Design of cryogenic long-wave infrared detection system

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Abstract. To address the demand for detection of point/dim targets in complex environments, a cryogenic long-wave infrared detection system was designed. In order to improve the target detection capability, the system adopts high-order aspheric surfaces to reduce the number of optical lenses and improve the system transmittance. At the same time, it corrects on-axis/off-axis aberrations and advanced aberrations to improve the imaging quality of the system. In order to effectively reduce the background radiation and improve the system signal-to-noise ratio, the system adopts cryogenic optical technology. Through the scheme design and calculation analysis of the active refrigeration unit, the requirements of the overall and optical technical indicators are met. The outline of the aircraft image obtained by the field experiment is clear and distinguishable, which meets the requirements of target detection. The system has a good application prospect in the field of infrared imaging in early warning systems.

1. Introduction

Infrared optical detection system has the advantages of high target detection accuracy, low false alarm rate, and all-day detection in complex environments [1-2]. It has been widely used in remote sensing, navigation and other fields. Many infrared detection systems need to effectively suppress background radiation in order to obtain a higher signal-to-noise ratio and detect point/dim targets. By thermally controlling the optical lenses and supporting structures in the detection system, and using active refrigeration technology to make them work at low-temperature environment, the thermal radiation of the detection system can be efficiently reduced, and its impact on the detection performance can be effectively suppressed. Thereby, the sensitivity and low noise performance of the detection system are improved [3-5].

In view of the important role of cryogenic optics in the field of infrared detection, research on this technology is very active at home and abroad. For example, the James Webb Space Telescope (JWST), jointly developed by the National Aeronautics Administration (NASA), the European Space Agency (ESA) and the Canadian Space Agency (CSA), uses a large expandable sun visor to avoid the background radiation of the instrument. The telescope system and the imaging systems have always been located on the back side of the sun visor, so that the operating temperature is always around 35K.
In order to suppress the background radiation, the Japanese ASTRO-F infrared astronomical satellite uses superfluid helium and a mechanical refrigerator to make its operating temperature around 5K. In addition, Xi’an Institute of Optics and Precision Mechanics, Shanghai Institute of Technical Physics and other scientific research institutes have also conducted in-depth exploration and research in the field of cryogenic optics [6-8].

In this paper, according to the requirements of the overall technical indicators and combined with the requirements of detection performance, volume envelope, weight, etc., the design and research of the cryogenic long-wave infrared detection system is carried out.

2. Design of cryogenic long-wave infrared optical system

2.1. Main technical parameters of the system

The main parameters of the cryogenic long-wave infrared detection system include focal length, relative aperture, FOV and so on. Limited by the diffraction limit, the minimum resolution of an optical system often depends on the relative aperture of the system. In this paper, the long-wave optical system adopts a cooled 640×512 area array detector with a pixel size of 25μm. Considering the envelope size, weight, detection performance and other factors of the cryogenic long-wave infrared detection system, the parameters of the optical system are shown in Table 1.

| Parameter                  | Value          |
|----------------------------|----------------|
| Wavelength / μm            | 7.7–9.7        |
| FOV /(°)                   | 12.64×10.12    |
| Focal length /mm           | 73             |
| F#                         | 1.6            |
| Operating temperature /°C  | -40±1          |

The cryogenic long-wave infrared optical system adopts the structural form of secondary imaging to reduce the aperture of the lens. In order to achieve the purpose of achromatic optical system, the optical system uses two materials, Ge and ZnSe. The purpose of correcting system aberrations and improving the imaging quality is achieved by adding aspheric surfaces, planning optical power and other methods. Use the CODE V optical design software to design the optical system, and the structure of the optical system is shown in Fig. 1.

2.2. Image quality evaluation

The cryogenic long-wave infrared detection system adopts a cooled detector with a pixel size of 25μm. So its characteristic frequency is 20lp/mm. The system adopts cryogenic optical technology. The optical lens is fixed inside the vacuum Dewar box. The temperature design of each part of the optical
system is shown in Fig. 2. The temperature of the lens and detector protection window is -40°C, and the temperature of the cold diaphragm and the detector target surface is -196.15°C. Since the optical window of refrigeration chamber is flat glass, it does not contribute optical power to the system. So the temperature change and temperature gradient will not affect the imaging quality. The modulation transfer function of the system is shown in Fig. 3. It can be seen from the Fig. 3 that the system has a higher transfer function.

![Figure 2](image)

**Figure 2.** Schematic diagram of temperature distribution of long-wave infrared system

![MTF curves at different temperatures](image)

(a) MTF curves at -39°C  
(b) MTF curves at -40°C  
(c) MTF curves at -41°C

**Figure 3.** MTF curves at different temperatures of LWIR optical system

### 3. Design of the active refrigeration unit

#### 3.1. Main technical indicators of the unit

According to the optical system design requirements, the main technical indicators of the LWIR active refrigeration unit are as follows:

- a) Refrigeration temperature: -40±1°C;
- b) Refrigeration time: ≤50min;
- c) Vacuum degree: ≤1.0×10⁻¹Pa;
- d) Continuous working time: ≥1hour;
3.2. Overall scheme design
Due to the limitation of overall volume and weight, the long-wave infrared optical lens is refrigerated by a Stirling refrigerator. The long-wave infrared optical lens is fixed inside the vacuum Dewar box. The vacuum Dewar box provides a high vacuum environment for the optical lens to achieve the purpose of isolating the thermal disturbance of the external environment. The long-wave infrared detector is fixed and sealed on the vacuum Dewar box through the flexible welded bellows flange. The flexible welded bellows flange has the function of multi-dimensional adjustment, which can realize the clear imaging of the system. The vacuum Dewar box also has an optical window to receive and transmit infrared light in the desired wavelength band [9-10]. The overall layout of the LWIR active refrigeration unit is shown in Fig. 4.

Figure 4. Schematic diagram of the overall layout

According to the overall envelope layout requirements and considering the refrigeration method between the cold head of the refrigerator and the long-wave infrared optical lens, the refrigerator placement method as shown in Fig. 5 is adopted. And the refrigerator is sealed with the vacuum Dewar box through the transition flange. At the same time, the support is used for support and fixation. Insulation gaskets are added between the vacuum Dewar box and the inner frame, which greatly reduces the heat transfer from Stirling refrigerator to vacuum Dewar box through bracket. Heat pipe is added between the walls to transfer the heat generated by the Stirling refrigerator to the side wall of the casing through the bracket and the heat pipe. The cold head of the refrigerator is coupled with the optical lens holder for cooling.

Figure 5. Stirling refrigerator layout
3.3. Calculation and analysis of refrigeration time

The refrigeration time is calculated and analyzed according to the total thermal load of the optical lens and the maximum cooling capacity provided by the refrigerator. The total thermal load of the optical lens includes the refrigeration capacity required by the optical lens and structural parts from normal temperature to -40℃ and the heat leakage of the system.

The materials of the lenses are single crystal germanium and ZnSe. And the rest of the structural parts are made of aluminum alloys. From formula (1), it can be calculated that the total thermal load required for the optical lens to drop from normal temperature to -40℃ is 14202.54 J.

\[ Q_T = C \cdot \Delta M \cdot (T_2 - T_1) \] (1)

After the optical lens has been cooled to a low temperature, the cooling maintenance power consumption depends on the leakage heat loss of the whole system. The leakage heat loss of the system mainly includes the heat conduction loss of the thermal insulation gaskets and the heat radiation loss of the vacuum Dewar box. According to the calculation formula (2) of radiation heat leakage, it is calculated that the radiation leakage heat from the inner surface of the vacuum Dewar box to the optical lens is about 0.65 W.

\[ Q_{Ra} = \bar{\varepsilon} \times A_1 \times \sigma \times \left( T_1^4 - T_2^4 \right) \] (2)

where \( Q_{Ra} \) is the radiation leakage heat of the optical lens, \( \bar{\varepsilon} \), \( \varepsilon_1 \), \( \varepsilon_2 \) is the surface blackness of the material, \( \sigma \) is the Stephen-Boltzmann constant, \( A_1 \), \( A_2 \) is the surface area of the material, \( T_1, T_2 \) is the temperature of the air and the material.

FRP, titanium alloy and other materials are used as thermal insulation components between the optical lens and the vacuum Dewar box. According to the thermal conductivity calculation formula (3), the thermal leakage of the optical lens thermal insulation components are calculated to be about 0.82 W.

\[ Q_c = \sum_{i=1}^{n} A_i \lambda_i \frac{T_{i+1} - T_i}{L_i} \] (3)

where \( Q_c \) is the thermal Leakage of insulation gaskets, \( \lambda_i \) is the thermal conductivity of the material, \( A_i \) is the thermal conductivity area of the material, \( (T_{i+1} - T_i)L_i^{-1} \) is the thermal conductivity gradient of the material.

The Stirling refrigerator selected in this paper can provide a maximum cooling capacity of 6.5 W at -40℃. After offsetting the cooling loss caused by radiation and thermal leakage, the remaining cooling capacity is 5.03 W. According to total thermal load and the remaining cooling capacity, the refrigeration time can be calculated by formula (4).

\[ t = \frac{Q_T}{\dot{Q}_c - Q_{Ra} - Q_c} \] (4)

It is calculated that the required refrigeration time is 47.1 min, which meets the requirement of the refrigeration time index.

3.4. Simulation analysis of temperature distribution of the optical lens

In order to verify the scheme design of the above active refrigeration unit, the finite element analysis of the long-wave infrared optical lens was carried out. The second lens was ZnSe, the other three lenses were Ge, and the other structural parts were made of aluminum alloy 7075-T6. The simulation results of temperature distribution of the optical lens are shown in Fig. 6.
Figure 6. Simulation results of temperature distribution of the optical lens

It can be seen from the simulation results that the uniformity of temperature distribution between the lenses of the optical lens is less than or equal to 1 °C, which meets the requirements of the optical design indicator.

4. Real experiment
In order to evaluate the imaging performance of the cryogenic long-wave infrared detection system, the field imaging experiment was carried out. Fig. 7 shows the image taken by the long-wave infrared detection system of the optical lens at -40°C. The outline of the aircraft is clear and distinguishable. The results show that the active refrigeration unit can effectively suppress the background radiation and greatly improve the signal-to-noise ratio of the system, so as to realize the purpose of point / dim target detection.

Figure 7. Experiment image captured by the detection system

5. Conclusion
In this paper, a cryogenic long-wave infrared detection system suitable for point / dim targets in complex backgrounds is studied. The optical system adopts high-order aspheric surfaces, which reduces the number of optical lenses and improves the transmittance of the system. The optical lens is cooled to -40°C by an active refrigeration unit, which suppresses background noise and improves the system signal-to-noise ratio. Through the field experiment, the outline of the obtained long-distance aircraft image is clear and distinguishable. The cryogenic long-wave infrared detection system has compact structure, light weight, excellent detection performance and high structural stability. The design and research of this paper have certain significance for the development of airborne/missile-borne early warning field.

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