Research on Adjustable Cold Field Stops in Optical Systems with Linear Array Detectors in AIMS (Postprint)

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Abstract

The infrared Fourier transform spectrometer requires a cold field stop to mitigate stray radiation. For infrared spectrometers equipped with linear array detectors, the light-transmitting portion of the field stop can be considered as a slit. When infrared detectors are small in size, the slit width becomes correspondingly narrow, leading to significant diffraction effects. If the dimensions of the field stop and optical system are designed based on geometric optics theory, the diffracted light cannot be completely captured by the detectors, resulting in energy loss. Conversely, increasing the field stop width introduces stray radiation. Additionally, the spectrometer' s subsequent optics must be maintained in a cryogenic environment to reduce the instrument' s infrared background. Due to varying thermal characteristics of optical materials, optical and mechanical structures undergo deformation at cryogenic temperatures, and since the cold field stop is installed at ambient temperature, it cannot be guaranteed to remain at its design position during cryogenic operation. This paper addresses these issues by designing an adjustable cold field stop installed within the cryogenic vacuum chamber. The width and position of the field stop can be adjusted during cryogenic operation without opening the chamber. By comparing the interference signals obtained from the detectors during the adjustment process, the system can determine the optimal width and position of the cold field stop. This work is based on the spectrometer employed in the study titled "Accurate Infrared Magnetic Field Measurements of the Sun" .

Full Text

Preamble

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Research on Adjustable Cold View Field Diaphragm in Optical System with Linear Array Detector in AIMS

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Abstract

Infrared Fourier transform spectrometers require a cold view field diaphragm to reduce stray radiation. For infrared spectrometers equipped with linear array detectors, the light-passing portion of the view field diaphragm can be regarded as a slit. When infrared detectors are small, the slit width must also be small, which causes severe diffraction phenomena. If the widths of the view field diaphragm and optical system are designed using geometric optics theory alone, the diffracted light cannot be fully received by the detectors, resulting in energy loss. Expanding the width of the view field diaphragm introduces additional stray radiation. Furthermore, spectrometer follow-up optics must be maintained in cold environments to reduce the instrument' s infrared background. Since optical materials have different thermal properties and the cold view field diaphragm is installed at room temperature, it is impossible to guarantee that the diaphragm remains in its design position when operating at cryogenic temperatures.

This paper addresses these challenges by designing an adjustable cold view field diaphragm installed within its cryogenic vacuum chamber. The width and position of the view field diaphragm can be adjusted during cold operation without opening the chamber. By analyzing the interference signals obtained by the detectors during the adjustment process, the system can determine the optimal width and position for the cold view field diaphragm.

This work is based on the spectrometer used in the Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) project.

Key words: instrumentation: interferometers -instrumentation: detectors -Sun: infrared -Sun: magnetic fields

1. Introduction

Infrared optical instruments frequently employ cold optics technology to reduce thermal infrared background noise while detecting fine spectral features of targets [?]. Infrared optical systems typically incorporate cold light shields, light-blocking rings, and stray light elimination diaphragms to suppress stray light and improve the system' s signal-to-noise ratio [?]. Due to differing thermal performance of optical and mechanical structures between room temperature and cryogenic conditions, it is difficult to guarantee low-temperature optical performance through precise design, error analysis, or material analysis alone [?]. Manufacturing and assembly errors also affect the dimensional and positional accuracy of optical and mechanical structures at low temperatures. For view field diaphragms with stringent positioning requirements and small dimensions, low-temperature size and position variations have an even more significant impact on signals.

OKSI Corporation in the United States achieved real-time adjustment of a cold diaphragm by implementing an external variable diaphragm driven by a worm gear and motor. This method required specialized refrigeration machines with large cooling capacity to cool the adjustable diaphragm [?, ?]. In 2014, the Changchun Institute of Optics, Fine Mechanics, and Physics developed an infrared variable diaphragm mechanism that integrated detectors, an aperture disk, and a filter disk within a dewar vessel. Different diaphragm sizes were installed on the diaphragm disk, and different frequency band filters were installed on the filter disk, with switching achieved by rotating the disks. However, this method could not continuously adjust the diaphragm size. For view field diaphragms at the micrometer level, diffraction effects seriously impact image quality. [?] designed a mechanism to compensate for the adverse effects of view field diaphragm diffraction, though this method is suitable only for specific temperature applications.

This paper explores a method and device for continuous adjustment of both width and position of a cold view field diaphragm in real time. The width and position are determined based on the spectrometer' s signal strength and instrument performance, thereby optimizing overall instrument performance.

2. Research on the Application of View Field Diaphragm

2.1. The Necessity of Adjustable Width in the View Field Diaphragm

For linear array detectors, if the view field diaphragm is designed using theoretical calculations alone, diffraction phenomena become more pronounced at the optical image plane. This is particularly problematic for small-size detectors, as longer wavelengths produce stronger diffraction effects. In ideal applications, all diffracted beams could be fully received by detectors without energy loss if the spectrometer’ s follow-up optics system were sufficiently large. However, in practical applications, optimal component sizes in optical systems are typically designed based on geometric optics, making it difficult for follow-up optics to collect all diffracted beams onto the detectors, thus causing energy loss. Meanwhile, diffracted beams from nearby view fields illuminate the detector, introducing stray light. Increasing the view field diaphragm width to reduce beam diffraction effects allows light from outside the view field to enter, which becomes stray light after multiple scatterings. This stray light incident on the detectors increases noise and decreases the system’ s signal-to-noise ratio. Therefore, in linear array imaging systems with small detector pixels and long detection wavelengths, the view field diaphragm width significantly impacts system performance. As noted in the introduction, the optimal width cannot be obtained through design alone, making adjustable width essential for cold view field diaphragms.

2.2. The Necessity of Position Adjustment in Cold View Field Diaphragm

Using low-temperature optical technology to cool the optical system effectively reduces background noise and improves signal-to-noise ratio and sensitivity. However, optical systems typically have installation errors, accurate data on deep low-temperature thermal expansion coefficients of materials are often unavailable, and users cannot accurately calculate optical structure deformation at cryogenic temperatures. Consequently, a view field diaphragm installed at room temperature often shifts from its design position when operating in a low-temperature environment. Therefore, to obtain the optimal position for the cold view field diaphragm, it is ideal to design a diaphragm that is adjustable during cryogenic operation.

2.3. Application Examples of Cold View Field Diaphragm

For the Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) project (supported by the National Natural Science Foundation of China, Grant No. 11427901), the fore-optical system is a solar telescope that introduces sunlight into the “Fourier Transform Infrared Spectrometer” (FTIR). After passing through the interferometer, the sunlight is incident on the FTIR detectors. FTIR converts the sunlight signals into electrical signals, and AIMS obtains the spectral signal through Fourier inversion of the interference signals. In FTIR, each detector element corresponds to a front view field of 1.5 arcseconds, the detector arrangement is 64 rows × 2 columns, each detector chip measures 50 × 50 m, and there is a 50 m distance between the two detector chip columns. The detection spectrum covers the solar spectrum near 12.32 m.

In FTIR, the view field is small, detector pixel resolution is high, and detection spectral bandwidth is narrow, so the signal obtained by a single detector chip is very small. To improve instrument signal-to-noise ratio, optical structures such as the view field diaphragm and filter wheel must operate in an 80 K environment, while also considering energy loss and infrared stray light effects. Because the detector chips are small, the view field diaphragm at the conjugate plane of the detector chip' s optical image can be regarded as a narrow single slit with high optical positioning accuracy at low temperature. The optical principle of this instrument is illustrated in [Figure 1: see original paper]. Based on this analysis, the cold view field diaphragm in FTIR should be adjustable, and by analyzing the interference signals obtained by the detectors during adjustment, AIMS can determine the most suitable width and position for the cold view field diaphragm.

3. Research on Adjustment Method and Implementation Mechanism

3.1. Research on the Adjustment Method of Cold View Field Diaphragm

The above analysis demonstrates the necessity of using a cold adjustable slit diaphragm in high spectral resolution infrared spectrometers when detecting thermal infrared bands, particularly for spectrometers with linear array detector chips. While many methods exist for adjusting view field diaphragms at room temperature, these cannot be directly applied to cryogenic situations. Few methods exist for adjusting low-temperature slit diaphragms, and this paper aims to explore a technique for such adjustments.

Considering that the view field diaphragm operates in a low-temperature environment, a vacuum environment is essential. The entire adjustment mechanism must be placed in a closed cryogenic vacuum chamber, making commercially available manual adjustment slits unsuitable. Using a motor-driven device for low-temperature diaphragm adjustment presents several unfavorable factors. First, the adjustable device requires a low-temperature vacuum motor and vacuum connectors, plus a room-temperature motor controller. This creates a distributed structure with components both inside and outside the cryogenic vacuum chamber, resulting in large volume and high cost. Second, small vacuum motors typically have very low torque, requiring vacuum grease in the transmission device to overcome resistance torque. During long-term operation, the vacuum grease slowly evaporates and contaminates optical components. Third, a low-temperature vacuum displacement measurement device must be installed to determine the view field diaphragm position, but common adjustment sensors and electronic devices cannot operate at cryogenic temperatures (such as 80 K).

Alternatively, replacing the view field diaphragm with a series of different-sized slits could accomplish adjustment, with the optimal slit selected after experimental testing. However, this method is cumbersome and time-consuming, requiring repeated opening of the cryogenic vacuum chamber. Before opening, the chamber must be reheated and re-pressurized, then opened for slit replacement, followed by heating, cleaning, evacuation, and gradual cooling. The cryogenic vacuum chamber contains insulation structures such as cold screens and multi-layer insulation that must be reinstalled when replacing narrow slits. This process is lengthy and involves many steps, and optimal performance cannot be achieved due to the discrete sizes of replacement slits.

After studying this problem, we determined that using a pure mechanical adjustable cold view field diaphragm can avoid these adverse factors while obtaining optimal diaphragm position and slit width. The method employs a micrometer head as the adjustment and displacement measurement component, bellows as the sealing component, two movable blades to form the slit, screws for pre-adjusting the initial position, and flexible cold chains to cool the blades. The specific implementation mechanisms and adjustment methods are described below.

3.2. Implementation Mechanism for Adjustable Cold View Field Diaphragm

3.2.1. Overall Mechanism for Adjustable Cold View Field Diaphragm

The view field diaphragm adjustment mechanism is illustrated in [Figure 2: see original paper], comprising bellows, diaphragm linkages, adiabatic tubes, micrometer heads, and other components. The diaphragm linkage and adiabatic tube are made of titanium alloy, with the adiabatic tube having a radial thickness of 0.2 mm to reduce heat loss. One end of the adiabatic tube connects to the bellows via threads, while the other end connects to the diaphragm linkage via threads, with the relative position fixed using a locking nut. The bellows are mounted on the cryogenic vacuum chamber through a flange, with the connection sealed using silver wire. Blades with sharp edges are designed on diaphragm linkage 1 and diaphragm linkage 2, forming the two sides of the view field diaphragm. Blade 1 and blade 2 form a narrow diaphragm, with the middle gap serving as the transparent aperture. The micrometer head applies force to the rod core, compressing the bellows and driving the diaphragm linkages to move left and right. This allows adjustment of blade 1 and blade 2 positions, with the optimal width and position determined by signals obtained from the detector chips.

3.2.2. Characteristic Requirements and Structure of the Bellows The bellows must have appropriate stiffness for view field diaphragm adjustment. If stiffness is too high, the micrometer head must apply excessive force and is prone to sticking during adjustment. Conversely, if stiffness is too low, the diaphragm linkage easily swings with the bellows. Bellows size should be minimized to save space. The bellows adopt a stacked waveform to generate large displacements while withstanding substantial external pressure loads. Design variables include ripple thickness, number of ripples, and outer-to-inner diameter ratio. The bellows structure is depicted in [Figure 3: see original paper], mounted on the cryogenic vacuum chamber wall through flange A. The B-end of the rod core has external threads to connect the adiabatic tube and adjust the relative position between the adiabatic tube and bellows. The B-end thread length exceeds the total adjustment amount required for the view field diaphragm slit. The micrometer head force is applied to the C-end of the rod core. Components D and E constitute a locking device that fixes the rod core position and maintains bellows compression.

3.2.3. Cold Position Calculation of View Field Diaphragm Blade During cooldown from room temperature to cryogenic temperature in the vacuum chamber, the diaphragm linkage and adiabatic tube contract, causing the blades to move toward the bellows and changing their initial position. This displacement must be compensated when designing structural parameters. A cold screen installed between the low-temperature optical system and cryogenic vacuum chamber is covered with multi-layer insulation, allowing thermal radiation from optical components to be ignored and only thermal conduction considered. As illustrated in [Figure 4: see original paper], the side of the diaphragm linkage near the blade connects to the cold chain, maintaining blade 1 and blade 2 at 80 K, while the end of the adiabatic tube J connects to the bellows at 295 K.

According to the heat conduction formula, the heat Q_N at connection position N between the diaphragm linkage and adiabatic tube can be expressed as:

$$Q_N = \frac{K \cdot S_1 \cdot (T_{\text{blade}} - T_N)}{L_1} = \frac{K \cdot S_2 \cdot (T_N - T_{\text{bellows}})}{L_2}$$

In this formula, the thermal conductivity coefficient K is 7.2 W/(m·K), the distance L_1 from blade to diaphragm linkage end N is 109.75 mm, and the adiabatic tube length L_2 is 37 mm. The diaphragm linkage inner radius r_1 is 0.875 mm, outer radius R_1 is 1.75 mm, and heat transfer area S_1 can be expressed as $S_1 = \pi(R_1^2 - r_1^2)$. The adiabatic tube inner radius r_2 is 0.875 mm, outer radius R_2 is 1.475 mm, and heat transfer area S_2 can be expressed as $S_2 = \pi(R_2^2 - r_2^2)$. Solving these equations yields the temperature at N: T_1 = 210.592 K, with cooling loss from the adjustment mechanism of 0.062 W.

At low temperature, the blade moves slightly rightward due to cold shrinkage of the diaphragm linkage and adiabatic tube. The movement amount is given by:

$$\Delta L = \int_0^{L_1} \alpha \cdot T_{x1} \, dL_{x1} + \int_0^{L_2} \alpha \cdot T_{x2} \, dL_{x2}$$

where the coefficient of thermal expansion α is 8.8 × 10^{-6}/K, T_{x1} is the temperature at any position L_{x1} on the diaphragm linkage, and T_{x2} is the temperature at any position L_{x2} on the adiabatic tube. After calculation, both blade 1 and blade 2 move rightward by ΔL = 0.137 mm from their initial design positions in the cold state.

3.3. Cold View Field Diaphragm Adjustment

Analyzing the thrust received by the bellows under compression: during installation, the blade is mechanically positioned and fixed to the theoretical design position at room temperature, with the bellows having an initial compression X_0. At this point, blade 1 and blade 2 are tightly attached, and the view field diaphragm is closed. Before adjustment, the displacement ΔL caused by cold shrinkage must be compensated, making the bellows compression X_0 + ΔL. During adjustment, twisting the micrometer head pushes the bellows rod core to produce axial displacement, allowing the blade to move from left to right. When bellows compression increases, the blade moves left; when compression decreases, the blade moves right. The blade's left and right adjustment amounts can be read directly from the micrometer head.

Denoting the maximum distance blade 1 can move left as X (position of maximum bellows compression), the maximum thrust F_{max} received by the bellows is:

$$F_{\max} = K_q \cdot (X_0 + \Delta L + X) + D + F_p$$

where K_q represents bellows stiffness, D is the thrust from the micrometer head, and F_p is the thrust from the pressure difference inside and outside the cryogenic vacuum chamber.

The maximum thrust f_{max} that the micrometer head exerts on the bellows is:

$$f_{\max} = K_q \cdot (X_0 + \Delta L + X) + D + F_p$$

Denoting the maximum distance blade 2 can move right as Y (position of minimum bellows compression), the minimum thrust F_{min} received by the bellows is:

$$F_{\min} = K_q \cdot (X_0 + \Delta L - Y) + D - F_p$$

The minimum thrust f_{min} that the micrometer head exerts is:

$$f_{\min} = K_q \cdot (X_0 + \Delta L - Y) + D - F_p$$

The thrust F on the bellows varies during blade adjustment, ranging between F_{min} and F_{max}. The requirement for F_{max} is that the resulting compression must be less than the theoretically designed maximum compression, and the reaction force on the micrometer head and support structure must not cause deformation. F_{min} must ensure the blade remains stable and does not move during FTIR operation.

Both X and Y should be less than the maximum bellows compression. For bellows length L, the maximum compression should be less than 0.6L - (X_0 + ΔL), while compression must remain greater than 0, meaning Y must be less than X_0 + ΔL. Selecting standard bellows specifications with natural length L = 15 mm and conducting mechanical tests shows that under one atmospheric pressure, bellows compression is 1.071 mm. The bellows characteristic curve is shown in [Figure 5: see original paper], with stiffness K_q = 8.31 N/mm, giving F_p = 8.904 N.

Setting the blade adjustment range parameters with initial bellows compression X_0 = 4 mm, maximum leftward movement X = 2 mm for blade 1, and maximum rightward movement Y = 2 mm for blade 2, the bellows receives thrust ranging from 50.998 N (F_{max}) to 17.758 N (F_{min}), sufficient to keep the blade stable during FTIR operation. The micrometer head provides thrust ranging from 42.094 N (f_{max}) to 8.854 N (f_{min}). The two micrometer heads are fixed to their support structures by screws, which are fixed to the substrate and will not deform under maximum reaction force.

In summary, using the initial closed position of the two blades as the center, any position and width of the view field diaphragm can be adjusted within a 2 mm range on both sides, with stable structure as shown in [Figure 6: see original paper]. The reading error of the adjustment amount depends on the micrometer head reading error. The micrometer head division line is 0.01 mm, with visual error between single and double division lines not exceeding 1/4 division value. Therefore, the displacement reading error of the adjustment mechanism is not greater than 2.5 m, much smaller than the 50 m detection element size. For FTIR, the width of the two detectors at this image plane is 0.15 mm, and the view field diaphragm adjustment range covers the application requirements.

4. Experiment

We installed the field diaphragm in the FTIR cryogenic vacuum chamber, as depicted in [Figure 7: see original paper]. Cold optical components inside the chamber are cooled by a pulse tube refrigerator connected to the cold optical substrate through a cold chain, with the diaphragm linkage also connected to the substrate via a cold chain, allowing blade temperature to reach 80 K.

In FTIR, the detector chip arrangement corresponds to the initial view field diaphragm position as diagrammed in [Figure 8: see original paper]. With the view field diaphragm closed and a 500°C blackbody as the light source, the interference signal amplitude collected by detection elements is 0. Although each detection element corresponds to a tiny field of view, the interference signal is very small. Therefore, the electronic system adopts a gain of 100,000 times with substantial electronic bandwidth, revealing some electronic noise when the diaphragm is fully closed, as shown in [Figure 9: see original paper].

Next, fixing bellows 1 and releasing bellows 2 opens the blade, as illustrated in [Figure 10: see original paper]. The interference signals received on the detector chips are shown in [Figure 11: see original paper]. Signals on even-numbered detector chips represent interference from the beam corresponding to the view field, while beams on odd-numbered chips are blocked by blade 1. The weak interference signals displayed on odd-numbered detector chips in [Figure 11: see original paper] result from diffraction and scattering effects of light passing through the diaphragm.

Locking blade 2 and compressing bellows 1 opens blade 1, as shown in [Figure 12: see original paper]. At this point, interference signals received on both columns of detection elements are displayed in [Figure 13: see original paper].

The experiment demonstrates that the adjustable cold view field diaphragm method and device explored in this paper can continuously adjust diaphragm width and position. By observing detector chip signal changes and reading displacement and width adjustment amounts from the micrometer head, this paper provides a method for studying optimal slit width and optimizing instrument performance while blocking excess light that would form stray light. This method has been verified as correct and feasible using FTIR in AIMS and can be similarly applied to other spectrometers using linear array detectors.

5. Conclusions

This study has achieved quantitative adjustment of cold view field diaphragm width and position, enabling optimization based on signal magnitude and instrument performance. The entire system contains no electronic devices or components, eliminating signal interference during adjustment. The structure is centralized, low-cost, and power-free during adjustment, with repeatable diaphragm adjustments that do not affect vacuum level or temperature inside the cryogenic vacuum chamber. The adjustment device requires no lubricating grease, eliminating jamming risk and preventing optical component contamination during long-term use. Diaphragm adjustment can be performed at cryogenic temperatures without reopening the chamber, significantly improving work efficiency.

For slit-type view field diaphragms, this method helps determine optimal slit width and position through detector signal analysis, balancing energy collection and stray light suppression. The approach has been successfully demonstrated in the AIMS FTIR instrument and is applicable to other spectrometers employing linear array detectors.

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