Application of harmonic diffraction in infrared

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Abstract

Harmonic diffractive surface element is successfully introduced to the system of infrared dual band in this paper. It has been simultaneously accomplished that the rectification of the Transverse ray, Lateral color and Longitudinal aberration in both band, wave front aberration less than 1/4 wave length and Modulation Transfer Function of dual band approaching or attaining the diffraction limit. The properties of action spectrum of harmonic diffractive are between refractive element and diffractive, which debased the demand for technical level. The practical design not only shows that the system is compact, few elements and high rates of transmission but also has better weaken-ray aberrations character. and 100% cool diaphragm efficiency. The harmonic diffractive element offers a new component for optics designs.

Keywords: Harmonic diffraction Infrared dual band Optics design

1. Introduction

Most modern infrard optics systems are single band, the development of image technology is very perfect from cell to line array and focal plane[1]. But it has many insufficiency in obtaining information due to limiting in single band, especially in military affairs. The communication of single band obtained becomes weak due to the difference of using district, variety of environmental temperature, camouflage of targets. and operating of the target or the changing of behavior result in moving of radiation band, the image system couldn't detect target or the veracity of target is low or it becomes false signal. Dual band image optics system has been put forward by some investigators in order to enhance self-survival and detect target of enemy. Infrared optics system of dual band has no match for more information, three-dimensional remote sensing, counterreconnaissance, counter-obscure, adapting performance of various circumstances[1]. The studies of infrared dual band, therefore, have important signification for military affairs domain and the development of civil technology. However, the rectification of ray aberration is difficult to conventional refractive optics system, so that it presents big size and weight, low precision and resolving power, as well as having important

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influence on design and manufacture. A hybrid optics system is composed of diffractive and refractive elements, which makes use of the high, opposite sign chromatic dispersion provided by a diffractive surface by comparison with refractive dispersion. It adds new degrees of freedom of optics design and make a great breakthrough to the limit of conventional optics system[2]. This high negative chromatic dispersion can be used in effect as a highly unusual optical material during the concept of an optical system to provide substantial benefits relative to conventional optics in terms of low cost, impact on the mass and improving image quality.

The big dispersion, whereas, is strongest disfigurement for a usually diffractive imaging lens. So a harmonic diffractive elements was recently introduced independently by Sweeney, Sommargren, Morris and Faklis. in 1995[3,4]. i.e., a single-element diffractive lens with multiwavelength path-length steps has the same optical power for number of discrete harmonic wavelengths and overcomes the chromatic aberrations of diffractive element in some extent. The harmonic diffractive lens can be extremely useful for applications such as color projection displays and hyperspectral imaging and it is able to provide high-quality imaging in broadband or multispectral illumination over wide fields of view. In this paper we investigate the infrared dual band optics designs containing harmonic diffractive lens. In addition, the design example of a three-lens optical system operating in the 3.7~4.3μm and 8.7~11.5μm regions is shown which has big view of sight, approaching diffractive limit of imaging quality.

2 The theory of dual band infrared system containing harmonic diffraction and refractive lens

Let us suppose an optical system containing one harmonic diffractive surface and three thin lenses in contact, operating in mid-infrared (band 1) and thermal infrared (band 2) which is considered equal in the number aperture , satisfactory image quality[5], imaging plane of two band should place in a same location, The requirements of overall optical power Φ , longitudinal achromatism demand that three conditions be satisfied:

Total power:

$$\Phi_1^1 + \Phi_1^2 + \Phi_1^3 + \Phi_{1d}^4 = \Phi \tag{1}$$

Achromatism of longitude of in band 1:

$$\frac{\Phi_1^1}{v_1^1} + \frac{\Phi_1^2}{v_1^2} + \frac{\Phi_1^3}{v_1^3} + \frac{\Phi_{1d}^4}{v_{1d}^4} = 0 \tag{2}$$

Achromatism of longitude of in band 2:

$$\frac{\Phi_2^1}{v_2^1} + \frac{\Phi_2^2}{v_2^2} + \frac{\Phi_2^3}{v_2^3} + \frac{\Phi_{2d}^4}{v_{2d}^4} = 0 \tag{3}$$

Where Φ_1^1 , Φ_1^2 and Φ_1^3 are respectively the optical power of the 1,2,3 refractive lens in band 1, and Φ_{1d}^4 is the optical power of harmonic diffractive surface in band 1. v_1^1 , v_1^2 and v_1^3 are respectively the chromatic dispersive powers of materials of lens in band 1, and v_{1d}^4 is the chromatic dispersive powers of harmonic diffractive surface in band 1. Similarly , Φ_2^1 ,Φ_2^2 and Φ_2^3 are respectively the optical power of the 1,2,3 refractive lens in band 2, and Φ_{2d}^4 is the optical power of harmonic diffractive surface in band 2. v_2^1 , v_2^2 and v_2^3 are respectively the chromatic dispersive powers of materials of lens in band 2, and v_{2d}^4 is the chromatic dispersive powers of harmonic diffractive surface in band 2. In order to achieve simultaneous longitudinal chromatism over band1 and band2, The power and diffractive index of lens should satisfy respectively equation as follow:

$$\frac{\Phi_2^i}{n_2^i - 1} = \frac{\Phi_1^i}{n_1^i - 1} \quad i=1,2,3 \tag{4}$$

To harmonic lens ,It's phase jump at the zone boundaries is taken to be $p\lambda_0$,where p is an integer ≥2, i.e. it is equivalent to conventional refractive lens which the design wavelength is $p\lambda_0$ and the focus is f_0. So that there are an infinite number of focal lengths given by

$$f_{m,\lambda} = \frac{p\lambda_0}{m\lambda} f_0 \tag{5}$$

Where p is integer Note that the focal length in Eq.(5)is proportional to P and inversely proportional to the illumination wavelength and the diffraction order, m. It is interesting to note that when the quantity in Eq.(6) is equal to unity several wavelengths within a given band can come to a common focus as follow:

$$\lambda m = p\lambda_0 \tag{6}$$

Where p is a construction parameter and is usually constant across to a common point are chosen from a set of diffraction orders. Thus, the parameter p now offers a mechanism to control specific wavelengths in given band or bands that will to come to a fixed focus. The power of band 1 and band 2 of harmonic diffractive surface is respectively given by

$$\Phi_1 = \frac{kp\lambda_1}{m_1} \qquad \Phi_2 = \frac{kp\lambda_2}{m_2} \tag{7}$$

Where k is constant related to the radius, magnitude of zone and period number of zone. It is important to note a well-known property of operation when higher diffractive orders are used. The dispersion power of harmonic diffractive over band 1 and band 2 is respectively given by

$$v_1 = \frac{\lambda_{(1)mid}}{\lambda_{(1)short} - \lambda_{(1)long}} \qquad v_2 = \frac{\lambda_{(2)mid}}{\lambda_{(2)short} - \lambda_{(2)long}} \tag{8}$$

We can confirm the original system structure base on Eqs.(1), Eq (2) and Eq (3) , and design the power of harmonic diffractive ,radius value, magnitude of zone and period number of zone of surface structure after performance optimization be accomplished by Zemax.

2. Design Example and Discussion

To illustrate the spectral characteristics of a harmonic diffractive lens over mid-infrared and thermal infrared, an optical element of harmonic diffractive lens is designed for operation in the at p=2 and m=2,3,4,5 base on Eq.(7). i.e., the harmonic wavelength is respectively 10μm,6.7μm,5μm,4μm. The design central wavelength is chosen to be 10μm.(λ_0 =10μm). We have calculated respectively the diffraction efficiency of harmonic wavelength by Matlab software, as shown in Fig.1.

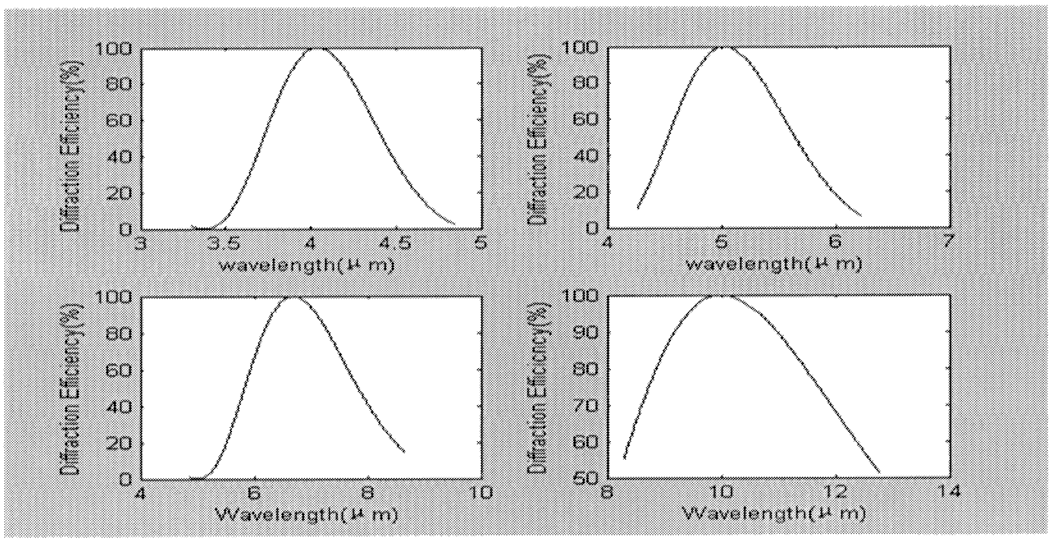


Fig.1 Diffraction efficiency of the difference diffracted order versus wavelength for the Harmonic diffractive element with p=2 (Respectively Harmonic wavelength is 4μm , 5μm , 6.7μm , 10μm)

The wavelength bandwidth of the diffraction efficiency around central wave length of 6.7μm and 5μm isn't the infrared windows, So the both harmonic wavelength isn't calculated for system design. However , the wavelength bandwidths of the diffraction efficiency around central wave length of 10μm and 4μm are lied in spectrum regions of thermal infrared and mid-infrared.

The spectrum regions in which diffractive efficiency is calculated to be 80% act as band operated in infrared system by using the harmonic order of m=2 and m=5. The specifications of system included three elements are chosen as following:

Wavelength range	band 1 is 3.7~4.3μm , band 2 is 8.7~11.5μm
Total Field of View(2*FOV)	5°

Effective Focal length(EFL)	122mm
F-number(F/#)	2.44

The cool diaphragm of system locates 60mm on the front of image plane and easily obtains 100% cool stop efficiency. The power of diffractive is very small with EFL about sixty-four times more than the one of whole systems and located in rear surface of the third lens. So that let us calculate the power and original structure of system after supposing the power of the diffractive lens is zero.

The band 1 and 2 we shall take to should be 3.7 to 4.3μm and 8.7 to 11.5μm. Relationship (4) implies that the curve of refractive index shall be similar in shape, i.e., If we draw two chords on each curve of the three materials joining the values of index at the extremes of three wavebands, then the ratio of the slopes of three chords over their respective wavebands should be equal according to Eq. (4). adding to the effect that harmonic diffractive lens rectifies the chromatism and spherochromatic aberration, system would obtain good ray aberration after selecting the materials of ZNS,AMTIR3 and GERMANIUM[6,7,8].

The harmonic diffractive lens is joined to systems, which is calculated by Zemax after selecting optical materials. We adjust again the location and power of refractive elements and harmonic diffractive lens by using the calculation capacity of software. Through elaborate optimization, the final system is obtained. The hybrid system designed has 3 pieces of lenses as shown in Fig.2. The binary surface is placed on the second surface of the third lens. Both aspherical surface are respectively placed on the second surface of the second lens and the first surface of the third lens of system, which aimed to rectify better ray aberration.

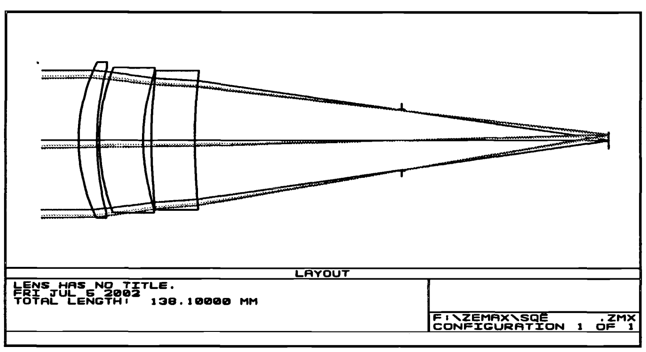
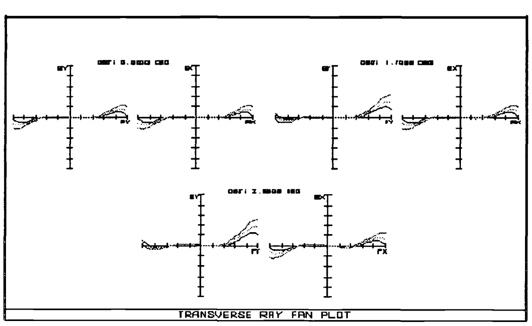
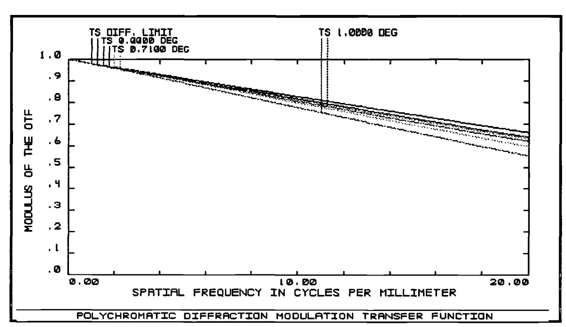
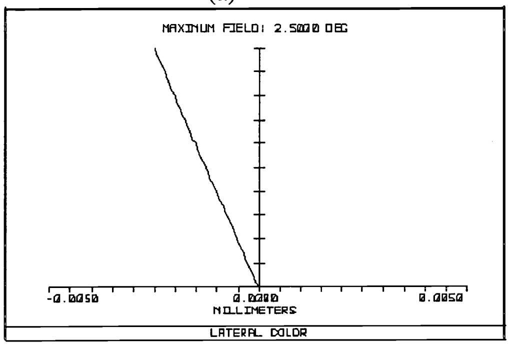


Fig.2 Optical layout of dual band system (The second surface of the third lens is the diffractive surface)





(a)



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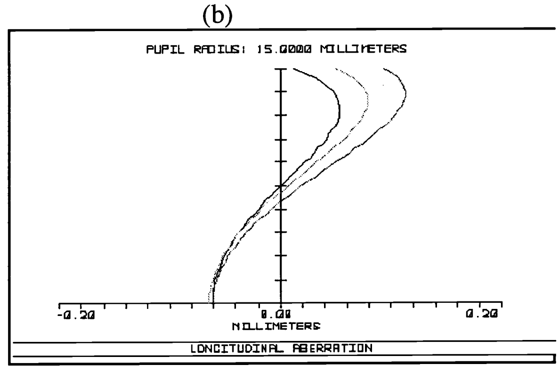
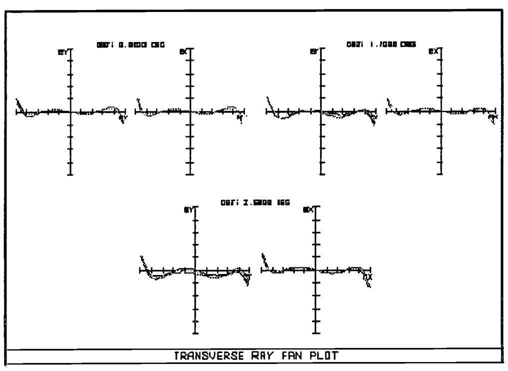


(c)

(d)

Fig.3 Several ray aberration of band 1 (a) Transverse ray fan plot of band 1 (maximal scale is 100μm) , (b) Modulation Transfer Function of band 1, (c) Lateral color of band 1 (d) Longitudinal aberration of band 1



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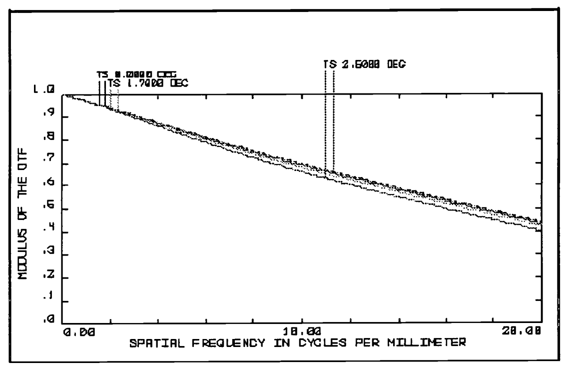

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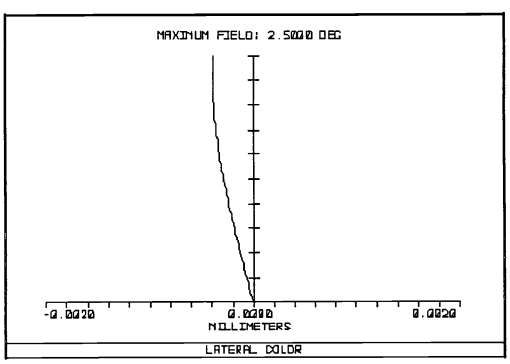
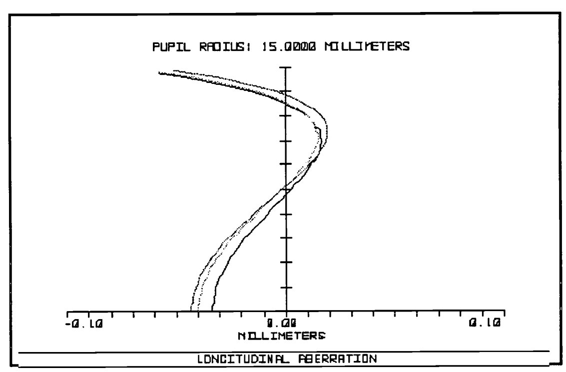


(c)



(d)

Fig.4 Several ray aberration of band 2 (a) Transverse ray fan plot of band 2 (maximal scale is 100μm) , (b) Modulation Transfer Function of band 2, (c) Lateral color of band 2 (d) Longitudinal aberration of band 2

Fig.3 and Fig.4 are respectively aberration plots of optical system over band 1 and band 2. The most transverse ray aberration is 50μm throughout all view of sight, Modulation Transfer Function approachs the diffractive limits, the most Lateral color is 0.0025mm, Longitudinal aberration is 0.17mm and wave front is 0.1247 λ_0 over band 1. The most transverse ray aberration is 30μm throughout all view of sight, Modulation Transfer Function(MTF) approachs the diffractive limits, most Lateral color is 0.0005mm, Longitudinal aberration is 0.08mm and wave front is 0.069 λ_0 over band 2.

Wave front aberration of system in two bands are all less than 1/4 λ_0 i.e., subtracting practically wave front from ideal wave front isn't more than λ_0/4, this wave surface is considered no defects, and the MTF approachs the diffractive limits, so this hybrid system can be use practically. But, we can also see that ray aberration rectified is better in thermal infrared band. The reason is that central wavelength designing is 10μm, the others are harmonic wave, the wavelength bandwidth of the given diffraction efficiency narrows with increasing of diffracted order values of m as shown in Fig.1, which make diffractive efficiency decrease, otherwise, the relation between powers of each lens and the materials selected isn't match for Eq.(4) over mid-infrared and thermal infrared. Furthermore, the ratio of the slopes of three chords over their respective wavebands should be very near in thermal infrared and not approach in mid-infrared. i.e., It can't satisfy the system requirements as shows in Fig.5 which represents favourable choice of materials and debases the quality of system.

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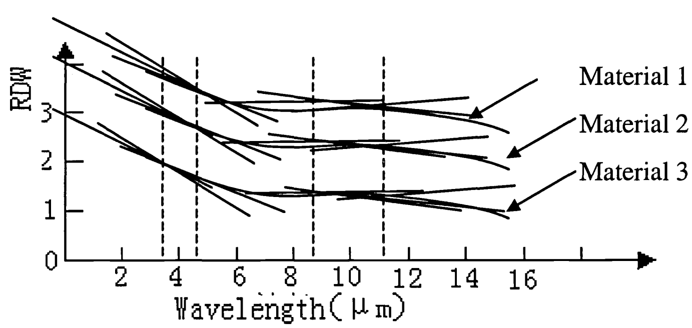

Fig.5 The sketch of ideal material of choice (RSD represent the ratio of refractive index to wavelength)

4. CONCLUSIONS

In this paper, harmonic diffractive elements, cooperating with spheric and aspheric, is successfully introduced to the optics system. Based on the windows characteristics of infrared and the properties of harmonic diffractive elements, we design a dual band infrared system. the phase jump of harmonic diffractive elements at the zone boundaries is taken to be a multiple of 2π, i,e., the optical path difference of zone boundary is the integer multiple p ($p\geq2$) of the central wavelength λ_0.By selecting suitable parameters p, central wavelength λ_0, and infrared materials in this paper, we obtain the image system that works in both 3.7~4.3μm and 8.7~11.5μm wavebands, with a focal length of 122mm,semifield of 2.5° , F number of 2.4 in this system. Transverse ray, Lateral color and Longitudinal aberration are rectified in dual band, Wavefront aberration is less than 1/4 wave length and Modulation Transfer Function of dual band approaches the diffraction limit. The properties of action spectrum of harmonic diffractive are between refractive and diffractive elements which relax the demand for technical level. The practical design not only shows the system is compact, few elements and high transmission but also has better performance. So the harmonic diffractive lens provides high-quality imaging in broadband or multispectral illumination over wide fields of view and has practical values in the design of infrared optics system and offers a new component for optics designs.

ACKNOWLEDGMENTS

This research is supported by the State Key Lab. of Applied Optics, Changchun Institute of Optics and Fine Mechanics and physics, and .Institute of Modern Optics, Nankai University

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