Design of coaxial dual-band IR optical system based on harmonic diffraction

Wang Mengjun[1,2], Zhao Cuiling[2], Han Bangjie[3], Geng Yaguang[2], Ma Tao[2]

(1. College of Automation, Harbin Engineering University, Harbin 150001, China; 2. Handan HanGuang Heavy Industry Co.,Ltd., Handan 056028, China;
3. Air Force Military Agent in Shijiazhuang, Shijiazhuang 050050, China)

Abstract: With the rapid development of precision guidance technology, simultaneous detection of both bands has become very important, the demand of the corresponding optical system and its design increase rapidly. According to the harmonic diffraction element with the characteristic of achromatism, athermalization, same focus on each low diffractive level and high diffractive efficiency, using the CODEV optical design program, a coaxial dual-band IR optical system was designed that worked at -45~+71℃ in the existing processing conditions of diamond cutting. The modulation transfer function(MTF) approached to the diffraction limit in the whole range of temperature and no need to focus, there was no vignetting in optical system and the efficiency of cold shield reached 100%. The dual band infrared optical system has the advantages of compact structure, fewer elements and high transmittance, it is a qualitative leap for improving detection accuracy and recognition ability of the seeker.

Key words: dual band; infrared; harmonic diffraction; processing
CLC Number: TN214 Document code: A Article ID: 1007-2276(2013)10-2732-05

基于谐衍射的共轴双波段红外光学系统设计

王孟军[1,2],赵翠玲[2],韩邦杰[3],耿亚光[2],马 萄[2]

(1. 哈尔滨工程大学 自动化学院,黑龙江 哈尔滨 150001; 2. 河北汉光重工有限责任公司,河北 邯郸 056028; 3. 空军驻石家庄地区军事代表,河北 石家庄 050050)

摘 要: 随着精确制导技术的快速发展,对两个波段的辐射同时进行探测已显得非常重要,对应的光学系统及其设计需求空前增长。文中根据谐衍射透镜的消色差、消热差特性,在各个较低衍射级次上的共焦以及极高衍射效率的特性, 在现有金刚石切削加工能力的条件下应用 CODEV 光学设计软件设计了适用于-45~+71℃的共轴双波段红外光学系统, 该系统在全温度范围内无需调焦其调制传递函数全部接近衍射极限,光学系统无渐晕,并且达到 100%冷光阑效率。该红外双波段光学系统结构紧凑、片数少、透射比高,对于提高导引头的探测精度、识别能力、打击精度有质的飞跃。

关键词: 双波段; 红外; 谐衍射; 加工

收稿日期: 2013-02-13; 修订日期: 2013-03-17

基金项目: 国家 973 计划项目

作者简介: 王孟军 (1967-),男,研究员级高级工程师,博士,主要从事火控技术、精确制导技术研究。Email:mt841115@163.com

0 Introduction

It is well known that the diffractive optical element not only has the unique characteristic of diffraction dispersion and temperature which made the optical system has a good effect on achromatism and athermalization, but also can be easily processed at arbitrary phase distribution in the use of advanced diamond turning technology. However, an optical system for wide-band or multiband, the average diffraction efficiency of ordinary diffractive optical element is very low, often less than 50%, which greatly limits its application on the hybrid optical system [1]. In 1995 Sweeny proposed the concept of harmonic diffractive lens, harmonic diffractive improved the problems of large dispersion aimed at the ordinary diffractive lens that works on the wide band, it can overcome the defocus that generated from the dispersion of ordinary diffraction element, and have the same optical power in a series of discrete wavelength, and be able to maintain 100% of the diffraction efficiency in theory.

Based on the characteristics of infrared imaging window and harmony diffraction lens, a dual-band infrared optical system works on 3~5 μm and 8~9 μm is designed in the paper, the image quality is close to the diffraction limit, this hybrid optical system is adapted to the application requirements of the dual-band infrared system.

1 Harmonic diffraction

1.1 Imaging theory of harmonic diffractive optical element

Harmonic diffractive optical element (HDOE) is derived from conventional diffractive optical element. Its characteristic is to produce the phasic difference of $2m\pi$ by changing the surface micro structure of the substrate material of the diffraction element; and the diffraction order extends from 1 to other orders, different diffraction order corresponds to different discrete wavelengths, each diffraction order having the theoretical diffraction efficiency of 100% and the same optical powers [2]. For the characteristic of harmonic diffractive lens, the optical path difference between the adjacent ring is integer $\mathbf{p}$ ($\mathbf{p}\geqslant 2$) times of the design wavelength λ_0, the mutation depth $\mathbf{d}$ is also $\mathbf{p}$ times of common diffractive lens, in the other words it can be considered that the design wavelength is $\mathbf{p}\lambda_0$, the mutation depth $\mathbf{d}=\mathbf{p}\lambda_0/(\mathbf{n}_0-1)$. As imaging in the diffraction order m at the wavelength λ, its focus is

$$f_{m,\lambda}=\frac{p\lambda_0}{ml}f_0 \tag{1}$$

According to $f_{m,\lambda}$ and the design focus f_0, it can be written as

$$ml=pl_0 \tag{2}$$

The formula(2) shows that, if the wavelength meets $l=pl_0/m$, it will converge to the same focus f_0 of harmonic diffractive lens. $\mathbf{p}$ is the determined parameters before design, the resonance wavelength can be selected according to the above formula, the greater $\mathbf{p}$ is, the greater the resonance wavelength in the spectral band is, $\mathbf{p}$ offers a new degree of freedom.

1.2 Process parameters of harmonic diffractive optical elements

The curved surface type of diffractive fundus, and the phase distribution of the diffraction surface is as follows

$$z(r)=\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}+f(r) \tag{3}$$

The phase distribution of diffractive optical element with circularly symmetrical structure can be expressed using $\mathbf{N}$-order polynomial, it can be written as

$$f(r)=\frac{2p}{l_0}\sum(C_n r^{2n}) \tag{4}$$

In accordance with the scalar theory, the phase increase or decrease 2π will not change the role of light-wave modulation that produced by the diffractive micro-structure, therefore the arbitrary phase distribution of the diffractive surface can be compressed between 0-2$m\pi$ according to the formula as follows

$$T_D(\phi)=\phi-\mathrm{int}\left(\frac{\phi}{2m\pi}\right)\times 2m\pi \tag{5}$$

int(x) is a rounding function, m is positive integer.

The borders of diffraction rings appeared in the location that the phase value is integer multiples of 2$m\pi$, make formula (4) equal to integer multiples of 2$m\pi$

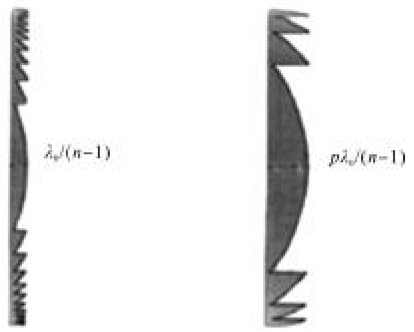
$$\left|\frac{2\pi}{\lambda_0}\sum(C_n r^{2n})\right|=2m\pi k \tag{6}$$

In the formula: k is the band number, the mutation radius r_k can be achieved from the formula, k is the serial number of ring that incremented from the lens center to the edge until it reaches the required aperture.

Figure 1 shows that compared with ordinary diffraction lens, the ring numbers of harmonic diffractive lens reduce p times, the mutation depth is increased p times, which greatly reduces the difficulty of processing, and make the processing of the element can be consistent with the design results.

$$d=\frac{p\lambda_0}{n_0-n} \tag{7}$$

According to the formula above, we can determine the correlative processing parameters of binary optical surface and the ring.



(a) Diffractive element (b) Harmonic diffractive element

Fig.1 Contrast between harmonic diffractive element and diffractive element

2 Diffractive optical system design

The focal length of dual band optical system is 73 mm, the field of view is 6.10°×6.10° and the F number is 2.

2.1 Phase design of dual-band optical system

The micro structure of harmonic diffractive surface makes the two center wavelength of dual-band optical system at the two position of harmonic wavelength, according the formula (2), finally selecting p=2, design wavelength λ_0=4.2 μm, harmonic diffraction wavelength is 8.4 μm, and the corresponding diffraction orders are respectively 2 and 1[3]. When optimizing the harmonic diffractive element by optical design software, the method of multiple structures (Multi-configuration) can be used to set the phase expressions in dual-band, and each coefficient of the expression must satisfy the following proportion:

The phase expression of harmonic diffractive optical element in mid-wave band is

$$\phi_m=\frac{2\pi}{\lambda_{M0}}\sum(C_n r^{2n}) \tag{8}$$

The expression in the long-wave band is

$$\phi_L=\frac{2\pi}{\lambda_{L0}}\sum(kC_n r^{2n}) \tag{9}$$

k is defined as

$$k=\frac{\lambda_{M0}}{\lambda_{L0}} \tag{10}$$

Make k =0.5 according to the center wavelength we set, so that it can realize the optimization design of harmonic diffractive infrared hybrid optical system[4].

2.2 Phase coefficient change caused by temperature

For the diffractive optical element, the phase coefficient change caused by temperature is as follows:

$$C_n'=C_n/(1+\alpha\Delta T)^{2n} \tag{11}$$

After simplified, It also can be written as follows

$$\Delta C_1=-2\alpha C_1\Delta T$$

$$\Delta C_1=-4\alpha C_1\Delta T$$

$$\cdots$$

$$\Delta C_n=-2n\alpha C_1\Delta T \tag{12}$$

2.3 Diffraction efficiency analysis

The diffraction efficiency of harmonic diffractive optical element in the m-order is as follows

$$\mathbf{h}_m = \mathrm{sinc}^2 \left\{ \frac{\lambda_0}{\lambda} \left[\frac{n_\lambda - 1}{n_{\lambda 0} - 1} \right] \mathbf{p} - \mathbf{m} \right\} \tag{13}$$

In the fomula, $\mathbf{n}_{\lambda 0}$ and $\mathbf{n}_\lambda$ are respectively the refractive index of grating material in wavelength λ_0 and λ, $\mathbf{m}$ is the diffraction order. Finally we calculate that the diffraction efficiency in the whole design band can reach more than 85% according to the method of band-width integral average diffraction efficiency[5].

2.4 Result of optical system design

According to the above analysis, using CodeV software for system design, optical system structure is shown in Fig.2, the diffraction surface is set on the front surface of the last piece of lens, and the fundus is plane, the material is germanium.

The diameter of harmonic diffractive element is about 36 mm, consisting of 5 cycles, the minimum processing cycle is 222.218 μm, it can meet the requirements of processing technology. According to the formula (7) we can obtain the mutation depth of diffraction element is 2.798 μm. The curve of phase modulation is as shown in Fig.3, and the curve of compression phase is as shown in Fig.4.

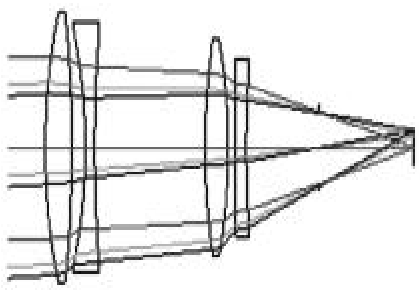


Fig.2 Structure of optical system

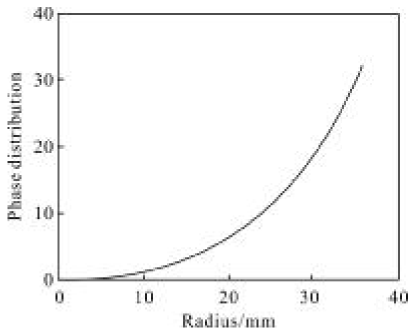


Fig.3 Curve of phase modulation

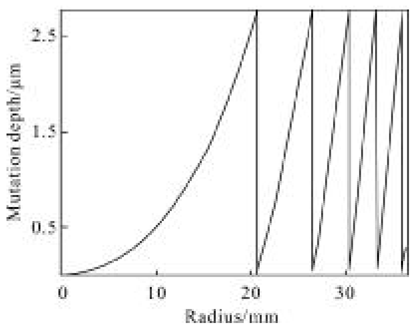


Fig.4 Curve of compression phase

2.5 Evaluation of image quality

The MTF in the mid-wave at 20 ℃, -45 ℃ and 71 ℃ is shown in Fig.5, Fig.6 and Fig.7. The MTF in the long-wave at 20 ℃, -45 ℃ and 71 ℃ MTF as

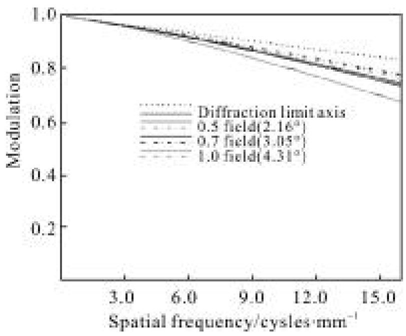


Fig.5 MTF of mid-wave at 20℃

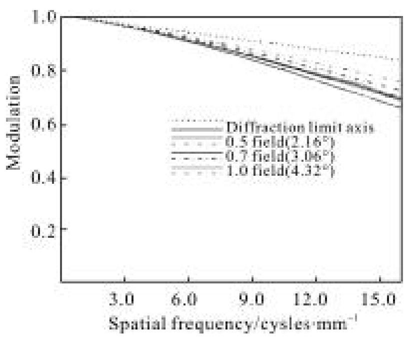


Fig.6 MTF of mid-wave at -45℃

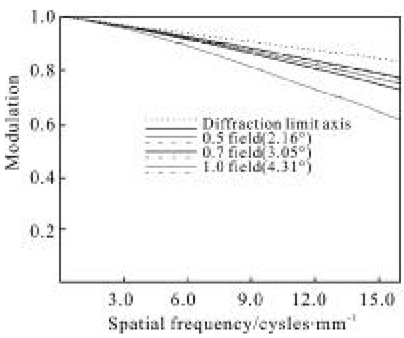


Fig.7 MTF of mid-wave at 71℃

shown in Fig.8, Fig.9 and Fig.10, and the cut-off frequency is 16 lp/mm. it can be seen that the curve of MTF was more than 0.5, approaching the diffraction limit in the whole temperature range[6].

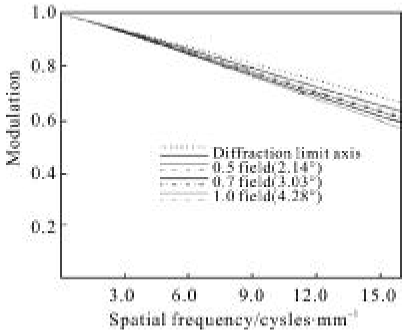


Fig.8 MTF of long wave at 20℃

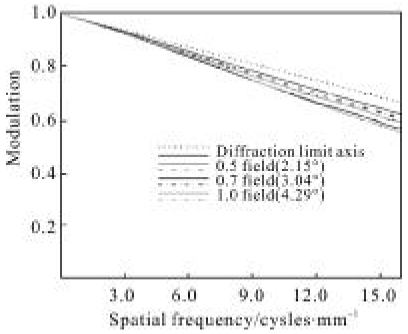


Fig.9 MTF of long wave at -45℃

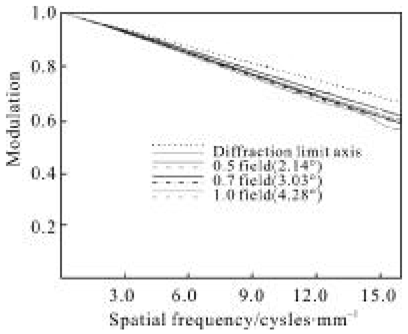


Fig.10 MTF of long wave at 71℃

3 Conclusions

According to the characteristics of harmonic diffractive lens, a coaxial dual-band infrared optical system designed in existing processing ability by selecting the harmonic orders **p** and center wavelength λ_0 properly, this system can achieve composite system that no need for spectral technology, as long as have the dual band detector. The application of harmonic diffractive lens not only simplified the structure of optical system, reduced the number of optical lens, improved the image quality, but also exploited a new field for the optical design and optical processing.

Reference:

[1] Sweeney D W, Sommargren G E. Harmonic diffractive lenses [J]. Applied Optics, 1995, 34(14): 2469-2473.

[2] Zhao Cunhua, Wang Jinyan, Zhu Jincheng. Design of hybrid refractive-diffractive infrared lenses with large relative aperture [J]. Infrared and Laser Engineering, 2007, 37(8): 756-758.

[3] Lou Di, Bai Jian, Hou Xiyun, et al. Application and research of harmonic diffractive/refractive optcis in visible spectrum. [C]// SPIE, 2004, 5636: 78-85.

[4] Yan Peipei, Fan Xuewu, He Jianwei. Design of hybrid refractive-diffractive star sensor optical system with small F-number [J]. Infrared and Laser Engineering, 2011, 40(12): 2458-2464.

[5] Sun Qiang, Wang Zhaoqi, Liu Hongbo. Optical system of harmonic diffractive/refractive for infrared dual-color detector [J]. Infrared and Laser Engineering, 2003, 32(3): 317-321.

[6] Wu Xiaojing, Sun Chiquan, Meng Junhe. Relationship between athermalizing infrared optical system and zoom lens [J]. Infrared and Laser Engineering, 2002, 31(3): 249-252.