Design of solar-blind UV optical system for missile approach warning

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Abstract: Ultraviolet (UV) warning technology is playing a very important roll in the field of military application. Based on the optimal working waveband of solar-blind UV optical system from 240 nm to 280 nm, an optical system was designed for missile approach warning. To enhance the received light energy, expand the detection range and simplify the system structure, aspheric surfaces and binary elements were adopted in the system. Only five elements were used to realize the focal length 50 mm and field of view (FOV) 43 degrees. iKon-L 936 from ANDOR company was selected as the UV detector, which has pixel size 13.5 μm×13.5 μm and active image area 27.6 mm×27.6 mm. After optimization, the maximum RMS radius is only about 11 microns, which is much less than pixel size of the detector and more than 86% of the light energy from each FOV is converged within the circle of radius 6.75 microns. The image quality shows the designed system can meet the working requirements of solar-blind UV optical system. If the focal length can be decreased, the FOV of the system can be enlarged further.

Key words: ultraviolet warning; solar-blind UV optical system; aspheric surface; binary element; point spread function; image quality

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用于导弹逼近告警的“日盲”紫外光学系统设计

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摘 要: 紫外告警技术在军事应用中扮演着重要的角色。基于“日盲”紫外光学系统的最佳工作波段 240~280 nm,设计了一款用于导弹逼近告警的光学系统。为提高系统接收的紫外辐射能、扩展系统探测范围以及简化系统结构,系统中采用了非球面和二元衍射光学元件。系统中含有 5 片透镜,其焦距为 50 mm,视场角为 43°。探测器采用 ANDOR 公司的 iKon-L 936 型 CCD,其像元大小为 13.5 μm×13.5 μm,有效成像面积为 27.6 mm×27.6 mm。系统优化后,最大 RMS 半径仅为 11 μm 左右,远小于像元尺寸。超过 86%来自物方各视场的紫外辐射会聚在半径为 6.75 μm 的圆内。像质表明,所设计的系统能够满足“日盲”紫外光学系统的工作条件。若减小焦距,则系统的视场角可进一步增大。

关键词: 紫外告警; “日盲”紫外光学系统; 非球面; 二元衍射光学元件; 点扩散函数; 像质

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0 Introduction

In modern wars, missile attack has become a main way to eliminate enemy targets. To reduce serious battlefield threat from anticraft missiles and air to air missiles, missile approach warning technology has been researched and developed very fast in recent years. In the development history of missile warning technology, infrared warning and radar warning have dominated the warning field for almost 30 years. Compared with infrared warning technology, UV warning technology has many advantages such as low false alarm rate, refrigeration independent, small volume and light weight[1-3]. Through fast development of 20 years, UV warning technology has become a main way for missile approach warning, which is playing a more and more important role in the field of optoelectronic antagonism[4].

Due to late start of UV warning technology in our country, there are few literatures in this field. In literature [5], structure analysis and design of UV warning system were given, but it was limited to theoretical derivation of system structure data. Optical design of UV warning system can not be found in this paper. In literature [6], optical system of diffractive refractive hybrid UV warning system was designed with field of view (FOV) 40 degrees and relative aperture 1:3.5. In this system, there exist five elements, in which one aspheric surface and two binary surfaces were adopted. In literature [7], the research on sun-tracking warning system in solar blind UV waveband was given. Cassegrain system was adopted in this paper. However, reflective system has rather small FOV, which can not meet the requirements of large FOV for UV warning system.

In this paper, an optical system for missile approach warning is designed, which works within the solar-blind region of solar spectrum. Only five elements are adopted to make the FOV of the system increased to 43 degrees. By jointing multiple CCD, missile approach warning can be realized within the whole airspace without blind zone.

1 Analysis of solar-blind UV optical system

1.1 Principle of solar-blind UV warning system

In nature, the main UV light source is the sun. When the UV radiation from the sun passes through the atmosphere, the ozone layer will have strong absorption for the waveband from 240 nm to 280 nm, which almost leads to no existence of this waveband in the atmosphere near the ground. Because it could not be received near the ground, this waveband is commonly known as solar-blind region of solar spectrum[5]. According to the characteristic of this waveband, a dark field will appear for solar-blind optical system if there is no special condition in nature. UV warning technology is just to utilize the characteristic of solar-blind waveband to detect the UV radiation signals emitting from the approaching hostile missile plume. Figure 1 shows a fighter aircraft installing missile approach UV warning systems, which are enclosed with round circles in this figure.

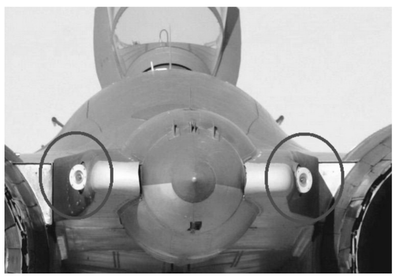

Fig.1 UV warning systems installed on fighter aircraft

Solar-blind UV system for missile approach warning is composed of optical system, UV narrowband filter and UV detector. The optical system needs to have large FOV to receive UV radiation from potential targets. UV narrowband filter is to suppress the UV radiation beyond solar-blind waveband as far as possible, which is commonly considered as the background noise. UV detector should be very sensitive to solar-blind UV radiation, which transforms the detected UV radiation to electric signals. iKon-L

936 from ANDOR company is selected as the UV detector, which has pixel size 13.5 μm×13.5 μm and active image area 27.6 mm×27.6 mm.

1.2 UV material

The choice of material is the top issue of optical system design. Working wavelength or waveband of the designed optical system is the primary factor for material selection. Most UV materials have strong absorption and obvious cutoff wavelength, which is associated with the type and purity of the chosen materials.

Most of the materials are not suitable for optical refractive elements. Actually, only CaF_2 and JGS1 are most commonly used as UV lens materials[6]. According to aberration correction theory, CaF_2 is chosen as the material of positive lens and JGS1 is chosen as the material of negative lens. These two materials have low refractive indexes and small difference of Abbe numbers, which is not helpful for aberration correction[7-8]. On the other hand, due to the hygroscopy of CaF_2 material, the designed optical system should be kept in a sealing system.

2 Solar-blind UV optical system desing

2.1 Structure selection of solar-blind UV optical system

Commonly, optical system can be divided into three types, namely, refractive type, reflective type and catadioptric type. No chromatic aberration is produced by reflective objectives[9]. Catadioptric objective is the combination of reflective and refractive objectives, which can increase the FOV to some extent. However, solar-blind UV warning system has the requirements for large FOV. Considering the above factors, refractive objective is adopted as the basic structure of the system in this paper.

Due to large FOV of solar-blind optical system, reversed telephoto objective should be adopted. The system not only can realize large FOV, but also can keep certain working distance. Reversed telephoto objective composes of a positive optical group and a negative one, which can realize longer back working distance than focal length. This characteristic meets the requirements of installing or adjusting other elements, such as CCD camera.

2.2 Aspheric surface and diffractive optical element

Aspheric surface is a general definition, which refers to all surface types except for spherical surfaces. The shape of an aspheric surface is determined by high order coefficients of the aspheric surface. In most actual applications, axisymmetric quadric aspheric surfaces are commonly used. By adding one or more aspheric surfaces in spherical optical system, spherical aberration can be corrected very well. Simultaneously, all off-axial aberrations can also be corrected except for field curvature, which makes relative aperture and field of view enlarged to realize miniaturization and light weight of system[10-11]. Besides, aspheric surfaces can simplify the system structure, still remaining good image quality.

By sculpturing multiple steps to form embossment structure on substrates or traditional optical elements, binary diffraction optics is generated based on the diffraction theory. Propagation direction, amplitude, phase and polarization state of light can be changed by modulating phase of diffractive optical elements. Thus, diffractive optical elements can perform more functions than traditional optical elements. Compared with traditional elements, diffractive optical elements have many advantages, such as miniaturization, integration and array.

A diffractive optical element has opposite sign to the dispersion coefficients of regular materials, which has negative dispersion coefficients and effects. Large partial relative dispersion is helpful to correct chromatic aberration and secondary spectrum. Traditional refractive optical elements can only correct aberrations by changing the radii or using different optical materials. However, diffractive optical elements can increase the designing freedom by adjusting the corresponding parameters of phase, step position, width and depth[12-14].

3 Design results and evaluation of image quality

To receive more radiation energy from an approaching missile, the UV optical system needs to have large relative aperture and field of view. For traditional spherical optical system, many elements are needed to meet the requirements. To simplify the system structure and improve image quality, two aspheric surfaces and one diffractive optical are adopted in this paper. According to Seidel coefficients of each surface, the sixth element of the system is reduced, which has minimum contribution to spherical surface. Using aspheric surfaces around the aperture stop can correct aberrations associated with field of view. While, using aspheric surfaces away from the aperture stop can correct aberrations associated with aperture size. In order to correct aberrations related to FOV of the system, the 2nd and 3rd surface of the system are selected as aspheric surfaces according to multiple attempts.

Optical materials fit for solar-blind UV system are extremely rare. Only CaF_2 and JGS1 are commonly used, which have little difference of Abbe numbers. This brings enormous difficulties of correct chromatic aberrations. To correct chromatic aberrations and secondary spectrum, the 1st surface is adopted as binary diffractive surface.

3.1 Selection of original configuration

The designed UV optical system has the following optical parameters as required in Tab.1.

Tab.1 Optical parameters of the designed UV warning system

Focal length/ mm	Relative aperture	Working waveband/nm	Field of view
50	1/4	240-280	43°

The field of view 43° is determined by the selected detector iKon-L 936 and the focal length. By searching literatures, a UV objective is found with similar parameters. The original configuration is composed of six lenses. The original data of the system is shown below in Tab.2.

Tab.2 Original data of the configuration

Surface number	r	d	n
1	20.235	3.648	CaF_2
2	332.185	2.687	
3	-24.593	5.890	F_SILICA
4	10.770	0.910	
5	11.821	7.410	CaF_2
6	-17.849	5.580	
Stop	Infinity	4.640	
8	23.635	6.400	CaF_2
9	38.075	2.778	
10	-12.613	2.196	F_SILICA
11	-41.047	2.210	
12	25.290	5.306	CaF_2
13	35.400	17.314	

The configuration of original system is shown in Fig.2. The original system has the following optical parameters: focal length 100 mm, $F/3$, FOV 20° and working waveband 240-280 nm. When adjusting the optical parameters to required values in ZEMAX, the spot diagram is shown in Fig.3.

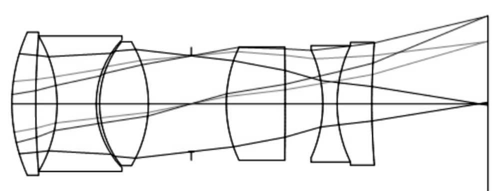

Fig.2 2D layout of original configuration

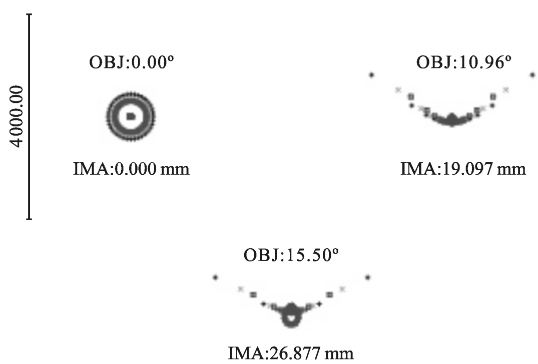

Fig.3 Spot diagram of original configuration

From Fig.3, the RMS radius of each FOV is very large. The image quality needs to be optimized.

3.2 Optimization of solar-blind UV missile warning system

Solar-blind UV warning system is an energy system instead of an imaging system. Traditional evaluation methods for imaging optical systems are not suitable for UV warning system. Other evaluation methods, such as spot diagram, point spread function and energy distribution curve, can be adopted to evaluate convergence degree of energy. The design results are shown from Fig.4 to Fig.7.

Figure 4 shows the reasonable structure of system after optimization. Figure 5 is the spot diagram after system optimization. Application of aspheric surface and diffractive optical element makes each FOV have similar spot size, which shows the system almost meets the requirements of isoplanatic condition. The maximum spot size is 11.988 μm, which is less than the pixel size of the selected CCD detector. The point spread function shown as Fig.6 confirms the high convergence degree for each FOV. Energy distribution curves in Fig.7 indicate light energy beyond 86% locates within a circle of radius 6.85 μm. The design result shows this system has good image quality with large FOV and relative aperture.

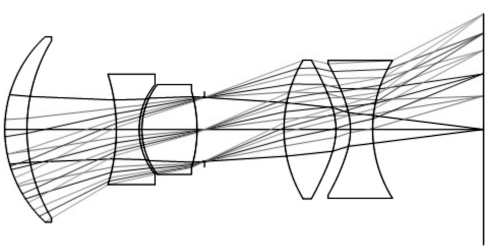

Fig.4 System structure after optimization

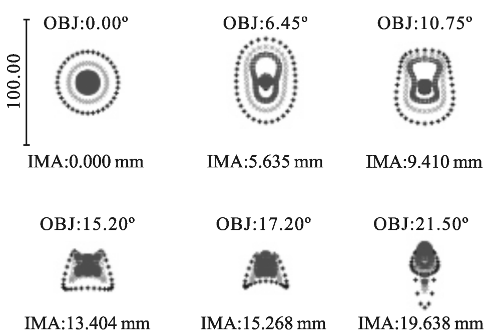

Fig.5 Spot diagram after optimization

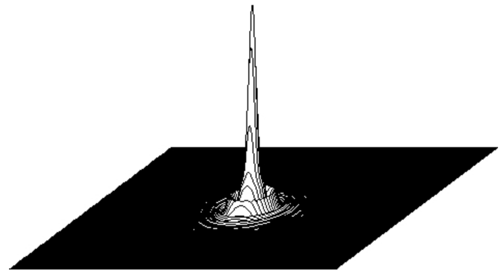

Fig.6 Point spread function

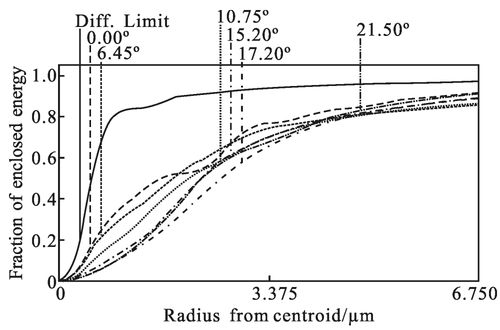

Fig.7 Energy distribution curves

4 Conclusion

Based on the principle of UV warning technology, a solar-blind UV optical system is designed in this paper. Spherical surface, aspheric surface and diffractive optical element are combined to correct chromatic aberration and high-order aberrations. The system structure is simplified with large FOV, relative aperture and compact system tube length. From the evaluations of spot diagram, point spread function and energy distribution curve, the designed system has high convergence degree of energy. Spot diagrams for each FOV are all less than the pixel size 13.5 μm, which meets the application requirements of solar-blind UV system for missile approach warning.

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