Optics Communications 338 (2015) 73–76

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High performance Czerny–Turner imaging spectrometer with aberrations corrected by tilted lenses

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ARTICLE INFO

Article history:
Received 28 June 2014
Received in revised form
26 September 2014
Accepted 3 October 2014
Available online 22 October 2014

Keywords:
Spectrometer
Imaging spectrometer
Plane grating
Tilted lens

ABSTRACT

The design of the high performance imaging spectrometer using low-cost plane grating is researched in this paper. In order to correct the aberrations well, under the guidance of the vector aberration theory, the modification of Czerny–Turner system with inserted tilt lenses is proposed. The novel design of a short-wave infrared imaging spectrometer working at between wavelengths of 1–2.5 μm is shown as an example, whose numerical aperture achieves 0.15 in image space. The aberrations are corrected well and the Modulation Transfer Function (MTF) performance is the same as the convex gratings systems. The smiles and keystones of the spectral image are acceptable. Advantages of the proposed design with a plane grating are obviously that the diffraction efficiency is high while the cost is very low.

1. Introduction

Optical designers started researching optical systems with tilted elements from the 1960s [1,2]. Currently, research on the aberration characters of tilted optical system using the vector aberration theory is very popular [3–7]. Many novel optical designs have been published. In order to utilize the low cost plane grating to acquire high performance in the imaging spectrometer system design, we attempted to correct the aberrations of traditional Czerny–Turner system by inserting tilted lenses and found it very useful. A new optical design is given in this paper. It is quite different from any other published designs in the field of imaging spectrometer although it looks like an existent modified Offner system with curved prisms. A high performance low-cost plane grating is used as the dispersion element. And its Modulation Transfer Function (MTF) performance is at the same level of convex grating systems with the same numerical aperture, while the distortion is acceptable.

Imaging spectrometer is a kind of optical sensing equipment that provides a collection of spectral images of an inhomogeneous scene. It is very useful in a wide variety of applications in astronomy, atmospheric sciences, medicine, pollution detection, spectroscopy, etc. A lot of current research on imaging spectrometer design is about compact concentric optical systems [8]. Among them, Offner systems are used the most [9,10]. The Offner system with a convex grating is very exceptional on aberration correction and distortion control. But there are many disadvantages brought by convex grating. For example, the low diffraction efficiency, the high polarization sensitivity, and the high-order diffraction stray light. Moreover, the convex grating is very expensive, so it is hard to be popular in commercial products.

Another type of modified Offner systems adapts curved prisms instead of convex grating for dispersion [11]. Except for dispersion, the prisms can correct aberrations well and have high energy efficiency. Although this type of system solves the problems brought by convex gratings, a big amount of keystone distortion is brought in because of the nonlinear index change with wavelength. The slit image of the short wavelength is much longer than the long wavelength, so the processing of the spectral image will be badly influenced.

After reviewing the two types of optical systems above, an interesting question is considerable. Is there any possibility to design a system having the similar performance as convex grating systems but without convex grating?

The classical Czerny–Turner spectrometer system attracts us. This simple system is composed of two spherical mirrors and a plane grating located in the parallel beam. Its imaging quality is badly influenced by a large amount of astigmatism. Many researchers did works on the astigmatism correction of the Czerny–Turner spectrometer. Some papers have shown that the wide waveband astigmatism can be corrected well by locating the plane grating in the divergent beam, but these system's numerical

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http://dx.doi.org/10.1016/j.optcom.2014.10.003
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aperture are limited [12–14]. The collected energy of the spectrometer is determined by the system's numerical aperture, so the performances of these kinds of modified Czerny–Turner spectrometer are very far from the Offner systems in the actual applications.

2. Theory of the design

Bilateral symmetric optical systems with tilted elements have many advantages in wide field reflective system design. Based on analysis of the Czern–Turner spectrometer system, we think tilted elements can be used to correct the main astigmatism. The aberrations character of the system with tilt elements can be described by the vector aberration theory. The third-order wave aberration of the *j*th surface of tilted system is given by [15]

$$\begin{aligned} W_j = {} & W_{040,j}(\vec{\rho}\cdot\vec{\rho})^2 + W_{131,j}[(\vec{H}-\vec{\sigma})\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}) \\ & + W_{222,j}[(\vec{H}-\vec{\sigma})\cdot\vec{\rho}]^2 \\ & + W_{220,j}[(\vec{H}-\vec{\sigma})\cdot(\vec{H}-\vec{\sigma})](\vec{\rho}\cdot\vec{\rho}) \\ & + W_{311,j}[(\vec{H}-\vec{\sigma})\cdot(\vec{H}-\vec{\sigma})][(\vec{H}-\vec{\sigma})\cdot\vec{\rho}] \end{aligned} \tag{1}$$

where $\vec{H}$ is the normalized field vector, $\vec{\rho}$ is the normalized aperture vector in the exit pupil plane, $\vec{\sigma}$ is the displacement vector of the *j*th surface's aberration contribution center.

Eq. (1) reveals the basic principles of the tilted systems' design. The characters of aberrations contribution can be deduced from this important equation. The decenter and tilt of the surface has no contribution to the system's spherical aberration. So the correction of the spherical aberration is the same as the axial symmetric systems. The decenter and tilt of the surface will introduce the constant coma. Because the constant coma contributed by every surface can be counteracted by adjusting the decenter and tilt, the total coma can be corrected.

Another important character of a tilted system is that its astigmatism has two nodal points:

$$\vec{H} = \vec{a} \pm i\vec{b} \tag{2}$$

where

$$\vec{a} = \frac{\sum_j W_{222,j}\vec{\sigma}}{\sum_j W_{222,j}}, \quad \vec{b} = \frac{\sum_j W_{222,j}\vec{\sigma}^2}{\sum_j W_{222,j}} - \frac{\sum_j W_{222,j}\vec{\sigma}}{\sum_j W_{222,j}}$$

The condition $\vec{b} = 0$ is pursued by adjusting the astigmatism contribution of tilted surfaces, and then the image quality in the center of the image plane will be optimized well.

In our design, two tilted lenses are inserted respectively in the object and image space. Their initial radii of curvature and thicknesses are mainly decided by magnification and spherical aberration formulas. Their directions of tilt are opposite in pupil coordinate for the correction of coma. The system's astigmatism is corrected collaboratively by decenter and tilt of all the spherical mirrors and lenses [16]. And for spectral imaging by an array detector, the curve of the slit image caused by distortion is corrected by the dissymmetrical change of the symmetrical elements arrangement. Based on the initial configuration from the Czerny–Turner system, the new kind of optical system presents a very good performance after optimization.

3. A design example

Because the highly efficient convex grating used in short-wave infrared waveband is much more expensive than that in the visible waveband, the displacement of the plane grating can extremely reduce the cost. Based on the reason above, in this paper, an imaging spectrometer system working in a 1–2.5 μm short-wave infrared waveband is taken for example. It proves tilted lenses in the Czerny–Turner system correct the aberrations well. Moreover, this waveband is very popular in airborne push-broom imaging spectrometers. The 2D layout of the optical system is shown in Fig. 1. The numerical aperture is 0.13 in object space and 0.15 in image space. The entrance slit is 15 mm. It uses a plane grating with 75 lines/mm and the dispersion width of the slit image is 7.2 mm. It can be easily deduced that, if using a 2D array detector with 30 μm pixel size, then 240 spectral channels can be acquired by this spectrometer and each channel's spectral resolution will be 6.25 nm.

The 3D layout of the final design is shown in Fig. 2. A circular plane grating is set as the system's aperture stop. The grating lines are parallel with the *x* direction. The panchromatic incident beam is dispersed in different wavelengths by the grating. Mirror-1 and Mirror-2 are all spherical. As in traditional Czerny–Turner systems, Mirror-1 collimates the objective rays to the plane grating. Mirror-2 focuses on the monochromatic rays to the focal plane as a linear image, which is conjugated with the entrance slit. Lens-1 and Lens-2 can be manufactured from two normal spherical lenses, with the useless part cutting off. They are titled in the system, according to the rotating axis of the aperture stop. In order to avoid the energy loss caused by material absorption, these two

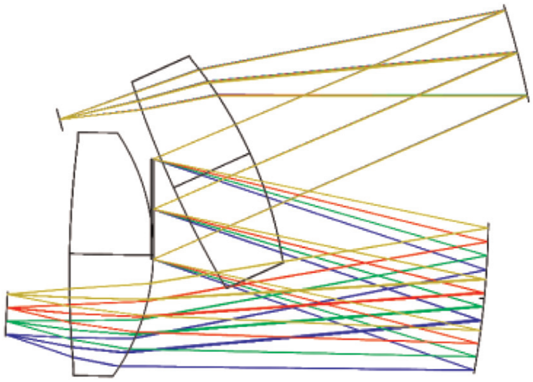

Fig. 1. 2D layout of the Czerny–Turner system with two inserted tilt lenses.

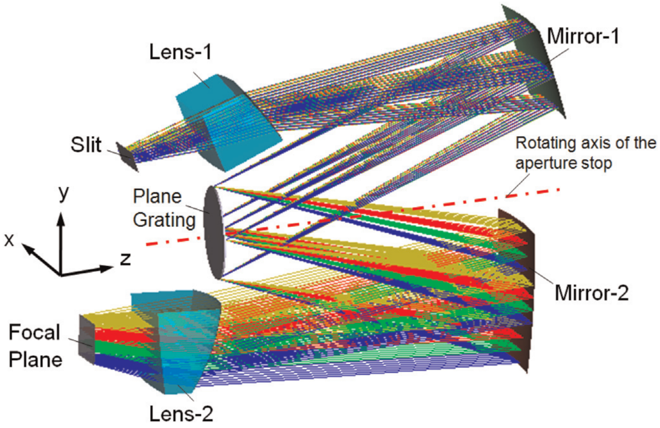

Fig. 2. 3D layout of the optical system design.

lenses are made of silica glass with excellent transmittance in the short-wave infrared waveband. The spectral images of the slit are distributed as parallel lines in the y direction. So, the *y* direction movement of the slit images will realize the hyper-spectral 2D images recording, with a 2D array detector assembled at the focal plane. Usually, this movement can be realized by a platform or a scanning mirror, under synchronized control relative to the detector's exposure times.

For the imaging optical systems, the MTF is a very important parameter for evaluating their qualities. The MTF is defined as the modulus of the Optical Transfer Function (OTF) or fourier transform of the point spread function. The calculated MTF curves of our optical system at different wavelengths are shown in Fig. 3. Because the typical short-wave infrared detector's pixel size is $a=30\ \mu m$, according to the Nyquist–Shanon sampling theorem, the Nyquist frequency is set at $1/2a=16.7$ lp/mm. It can be obtained the average MTF at 16.7 lp/mm is more than 0.7 with different working wavelengths from 1 μm to 2.5 μm, which means, this optical design can well guarantee to realize the designed resolution of the equipment after the detector's sampling, and the imaging quality of this spectrometer will also be fine experientially.

The system's distortion of the spectral image is evaluated by spectral smile and keystone. The spectral smile describes the departure of slit images in different wavelengths from a beeline, as shown in Fig. 4.

The spectral keystone is caused by different magnifications of the slit image in different wavelengths, which can be presented by the difference between image heights, as shown in Fig. 5.

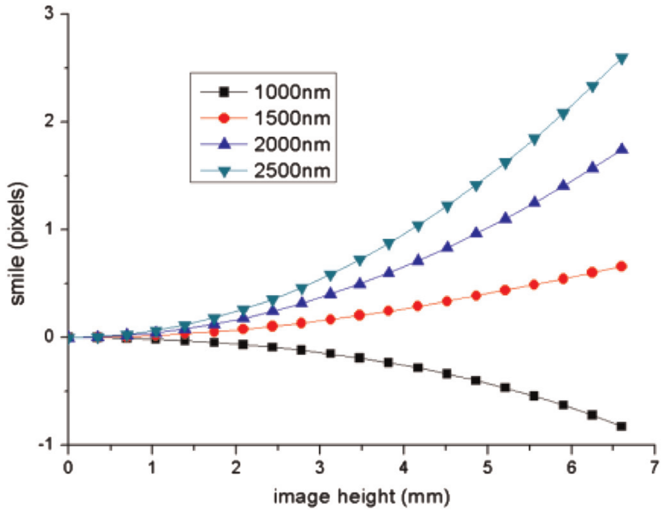

Fig. 4. Spectral smile.

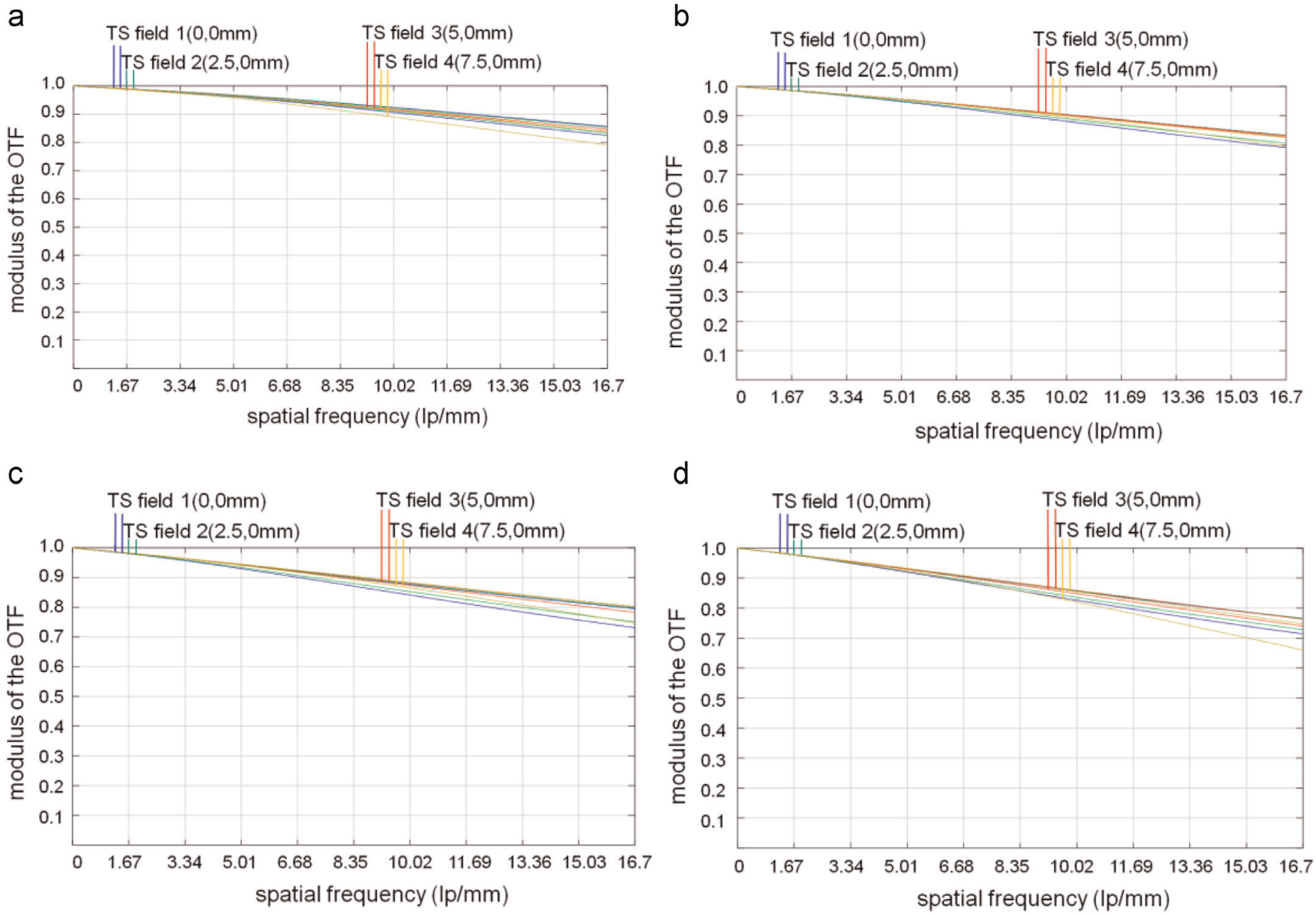

Fig. 3. Modulate transfer function of the optical system (a) $\lambda=1\ \mu m$ (the average MTF at Nyquist frequency is 0.843) (b) $\lambda=1.5\ \mu m$ (the average MTF at Nyquist frequency is 0.832) (c) $\lambda=2\ \mu m$ (the average MTF at Nyquist frequency is 0.776) (d) $\lambda=2.5\ \mu m$ (the average MTF at Nyquist frequency is 0.737).

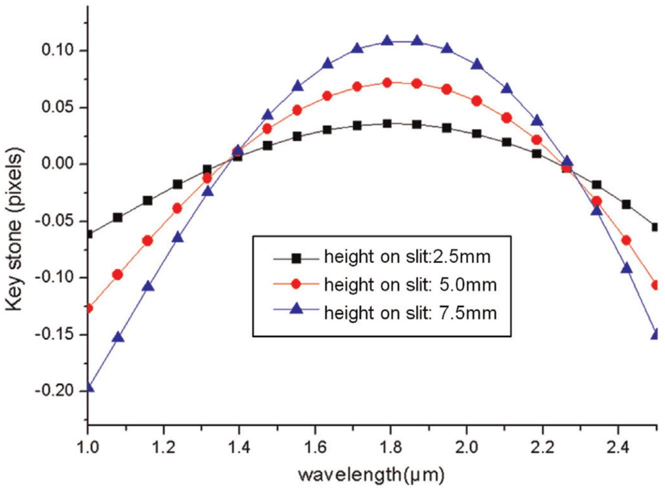

Fig. 5. Spectral keystone.

4. Summary

The existent systems of high resolution imaging spectrometer are researched and compared in this paper. The classical Czerny–Turner system is low-cost, but its imaging quality is not suitable for highly accurate sensing. The Offner system has good imaging quality, but the convex grating in it is badly influence its cost. Although the modified Offner systems using curved prisms can acquire acceptable image quality while its cost is low, its spectral images' distortion is hardly to be corrected well. In order to solve these problems which limit the imaging spectrometers′ wide application, a novel solution for a low-cost high performance imaging spectrometer is given in this paper. The modified Czerny–Turner system utilizing a plane grating for working in a large numerical aperture is designed, which is very compact. Its MTF performance is similar to the convex grating systems while the distortion is acceptable. Because all the optical elements in this system are very ordinary, especially the plane grating, comparing with the other systems which can achieve the similar performance, the proposed system has evident advantages on cost. Besides, it is proved that, tilted optical elements are very effective for this kind of system's optimization, which are deserved to be further researched. Although only one example in the short-wave infrared band is given, the researchers in this field can easily design imaging spectrometer systems with different parameters in the same way. The imaging spectrometer system proposed in this paper is simple, compact and low-cost. It is very suitable to be applied in many fields, and can easily be manufactured to satisfy the commercial production.

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