Research Article

Design and Management of Stray Light for Compact Final Optics Assembly on the High Energy Laser System

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1. Introduction

Final optics assembly (FOA) is the last stage of high power laser equipment, which bears the highest laser energy. It is composed of frequency crystals, focusing lens, vacuum window, and other expensive transmission optical elements [1–3]. Residual reflecting of each optical surface can generate stray light. When the fluence of stray light is strong on the optical components and structural parts of the terminal, hundreds of thousands of pollution particles will be added to the optical system, which will reduce the lifetime of the optical elements and limit the output energy of the laser system [4–6]. Therefore, it becomes an important issue in the compact FOA to avoid the deterioration of stray light on the clean environment of the system in the FOA design of the high power laser system, which is important for the improvement of system output energy and the safe operation of the laser system. The FOA design scheme determines the limiting factor of output capability for high power laser facility [7–9].

The National Ignition Facility (NIF) consists of 192 channels of FOA, which is a compact arrangement in the atmosphere chamber environment, and the stray light distribution is dense and complex. Since 1994, it took 9 years to complete its engineering design [10–12]. The first integration verification with the beamlet caused serious damage to the optical elements. Therefore, FOA was set as 10 Torr of clean dry air maintained between the 1w window and the GDS. The second integration verification of FOA was carried out in 2006, which still exposed a lot of problems. The overall design of the system was completed in 2007. However, terminal contamination due to stray light and severe damage to optical elements was still reported in 2017 [7–10].

Due to the small distance from the crystal to the focusing lens of compact FOA, the stray light interacting with each other is increasing complex [13]. Among them, the fluence...
of high-order stray light (reflected twice or more times) is low. It is necessary to avoid high-order stray light focusing on the optical components and structural parts by controlling the distance and angle of the vacuum window and shield. The first-order (single reflection) stray light has the characteristics of high fluence. Special absorbers should be designed by controlling the distance from the fundamental frequency window to the focusing lens [14–16].

In this study, we propose a model to design and manage the stray light of compact FOA on the high energy laser system. An optimized design method of beam trap is proposed. The stray light is bound in the beam trap, and the terminal system is not polluted by the absorbing glass. Additionally, we accomplish the experiment, and the result demonstrates that the compact FOA can achieve the great improvement of cleanliness from ISO Class 5 to Class 3, and the field characteristics and position calculation of stray light are reliable.

2. Design of Compact FOA

2.1. Basic Principle of Compact FOA. Compared with separate FOA, compact FOA has four characteristics. First, the thickness of the vacuum window is effectively controlled, and the modulation and risk of vacuum explosion is relatively low. Second, the total length of the system must be shortened as far as possible because the components work in the atmosphere environment, and the degree of freedom of the system design is greatly reduced. Third, all pollution sources, especially stray light, must be strictly controlled due to the atmosphere environment which leads to no effective auxiliary cleaning control measures that can be added in the system. At last, the distance between frequency conversion and focus lens is small, which makes the stray light crosstalk. The compact FOA optical configuration, as shown schematically in Figure 1, is designed to deliver the required functionality with the fewest possible components.

The 1.053 μm beam from the main laser enters the package through a fused silica window (1w window). Optical components between the 1w window and the vacuum window are installed with 10 Torr of clean dry air, separated from the argon environment of the beam transport system by a 1w window and the hard vacuum of the target chamber by a 2.0 cm thick vacuum window. The terminal optical elements are arranged along the longitudinal direction. In a compact distance range, there are eight optical elements, which are placed in two modules: frequency conversion module and focusing module. Frequency conversion module is consisted by a 1w window and crystals (SHG, THG, and PS). Focusing module is consisted by a focusing lens, vacuum window, and shield. Two points must be ensured in design. First, the first-order stray light reflected by the optical elements behind the focusing lens does not interact with the frequency conversion. Second, the first-order stray light does not act on the junction, while the fluence of the first-order stray light from the focusing lens itself acting on the optical elements of the frequency conversion is acceptable.

Therefore, the design and management logic for stray light of separate FOA is as follows:

1. The spacing of optical elements in the focusing module is optimized to ensure that the high-order stray light can be controlled
2. The distance between the frequency conversion and the focusing module is optimized to ensure that the first-order stray light of the focusing lens can be controlled
3. The angle of the focusing module is optimized to ensure that the first-order stray light of the optical element after the focusing lens deviates from the optical path and can be absorbed
4. The optimal design of the beam trap ensures that the high-throughput first-order stray light can be controlled

2.2. Design and Management of Stray Light. Stray light is unwanted radiation that generally takes the form of scattered light, thermal radiation, or specular reflections (ghost reflections) from nominally transmissive surfaces. In a high power laser system, stray light behavior can be critical to system operation. Compact FOA pulls small spacing from the crystal to WFL and increases the crosstalk of stray light and concentrates the stray light on management. It makes the fluence of first-order ghosted stray light higher than the damage threshold of the absorbing glass. Catastrophic failure of optical components and metal structures from ghosted stray light have occurred with other laser systems and can cause runaway damage that would lead to poor system performance and/or poor reliability and availability. How to manage stray light and avoid the generation of contamination is a core issue in separated FOA.

2.2.1. Design and Management Principles of Stray Light. In view of the complex distribution of high-order stray light in compact FOA, the optical characteristics of stray light are analyzed theoretically, and the stray light analysis model is established, as shown in Figure 2.

The light beam emitted from the same position is reflected by multiple surfaces of the optical elements in the system. The stray light acts on the P point together, and the light field can be expressed as follows:

\[
E_p = E_1(t) + E_2(t + \tau),
\]

\[
I_p = \frac{1}{T} \int_0^T E_p(t) \cdot E_p^* \cdot dt,
\]

\[
I_p = I_1 + I_2 + 2\sqrt{I_1 I_2} \Re\{y_{12}(\tau)\}, \quad y_{12} = |y_{12}(\tau)| \cdot e^{i\phi_{12}},
\]

\[
I_p = I_1 + I_2 + 2\sqrt{I_1 I_2} |y_{12}(\tau)| \cdot \cos \phi,
\]
where $E$ represents the wave function of the light field. $I$ represents the light intensity, and $\tau$ represents the time difference between the two beams arriving at point $P$. Multiple reflecting surfaces will interfere at the same position after reflection superposition due to the strong coherence of the laser from equation (2). The simulation results are shown in Figure 3.

2.2.2. Design and Management of High-Order Stray Light.
For the high-order stray light, the design model is established, as shown in Figure 4. First, the light is reflected on each flat optical element in the focusing module, and then, it is reflected twice through the front surface of the focusing lens. After the second reflection, the focus is kept away from the DDS. After three times of reflection, the focus is between the two elements in the focusing module or far away from the focusing module. To keep the high-order stray light away from the components and structural parts, the distance must be designed as follows.

\[
\begin{align*}
\quad &d_1 + d_2 + d_3 \leq \frac{f}{6}, \\
\quad &3d_1 \leq \frac{f}{6}, \\
\quad &3d_1 + 2d_2 \geq \frac{f}{6}, \\
\quad &2d_1 + d_2 \leq \frac{f}{3}, \\
\quad &3(d_1 + d_2 + d_3) \geq \frac{f}{6}, \\
\quad &2d_1 + 3d_2 + 3d_3 \geq \frac{f}{6}.
\end{align*}
\]

(3)

According to equation (3), the optimal numerical solution of the optical element spacing behind the focusing lens is obtained as follows.
Foreach reflector in the system, the reflection theorem is used to analyze the reflected light of each discrete ray passing through multiple reflectors. At the same time, all beam focal points with flux greater than 0.1 J/cm² in the system are displayed, and then, the path of the stray light focus is deduced according to the focus searched. The analysis results are shown in Figure 5.

It can be seen from Figure 5 that the focus of stray light is far away from the optical elements and structural parts. There is no third-order or higher-order stray light focus in the system. Only the second-order stray light is formed by DDS reflection and WFL reflection. The second-order stray light focus is close to the vacuum target chamber, which has no impact on FOA. The high-order stray light control of the system is effective.

2.2.3. Design and Management of First-Order Stray Light. For the first-order stray light, the design model is established, as shown in Figure 6.

The $d_4$ ensures that the focus of the first-order stray light reflected from the first surface of the focusing lens is in the middle of frequency conversion and the focusing module. At the same time, the aperture of the first-order stray light on SW and PS should be larger than 10 cm by optimizing $d_5$. To ensure that the focus of the first-order stray light of the focusing lens is located between the polarized smooth crystal

\begin{align}
  d_1 &= \frac{f}{20} \\
  d_2 &= \frac{f}{40} \\
  d_3 &= \frac{f}{120}
\end{align}  

For each reflector in the system, the reflection theorem is used to analyze the reflected light of each discrete ray passing through multiple reflectors. At the same time, all beam focal points with flux greater than 0.1 J/cm² in the system are displayed, and then, the path of the stray light focus is deduced according to the focus searched. The analysis results are shown in Figure 5.

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and the focusing lens, the distance must be designed as follows.

\[ d_4 = \frac{f}{5} \]  
\[ d_5 = \frac{f}{10} \]  
(5)

The control diagram of the first-order stray light of the focusing lens is shown in Figure 7.

Considering that the transmittance of the elements decreases and the reflectivity increases after the device has been running for a period of time, the reflectance in the worst case is 2%. The input energy is 4000 J, and the beam aperture is 360 mm; the fluence estimation at the fundamental frequency window is shown in equation (6), and the fluence estimation at the polarized crystal is shown in equation (7).

\[ F_{SW} = \frac{4000 \text{ J}}{20 \text{ cm} \times 20 \text{ cm}} \times 2\% = 0.2 \text{ J/cm}^2 \]  
(6)

\[ F_{PS} = \frac{4000 \text{ J}}{10 \text{ cm} \times 10 \text{ cm}} \times 2\% = 0.8 \text{ J/cm}^2 \]  
(7)

It can be seen from formulas (6) and (7) that the first-order stray light does not act on the structural parts, and the fluence of stray light at the optical element is less than 1 J/cm². It is acceptable that the first-order stray light control of the focus lens is effective.

The first-order stray light of the vacuum window is shown in Figure 8.

Absorbing glass is set at the maximum aperture of the straylight beam deviated from the main optical path, and the fluence of the stray light at the absorbing glass can be calculated as follows:

\[ F_{\text{Armor}} = \frac{4000 \text{ J}}{20 \text{ cm} \times 20 \text{ cm}} \times 6 \times 2\% = 1.2 \text{ J/cm}^2 \]  
(8)

Absorbing glass may produce contaminants because of high fluence.

3. Experiment of Compact FOA

To verify the influence of the first-order stray light on the cleanliness of the system, the absorbing glass was placed in the clean environment in the laboratory. The 351 nm pulse laser with the output fluence of 1 J/cm² was used to directly act on the AB5 glass (absorbing glass). At the same time, a particle counter is placed near the absorbing glass to measure the maximum concentration limit of particles greater than 0.1 μm (air particles per cubic meter), observe the cleanliness change of the system, and count the maximum concentration limit of particles after 9 laser actions. The results are shown in Figure 9.

A silicon glass is added in front of the absorbing glass. At the same time, a pair of optimized glass combination is used to repeatedly absorb and process the first-order stray light to ensure that the first-order stray light does not escape from the trap composed of fused quartz and AB5 glass. The specific design is shown in Figure 10.

A particle counter is placed near the beam trap under the action of a 351 nm pulsed laser of 1 J/cm². The maximum concentration limit of particles larger than 0.1 μm (number of air particles/m³) is measured by the particle counter, and the cleanliness change is observed. The results are shown in Figure 11.
Figure 9: Number of particles generated by the absorbing glass with 351 nm pulse at 1 J/cm². Under the action of 1 J/cm² stray light of the absorbing glass, the number of particles larger than 0.1 μm will deteriorate to 100000.

Figure 10: Design of stray light trap. The pair of absorbers forms the stray light trap. Among them, the first absorber needs to form an angle of nearly 30° with the incident stray light to ensure that the position of the second absorber can be as close to the first absorber as possible. At the same time, the light near the normal direction enters the second absorber and then reflects back to the first absorber.

Figure 11: Number of particles generated by stray light trap with 351 nm pulse at 1 J/cm². The use of fused and ABS makes the number of particles larger than 0.1 μm change to 1000 levels (ISO Class 3) even if the stray light of 1 J/cm² acts, and the stray light control of the system is effective.

Figure 12: Results of the optical field paper.
To verify the light field characteristics of stray light and the reliability of position calculation, a field drawing is added before the fused silica to observe the field drawing after the action of a 351 nm laser at 4 J/cm², as shown in Figure 12.

It can be seen from Figure 12 that stray light exists at the drawing position of the field, and the stray light has an interference modulation phenomenon. The calculation of stray light optical properties and position is reliable.

4. Summary

FOA is an important subsystem of the high power laser system, which provides the last stage beam control for laser beam-target coupling, realizing harmonic conversion, beam focusing, debris protection, and other functions. The more important things are to keep the system clean environment, slow down the damage speed of components, and ensure the high-throughput and stable operation of the system. In this study, we propose a kind of the model to design and manage the stray light. With our proposed method, both the high-order and first-order stray light can be managed at the same time. It is also proved from the actual experimental results that our method can obtain high cleanliness. We now conclude that our method can help accomplish the design and management of stray light for a compact system well.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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