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Application of a three-lens slit spatial filter in high power lasers

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ABSTRACT

Combined with partial parameters in National Ignition Facility, the conceptual design of off-axial four-pass main laser optical system with a three-lens slit spatial filter has been discussed. Since the three-lens slit spatial filter can decline the focal intensity by about 3 orders of magnitudes than that in NIF system, the cutoff frequency in main amplifier cavity can be reduced from 51 × DL to 39 × DL for better beam quality. The main laser system for single beam line can be shortened from 174.7 m to 155.7 m and the spatial filter in high vacuum becomes 60 m instead of the original 83.5 m. Additionally, the pinhole closure could be avoided since the declining of focal intensity in slit spatial filter and the absence of pinhole aperture in the other (pinhole) spatial filter, which provides new ideas for the future high-power lasers.

1. Introduction

Spatial filter [1–4] (SF) is the conventional equipment used to clean off the rapidly growing spatial frequencies, inhibiting the small-scale self-focusing [5] and improving the load capacity and the output beam quality [1,6], especially in inertial confinement fusion that have higher intensities. Besides, SF bears the functions of image relay and aperture matching [7–9]. Convenient SF consists of two convex lenses and a pinhole placed at their common focus [10]. The focal intensity in high-power laser is so powerful that the pinhole aperture has to bear high intense irradiation, which may induce pinhole closure [11–13]. Therefore, focal lengths of the lenses in SFs have to be long enough to enlarge the focal area. Moreover, a high vacuum environment is also required to avoid air breakdown [14–16] by the powerful peak intensity. The above problems will lead to large laser systems and give rise to difficulties in building, collimation and maintenance of the lasers.

In order to reduce the system size and decline the required vacuum, the conventional pinhole SF (PSF) has to be improved. In 2012, A. C. Erlandson in Lawrence Livermore National Laboratory proposed a slit SF (SSF) with four cylindrical lenses and two slit apertures in common focal planes [17], which enlarged the focal area and reduced the focal intensity by changing the original focal spot into focal lines with cylindrical lenses. In 2014, we proposed a three-lens slit SF [18] for simplicity, which consists of two cylindrical lenses, one spherical lens and two slit apertures, as shown in Fig. 1(a). The cylindrical lens-I [as marked in Fig. 1(a)], slit-I and spherical lens are used for y-directional filtering, and the cylindrical lens-II, slit-II and spherical lens are for x-directional filtering. According to the theoretical and experimental analyses [18,19], the three-lens slit SF is equivalent with pinhole SF on image relay and spatial filtering except the decrease of focal intensity by about 3 orders of magnitudes, which could significantly postpone or even avoid the pinhole closure in high-power lasers. Thus it is beneficial for shortening the SF and declining the required vacuum.

In this paper, the application of the three-lens slit SF in high-power lasers has been theoretically discussed. The slit SF is applied to replace the cavity SF in the national ignition facility (NIF) system, and better performances are shown compared to the original cavity SF.

2. Main laser system with a three-lens slit SF

The image relay model of slit SF is different with that of pinhole SF since the introduction of cylindrical lenses. According to the theoretical and experimental analyses [18,19], the front (or back) focal plane of the three-lens slit SF system locates at the front (or back) cylindrical lens resulting into a zero relay distance. Thus, the three-lens slit SF cannot construct a multi-pass amplifier cavity itself to deliver a light beam to final optics assembly without diffraction. To solve the problem, the slit SF has to be embedded into a pinhole SF to utilize its function of image relay and movable focal plane. The specific method is to add a space [the added space is between plane 1 and plane 2 as shown in Fig. 2(b), and in Fig. 2(a) the plane 1 is just located at the plane 2] into one side of the pinhole SF, and insert a three-lens slit SF, being as long as the empty space, into the space. According to the image relay model of the slit SF, a light beam on one cylindrical lens [located at plane 2 in Fig. 2(b)] will be imaged on the other cylindrical lens [located at plane 1 in Fig. 2(b)]. Thus the inserting of the slit SF will not affect the image relay function of the pinhole SF.

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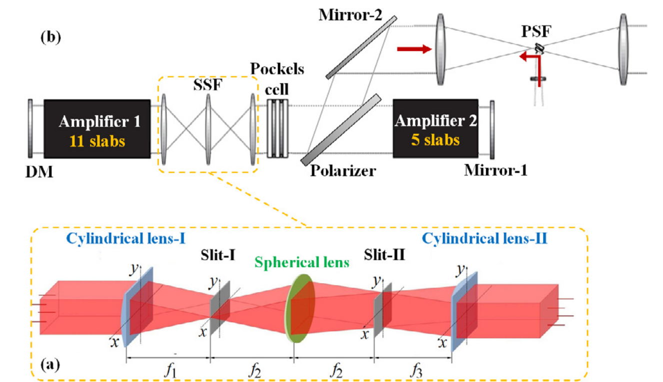

Fig. 1. (a) Schematic diagram of three-lens slit SF and (b) Main laser system based on the three-lens slit SF.

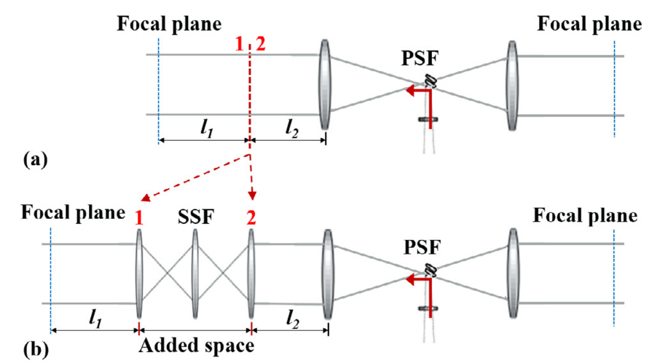

Fig. 2. (a) is a pinhole spatial filter and (b) is the pinhole spatial filter with an added space in which the three-lens slit spatial filter is embedded.

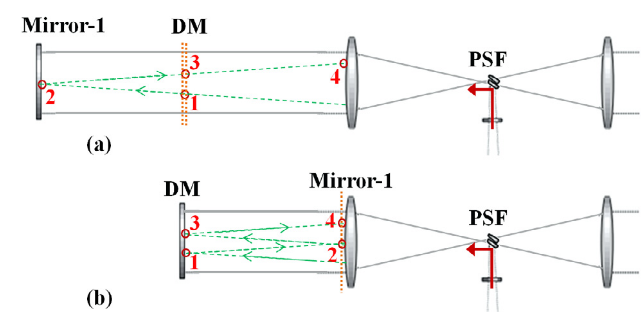

Fig. 3. (a) The equivalent and (b) the actual positions of the left focal plane of pinhole SF.

Combined with some optical parameters in NIF system, the conceptual main laser system is designed as shown in Fig. 1(b), in which the multi-pass amplifier cavity consists of cavity mirror (Mirror-1), deformable mirror (DM), amplifiers (Amplifier 1 and Amplifier 2), pockels cell, polarizer and a three-lens slit SF, etc. The left focal plane of the pinhole SF is translated towards left side due to the imbedding of slit SF. Nevertheless, here comes another problem that the light beam at deformable mirror cannot be delivered to Mirror-1 without diffraction since they are not the focal planes for each other. To solve this problem, the left focal plane of the pinhole SF has to be translated again towards left side, so that the left focal plane will finally be reflected to the position of Mirror-1 by the deformable mirror, as illustrated in Fig. 3.

The light beam output from optical pulse generation system is injected into the main laser system through the pinhole SF, which will be reflected by Mirror-2 and then get into the four-pass amplifier cavity. The light beam passes in turn through slit SF (for spatial filtering) and Amplifier 1 (for extracting energy), and then passes again through Amplifier 1 and slit SF due to the reflection of the deformable mirror. At the present time, the pockels cell is active so that the light beam can go through the polarizer to Amplifier 2 and Mirror-1 (where is the left focal plane of pinhole SF). Subsequently, it will go back and forth again through the cavity until reach the polarizer twice. Since the pockels cell is not active now, the light beam will finally be reflected by the polarizer and get away from the cavity, going through the pinhole SF to the final optics assembly. The pinhole SF needs no pinhole aperture since the beam output form four-pass amplifier cavity was just been filtered with slit SF.

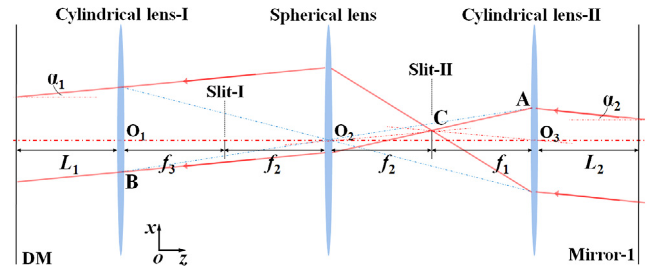

Fig. 4. The relationship between the deflection angle and focal length.

3. Off-axial four-pass amplifier cavity

Amplified spontaneous emission (ASE) will induce continually increasing gain loss [20] to the regenerated laser. In order to suppress the ASE, the light beam in the four-pass amplifier cavity has to be off-axial [21], which will lead to a complicated off-axial construction if following the conventional off-axial amplifier cavity with pinhole SF due to the two orthogonal slit apertures in slit SF. A solution to this problem is to limit the off-axial light beam into x–z plane. Thus, there will exist x-axial distances among all the focal lines of the passes. As a result, slit-I plane will need only one slit aperture and slit-II plane will need four slit apertures since the focal lines in slit-I and slit-II plane are x- and y-directional, respectively.

As shown in Fig. 4, the focal lengths of cylindrical lens-I, spherical lens and cylindrical lens-II are assumed as f_1, f_2 and f_3, respectively. The distance between the deformable mirror and the cylindrical lens-I is L_1, and the distance between cylindrical-lens-II and Mirror-1 is L_2. The deflection angles of light beam in left and right sides of the cavity is a_1 and a_2, respectively, and they satisfy $f_2 \cdot \alpha_1 = f_1 \cdot \alpha_2$. In order to control the passes within the amplifier cavity, slight tilts are introduced to the deformable mirror and the cavity mirror. For simplicity, the amplification of the three-lens slit SF is set as 1 time, which resulting into a uniformed focal length f for all lenses in cavity and a tilt angle of $\alpha/2$ for both the deformable mirror and the cavity mirror. According to the Ref. [18], the focal length should no less than 7 m due to the aberration, so that the three-lens slit SF will be 28 m at least.

For a theoretical comparison, Matlab is used to simulate the light propagations in a 7-m-long focal length slit SF and a 30-m-long focal length transport SF in NIF system. Based on partial parameters in NIF system, the incident beam is an 8th-order super-Gaussian square beam with beam area of 350 mm × 350 mm, pulse energy of 20 kJ, pulse width of 3.5 ns, wavelength of 1053 nm and cutoff frequency being set at 39 times diffraction limitation (×DL). The simulation of slit SF shows that the peak intensity and the intensity on inner edge of aperture are about 10^{13} W/cm^2 and 10^8 W/cm^2, respectively, which are both below that of the transport SF in NIF system by 3 orders of magnitudes. The threshold to produce plasma by laser ablation is about in range of 10^9–10^{11} W/cm^2 for most metal material, and the threshold for gold is 10^{12} W/cm^2. Therefore, the pinhole closure will be avoided or significantly weakened in slit SF if the slit apertures are made from high-Z material,