Optimal design of high energy laser spatial filter with vacuum maintenance

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Abstract. Spatial filter is an important device of high energy laser. In order to ensure the above functions, it is necessary to keep a certain vacuum inside the spatial filter. The structure of the existing vacuum maintaining filter is complex and inconvenient to debug. In this paper, a space filter based on titanium pump maintenance is designed by improving the design and process of spatial filter. After testing, the vacuum degree inside the filter can reach 10^-5 Pa, which can meet the spatial filtering function of high-energy laser beam.

1. Introduction

In high-power laser system, spatial filter is a key technology unit, which is mainly used to remove the high-frequency modulation caused by diffraction or nonlinear effect in the process of light transmission. At the same time, by reducing the effective transmission distance of light in the system, the diffraction effect of light is suppressed [1]. Therefore, it can effectively improve the beam quality of the system. The optical structure of spatial filter is simple. It is composed of a pair of confocal positive lens and a small aperture filter diaphragm at the focus position, as shown in Figure 1 [2]. In order to avoid air breakdown and energy loss caused by laser focusing at the position of the filter aperture, the filter aperture must be placed in a vacuum environment to ensure a vacuum level of 10^-6 Torr (10^-4 Pa) around the filter aperture [3]. Usually for quick and easy optical debugging, choose to fix a pair of orthogonal lenses separately, and place a vacuum container between them to provide a vacuum environment for the aperture. The device is mostly a vacuum pipeline structure, with high transmittance planar mirrors at both ends as end-sealing devices.

Figure 1. Composition diagram of spatial filter.

Existing spatial filters can be divided into two categories. One type is non-maintainable filter. The vacuum pipes of such spatial filter are made of glass material. Depending on the material characteristics of glass material with low exhaust rate, it will be sealed permanently after the first vacuum pumping meets the requirements. This kind of filter is characterized by simple structure and debugging. However, because the material exhaust rate cannot reach the absolute zero value, its internal vacuum has been increasing. Another type is a maintainable filter, which needs to be connected to a Titanium pump to maintain the internal vacuum of the pipeline. It can detect whether
the internal vacuum of the filter meets the requirements in real time. Due to the requirements of installation and structural strength, the vacuum pipes of such filters are made of metal materials. The advantage of this kind of filter is that it can monitor the vacuum inside the filter, but because of the relatively complex system and heavy structure, it is not easy to debug. It is mostly used in laboratory scientific research environment, but less used in engineering.

Unmaintainable filters have great advantages in volume, weight, cost and technical maturity. At present, the research on spatial filter is mainly focused on beam shaping [4], optimum design of aperture [5, 6] and collimation technology [7, 8]. With the increasing application of high-energy lasers, complex systems like SG-II [9] and SG-III [10] are applied to multiple high-energy lasers at the same time. The system is complex and inconvenient to maintain, so it requires each device to be able to monitor the state in real time [11, 12]. Maintainable filters have certain application prospects in high-energy laser due to their monitorable state of internal vacuum. However, their complex structure and inconvenience for debugging have been limiting their application prospects.

In order to overcome the disadvantage of complex structure and inconvenient debugging of the maintainable filter, a small spatial filter is designed by optimizing the design and process, which is small in size and light in weight and easy to debug.

2. Structure analysis of maintainable filter
As shown in Figure 2, the maintainable filter consists of 8 parts. It includes assembly 1, assembly 2, assembly 3, angle valve, titanium pump, observation window, small aperture and two flat mirrors. The main structure of the maintainable filter can be divided into a component 3 to receive an observation window and a small aperture diaphragm, and a component 1 and a component 2 which are divided into left and right parts by the component 3; the component 1 and the component 2 are respectively sealed at the other end not connected with the component 3 to install a plane mirror for end surface sealing; the filter aperture is placed inside the component 3 and fixed; the component 3 is provided with a glass observation window, It is used to debug and observe the light spot, and can be used to upgrade the on-line monitoring system; component 1 and component 2 are respectively connected with the titanium pump and the angle valve. When the equipment is vacuumized, the angle valve is connected with the vacuum pump group and opened for vacuumizing operation. When a certain vacuum degree is reached, the titanium pump is opened. After the titanium pump is opened, the angle valve is closed and the vacuum pump group is removed.

![Figure 2. Structure diagram of spatial filter.](image)

Compared with the non-maintainable filter, the maintainable filter has heavy structure and complex operation. It is mainly reflected in two aspects:
1) The seal between glass and metal pipe adopts detachable connection, which makes the outer diameter of metal pipe filter with the same function twice that of glass pipe filter;
2) Large volume takes up a lot of installation space and compresses the debugging space; heavy quality increases the difficulty of ground repair when debugging the aperture.

For the above three problems, the most direct solution is to reduce the volume and weight, which can be achieved through the following two aspects:
1) The vacuum pipeline integrated design. As shown in Figure 2, the existing connection mode of components of pipeline structure adopts detachable connection, which is complex in structure and
occupies a large space. The filter volume can be reduced by selecting the non-detachable connection and redesigning the structure of each component, and connecting the components into one;

2) Choose a smaller titanium pump. As shown in Figure 2, Titanium pump occupies the largest volume and weight in the space filter. The higher the pumping speed is, the larger the volume and weight of titanium pump is. To reduce the pumping speed, the smaller the volume and weight of titanium pump can be selected.

3. The vacuum pipeline integrated design

3.1. Process analysis of non-detachable connection

Non-detachable connection includes argon arc welding, brazing and adhesive. Argon arc welding and other welding methods are mostly used for the connection between the same materials. Brazing and adhesive methods are mostly used for the connection between different materials. Non-detachable connection can be used for the connection between different materials, but it can only be repaired or replaced as a whole during maintenance. In this design, considering the application of a variety of materials in the spatial filter, the way of non-detachable connection is selected, and the way of offline overall debugging and overall replacement is selected during maintenance.

The welding method is selected for the connection of metal materials, and the following principles shall be followed in the design of welding structure:

1) Same material principle: the same material is used for all parts to reduce cracks and pores;
2) The principle of reducing welding seam: reduce the number and length of surface welding seam as far as possible;
3) Principle of easy surface treatment: easy surface treatment after welding;
4) Convenient leak detection principle: convenient connection of helium simple leak detector for leak detection.

The connection of different materials is mainly the connection between glass and metal structure in this design. Brazing is one of the main connection methods of glass metal connection in vacuum system, which is to fill the gap between glass and transfer alloy by high temperature liquid solder under capillary force in vacuum environment, so as to realize the welding of glass and transfer alloy. Among them, the transfer alloy is mostly made of metal materials with the same expansion coefficient as the glass, and then the alloy and metal materials are welded together to realize the connection between the glass and metal. There are many procedures in the brazing process, and the operation is cumbersome. It is easy to lead to the overall scrap due to improper individual parameters. Adhesive is a common connection between glass and metal in optical system. Due to the difference of expansion coefficient between metal material and glass material, when the temperature changes, it will bring additional stress to the glass lens, cause tiny deformation inside the lens, and affect the quality of laser beam. The adhesive method of silicone rubber can realize the connection between metal and glass, and at the same time, according to the temperature Depending on the characteristics of silicone rubber after curing, the stress changes caused by different expansion coefficients between the two can be eliminated, so as to ensure the state of the lens.

Through comprehensive comparison of the two connection modes, it is concluded that the silicone rubber adhesive mode is more suitable for the application environment of spatial filter. However, silicone rubber has high outgassing rate, and it is easy to cause leakage when adhesive. It is necessary to improve the adhesive process of optical lens in vacuum environment, including the following three aspects:

1) Before adhesive, the silicone rubber adhesive is placed in a vacuum environment for degassing, and then used after degassing;
2) The adhesive method was changed from multi-point adhesive to full seam adhesive, and the joint between the lens and the pipe port was filled with silicone rubber to prevent the occurrence of leakage;
3) After the adhesive, after the silicone rubber solidifies, the helium mass spectrometer leak detector is used to detect the leakage and repair the leakage.
3.2. Integrated structural design

As shown in Figure 3, in the design, the detachable connection between the various components is canceled and changed to non-detachable connection. The connection between the various components is made by means of welding and adhesive. Cancel the link flange, optimize the structure of component 3, and select the small titanium pump. At the adhesive port of the plane mirror and the adhesive port of the observation window, the adhesive table is designed to prevent the burr formed by cutting the end face of the metal tube from damaging the lens. The guide grooves are designed at both ends of the assembly 3 to ensure the coaxiality of the assembly 1 and assembly 2 at both ends before and after welding.

![Figure 3. Schematic diagram of the connection of each part of the spatial filter.](image)

The comparison between the structure optimization of component 3 with the largest cross-section area is shown in Figure 4. With detachable connection, the cross-sectional diameter of filter main pipe at each connection port is 74mm; with non-detachable connection, the maximum cross-sectional area of filter main pipe is 30mm x 30mm, and the circular envelope diameter is 42mm.

![Figure 4. Comparison between the structure optimization of component 3 with the largest cross-section area.](image)

The leakage rate of detachable and non-detachable connection is less than 10⁻¹⁰pa · m³ / s measured by helium mass spectrometer. After changing the connection mode, the air leakage rate of the system has no obvious change.

4. Choose a smaller titanium pump

Calculation formula of pumping speed according to demand [13]

\[
S_p = \frac{SU}{u-S}
\]  

Where:

- \(S\): Effective pumping speed of the system
- \(S_p\): Demand pumping speed
The selection of pumping speed of titanium pump is affected by two factors, i.e. flow conductivity and effective pumping speed. Therefore, the smaller titanium pump can be realized by increasing the flow conductivity and reducing the effective pumping speed.

4.1. Improving the flow conductivity of the extraction port

The conductance at the pump of the spatial filter is limited by the aperture at the minimum cross-sectional area of the filter system.

According to the calculation formula of the conductance and the pumping speed of the molecular flow in the circular hole [13]:

$$ U = 9.12d^2 $$  \hspace{1cm} (2)

Where:
- $U$: The conductance of a circular hole in the state of molecular flow (L / s)
- $d$: Diameter of round hole (cm)

Optimization design of small aperture diaphragm

When the laser blocked by the small aperture is up to GW / cm², plasma will be produced, and a plasma region will be formed near the small aperture. When the laser passes through the region, it will be deflected or blocked, resulting in the degradation of beam quality. Due to the interaction between the obstructed medium and high frequency light and the keyhole plate will produce plasma sputtering, which will affect the beam quality, especially in the case of long pulse, it may also hinder the optical transmission channel. Therefore, the size of the filtering keyhole is a key parameter, which is directly related to the filtering effect. The low-pass filtering function of the small aperture diaphragm only allows the low-frequency component to pass through and hinders the high-frequency component. The aperture of the small aperture diaphragm should not be too large, otherwise there is no filtering function. At the same time, the aperture of small aperture diaphragm should not be too small due to the blocking effect of plasma sputtering. In order to improve the flow conductivity of the extraction port and ensure the function of the small aperture, it is necessary to optimize the structure of the small aperture. The size of the keyhole should not be less than 20 times the diffraction limit [14].

The calculation formula of the small hole under the diffraction limit of 20 times is [14]

$$ d_k = 20 \times \frac{2.44\lambda f}{D} $$  \hspace{1cm} (3)

Where:
- $d_k$: Hole diameter
- $D$: The diameter of the incident spot, if the spot is round, D is the spot diameter; if the spot is square, D is the diagonal diameter
- $\lambda$: Laser wavelength
- $f$: Lens focal length

If $\lambda = 1053$ nm, $d = 20$ mm and $F = 400$ mm, we can get $d_k = 1.37$ mm.

In order to ensure the beam quality, it is necessary to isolate the laser from passing through the aperture. In order to achieve the above functions, the traditional single board filter hole structure is optimized and improved. The double-layer light barrier design is adopted. On each layer of light barrier, a gap is opened to form an S-shaped gas flow path, and the laser transmission path is cut off at the same time. As shown in Figure 5, when there is a gas flow, it can flow through the S-shaped path, and when there is a laser passing through, it is blocked from transmission.

![Figure 5. Schematic diagram of S-type access.](image-url)
Figure 6 shows the structure model of the filtering hole, and Figure 7 shows the gas flow area, which can be equivalent to a circular hole with a cross-sectional area of 13.6 mm.

Comparison of optimization results

As in Equation (1), after optimization, the conductance of gas flow area is \( u = 9.12 \times 1.36 \times 1.36 = 16.9 \) (L / s).

4.2. Reduce the effective pumping speed

Because the leakage rate of spatial filter can only be infinitely close to 0, but can not reach 0. For the vacuum system of vacuum maintaining equipment, an effective pumping speed must be loaded in order to maintain the equilibrium pressure and achieve the required vacuum. According to the gas balance formula in vacuum system [13]

\[
P = \frac{Q}{S} + P_0
\]

Where:
- \( P \): Pressure reached by the system
- \( P_0 \): limit pressure of vacuum pump
- \( S \): Effective pumping speed of the system
- \( Q \): System leakage rate

We can get [13]

\[
S = \frac{Q}{P - P_0}
\]

It can be seen that the pumping speed \( S \) of the system is proportional to the leakage rate \( Q \) of the system. In order to select a smaller vacuum pump, the leakage rate of the spatial filter must be reduced. The leakage rate of the vacuum system can be divided into three parts: 1) the real leakage rate of the system, 2) the outgassing rate of the material in the system, and 3) the gas rate produced during the system operation. It can be expressed by the following formula:

\[
Q = Q_1 + Q_2 + Q_3
\]

Where:
- \( Q_1 \): air leakage rate of spatial filter, where the value is \( 10^{-10} \text{pa} \cdot \text{m}^3 / \text{s} \),
- \( Q_2 \): outgassing rate of spatial filter material,
- \( Q_3 \): the gas generation rate of the spatial filter is 0.

The material outgassing in the system is the main source of the leakage rate, which is generally several orders of magnitude higher than the real leakage rate of the system. Therefore, to reduce the leakage rate of the system, the main consideration is to reduce the outgassing rate.

Reduce outgassing rate

The outgassing of materials is the main source of leakage rate in vacuum system. The outgassing rate of materials can be reduced by pretreatment process [13]. Table 1 shows the outgassing rate per unit
area of each material under different surface treatments under vacuum for 1 h and 10 h. It can be seen from Table 1 that the silicone rubber used for bonding and sealing has the highest outgassing rate per unit area, and the metal material constituting the main structure has the largest area, which is one of the main components of the total outgassing rate.

**Table 1. Outgassing rate per unit area of different materials [15].**

| Material                          | Vacuum pumping 1h | Vacuum pumping 10h | Use location          | Total area (cm²) |
|----------------------------------|-------------------|--------------------|-----------------------|-----------------|
| Stainless steel (untreated)      | 2.8×10⁻⁸          | 3×10⁻⁹            |                       |                 |
| Stainless steel (electropolishing) | 8×10⁻⁹            | 6×10⁻¹⁰           |                       |                 |
| Stainless steel (ultrasonic cleaning) | 3.2×10⁻⁹         | 5.5×10⁻¹⁰         |                       |                 |
| Aluminum alloy (untreated)       | 7×10⁻⁸            | 7.7×10⁻⁹          | Main pipeline         | 377.0           |
| Aluminum alloy (chemical polishing) | 4.3×10⁻⁹         | 3.4×10⁻¹⁰         |                       |                 |
| Oxygen free copper (untreated)   | 1.85×10⁻⁸         | 1.2×10⁻⁹          |                       |                 |
| Oxygen free copper (mechanical polishing) | 1.9×10⁻⁹        | 1.6×10⁻¹⁰         |                       |                 |
| Silicon rubber                   | 1.7×10⁻⁵          | 2.2×10⁻⁷          | Adhesive seal         | 0.5             |
| Glass                            | 10⁻¹⁴–10⁻¹⁵       | ——                | Both ends / observation window | 10.3 |

Among the materials that can be used as the main structure of filter pipeline, there is not much difference in the outgassing rate among stainless steel, oxygen free copper and aluminum alloy. Based on the principle of the same material, the stainless steel material consistent with the angle valve and titanium pump shell material is selected. After surface treatment, the outgassing rate of stainless steel material will be improved by an order of magnitude. Therefore, the electropolishing process of stainless-steel material is added in production, and the ultrasonic cleaning process is added before assembly.

**Comparison of optimization results**

The total outgassing rate of spatial filter can be calculated according to the following formula:

\[
Q_2 = \sum_{i}^{n} Q_{oi} \cdot A_i
\]  
(7)

Where:

- \( Q_{oi} \): outgassing rate per unit area of various materials
- \( A_i \): Total area of various materials

The results show that the total outgassing rate is \( Q_2 = 1.24 \times 10^{-5} \) (Torr · m³ / s), the total outgassing rate is \( Q_2 = 3.4 \times 10^{-7} \) (Torr · m³ / s), the total outgassing rate reduced by 72%.

**4.3. Election of titanium pump**

According to Formulas (5) (6), where \( P-P_0 = 10^{-6} \)torr, and \( s \approx 0.34 \) (L/s)

According to Formula (1), it can be calculated

The demand pumping speed is 0.35 (L/s). Considering the mature product model and redundant design needs, the 2 L/s pumping speed titanium pump is selected to replace the original 10L/s titanium pump.

**5. Performance test after optimization**

**5.1. Optimization results**

Before optimization, the cross-section diameter of filter main pipe is 74mm, the pumping speed of titanium pump is 10L / s, the weight of titanium pump is 5kg, and the total weight of system is more than 8kg. After optimization, the assembled spatial filter is shown in Figure 8. The main pipe section
of the filter is 30mm, the pumping speed of the titanium pump is 2 (L/S), which is used to maintain the internal vacuum of the spatial filter. The weight of the titanium pump is 1kg, and the total weight of the system is less than 3kg.

5.2. Test method
The assembled spatial filter is selected for the test, as shown in Figure 8. In the process of testing, the helium mass spectrometer leak detector is used to detect the leakage rate of the spatial filter, and the leakage rate is $9 \times 10^{-11} \text{Pa} \cdot \text{m}^3/\text{s}$, which meets the requirements of the spatial filter. The combination of mechanical pump and molecular pump is used to pump the space filter, and the titanium pump is started when the vacuum degree reaches $10^{-3}$Pa. After the titanium pump can work stably, close the vacuum valve and disconnect the connection between the space filter and the molecular pump group. At this time, observe and record the titanium pump current displayed on the power supply of the titanium pump. The discharge current $I(A)$ of titanium pump is directly proportional to the $n$th power of gas pressure $P$(Torr) [13]

$$I = k \cdot P^n$$

(8)

Where:
- $k$: Scale factor,
- $n$: A factor more than 1.

For a specific titanium pump, $k$ and $n$ are known, and the pressure in the pump can be measured according to the discharge current[5].

5.3. Test results
During the test, observe and record the voltage and current displayed on the power supply of the titanium pump, as shown in Figure 9. As in Equation (8), according to the test data of titanium pump manufacturer, $k$ is 0.95, $n$ is 1.12, and the corresponding vacuum degree is calculated. The results are shown in Table 2.
| Recording time | Voltage (V) | Current (μA) | Vacuum (10⁻⁴Pa) |
|----------------|------------|-------------|-----------------|
| 9:06           | 3921       | 1.13        | 3.26            |
| 11:06          | 3925       | 0.24        | 0.81            |
| 13:06          | 3948       | 0.12        | 0.44            |
| 15:06          | 3958       | 0.10        | 0.37            |
| 17:06          | 3964       | 0.08        | 0.31            |
| 21:06          | 3966       | 0.08        | 0.31            |
| 1:06           | 3968       | 0.07        | 0.27            |
| 5:06           | 3973       | 0.07        | 0.27            |
| 8:15           | 3974       | 0.06        | 0.24            |

After the titanium pump worked independently for 2h, the vacuum degree inside the equipment reached $6.1 \times 10^{-5}$pa and continued to decrease. It can meet the requirement of vacuum environment for filtering aperture.

6. Test result

In this paper, a miniaturized maintainable filter for high energy laser is designed based on the common design ideas and production process in laser and vacuum engineering. After testing, the vacuum degree of the filter can reach $10^{-5}$pa, which can meet the spatial filtering function of high energy laser beam. Under the condition of meeting the original index, the cross-sectional area diameter of the filter is reduced from $φ74$mm to $φ42$mm, and the weight of the filter is reduced by 62.5%. It provides some technical accumulation for the engineering application of high energy laser maintainable filter in complex system. But there is a big gap in volume and weight compared with the unsustainable filter. The next step is to optimize the corner valve structure and titanium pump connection structure, and further optimize the miniaturization of the unsustainable filter.

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