HYPERSPECTRAL IMAGING SPECTROMETER WITH A NOVEL ZOOMING FUNCTION

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ABSTRACT:

A novel hyperspectral imaging spectrometer controlling spatial and spectral resolution individually has been proposed. This imaging spectrometer uses a zoom lens as a telescope and a focusing element. It can change the spatial resolution fixing the spectral resolution or the spectral resolution fixing the spatial resolution. Here, we report the concept of the hyperspectral imaging spectrometer with the novel zooming function and the optical design of a zoom lens as the focusing element. By using lens module and third-order aberration theory, we have presented the initial design of four-group zoom lens with external entrance pupil. And the optimized zoom lens with a focal length of 50 to 150 mm is obtained from the initial design by the optical design software. As a result, the designed zoom lens shows satisfactory performances in wavelength range of 450 to 900 nm as a focusing element in an imaging spectrometer. Furthermore, the collimator lens of the imaging spectrometer is designed through the third-order aberration correction by using an iterative process.

KEY WORDS: Imaging Spectrometer, Imaging Spectrometry, Optical System Design, Lens Design

1. INTRODUCTION

Since the mid-1980's, much attention has been focused on the imaging spectrometer for remote sensing.[1-4] The imaging spectrometer is the optical system to observe two-dimensional spatial image and to measure the spectrum of the light that is collected from each position of the image at once. This spatial and spectral information is used to determine the constituent composition through the spectroscopy for scientific research, military purpose, and others applications over the regional scale of the image.[2,5]

The imaging spectrometers are classified by the method of acquiring the date cube.[6,7] Among theses classes, we concentrate on the pushbroom scanning imaging spectrometer with a dispersion element. Since the approach using pushbroom scanning and a dispersion element offers good signal-to-noise ratio performance,[8,9] it is widely used for many imaging spectrometers.[10-12]

The Image Information Research Center of KAIST (Korea Advanced Institute of Science and Technology) in Korea has been developing the dispersive pushbroom imaging spectrometers operated in the visible range for military purpose and others applications since 2004. In this paper, we present the dispersive pushbroom imaging spectrometer individually controlling the spatial and the spectral resolutions. To increase the discriminative power, the imaging spectrometer with high spatial and spectral resolutions is required. In conventional imaging spectrometers, however, the high resolution can not help suffering loss on the field of view (FOV) or the spectral range. This problem can be overcome by adding the novel zooming function on the imaging spectrometer. Moreover, the present optical system can control the spatial resolution with fixing the spectral resolution or the spectral resolution with fixing the spatial resolution. These functions will be useful for special purposes such as detection or search on the imaging spectrometry. This proposed imaging spectrometer uses zoom lenses as the fore-optics and the focusing lens. The spectrometer using the zoom lens as the focusing lens was reported previously but it was constructed by using commercial lenses.[13]

2. IMAGING SPECTROMETER WITH A NOVEL ZOOMING FUNCTION

A typical dispersive pushbroom imaging spectrometer consists of a scanner, a fore-optics, a slit, a collimator, a dispersion element, and a focusing lens, as shown in Figure 1.[1] The fore-optics is used to image an observed scene onto the slit that is the entrance to the spectrometer. The light passing through the slit is collimated, dispersed by the dispersion element, and re-imaged along one dimension (spatial axis in Figure 1) of the detector array. And the spectrum of each spatial pixel is dispersed along the other dimension (spectral axis in Figure 1) of the detector array. The second spatial dimension of the scene is then constructed by scanning, so that it causes the image projected on the slit to change continuously.

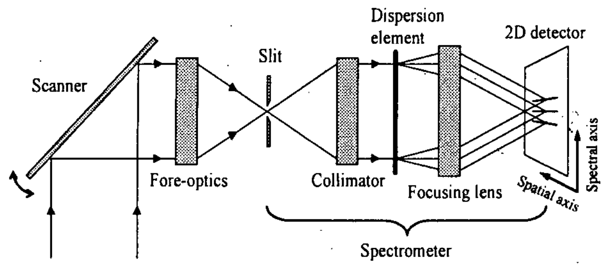

Figure 1. Schematic diagram of a typical dispersive pushbroom imaging spectrometer.

The dispersive pushbroom imaging spectrometer controlling individually the spatial and the spectral resolutions uses zoom lenses as the fore-optics and the focusing lens. By varying the focal length, the focusing lens controls both the spatial dimension and the spectral dimension while the fore-optics controls only the spatial dimension. Therefore, the spectral resolution and the spectral range are affected by the zoom ratio of the focusing lens, while the spatial resolution and an FOV are affected by the multiplication of the zoom ratios between the fore-optics and the focusing lens. Two kinds of zoom lenses are arranged in various configurations, as summarized in Table 1.

Config.	Zoom ratio of Fore-optics	Zoom ratio of Focusing lens	Resulting specification
Type 1	1 x	1 x	$\Delta\lambda$ = 450 nm, FOV = 12°
Type 2	1 x	3 x	$\Delta\lambda$ = 150 nm, FOV=4°
Type 3	1/3 x	3 x	$\Delta\lambda$ = 150 nm, FOV = 12°
Type 4	3 x	1 x	$\Delta\lambda$ = 450 nm, FOV = 4°

Table 1. The zoom ratios of the fore-optics and the focusing lens, and the resulting wavelength range ($\Delta\lambda$) and field of view (FOV) of the imaging spectrometer.

Operated thus, the spatial resolution and the spectral resolution are controlled individually by zoom lenses as the fore-optics and the focusing lens.

In this paper, the focusing lens and the collimator lens for the imaging spectrometer with the novel zooming function are designed. The zoom lens as a focusing lens has the fixed entrance pupil diameter of 20 mm, a focal length of 50 mm varying to 150 mm, and the wavelength range of 450 nm to 900 nm. In the imaging spectrometer, the stop is located at a dispersion element, so that the stop of the designed zoom lens is set apart from the first lens element by 10 mm, considering the mounting configuration. The image has sizes of about 10 mm in the spatial dimension and about 7 mm in the spectral dimension so that the total field of view is 12 degrees when a focal length is 50 mm. The designed collimator lens, on the other hand, represents an objective lens with an aperture of F/2.5 and a focal length of 50 mm operating in the wavelength range of 450 nm to 900 nm. And the stop of the collimator lens is also set apart from the first lens element by 5 mm.

Field of View	12° (4° when spatial zooming)
Entrance pupil diameter	20 mm
Focal length of a focusing lens	50 mm (150 mm when zooming)
Focal length of a collimator lens	50 mm
Image size	10 mm (spatial dimension) × 7 mm (spectral dimension)
CCD Pixel size	12 μm × 12 μm
Spectral Coverage	From 450 nm to 900 nm
Spectral Bandwidth	450 nm (150 nm when spectral zooming)
Spectral Channel	150
Spectral Resolution	3 nm (1nm when spectral zooming)

Table 2. The desired specification of the imaging spectrometer.

The primary criteria to select the detector are the high quantum efficiency, the large dynamic range, and the low noise because the line image passing through the slit is dispersed over the detector. Under the circumstances, the backside-illuminated full-frame S100AB charge-coupled device (CCD) of SITe® has been selected.[14] The CCD has the pixel size of 12 μm by 12 μm and very high quantum efficiencies over 50% in the visible wavelength range. When the S100AB CCD is used as the detector, the expected specifications of the designed optical system are summarized in Table 2. The imaging spectrometer with the novel zooming function will have 150 spectral channels and the spectral resolution of 3 nm (1 nm resolution in the case of the spectral zoom).

3. OPTICAL DESIGN

3.1 Collimator lens design

Considering required specifications, we have picked up a Petzval lens as a basic configuration of the collimator lens. We have configured the front and the rear group, as a cemented triplet and doublet, respectively. From Tesar's catalog,[15] we have selected N-LaF2, NK5, SF4 of Schott as the glasses of the triplet and N-BK7, SF4 as those of the doublet. Fraunhofer C, d, and F lines are used to calculate chromatic aberration in the initial design.

To design the collimator lens, we have used 'the third-order aberration correction by iterative process,' recently reported by our group.[16] The desired optical system is separated into each group and, then, the aberrations of each group are calculated iteratively under following conditions. Spherical aberration is corrected for each group individually. Coma and astigmatism are calculated iteratively to compensate for each other. Moreover, chromatic aberration of the doublet is cancelled by the triplet.

By iterative calculations, we have obtained the initial design for the collimator lens. Since this optical system is the Petzval lens type having positive-positive refracting power, however, it is natural that Petzval curvature is very large. In convention, Piazzi-Smyth field flattener is used to correct the situation. The field flattener is a strongly negative lens close to the focal plane, where it has little effect on the focal length and most aberrations, but it corrects the Petzval field curvature. Inserting the field flattener of SF4 glass into the Petzval lens, we have optimized the system by the optical design software, CODE V.[17] We have set the curvatures and distance between the front group and rear group as variables for optimization. Furthermore, we used three fields corresponding to the half-image sizes of 0 mm, 3.5 mm, and 5 mm and ten wavelengths with the interval of 50 nm from 450 nm to 900 nm. In result, the optimized lens has the modulated transfer function (MTF) of >0.4 at 50 cycles/mm, the root-mean-square spot size of < 13 μm, and the distortion of < 0.15 %.

3.2 Focusing lens design

The mechanically compensated zoom lens with an external entrance pupil for the imaging spectrometer was designed by the method using the lens modules, reported by Park.[18] The lens module is the mathematical construct that has the same first-order properties and the third-order aberration characteristics as those of the lens group composed of the thick lenses. We used the lens modules to find the optimized initial design of the four-group front focus zoom system satisfying specific requirements. By the third-order aberration theory, then, real lenses were numerically transformed from the lens module so as to match the first-order quantities and the third-order aberrations. And the optimized zoom lens with a focal length range of 50 mm to 150 mm was attained by the optical design software.

The four-group front focus zoom system is composed of the fixed front lens group, the second lens group for zooming, the third lens group for focusing, and the fixed fourth lens group. To get an optimum configuration, the prescriptions of the lens modules were optimized under the constraints by the optical design software CODE V. In transformation from the lens modules to real lens elements, we used a cemented doublet as the front lens group, a singlet plus a cemented doublet as the second lens group, a cemented doublet plus a singlet as the third lens group, and a cemented doublet as the fourth lens group with all spherical surfaces. The curvatures and the thicknesses of the thick lenses in the group, both have been numerically solved from the condition that the group has the same effective focal length, back focal length, front focal length, and third-order aberrations as those of the lens modules. The arrangement of the glasses was made in order of N-BK7 and SF4 as the first group, N-LaF2, CaF2, and SF4 as the second group, SF4, CaF2, and N-LaF2 as the third group, and SF4 and N-BK7 as the fourth group. We have used Calcium Fluoride, CaF2, to correct chromatic aberration, which occurs in the broad wavelength range of 450 nm to 900 nm.[19]

In optimized result, the root-mean-square spot sizes are below 15 μm and the spot sizes encircled 100% energy are under 50 μm for all fields at position 1, 2, and 3. The optimized lens has the MTF over 0.36 at 41.6 cycles/mm, Nyquist frequency of the detector. Furthermore, the distortion is below ±1% across the overall FOV for the wavelength range. We have used this zoom lens as the focusing lens for the imaging spectrometer.

3.3 Spectrometer design

We have used the transmission grating at the Littrow mount as the dispersion element for the imaging spectrometer. The diffraction angle of a grating with a groove spacing d is obtained by the grating equation $m\lambda = d(n\sin\alpha + \sin\beta)$, where m is the diffraction order and n is the refractive index of the grating at the wavelength λ. α and β are the incident and the diffraction angles of the wavelength λ, respectively. Here, the Littrow configuration corresponds to the case that $n\sin\alpha$ equals to $\sin\beta$. When we consider the center wavelength of 675 nm and the grating with 300 grooves per mm, the diffraction angle at the Littrow mount is given as 5.81 degrees at the first order diffraction. We have configured the designed collimator lens and the designed focusing lens symmetrically with respect to the grating. The transmission grating of the Littrow configuration is inserted in front of the focusing lens and in back of the collimator lens. The stop is located at the groove surface of the grating, which is set apart from the first lens element by 5 mm. An FOV and the wavelength range of each position are defined as followings: The position 1 covers an FOV of 12.0 degrees and the spectral range of 450 nm (from 450 nm to 900 nm). The position 2 covers an FOV of 5.9 degrees and the spectral range of 225 nm (from 562.5 nm to 787.5 nm). And the position 3 covers an FOV of 3.9 degrees and the spectral range of 150 nm (from 600 nm to 750 nm). If the zoom lens or the transmission grating is rotated around the center of the stop, the spectral ranges of position 2 and 3 are varied from 450 nm to 900 nm. We have optimized once again the zoom system at the defined FOV and wavelength. Figure 2 presents the ray tracing of the optimized spectrometer at position 1, 2, and 3. As a focal length of the zoom lens is varied to 150 mm, the spatial and the spectral resolutions are increased to 3 times, as the type 2 in Table 1. The limited wavelength ranges of positions 2 and 3 are changed from 450 nm to 900 nm by rotating the focusing lens about ± 2 degrees at position 2 and ± 2.6 degrees at position 3. When the object size is 10.0 mm, the spatial and the spectral image sizes in the image plane are about 10.0 mm and 6.8 mm, respectively, as desired requirements at position 1, 2, and 3. The RMS spot sizes are smaller than 17 μm. And the MTFs along the spatial axis and the spectral axis are over 0.25 at Nyquist frequency of the detector for all fields and all wavelengths, although the zoom lens is rotated to vary the spectral range of position 2 and 3.

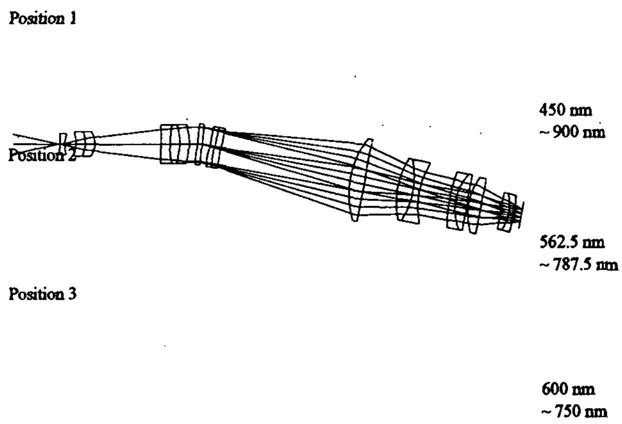

Figure 2. Layout of the optimized spectrometer at position 1, 2, and 3.

4. CONCLUSION

The concept of the imaging spectrometer controlling the spatial and the spectral resolutions individually has been reported at first. This imaging spectrometer uses zoom lenses as the telescope and the focusing lens. It can control the spatial resolution with fixing the spectral resolution or the spectral resolution with fixing the spatial resolution. We have reported the concept of the imaging spectrometer with the novel zooming function and the optical design of the zoom lens as the focusing lens and the collimator lens, for the imaging spectrometer operating in the wavelength range of 450 nm to 900 nm.

5. ACKNOWLEDGEMENTS

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