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含三层衍射元件的 60°视场折/衍混合头盔目镜

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摘 要:设计了一种含有三层衍射光学元件的 60°视场头盔显示目镜,并给出了系统优化过程和结果. 在整个视场和设计波段范围内三层衍射光学元件的衍射效率均在 90%以上,提高了系统的光能利用率和像的对比度. 此目镜光学系统的出瞳直径为 8 mm,出瞳距离为 22 mm. 整个系统重量仅为 8 g,总长度为 26.8 mm,结构轻便紧凑,具有良好的光学性能,满足头盔显示目镜的使用需求.

关键词:光学设计;头盔目镜;折/衍射混合;多层衍射光学元件

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Hybrid Diffractive-refractive 60° Field of View Eyepiece with Three-layer Diffractive Optical Element

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Abstract: A hybrid diffractive-refractive 60° field of view (FOV) eyepiece for head-mounted display (HMD) with a three-layer diffractive optical element (DOE) is designed, and the design performance is given. The diffraction efficiency of the three-layer diffractive optical element is larger than 90% at each FOV and wavelength in designed band, so that the utilization rate of energy and contrast ratio of image can be improved. The system has an 8 mm exit pupil and a 22 mm eye relief, and the feature of 8 g weight and 26.8 system size guarantee the lightness and compactness of the structure, which are well to be a eyepiece for HMD.

Key words: Optical design; Eyepiece for head-mounted display; Hybrid diffractive/refractive; Three-layer diffraction element

0 Introduction

Head-mounted display (HMD) is a new technology in modern display areas, which plays an important role in augmented reality and virtual reality. In the head-mounted displays, the users receive images through the visual system in front of them, which requires high image quality of the optical system and includes such optical performances as high resolution, wide field of view, and large exit pupil diameter, and that requires the structure of the HMD to be portable and compact compared to traditional refractive HMD[1].

Up to now, the introduction of diffractive optical elements into the optical system has been a significant means for overcoming weaknesses of traditional refractive HMD. The combination of diffraction and refraction contributes to lightening the weight, and simplifying the structure[2-4]. At the same time, the aspheric coefficient of three-layer diffractive element (DOE) can be used to balance the higher-order aberrations. On the contrast, the single-layer DOE only works well at

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the accurate designed wavelength and cannot be applied to wide waveband imaging of the optical system. The double-layer DOE can realize the high efficiency of wide waveband, but it damages the diffraction efficiency and the imaging quality of the optical system at the large field of view (FOV)[5]. The three-layer DOE replace the air (between the two microstructures of the double-layer DOE) with the material with different dispersions and refraction efficiency, which make sure 90% diffraction efficiency in wide waveband and large FOV. The study of the three-layer DOE broadens the application scope of the DOE in many optical systems.

This paper has designed a hybrid diffractive-refractive 60° FOV eyepiece for head-mounted display with the three-layer DOE which makes the high quality of imaging within the wide waveband and large FOV, and helps to the 3D application for the purpose of entertainment and virtual reality.

1 Diffraction efficiency of three-layer DOE

The structure of three-layer DOE is shown in Fig. 1. It can be seen that the double-layer DOE is filled with optical plastic , so that the more

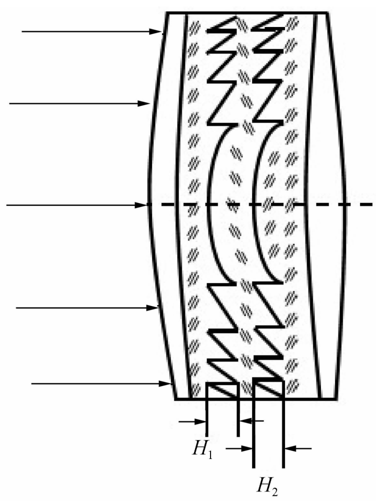

Fig. 1 Structure of the three-layer DOE

parameters can be got to control the diffraction efficiency. The phase retardation of the three-layer DOE can be written as

$$\varphi_f = H_1[n_f(\lambda) - n_1(\lambda)] + H_2[n_2(\lambda) - n_f(\lambda)] = m\lambda \tag{1}$$

where H is the height of the relief pattern, $n(\lambda)$ is the refractive index of the element when the wavelength is λ. Generally, the diffraction order m is taken as 1. Two equations will be obtained after selecting three materials with different dispersion and two wavelengths (λ_1, λ_2). The Eq. (2) and Eq. (3) are the solutions of the equations.

$$H_1 = \{\lambda_1[n_2(\lambda_2) - n_f(\lambda_2)] - \lambda_2[n_2(\lambda_1) - n_f(\lambda_1)]\} / \{[n_f(\lambda_1) - n_1(\lambda_1)][n_2(\lambda_2) - n_f(\lambda_2)] - [n_2(\lambda_1) - n_f(\lambda_1)][n_f(\lambda_2) - n_1(\lambda_2)]\} \tag{2}$$

$$H_2 = \{\lambda_1[n_f(\lambda_2) - n_1(\lambda_2)] - \lambda_2[n_f(\lambda_1) - n_1(\lambda_1)]\} / \{[n_2(\lambda_1) - n_f(\lambda_1)][n_f(\lambda_2) - n_1(\lambda_2)] - [n_f(\lambda_1) - n_1(\lambda_1)][n_2(\lambda_2) - n_f(\lambda_2)]\} \tag{3}$$

The diffraction efficiency of the three-layer DOE is expressed as[6]

$$\eta_f'(\lambda) = \sin c^2\{m - \{H_1[\sqrt{n_f^2(\lambda) - n_1^2(\lambda)\sin^2\theta} - n_1\cos\theta] + H_2[\sqrt{n_2^2(\lambda) - n_1^2(\lambda)\sin^2\theta} - \sqrt{n_f^2(\lambda) - n_1^2(\lambda)\sin^2\theta}]\}/\lambda\} \tag{4}$$

where θ is the incident angle of the three-layer DOE. The Eq. (4) shows that the diffraction efficiency of three-layer DOE is determined by wavelength, height of relief pattern, refractive index of the materials.

2 Eyepiece design

2.1 Design specification

The eye imaging system connects to the HMD eyepiece system directly, and eyepiece pupil is required to match the user's eye pupil. Therefore, the eyepiece must be designed to take full account of the visual mechanism and physiological feelings of the user. To widen the FOV, the entrance pupil of the eye should be placed at the exit pupil of eyepiece. It means that the eyepiece for HDM needs a large exit pupil diameter and eye relief. According to the studying of many visual optical systems for helmet display, the design specifications are determined in Table 1.

Table 1 Design specification

Parameter	Specification
Wavelength rang	Visible
FOV/(°)	60
Exit pupil diameter/mm	8
Eye relief/mm	22
MTF	≥0.5(axis)
Display mode	VGA
Distortion/(%)	≤10
Lateral color aberration/μm	≤15

2.2 Procedure and results of design

For this design of eyepiece, the first layer of the three-layer DOE is FCD1, which has a low refractive index and high dispersion, and the second layer is FD6, which has a high refractive index and low dispersion, and the filler material is optical plastic named Polystyr (PS), which has low abbe number. Choose two wavelengths in designed waveband which covers visible spectrum (from 0.4 μm to 0.7 μm) to make the corresponding diffraction efficiency attain 100%. Using Eq. (2) and Eq. (3), the height of the relief of the three-layer DOE are 19.57 μm for H_1 and 11.26 μm for H_2. Fig. 2 illustrates that the diffraction efficiency versus the wavelength and FOV using Eq. (4). It shows that the diffraction efficiency is larger than 90% at wavelength of 0.4 μm when the half FOV is less than 32°. As the wavelength gets lager, the half FOV corresponded to the diffraction efficiency of 90% become larger, and the half FOV attains 56° at wavelength of 0.7 μm. Therefore, it absolutely satisfies the imaging of the optical system which has the requirement of large FOV and wide waveband.

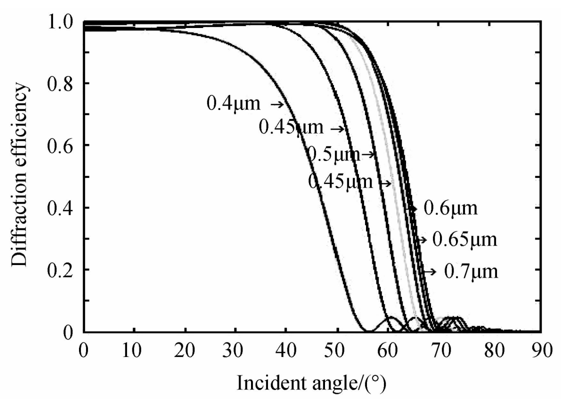

Fig. 2 Diffraction efficiency of MDOE in designed band versus FOV

We selected one suitable refractive Erfle eyepiece as the initial structure before the design[7]. This eyepiece consists of one biconvex lens and two cemented doublet lens. The features of 60° FOV, 140 mm eye relief, 28 mm exit pupil diameter, 88 g weight and 60 mm total length is not appropriate for helmet eyepiece, apparently. In order to simplify the structure, the three-layer DOE described above is introduced in the system. The final designed structure of the hybrid refractive/diffractive optical system is shown in Fig. 3 and Table 2, which contains four refractive lenses and a three-layer DOE, and the effective focal length of the new structure is 17 mm.

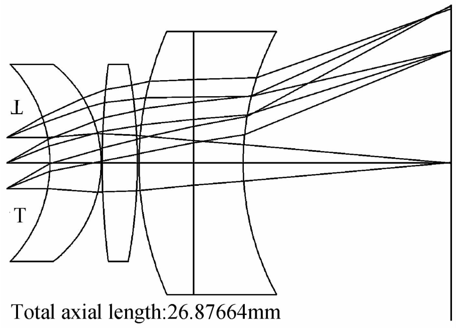

Fig. 3 Layout of the refractive/diffractive eyepiece system

Table 2 Structural parameters of the refractive/diffractive eyepiece system

Surface	Radius/mm	Thickness/mm	Glass	Semi-Diameter/mm
STO	Infinity	2.600		3
2(standard)	−8.698	3.100	LAK33	6
3(standard)	−7.657	0.066		6
4(standard)	48.217	2.132	LACL60	6
5(standard)	−32.602	0.100		6
6(standard)	19.859	3.300	FCD1	8
7(binary2)	Infinity	0.001	Polystyr	8
8(binary2)	Infinity	3.000	FD6	8
9(standard)	16.861	12.578		8
IMA	Infinity	—		9.594

The weight of the eyepiece is only about 8 g, and the maximum diameter and total size of the lens are 16 mm and 26.8 mm, respectively. Apparently, the structure is compact and small in comparison with Erfle eyepiece. The features of 60° FOV, 22 mm eye relief and 8 mm exit pupil diameter provide a complete FOV for the user, so that they would be hard to feel visual fatigue. From those curves of the modulation transfer function (MTF) plotted in Fig. 4, a 25 lp/mm spatial frequency is shown that the MTF value at 0° FOV is greater than 0.58, greater than 0.38 for all FOV. This means that the lens can match the VGA resolution for liquid crystal display (LCD) which has a format of 480×640 pixel. As shown in Fig. 5, the longitudinal aberration of the refractive/diffractive eyepiece system is less than 0.43 mm, and it can be seen that the maximum distortion of the systems is 4.8%, the field curvature is 0.3D (Dioptre of human eye) in Fig. 6. The lateral color curve shown in Fig. 7 illustrates that the maximum later color is less than 10 μm.

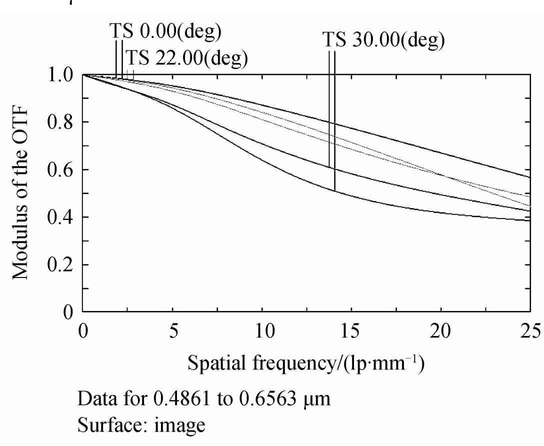

Fig. 4 MTF of the refractive/diffractive eyepiece system at each FOV

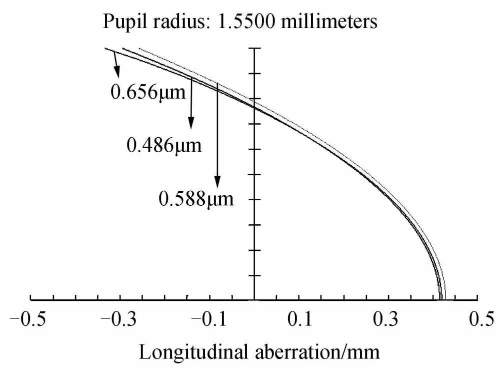

Fig. 5 Longitudinal aberration of the refractive/diffractive system

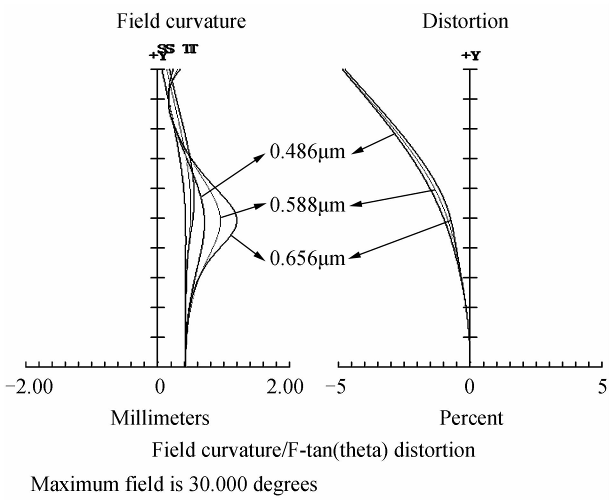

Fig. 6 Field curvature and distortion of the designed system

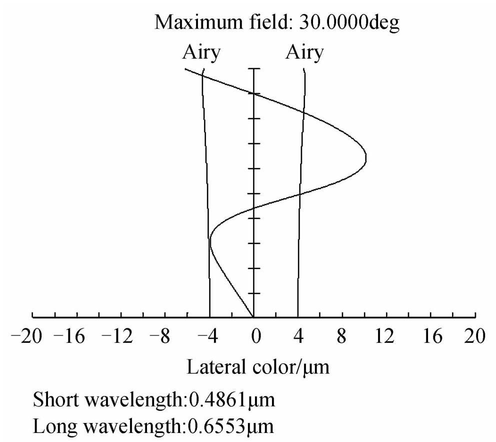

Fig. 7 Lateral color of the designed eyepiece system

Fig. 8 (a) and (b) show the characteristic curves of the two binary diffraction surfaces. The materials are FCD1 for the seventh surface, FD6 for the eighth surface, respectively. The maximum line frequency is 48 lp/mm, and the corresponding width of the minimum period is 21 μm. The diffraction efficiency of 95% can be obtained when the number of etching levels is eight. In this way, the minimum characteristic size of the diffractive surface is 2.6 μm, which can be manufactured and assembled easily using the laser writing technology.

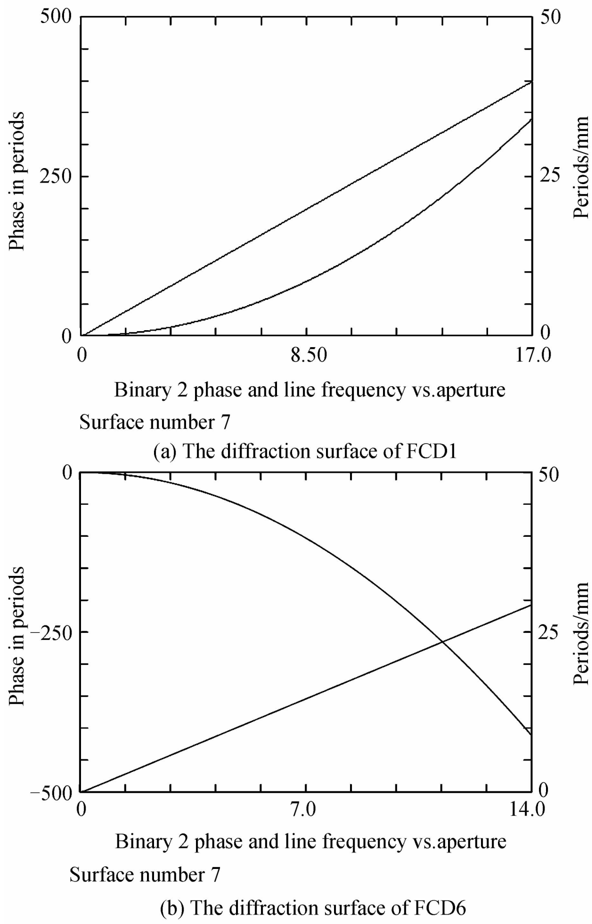

Fig. 8 Characteristic curves of the binary diffraction surface

3 Conclusion

The light-small hybrid refractive/ diffractive eyepiece for HMD is designed, which introduces a three-layer DOE for the first time. This eyepiece optical system has a 22 mm eye relief and 8mm exit pupil with 60° FOV. The three-layer DOE overcomes the difficulties of single-layer DOE and double-layer DOE using in the optical system, and improve the image contrast and the performance significantly due to the diffraction efficiency of the three-layer DOE is larger than 90% in wide waveband and large FOV range. The materials of three-layer DOE are FCD1 for first layer, FD6 for second layer, PS for the filler layer. Moreover, the weight of the eyepiece system is only 8 g, and the diameter of lens is 16mm. The MTF performance can satisfy the requirement of display with VGA resolution. Besides, the lateral color and distortion are 4.8% and 10μm, respectively. The properties of the helmet eyepiece system are excellent.

References

[1] WOOD A P. Design of infrared hybrid refractive-diffractive lenses[J]. *Applied Optics*, 1992, **31**(13): 2253-2258.

[2] JIAO Ming-yin. The application of diffractive optical elements in imaging systems[J]. *Journal of Applied Optics*, 2000, **21**(6): 17-20.

[3] BAI Jian, SUN Ting, SHEN Yi-bin, *et al*. Athermalization analysis of infrared hybrid refractive-diffractive optical systems [J]. *Acta Optica Sinica*, 1999, **19**(17): 997-1002.

[4] KNAPP W, BLOUGH G, KHAJURIVALA K, *et al*. Optical design comparison of 60° eyepieces: one with a diffractive surface and one with aspherics[J]. *Applied Optics*, 1997, **36**(20): 4756-4760.

[5] PEI Xue-dan, CUI Qing-feng, LENG Jia-kai. Effect of incident angle on diffraction efficiency of a two-layer diffractive optical element[J]. *Acta Optica Sinica*, 2008, **29**(1): 20-125.

[6] FAN Chang-jiang, ZHAO Ya-hui, YING Chao-fu, *et al*. Multilayer diffraction element with wide field of view and high diffractive efficiency[J]. *Chinese Journal of Lasers*, 2012, **39**(5): 0516001.

[7] MICHAEL D M, MORRIS G M. Diffractive optics applied to eyepiece design[J]. *Applied Optics*, 1995, **34**(14): 2452-2461.

·下期预告·

星载均匀像面低畸变广角气溶胶探测仪的研制

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摘　要:为满足空间遥感的迫切需求,设计并研制了一个星载均匀像面低畸变广角气溶胶探测仪样机.该仪器通过利用光阑像差产生的有效像差渐晕提高像面照度的均匀性,解决了广角系统中像面照度不均匀的问题.合理选择结构型式校正了畸变,并且采用全球面光学系统,易于加工和检测.广角气溶胶探测仪的中心波长为670 nm,带宽20 nm,全视场72°,相对孔径1/3.6,焦距20 mm.实验结果表明:研制的星载广角气溶胶探测仪镜头其入瞳大小5.6 mm,边缘视场的相对照度达到95.6%,在36 lp/mm处,轴上视场的调制传递函数值大于0.61,轴外视场的调制传递函数值高于0.58,最大畸变量为−1.95%,完全满足设计指标要求,体积小,适合空间遥感应用.

关键词:光学设计;广角;气溶胶;均匀像面;光阑像差;像差渐晕