Research Article

Design and Analysis of Optical Window Encapsulation Structure for Laser Doppler Deep-Sea Hydrothermal Velocity Measurement System

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The optical window is an essential channel for optical signal transmission and return of a deep-sea hydrothermal velocimetry system. Due to its unique structural design, the stress concentration of the optical window will occur under the action of deep-sea high pressure, resulting in cracks at the corner of the high-pressure surface of the optical window, which leads to the inaccurate convergence of the optical signal. A pressure self-balancing optical window package structure is designed to solve the problem. The stress at the optical window is numerically analyzed, and the forces of self-balancing and non-pressure self-balancing optical windows under the same seawater pressure are compared. The results show that the maximum stress at the stress concentration can be reduced by 53% using the pressure self-balancing method, and the phenomenon of stress concentration can be effectively eliminated. In addition, to verify the feasibility of the design and the accuracy of the numerical calculation results, the optical window and its encapsulation structure were experimentally studied, and the deep-sea performance test experiment was carried out on the “Jiaolong” submersible, which further verified the accuracy of the results.

1. Introduction

Submarine hydrothermal flow rate is of great significance to the research on the material output flux of hydrothermal vents, the seafloor changes in seafloor geological structure, and the distribution of biological communities [1–3]. The deep-sea hydrothermal velocity measurement system based on the principle of laser Doppler velocity measurement is the primary measurement method to measure velocity. The encapsulation structure of the measurement system, as the carrier of internal components, is the premise to ensure the safety and reliability of the system [4].

As an external upgrade component of the “Jiaolong” submersible, the laser Doppler deep-sea hydrothermal velocity measurement system will be equipped with the “Jiaolong” for in situ measurement experiments at a water depth of 7000 m. The optical window is crucial for the entire system as the deep-sea hydrothermal fluid velocity measurement system’s optical signal sending and receiving channel. The main technical issues involved are as follows:

1) The optical window belongs to the light-transmitting element, and the material is sapphire crystal. Therefore, compared with the metal pressure chamber, the optical window will be the weakest position in the entire package structure due to the limitation of the pressure resistance of the glass material.

2) The pressure plate of the optical window squeezes the optical window inward, resulting in the stress concentration at the corner of the optical window. As a result, the highly brittle optical window is crushed, the refractive index of the medium is changed, and the optical signal emission path is changed so that the optical signal cannot be collected in the hydrothermal fluid.
The optical window, as an isolation window or observation window of the internal and external environment, is an important part of optical instrument. Historically, theoretical or experimental methods have been used to study optical windows subjected to uniform external pressure. In the late 1930s, Professor Piccard [5] first introduced plane disc windows with conical bearing surfaces that resemble the shapes of conical frustums into the ocean engineering field. ASME PVHO-1 also made detailed regulations on the observation window for manned submersibles [6].

Li et al. [7] calculated the deformation of the optical window under the condition of force-thermal coupling. They optimised the glass thickness of the optical window in a complex environment, which provided a basis for the design of the window. Zhang et al. [8] showed that a reasonable support structure could effectively improve the window support efficiency, reduce the thickness and quality of the window, and reduce the volume absorption rate of the incident light. Li et al. [9] also studied the influence of pressure, temperature, and vibration on the measurement results of the optical window under dynamic pressure by experimental methods.

Stachiw [10] showed that stress concentration would cause damage to the observation window and reduce the refractive index of the material. In contrast, Kemperor et al. [11] analyzed the acrylic observation window’s fatigue and stress using the finite element method. Du et al. [12] also studied the stress and deformation of the thick conical observation window under uniform external pressure through the finite element method. The damage reason and design criterion of the acrylic acid observation window have been studied in detail.

Mattheck et al. [13, 14] have developed and used the biological growth method, which reduces stress concentration using the fillet radius technique and biological growth method. Pranesh et al. [15, 16] also showed that stress concentration occurred at the corners of the low-pressure surface of the observation window and the notch regions of the flange. Using the fillet radius method can reduce the maximum stress at the stress concentration by 64%. The maximum stress at the stress concentration can be reduced by 71% with the biological growth method.

In this study, the sapphire crystal is tough (second only to diamond), and it is extremely difficult to process. The commonly used fillet radius and biological growth method to reduce stress concentration will substantially increase the cost. Therefore, a pressure self-balancing optical window package structure is proposed. Firstly, the pressure self-balancing is realized by changing the position of the O-ring at the optical window. Secondly, the numerical simulation method is used to analyze the stress distribution of the optical window under the external pressure of seawater. Then, the stress distribution of the self-balancing optical window and nonpressure self-balancing optical window under the same seawater pressure is compared. Finally, combined with the actual working conditions, the experimental scheme of water tightness and pressure resistance test of pressure self-balancing optical window packaging structure is designed. The complete package structure test is completed in the deep-sea high-pressure environment simulation laboratory. The deep-sea performance test is carried out with “Jiaolong” submersible, which verifies the feasibility of the design scheme. This study provides a basis for designing optical window packaging structures in deep-sea optical instruments.

2. Materials and Models

2.1. Deep-Sea Hydrothermal Velocity Measurement System and Its Encapsulation Structure. Figures 1 and 2 show the schematic diagram of the laser Doppler deep-sea hydrothermal velocity measurement system and its encapsulation structure. The system consists of the light source, transmitting optical path, receiving mirror group, optical platform, and a signal processing circuit. Two single-frequency narrow-linewidth green fiber lasers emit the signal in the transmitting optical path, converging in the hydrothermal and reflected and received by the receiving mirror group. The pressure chamber encapsulates the whole system. The pressure chamber comprises an optical window, optical window flange, optical window pressing plate, shell, and flat cover head.

2.2. Structural Design. ASME PVHO-1 specifies a variety of standard geometrical optical windows [6]. Among them, cylindrical and conical optical windows can resist higher pressure loads, have good development prospects, and are widely used. However, to meet the requirements of optical design and optical path propagation and minimize the contact area between the high-pressure surface of the optical window and seawater, the combination of cylindrical and the conical structures is adopted in the design process. The designed operating depth of the optical window is 7000 m, the inner diameter is 150 mm, and the thickness is 60 mm. The cone angle is 27°, which is the maximum value under the condition that the optical path is not obstructed. It not only blocks the optical path but also minimizes the contact area between the optical window’s high-pressure surface and seawater. The structure and size of the optical window are shown in Figure 3.

The optical window and its encapsulation structure, as shown in Figure 4, are composed of an optical window, optical window flange, optical window pressure plate, and O-ring. Three optical transmission channels are set up on the flange of the optical window for sending and returning optical signals. A first annular notch 4a is provided on the side of the optical window flange close to the optical window. The optical window pressing plate is provided with a second annular notch 5a matching the first annular notch 4a on the side close to the optical window. The first annular notch and the second annular notch are spliced together to form an annular groove. Install the optical window in the annular groove. The optical window pressing plate related to the optical window flange through screws to fix the optical window firmly.

In the prior art, a sealing device is arranged between the optical window pressing plate and the optical window, as
When subjected to external seawater pressure, the optical window pressing plate squeezes the optical window inward, causing stress concentration at the corners of the optical window. As a result, the optical window will be crushed, and stress failure will occur. In this design process, there is no longer a sealing device between the optical window pressing plate and the optical window. The sealing device is arranged between the cylindrical surface of the optical window and the flange of the optical window, as shown in the seal B of Figure 6. And, a gap G is left between the conical surface of the optical window and the pressing plate of the optical window, as shown in Figure 6. At the same time, to make it easier for seawater to flow into the gap G along the contact surface between the optical window pressing plate and the optical window. The side of the optical window pressing plate near the optical window should be designed as a frosted or embossed surface. Besides, the seawater can flow into the gap G along the contact gap between the optical window pressing plate and the optical window by changing the position of the sealing structure at the optical window so that the pressure on both sides of the optical window pressing plate is equal to the seawater pressure at this depth to balance the seawater pressure on the optical window pressure plate. In diving from 0 to 7000 meters, the external seawater pressure rises, and the seawater pressure inside the optical window pressing plate rises constantly and is always equal to the external seawater pressure. Therefore, the pressure plate of the optical window can adapt to the change of the external seawater pressure to eliminate the stress concentration phenomenon at the corner of the optical window caused by the bending and deformation of the optical window pressing plate under high-pressure deep-sea conditions.

Figure 4 shows the location of the seal in the optical window encapsulation structure. The seals A, B, D, and E play a major sealing role to prevent seawater from flowing into the pressure chamber along the contact gap. The sealing form is the O-ring seal. Seal C plays a sealing role and has a buffering effect to protect the optical window from damage caused by local stress. The material of seal C is copper, and the sealing form is gasket seal.

2.3. Material Properties. Commonly used materials for optical windows are fused quartz, magnesium fluoride, spinel, and sapphire crystal [17]. Among them, sapphire crystal has high infrared transmittance, which is an ideal material for working in infrared band windows. The laser Doppler deep-
sea hydrothermal fluid velocity measurement system puts forward higher requirements for the infrared permeability of the material at the optical window. Therefore, the sapphire crystal is selected as the optical window material in this design. In addition to its excellent infrared transmittance, it also has other favourable properties, such as high hardness and chemical stability. TC4 titanium alloy is selected for the optical window pressing plate, optical window flange, cylinder, and flat cover head. It ensures sufficient strength and rigidity and has strong corrosion resistance. Table 1 shows the material properties of TC4 and sapphire crystal.

### 3. Stress Analysis by the Numerical Method

#### 3.1. Mathematical Model

Transient structural analysis is also called time history response analysis, a method used to analyse the dynamic response of a structure under a load that varies with time. As the optical window is constantly changing with the increase of seawater pressure in the diving process of the “Jiaolong” submersible, it is always in a high-stress environment, so the transient structure is used for analysis in this study. The motion equation of the second-order system is

$$\begin{align*}
&M\dddot{\mathbf{u}} + C\dot{\mathbf{u}} + K\mathbf{u} = F^a,
\end{align*}$$

where $[M]$ is the structural mass matrix; $[C]$ is the structural damping matrix; $[K]$ is the structural stiffness matrix; and $[F^a]$ is the applied load vector. $\dot{\mathbf{u}}$ is the node acceleration vector; $\ddot{\mathbf{u}}$ is the node velocity vector; and $\mathbf{u}$ is the nodal displacement vector. Suppose

$$\begin{align*}
&\mathbf{u}_n + 1 = \mathbf{u}_n + [(1 - \delta) \mathbf{u}_n + \delta \mathbf{u}_n + 1] \Delta t, \\
&\mathbf{\dot{u}}_n = \mathbf{\dot{u}}_n + \frac{1}{2} \mathbf{\ddot{u}}_n + \frac{1}{2} \alpha \mathbf{\dddot{u}}_n + \frac{1}{2} \mathbf{\dddot{u}}_n + 1 \Delta t^2,
\end{align*}$$

where $\alpha$ and $\delta$ is the Newmark time integration constant and $\Delta t$ is the time interval, $\Delta t = t_{n+1} - t_n$. The iterative equation can be obtained as follows:

$$\begin{align*}
&M[\dddot{\mathbf{u}}] + [C][\dot{\mathbf{u}}] + [K][\mathbf{u}] = [F^a],
\end{align*}$$

According to equation (3), $\mathbf{u}_n$ can be expressed by $\mathbf{u}_n$, $\mathbf{\dot{u}}_n$, $\mathbf{\ddot{u}}_n$, and $\mathbf{\dddot{u}}_n$, as

$$\begin{align*}
&\mathbf{u}_n = \frac{1}{a\Delta t^2} \left[ \mathbf{u}_n + 1 - \frac{1}{2}\mathbf{u}_n - \frac{1}{2} \mathbf{\dot{u}}_n - \left( \frac{1}{2} - \frac{1}{2}\alpha \right) \mathbf{\ddot{u}}_n \right].
\end{align*}$$

Substituting equation (5) into equation (2), $\mathbf{\dddot{u}}_n$ can be expressed by $\mathbf{u}_n$, $\mathbf{\dot{u}}_n$, $\mathbf{\ddot{u}}_n$, and $\mathbf{\dddot{u}}_n$, as

---

### Table 1: Material properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>TC4</th>
<th>Sapphire crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>MPa</td>
<td>106000</td>
<td>380000</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>—</td>
<td>0.3</td>
<td>0.28</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>4550</td>
<td>3950</td>
</tr>
<tr>
<td>Yield strength</td>
<td>MPa</td>
<td>824</td>
<td>—</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>—</td>
<td>2000</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>—</td>
<td>260</td>
</tr>
</tbody>
</table>

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Figure 5: A window with a sealing device between the optical window pressing plate and the optical window. (a) Optical windows for optical instruments. (b) Observation window for manned.

Figure 6: Partial enlarged of gap G.
In summary, we can gradually solve the displacement, velocity, and acceleration response of the object at any time according to the initial state of the object under the excitation of the dynamic load.

### 3.2. Failure Criterion
Sapphire crystal is a brittle material, and its failure criterion generally uses the first strength theory [18]. It is expressed that the maximum tensile stress causes the material fracture. When the maximum tensile stress reaches a specific limit value, the material will fracture. The strength condition is shown as follows:

\[
\sigma_1 \leq [\sigma] = \frac{\sigma_0}{n},
\]

where \(\sigma_1\) is the first principal stress, MPa; \([\sigma]\) is the allowable stress of the material, MPa; \(\sigma_0\) is the tensile strength of the material; MPa; and \(n\) is the safety factor. For brittle materials subjected to dynamic load, the safety factor is taken as \(n = 2.0\), and then the allowable stress of the material is \([\sigma] = 260/2 = 130\) MPa.

### 3.3. Nonpressure Self-Balancing Optical Window Stress Analysis
Figure 7 shows the geometric model of the stress analysis of the nonpressure self-balancing optical window, in which the three-dimensional assembly model is used for stress analysis. The optical window constantly changes with the seawater pressure experienced by the “Jiaolong” submersible during its dive, so the transient structural module in ANSYS Workbench is selected for analysis. In the optical window stress analysis, it is assumed that the optical window pressing plate will be in complete contact with the surface of the optical window under high pressure. Therefore, O-rings are not considered in the numerical analysis. The upper-end cover adopts fixed restraint. The seawater pressure \(p\) is applied to the total outer surface in contact with seawater, and \(p\) is a function of the depth, salinity, and temperature, which can be calculated as follows derived by Leroy [19].

\[
p = 1.04 + 0.102506 \left(1 + 0.00528\sin^2\phi\right)z + 2.524 \times 10^{-7}z^2,
\]

where \(p\) is the seawater pressure, kg/cm²; \(\phi\) in degrees of latitude, 30°S; and \(z\) is the seawater depth, m. Meanwhile, \(z\) is also a function of the dive time. The diving speed of “Jiaolong” is about 40 m/min, and it takes about 10500 s to dive from the sea to 7000 m at the bottom of the sea. Therefore, the pressure load can be defined as

\[
p = 1.04 + 0.102506 \left(1 + 0.00528\sin^230^\circ\right)\left(\frac{40}{60}t\right) + 2.524 \times 10^{-7}\left(\frac{40}{60}t\right)^2,
\]

where \(t\) is the dive time, s.

### 3.4. Pressure Self-Balancing Optical Window Stress Analysis
Figure 8 shows the geometric model of the pressure self-balancing optical window stress analysis. The setting of the boundary conditions and the size of the pressure load \(p\) is consistent with the nonpressure self-balancing optical window. The difference lies in the position where the pressure load is applied. The pressure self-balancing optical window allows seawater to flow into the gap \(G\) along the
contact gap between the optical window and the optical window pressing plate. At this time, the inner and outer surfaces of the optical window pressing plate are simultaneously subjected to seawater pressure. Meanwhile, the high-pressure surface and the conical surface of the optical window are also subjected to seawater pressure.

### 3.5. Results and Discussion

In the simulation, five mesh densities are adopted in the calculation, as shown in Table 2. It found that, for the pressure self-balancing optical window, a mesh number of 986820 is enough to represent the simulation results correctly. For the nonpressure self-balancing optical window, the mesh number 1492959 is enough to represent the simulation results correctly.

Table 2: Simulation analysis results under different mesh numbers.

<table>
<thead>
<tr>
<th>Group</th>
<th>Self-balancing optical window</th>
<th>Non-self-balancing optical window</th>
<th>Maximum tensile stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>335625</td>
<td>452801</td>
<td>83.60</td>
</tr>
<tr>
<td>2</td>
<td>584347</td>
<td>84099</td>
<td>96.59</td>
</tr>
<tr>
<td>3</td>
<td>877759</td>
<td>1019468</td>
<td>99.04</td>
</tr>
<tr>
<td>4</td>
<td>986820</td>
<td>1492959</td>
<td>113.30</td>
</tr>
<tr>
<td>5</td>
<td>1184763</td>
<td>1848772</td>
<td>110.85</td>
</tr>
</tbody>
</table>

Figure 9 shows the distribution of the first principal stress of the nonpressure self-balancing optical window. (a) High-pressure surface. (b) Low-pressure surface.

Figure 10 shows the distribution of the first principal stress of the pressure self-balancing optical window. Compared with Figures 9 and 10, it can be found that, on the one hand, the inflow of seawater can balance the inward bending deformation of the optical window pressing plate; on the other hand, the inflow of seawater makes the stress of the optical window simple, all of which are compressive stresses. Moreover, we know that the stress gradually changes from compressive stress to tensile stress from the high-pressure surface to the low-pressure surface. And, the maximum tensile stress is only 113.3 MPa, which appears at the edge of the low-pressure surface. The maximum tensile stress of the optical window is reduced by 53% by means of pressure self-balance. Figure 11 shows the relationship curve between the maximum stress of the optical window of the two structures and the depth of diving obtained through numerical analysis. The relationship between the maximum stress of the optical window of the two structures and the depth of the diving is linear. The maximum tensile stress increase with the increase of the diving depth. Among them, the maximum tensile stress of the nonpressure self-balancing optical window increases rapidly, which reaches the allowable stress of sapphire crystal at a water depth of 3981 m. The reason is that the nonpressure self-balancing optical window will produce greater stress under a small pressure due to the squeezing action of the optical window pressing plate after entering the water. The stress concentration of the optical window is caused by the extrusion of the optical window pressing plate. The maximum tensile stress increase of the
pressure self-balancing optical window is much smaller than that of the non-pressure self-balancing optical window. The maximum tensile stress is always less than the allowable stress of sapphire crystal. The results show that using the pressure self-balancing method can minimize stress and reduce stress concentration.

Figure 12 shows the deformation cloud image of the pressure self-balancing optical window. The maximum deformation appears at the center of the low-pressure surface, and the maximum deformation is only 0.095 mm. Figures 13 and 14 show the radial and axial stress distribution of the pressure self-balancing optical window. On the high-pressure surface, both the radial and axial stress are compressive stresses, and the stress distribution is relatively uniform. On the low-pressure surface, the maximum radial stress appears at the edge of the low-pressure surface, and the maximum axial stress appears at the edge of the optical path emission channel on the low-pressure surface. And, the maximum radial tensile stress and the maximum axial tensile stress are less than the allowable stress of sapphire crystal.

Figures 15 and 16 show the variation curve of the maximum radial and axial pressures of the pressure self-balancing optical window with the dive time. It can be found that the maximum radial tensile stress and maximum radial compressive stress have a linear relationship with the dive time. The maximum axial stress increases linearly between 0 s and 7500 s (0–5000 m) and nonlinearly increases between 7500 s and 10500 s (5000 m–7000 m). The optical window material is sapphire glass, brittle material with no yield stage. In addition, it can be inferred from the position of the maximum axial stress in Figure 14(b) that the cause of the nonlinear change is the plastic deformation of the copper gasket. As a result, the contact state between the optical window and the copper gasket changes, and the contact nonlinear change is produced. Therefore, the stress of the...
copper gasket is analyzed. Figure 17 shows the variation curve of the equivalent (von Mises) stress and equivalent plastic strain of the copper gasket with the dive time. The maximum equivalent (von Mises) stress of the copper gasket increases linearly between 0 and 5000 s and tends to be flat between 5000 s and 10500 s. Moreover, the copper gasket generates plastic strain when the dive time is 5000 s. At this time, the copper gasket entered the yield stage and produced plastic deformation. Eventually, the contact state between the optical window and the copper gasket changed from “open” to “closed,” which caused a nonlinear change in the axial stress.

4. Experiment

4.1. Water Tightness and Pressure Resistance Test. The equipment will be tested at China National Deep Sea Center. The National Deep Sea Center has a deep-sea high-pressure environment simulation laboratory. It mainly undertakes the long-term strength experiment, stability experiment, and sealing experiment of the pressure-resistant structure under deep-sea low-temperature and high-pressure conditions. The experimental object is a complete encapsulation structure. It is composed of an optical window, optical window pressing plate, optical window flange, shell, flat cover head, and O-ring. A waterproof connector is installed on the flat cover head to seal the encapsulation structure (it will also be used to transmit the power supply signal during actual use). The test object is put into a pressure cylinder, and the encapsulation structure is pressurized by water, as shown in Figure 18. According to the rule requirement, the test pressure is 1.25 times the design pressure, calculated as follows. Moreover, the calculated value is 91.5 MPa.

\[
p = 1.25 \left[ 1.04 + 0.102506 \left( 1 + 0.00528 \sin^2 30^\circ \right) \left( \frac{40}{60} t \right) \right] + 2.524 \times 0^{-7} \left( \frac{40}{60} t \right)^2 .
\] (12)

The experiment consists of a hydrostatic pressure experiment and a dynamic pressure experiment. Firstly, the hydrostatic pressure experiment is carried out:

(i) The pressure gradually increases from 0 MPa to 91.5 MPa after the start of the experiment.
The pressure is released after holding for 8 hours.

The encapsulation structure is taken out and inspected.

Then, the dynamic pressure experiment is carried out after the success of the hydrostatic pressure experiment: the pressure is gradually increased from 0 MPa to 91.5 MPa, and then the pressure is released. The encapsulation structure is taken out after 6 cycles of pressure and pressure relief. To simulate the working state of the velocity measurement system accurately, the pressure rise and fall rate is the same as that of "Jiaolong" submersible during the experiment.

As shown in Figure 19, the encapsulation structure is taken out and inspected after the pressure experiment. After inspection, it can be found that the sapphire crystal at the optical window is in good condition without crack and breakage. There is no water drop and water vapor inside the encapsulation system, and the shell has no instability. The whole encapsulation structure has no damaged and leakage, and the sealing and pressure resistance can meet the use requirements of 7000 m underwater. Then feasibility of the design is verified.

4.2. Underwater Performance Test. The performance of the laser Doppler deep-sea hydrothermal velocity measurement system was tested with "Jiaolong" submersible. The equipment was installed on the sampling column of "Jiaolong" submersible for appearance and electrical inspection before launching. After the inspection, they began to dive and turned on the speed measurement system when it reached the bottom of the sea. The results show that the optical signals can be accurately converged, and the equipment works properly during the whole test. The appearance inspection and underwater working status of the equipment before launching are shown in Figure 20.
Figure 14: Distribution of axial stress in pressure self-balancing optical window. (a) High-pressure surface. (b) Low-pressure surface. (c) Section view.

Figure 15: The variation curve of the radial stress of the pressure self-balancing optical window with the dive time.

Figure 16: The variation curve of the axial stress of the pressure self-balancing optical window with the dive time.
Figure 17: The variation curve of the equivalent (von-Mises) stress and equivalent plastic strain of the copper gasket with the dive time. (a) Equivalent (von-Mises) stress. (b) Equivalent plastic strain.

Figure 18: Experimental setup details. (a) Assembled complete package structure. (b) The package structure is placed in the experimental device.

Figure 19: Experimental results.
5. Conclusions

Aiming at the stress concentration problem in the optical window of the deep-sea hydrothermal velocity measurement system, design a pressure self-balancing optical window packaging structure. The optical window is studied by numerical analysis and verified by experiment. The main conclusions of this study are as follows:

1. Compared with the conventional optical window package structure, the pressure self-balancing optical window package structure only needs to change the position of the sealing structure at the optical window. In this process, the optical window pressure plate can adapt to the change in external seawater pressure, and the phenomenon of stress concentration in the optical window can be eliminated under deep-sea high pressure. Therefore, introducing the pressure self-balancing method provides a new idea for designing the package structure of the deep-sea optical window. Moreover, for hard sapphire glass, the pressure self-balancing method can reduce the processing difficulty and manufacturing cost more than the fillet radius and biological growth methods.

2. The maximum tensile stress on the nonpressure self-balancing optical window is 238.41 MPa. The maximum tensile stress can be reduced to 113.3 MPa by pressure self-balancing. Applying the pressure self-balancing method solves the contact problem between the pressing plate of the optical window and the optical window and makes the stress of the optical window simple, thus reducing the stress.

3. The hydrostatic pressure test, dynamic pressure test, and deep-sea performance test show that the pressure self-balancing packaging structure has high strength and sealing performance, and the optical signals can converge accurately can meet the requirements of 7000 m underwater.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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