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Design and performance of curved prism-based mid-wave infrared hyperspectral imager

Maoxing Wen[a,b], Yueming Wang[a,b,*], Yi Yao[a], Liyin Yuan[a], Shiyao Zhou[a,b], Jianyu Wang[a]

[a] Key Laboratory of Space Active Opto-Electronics Technology, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Mid-wave infrared hyperspectral imagers (MWHSIs) can be used to detect flames, high-temperature targets, and the radiance of Earth's surface. The acquired spectral signatures can be utilized to distinguish them even though the radiance are the same. In addition, in these applications, it is necessary to acquire the signatures of targets with sufficient radiometric performance and the spatial information of the targets with high resolution simultaneously. To meet these requirements, high resolution, high optical efficiencies, and appropriate spectral intervals must be balanced. Curved prisms with a modified Offner structure can address this problem perfectly and is employed in this study as the spectrometer of the MWHSI. It also enables integrated systems to have a low spectral smile, volume, and mass. Different flames and heated materials could be discriminated using their spectral features. These features of MWHSI make it valuable in airborne and spaceborne remote sensing applications. The image of flying plane is acquired and it satisfied the scientific goal.

1. Introduction

The hyperspectral imager provides both spatial and spectral information while imaging and is widely applied in the detection of environmental changes [1,2], object classification [3,4], real-time identification [5], target tracking [6], and industrial emissions monitoring [7]. Several high-performance airborne and spaceborne hyperspectral imagers have been developed with a spectral range from visible to short-wave infrared wavelengths. Few mid-wave infrared hyperspectral imagers (MWHSIs) have been reported, and they have been used to monitor industrial emissions, map the surface composition of Vesta and Ceres, and improve target/background classification [8–15]. In this paper, the hyperspectral imager is designed to detect a flying civil plane with a distance over 2 km. In order to acquire spatial information and spectrum with enough signal-to-noise ratio (SNR), high instantaneous fields of view (IFOVs), high optical efficiencies and appropriate spectral intervals should be considered carefully. Spectrometers are one of the most important components in hyperspectral imagers and their dispersing capabilities have a direct influence on the performance of the spectra imaged onto the detector. In a spectrometer, gratings are widely used as the common dispersing component to provide spectra while imaging and the primary advantages are compact size, low distortion, and linearly dispersed spectra, acquired without the need for post-processing [16]. However, the limitations of grating-based systems, such as low optical efficiency, polarization sensitivity, and multiple diffraction orders, limit the robustness of the subpixel discrimination and imaging performance [16].

For example, various details of an Offner grating spectrometer have been described and six segmented filters have been used to stop the superimposition of higher diffraction orders coming from the grating and reduce the background thermal radiation [9,13]. The methods to segment filters give rise to a highly complex system design, difficult assembly, and high cost. Another study demonstrated a dual-band hyperspectral imager that uses a diffractive optical element to focus different spectra at different focal lengths [10]. The diffractive optical element is a blazed circular grating, which is etched on a transparent substrate, and it has a diffraction efficiency of over 80% in the long-wave infrared region, but for the spectral region below 3.5 μm, the diffraction efficiency is only greater than 40%. The efficiency of the grating limits the detection ranges of the system because considerable radiance from the objects is wasted by the grating. In addition, time delay and integration technology and the integrated stepwise filter have been proposed and attain good values in the miniaturization design of a hyperspectral imager, but the study was only conducted in the spectral range of 2–2.5 μm [17].

In order to acquire a purer and lower distortion spectrum, some

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* Corresponding author at: Key Laboratory of Space Active Opto-Electronics Technology, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China.

E-mail address: wangym@mail.sitp.ac.cn (Y. Wang).

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extra optical components have been applied, which results in a complex hyperspectral imager design, low optical efficiency, and high mass, with the limitation of considerably expensive and difficult-to-acquire production technology for the high-performance grating. Compared with traditional grating-based systems, curved prism based system have high optical efficiencies and without high order spectral influence. In addition, angular dispersion is smaller than grating to obtain broader spectral intervals. Compared to traditional prism-based systems, curved prism has stronger abilities to correct smile and aberration. Therefore, curved prism based system has a smaller volume. A curved prism is suggested to acquire high-quality spectra [18], and some modified curved prism-based hyperspectral imagers combined with the Offner design have been developed successfully. They provide high imaging qualities and optical efficiency performances with spectra from the 400 to 2450 nm domains [19–23].

To satisfy the application goals and search for more sophisticated and low cost designs that narrow the IFOV, in this study, high optical efficiencies and appropriate spectral intervals are balanced in the MWIR range. In order to acquire narrow spectral sampling distance (SSD), CHRIS and ENMAP both have two curved-prisms in their designs. However, broad SSD is needed in our design. BITTNER can provide broad SSD with one curved-prism. Dispersion linearization is close to linear since material dispersion in MWIR is close to linear. In addition it has less refracting elements and mirrors which permits good control of out-of-band stray light. BITTNER is more sophisticated than CHRIS and ENMAP in terms of size and weight. Therefore, BITTNER is more suitable for our demand.

The curved prism-based MWHSI is evaluated and described in this paper. It has an IFOV of 0.25 mrad, low mass of 17 kg, and low cost. The mass can be further reduced by the special design and selection addressing structure and material. The smile and keystone of the instrument are less than 1/10 of a pixel. The urban building imaging experiment show the gap at 4300 nm will change narrower when the building distance from MWHSI changes nearer. The flame and metal imaging experiment distinguished kerosene flame, alcohol flame and heated metal with their spectral curves. The spectra of plume and skin are acquired and the instrument design satisfied the needs in this paper.

2. Sensor design

A curved prism-based MWHSI is designed in this study. The optical system is designed to be capable of operating in the MWIR range of 2.5–4.8 μm, but with the spectral response limitation of the detector, the MWHSI operates in the range of 3.7–4.8 μm. The key performance parameters of the instrument are shown in Table 1.

The MWHSI consists of a telescope, prism-based spectrometer, MWIR detector, and metal structure, and all the components are integrated together with the metal structure. The ray-trace of the integrated system is illustrated in Fig. 1(a) and the physical configuration of the MWHSI is shown in Fig. 1(b).

The IFOV of the MWHSI is 0.25 mrad and the swath is 256 pixels in width. The slit width is 30 μm. The speed of the system is f/2. The exit pupil of the telescope and the input pupil of the spectrometer is located at the same location before the slit as shown in Fig. 1(a). The exit pupil of the telescope and the input pupil are matched.

Table 1
The key parameters of the instrument.

Parameter	Specification
Pixel size	30 μm
Instantaneous field of view (IFOV)	0.25 mrad
The speed of the optic system	f/2
Focal length	125 mm
Spectral range	3.7–4.8 μm
Bands	30 (Spectral sampling distance 40 nm)
Signal-to-noise rate (SNR)	80 (Plume at 4.2 μm)
Smile	< 10%
Keystone	< 10%

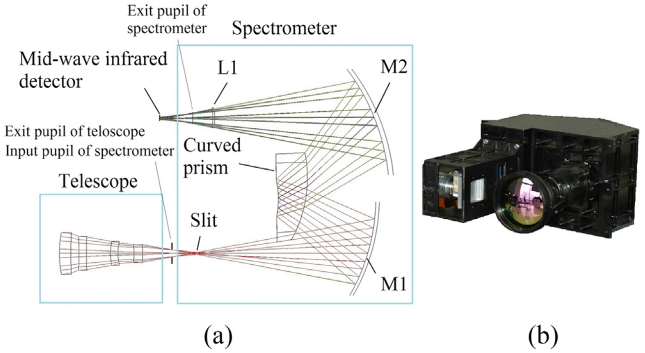

Fig. 1. Ray-trace of the integrated system and the physical configuration of the MWHSI: (a) MWHSI optical system, where M1 denotes the collimating mirror, M2 denotes the converging mirror, and L1 denotes the lens used to improve the image quality. The surfaces of M1, the curved prism, M2, and L1 are all spherical. (b) MWHSI physical configuration.

2.1. Telescope

A conventional refractive telescope is applied to collect light and image the object onto the slit. The telescope has four lenses and an entrance pupil diameter of 62.5 mm, and it operates at a focal length of 125 mm. Silicon and germanium are used to manufacture the lens to compensate for the aberrations. The telescope performs well and its spot diagrams are shown in Fig. 2(a). Fig. 2(b) was obtained by the telescope with the MWIR detector in the range of 3.7–4.8 μm.

2.2. Spectrometer

A BITTNER spectrometer is used to disperse light from the slit and reimage the spectrum onto the detector. The Offner structure modified with a grating is used as the spectrometer [24], while the curved prism replaces the second mirror in the Offner system and two independent concave mirrors replace the concave mirror. Thus, purer spectra are acquired without higher order diffraction spectra compared with grating-based systems.

The Offner structure has many advantages such as low smile and keystone at good image quality and fast speed. In addition, spherical

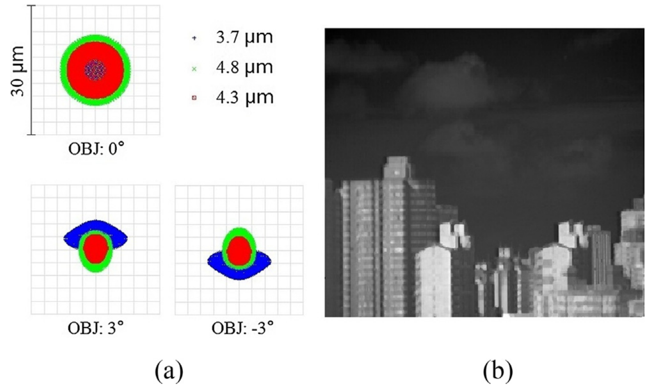

Fig. 2. (a) Spot diagrams of the telescope for three fields (0°, 3°, −3°) of three wavelengths of 3.7, 4.3, and 4.8 μm. Central FOV is considered as 0 FOV. The left view is positive and the right is negative. The size of the scale box is equal to that of one detector pixel. (b) Image taken by camera assembled with the telescope and MWIR detector operating in wavelength range of 3.7–4.8 μm. The responsivity non-uniformity of image was corrected. The detector pixel size is 30 μm.