

Design of spectrum-dividing system for binary optic infrared imaging spectrometer

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ABSTRACT

In the spectrum range of middle wave infrared region (MWIR) and the long wave infrared region (LWIR) radiation, the infrared spectral imaging technology is far from mature in comparison with its counterpart in visible region because infrared radiation is relative weak, the corresponding solid-state detectors and dispersive elements are extremely expensive. The paper reports a novel configuration that exploits the abundant chromatic aberration of binary optical lens to create a dual band infrared imaging imager. The design method of spectrum-dividing systems is presented for infrared imaging spectrometer. The system was analysed and evaluated by optical design software ZEMAX, theoretical formulas were then established. The practical design shows that the system has the very simple optical design that enables a very low cost lightweight robust dual band infrared imaging spectrometer.

Key words: imaging spectrometer; binary optical elements; infrared imaging

1. INTRODUCTION

The field of multi- and hyperspectral imaging, also known as Imaging Spectrometry, has a long history and has been receiving increased attention since the mid-1980's. As discussed elsewhere, Imaging Spectrometry adds the ability to examine the spectral distribution of two-dimensional scenes to the fundamental power of imaging systems. The availability of known spectral radiance, reflectance and absorption curves coupled with an imaging spectrometer allows identification and classification of targets with an accuracy and resolution previously unknown for application of requirements of agriculture, resource survey, environment monitor and military.

Over the last decade several many approaches to hyperspectral imaging have been developed and put into extensive flight experiments and application researches¹⁻⁵. The hyperspectral imaging technology for the spectral regions from visible (VIS 0.4 to 1.0 microns), near infrared (NIR 1.0 to 2.0 microns) and shortwave infrared region (SWIR 2.0 to 3.0 microns) is reasonably mature, however, the midwave infrared region (MWIR 3.0 to 5.0 microns) and especially the longwave infrared region (LWIR 8.0 to 12.0 microns) is not, because the infrared radiation is relative weak, the corresponding solid-state detectors and dispersive elements are

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extremely expensive⁶⁻⁹. Binary optical elements, also known as phase zone plate lenses, have been proposed for many applications. One of the principle limitations of these lenses is abundant chromatic aberration that prohibits broadband use without design compensation. In 1995, at the World Optical Engineering Conference, Denise Lyons¹⁰ proposed a novel structure that exploits this typically unwanted effect to create an imaging spectrometer, which applies to the visible and infrared spectral range.

In this paper, a novel configuration that exploits the abundant chromatic aberration of binary optical lens to create an infrared imaging imager is presented. The design method of spectrum-dividing systems is presented for dual band infrared imaging spectrometer. The system is analysed and evaluated by optical design software ZEMAX, theoretical formulas are then established. The practical design show that the system has the very simple optical design that enables a very low cost lightweight robust dual band infrared imaging spectrometer.

2. Design theory analysis of infrared imaging spectrometer

2.1 Fundamental principles

In the method of hyperspectral imaging, BOE is a diffractive lens, serving to focus incident optical radiation, but it operates on the principle of the diffraction rather than refraction. This dependence on diffraction leads to chromatic aberration where the effective focal length is inversely proportional to wavelength, especially in the infrared band. This shows that BOE has the characteristics of abundant chromatic aberration. It can be expressed as¹⁰

$$f(\lambda) = \frac{\lambda_0}{\lambda} f_0 \quad (1)$$

where f_0 is the focal length of designed wavelength λ_0

Substituting eq. (1) into the first order diffractive lens formula:

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \quad (2)$$

We obtain the expression of image distance

$$s_i(\lambda) = \frac{fs_o}{s_o - f} = \frac{\lambda_0 f_0 s_o}{\lambda s_o - \lambda_0 f_0} \quad (3)$$

Where s_i and s_o are image distance and object distance, respectively. When using the first order diffractive formula, the image distance in the axial direction is dependent on wavelength λ . If s_i and s_o are known, the wavelength λ can be calculated. With this theory, an infrared hyperspectral detector can be designed. With formula (3), we have

$$S_I = \frac{y^4 \varphi^3}{4} (1 + T^2 + 4TC + 3C^2) - 8mA_2 y^4 \quad (7-1)$$

$$S_{II} = -y^2 \varphi^2 J(T + 2C) / 2 \quad (7-2)$$

$$S_{III} = J^2 \varphi \quad (7-3)$$

$$S_{IV} = 0 \quad (7-4)$$

$$S_V = 0 \quad (7-5)$$

Where y is the height of the paraxial marginal ray at the element, J is the Lagrange invariant; T and C are dimensionless bending and conjugate parameters, defined as

$$T = \frac{2c_s}{\varphi} \quad (8)$$

$$C = \frac{u + u'}{u - u'} \quad (9)$$

Where c_s is the curvature of the diffractive lens substrate, u and u' are the angles of the paraxial marginal ray before and after passing through the thin lens.

For the case of a plane substrate, the bending parameter T is equal to zero. Thus the Seidel sums for a planar diffractive lens, stop in contact are

$$S_I = \frac{y^4}{4} \{ \varphi^3 (1 + 3C^2) - 32mA_2 \} \quad (10-1)$$

$$S_{II} = -y^2 J \varphi^2 C \quad (10-2)$$

$$S_{III} = J^2 \varphi \quad (10-3)$$

$$S_{IV} = 0 \quad (10-4)$$

$$S_V = 0 \quad (10-5)$$

Hence we may obtain the phase coefficients A_1, A_2 of DOE by solving the above equations. Additionally, the DOE design can be optimized using computer design codes such as ZEMAX to reduce aberrations both on and off axis. The substrate surface curvatures are used for minimizing aberrations by producing a kinoform, which adds a low power refractive surface for balancing aberrations such as spherical and coma.

2.3 Diffraction efficiency

The diffractive optical element is designed for maximum performance in a certain free spectral range (spectral bandpass). The other critical figure of merit for this application is the diffraction efficiency η . We now consider the wavelength dependence of diffraction efficiency. Based on the scalar theory, the diffraction efficiency for the m^{th} diffraction order is stated by¹⁵

$$\eta_m(\lambda) = \sin^2 \left(\frac{\lambda_0}{\lambda} - m \right). \quad (11)$$

Where λ_0 is design wavelength.

Based on the equation (11), we can select the appropriate designed wavelength to obtain the maximum diffraction efficiency over a given spectral band. An example of this is shown in Fig.2, where the diffraction efficiency η as a function of the wavelength and order over the free spectral range is shown. The lens was designed with a blaze at $7.5\mu\text{m}$, 1st order where it is important to have high efficiency through a spectral range and not at just one wavelength, such as in infrared imaging spectrometer. The diffraction efficiency is over 50% at the longwave infrared region (LWIR 8.0 to 12.0 microns) for the 1st order, and over 40% at the midwave infrared region (MWIR 3.0 to 5.0 microns) for the 2nd order. So we can use the effect to design a dual band infrared imaging spectrometer system.

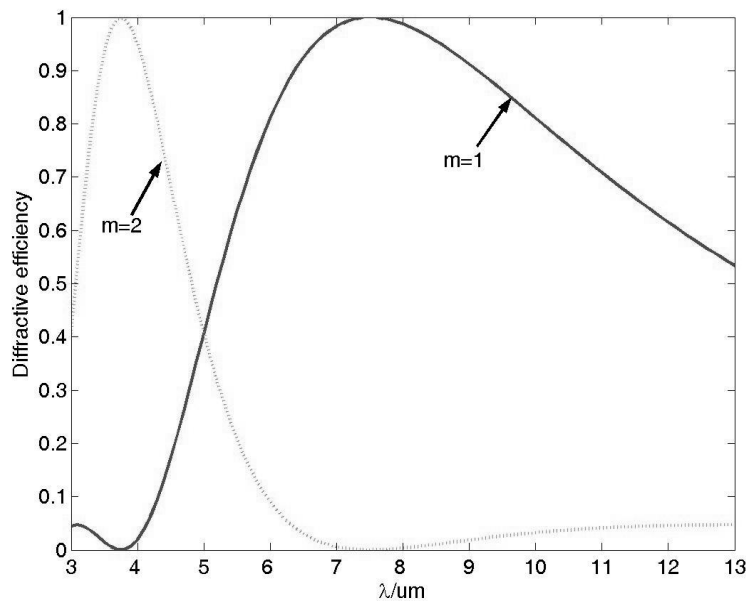


Figure.2 Diffraction efficiency for the first in the LWIR region and the second order in the MWIR region

3. Design example and analysis

In order to illustrate the design principles that have been presented, a specific example of the performance of the diffractive lens for dual infrared imaging spectrometer is presented. Considering the manufacture of

diffractive lens, we select a planar substrate that is easy to manufacture. In the case, the diffractive lens has been designed with the ZEMAX optical design software and has been evaluated with the following parameters: free spectral range: LWIR 8~12 μm , MWIR 3~5 μm , design wavelength: $\lambda_0 = 7.5\mu\text{m}$, focal length: $f_0 = 111\text{mm}$, F/No.: F/2.6. Field of view (FOV): $\pm 0.6^\circ$. The construction parameters for the diffractive lens are given in Table 1.

Table 1. System Specifications for spectrum dividing system

Surface	Radius (mm)	Thickness (mm)	Glass	Semi-Diameter(mm)
1(Binary)	Infinity	3	Ge	21.346154
2	Infinity	110.240340	Air	21.212433
IMA				1.228616
Binary Surface data: $A_1=-1664.195000$, $A_2=14.405867$				

The diffractive lens was modeled in ZEMAX as described in the previous section and the resulting modulation transfer function (MTF) at 7.5 μm wavelength of this system are shown in Fig.3. As can be seen from Fig.3, the performance is almost close to the diffraction limit.

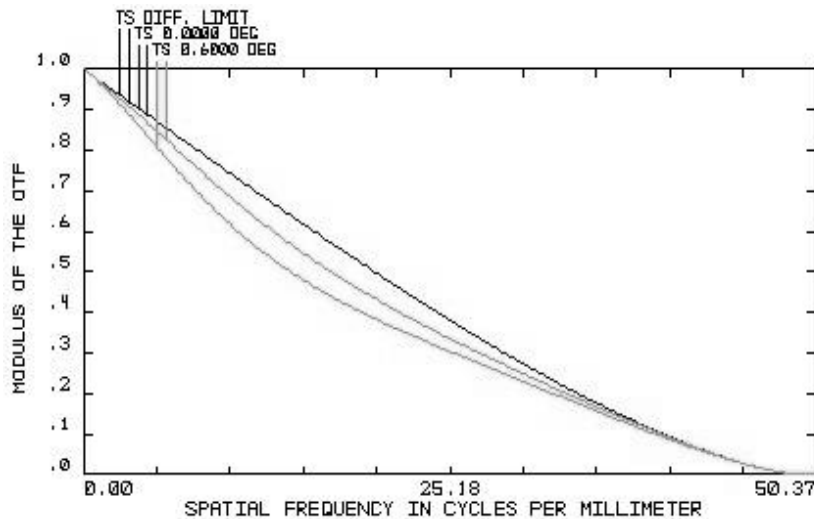


Figure 3: Modulation transfer functions for design wavelength 7.5 μm

It is worth pointing out that the resolution of the manufacturing process used to fabricate the diffractive lens determines the maximum feasible aperture. One can easily show that the minimum zone width s_{\min} is given approximately by¹⁶

$$s_{\min} = 2\lambda_0 F/No. \quad (12)$$

For the infrared imaging spectrometer, $\lambda_0 = 7.5\mu\text{m}$, $F/No. = 2.6$, $s_{\min} = 39\mu\text{m}$, Figure 4 gives the relationship between phase and periods with radial distance of this DOE. So the diffractive lens can be manufactured as binary optical lens which has multilevel phase relief profile by ion beam etching or as continuous profile by single-point diamond turning.

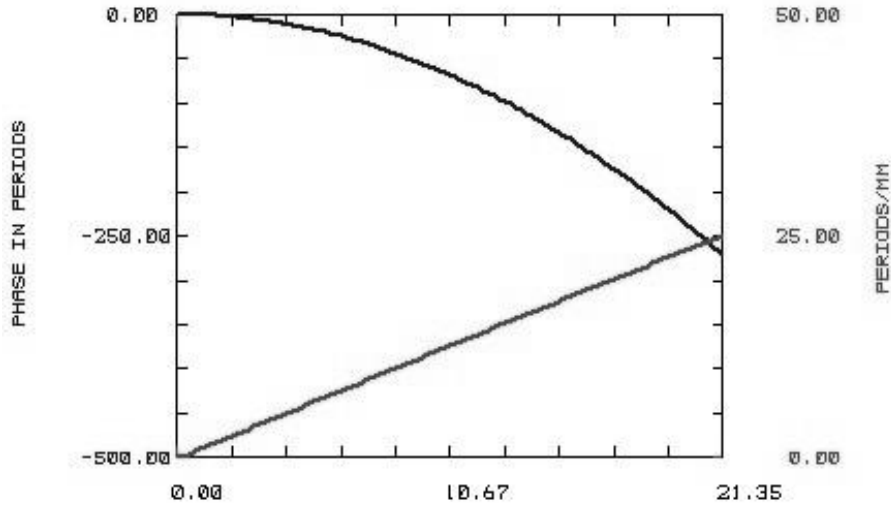


Figure 4: The relation between binary surface phase, line frequency and aperture radius

Also illustrated in Table 2 is the wavelength dependence of the focal length. As we can see, in middle wave infrared region (MWIR 3.0 to 5.0 microns), the focal shift dispersion is about 56mm, and in the long wave infrared region (LWIR 8.0 to 12.0 microns) the focal shift dispersion is about 35mm. So the diffractive lens has enough dispersion along the optical axis to create dual band infrared imaging spectrometer.

Table 2: Focal length of binary optical lens

$\lambda_1/\mu m$	$\lambda_2/\mu m$	f/mm
6	3	138.8
6.5	3.25	128.1
7	3.5	118.9
7.5	3.75	111
8	4	104.1
8.5	4.25	97.9
9	4.5	92.5
9.5	4.75	87.6
10	5	83.3
10.5	5.25	79.3
11	5.5	75.4
11.5	5.75	72.4
12	6	69.4

4. CONCLUSIONS

The purpose of the analysis conducted in this paper is to demonstrate the potential for a new kind of dual band

infrared imaging spectrometer that operates on a new principle of spectral separation. In this system, it uses only a BOE that provides both the spatial imaging and the spectral dispersion, so it can be made very small and lightweight for all kinds of applications. A design example for dual band infrared imaging spectrometer was presented. It shows the effectiveness of the proposed method and the application of binary optical lens in infrared hyperspectral imager is promising. It will help design and manufacture portable and practical infrared hyperspectral detectors, especially detectors used in military affairs.

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