy of the FF adjustment was 14.3 μrad.

This work was supported by the National "863" Program of China. The authors would like to express thanks to the Fusion Research Center of China Academy of Engineering Physics (CAEP) for the supports in the experiments. D. Liu's e-mail address is dzhliu@mail.shcnc.ac.cn.

References

1. J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, Appl. Opt. **17,** 2053 (1978).
2. J. T. Hunt, P. A. Renard, and W. W. Simmons, Appl. Opt. **16,** 779 (1977).
3. H. Peng, X. Zhang, X. Wei, W. Zheng, F. Jing, Z. Sui, D. Fan, and Z. Lin, Proc. SPIE **3492,** 25 (1999).
4. D. Y. Fan, Acta Phys. Sin. (in Chinese) **3,** 319 (1983).
5. D. Y. Fan, Acta Phys. Sin. (in Chinese) **1,** 395 (1981).
6. S. J. Boege, E. S. Bliss, C. J. Chocol, F. R. Holdener, J. L. Miller, J. S. Toeppen, C. S. Vann, and R. A. Zacharias, Proc. SPIE **3047,** 248 (1997).
7. F. R. Holdener, E. Ables, E. S. Bliss, S. J. Boege, R. D. Boyd, C. J. Chocol, D. T. Davis, R. D. Demaret, R. E. English, C. W. Laumann, J. L. Miller, and S. W. Thomas, Proc. SPIE **3047,** 692 (1997).
8. Q. Chen, R. Xu, Z. Peng, C. Zu, and Y. Zhuang, Acta Opt. Sin. (in Chinese) **15,** 531 (1995).
9. C. D. Swift, E. S. Bliss, W. A. Jones, R. J. Reeves, L. G. Seppala, R. T. Shelton, and P. J. VanArsdall, Proc. SPIE **608,** 2 (1986).
10. P. J. Van Arsdall and R. J. Reeves, Proc. SPIE **608,** 29 (1986).
11. D. Liu, J. Zhu, R. Xu, and D. Fan, Opt. Eng. **43,** 2066 (2004).
12. D. Liu, J. Zhu, R. Xu, and D. Fan, High Power Laser and Particle Beams (in Chinese) **16,** 582 (2004).
13. D. Liu, R. Xu, and D. Fan, Chin. Opt. Lett. **2,** 92 (2004).