Optik 115, No. 1 (2004) 11–14
http://www.elsevier.de/ijleo

Optik Optics
International Journal for Light and Electron Optics

Head-mounted display with LCOS using diffractive optical element

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Abstract: We designed a 60° hybrid refractive-diffractive eyepiece for head mounted display (HMD), and applied it in micro-display of liquid crystal on silicon (LCOS) by introducing a relay system. The hybrid eyepiece design is based on a traditional Erfle eyepiece. It has a 10mm exit pupil and a 22mm eye relief, which satisfies the requirements of HMD used in computer entertainment and visual reality. Moreover, the proposed eyepiece possesses better performances with a considerable reduction in physical size and weight compared to the traditional refractive type. The relay system can solve the matching problem between micro-display device and eyepiece, and provides the space for illuminating light source. The whole optical system is suitable for display of 18 mm-diagonal LCOS with a VGA resolution.

Key words: Head-mounted display – refractive-diffractive – micro-display – LCOS

1. Introduction

Various kinds of flat panel display devices have been developed at present [1], such as liquid crystal display (LCD), active matrix electroluminescent (AME), field emission display (FED), organic light emitting device (OLED), etc. They are contributing to the development of head-mounted display (HMD) system, which make the whole structure simplified and provide the precondition for better application of HMD.

Optical imaging system is an important part of the HMD system, which causes direct effects on image quality, so design of optical system is becoming of significance. Although requirements of optical systems are different for different applications [2, 3], generally, HMD functional requirements lead to one optical system with a long eye relief, a large exit pupil, and a wide field of view (FOV). In addition, a diameter limitation is required for binocular system to accommodate the interpupillary distance. Besides, for comfortable requirement of the user, the eyepiece should have a small size and a light weight. All requirements present a difficult design problem. With pure refractive optics, the optical system can't meet these requirements preferably, such as Erfle wide-angle eyepiece, in which suitable Gaussian parameters of the optical system can be provided, but the structure for HMD system is too bulky. Considering the special characteristic of the diffractive optical element, which has a negative color dispersion coefficient [4, 5, 6], we designed one wide-angle refractive-diffractive hybrid eyepiece for HMD based on traditional Erfle eyepiece. It has better performances with smaller size and lighter weight.

Then we applied the hybrid eyepiece in micro-display of Liquid Crystal on Silicon (LCOS), by introducing a relay system. For good performances and potential low price, LCOS attracts a great deal attention in research and in industry. But LCOS is a kind of reflective micro-display device, which needs enough working space to place the light source. In addition, there exist matching problem between the eyepiece and the micro-display device. Under a given wide field of view and a suitable focal length, the object linear field of the eyepiece can't match with the small size of the micro-display device. To solve these problems, we introduced a relay system and achieved an optical imaging system for HMD with LCOS diagonal of 18 mm.

2. Hybrid refractive-diffractive eyepiece design

2.1. Design of the hybrid eyepiece

HMD with different applications have different specific requirements about field of view, exit pupil, and eye relief. For applications in computer entertainment and virtual reality, generally the optical systems should possess a field of view more than 60° in diagonal. The minimum diameter of the exit pupil depends upon the

Received 15 October 2003; accepted 10 January 2004.

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0030-4026/04/115/02-000 $ 15.00/0

FOV of the optical system and the eye pupil diameter [7]. For a 60° FOV and a 4-mm eye pupil diameter, the minimum exit pupil diameter is about 9 mm. We designed the optical system with a 10-mm exit pupil. An eye relief more than 20 mm is required to accommodate users with eyeglasses. The interpupillary distance (IPD) of different individual is about 50–74 mm [8], so the diameter of the lens should be limited for adjustment of the binocular HMD.

Traditional Erfle eyepiece is the most typical wide-angle eyepiece. We selected a suitable Erfle eyepiece with focal length of 30 mm and FOV of 60°, which consists of 5 elements, two cemented doublets and one double convex lens as shown in fig. 1a. The first cemented doublet (near to the exit pupil) and double convex lens share the optical power of the eyepiece, while the second cemented doublet (near to the focal plane) plays roles of correcting field curvature and increasing eye relief. The specifications of Erfle eyepiece is given in table 1. We can see that, with 10 mm exit pupil and 20 mm eye relief, the overall weight is up to 391 g and the diameter is 49 mm, which is too big for modern HMD.

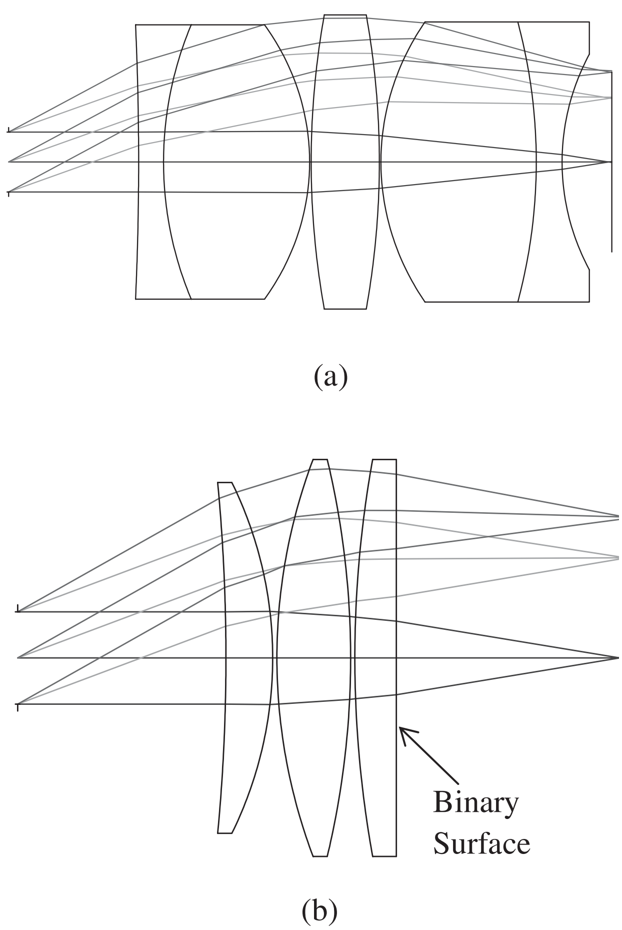

Fig. 1. 2D layout of the eyepiece. a) Erfle eyepiece; b) Hybrid refractive-diffractive eyepiece.

Table 1. The specifications of the proposed hybrid refractive-diffractive eyepiece in comparison with the traditional Erfle eyepiece.

Parameter	Eyepiece	Type
	Erfle	Hybrid
FOV	60°	60°
EFFL	30 mm	30 mm
Eye Relief	20 mm	22 mm
Exit Pupil Diameter	10 mm	10 mm
Transverse Aberration (0°)	$< \pm 102$ μm	$< \pm 64$ μm
Transverse Aberration (21°)	$< \pm 300$ μm	$< \pm 164$ μm
Transverse Aberration (30°)	$< \pm 410$ μm	$< \pm 279$ μm
Field Curvature	$< \pm 1.1$ D	$< \pm 1.67$ D
Distortion	$< \pm 12\%$	$< \pm 12\%$
Lateral Color	$< \pm 0.16$ mm	$< \pm 0.08$ mm
Weight	391 g	55 g
Diameter	49 mm	43 mm
Total Track	94 mm	64 mm

FOV: Field of View; EFFL: Effective Focal Length

Based on above Erfle eyepiece, keeping focal length, exit pupil, and field of view unchanged, we designed one refractive-diffractive hybrid eyepiece. The primary designing and optimizing procedure is as follows:

(1) Replacing the cement-doublet near to the exit pupil of the Erfle eyepiece with one double convex lens. Defining both curvature radii of the double convex lens and the back focal length as variables, and making optimization on the first-order feature, i.e., maintaining the effective focal length of 30 mm.
(2) Replacing another cement-doublet of Erfle eyepiece with one plane-convex lens. Similarly, defining the curvature radius of convexity of plane-convex lens and the back focal length as variables and making optimization on the first-order feature.
(3) Setting the binary surface on the planar side of the plane-convex lens, and making optimization on chromatic aberrations and monochromatic aberrations. Considering the surface internal to the visual system would be environmentally protected, we selected the surface nearest to the focal plane to be the diffractive surface. It is found that this arrangement also offers better aberration correction compared with the surface near to the exit pupil. Software ZEMAX provides a diffractive surface with symmetrical phase polynomial, described as [9]

$$\varphi(r) = A_1 r^2 + A_2 r^4 + A_3 r^6 + \dots \quad (1)$$

Where r is the normalized radial aperture coordinate related to normalization coefficient set in the program. Every coefficient of the phase polynomial can be used as variable in the course of designing and optimizing, which provide more variables than pure refractive optics. The first term can be used to correct chromatic aberrations and relates to the paraxial power of the diffractive element, while the other aspherical terms can be used to correct monochromatic aberrations. In our design, only the first two terms are used. Before defining the weights of merit functions, the balance between various aberrations and the characteristic size of the diffractive surface should be taken into account.

Fig. 1b shows the hybrid refractive-diffractive eyepiece with three refractive elements and one diffractive surface. Refractive elements all use the same ordinary glass named SK16. The hybrid eyepiece possesses the following Gaussian parameters: 30 mm focal length, 60° FOV, 10 mm exit pupil, and 22 mm eye relief. Table 1 also shows the specifications of the hybrid eyepiece. It can be seen that distortion of the hybrid refractive-diffractive eyepiece almost equal to that of the Erfle eyepiece; the field curvature is slightly more than Erfle eyepiece, but 1.67 diopters in maximum is acceptable for a 60° FOV. However, other aberrations are improved greatly. For example, the maximum lateral color aberration is 0.08 mm, which is half of that of the Erfle eyepiece. The transverse aberration of the hybrid eyepiece is reduced considerably, 32% in maximum field of view, 49% in 0.7 field of view, and 37% in zero field of view, respectively. More importantly, the size and weight of the hybrid eyepiece are both reduced greatly, the total track is reduced to 2/3, while the weight is ruduced to 1/7 in comparison with the Erfle eyepiece. The diameter of the lens drops to 43 mm, which can satisfies the requirement of the binocular HMD. So the hybrid refractive-diffractive eyepiece has a better performance, which can be used in HMD system.

2.2. Fabrication issues of the diffractive element

In the above hybrid diffractive-refractive eyepiece design, we adopted ZEMAX software, and the phase polynomial is described by equation (1). When only first two terms exist, it is the case in our design, the periods number of diffractive surface n is given by:

$$-2\pi n = A_1 r^2 + A_2 r^4 \,. \tag{2}$$

The normalized radius of the nth ring can be then calculated by:

$$r_n = \sqrt{\frac{-A_1 - \sqrt{A_1^2 - 8\pi n A_2}}{2A_2}} \,. \tag{3}$$

The maximum number of periods is given by:

$$n_{\max} = \mathrm{Int}\left|\frac{A_1 r_0^2 + A_2 r_0^4}{2\pi}\right| , \tag{4}$$

where r_0 is the normalized radial aperture of the diffractive element, and Int denotes the integration operation. Apparently, by controlling A_1 and A_2 properly, there might be fewer periods on the binary surface. Thereby we can achieve a bigger line width, which is beneficial to manufacturing. Fig. 2 shows the phase and line frequency vs. aperture of the binary surface. Curve A depicts the distribution of line frequency and curve B gives the phase in periods. In our design, the number of total periods is 590, the maximum line frequency is 39 periods/mm. Consequently, the width of minimum period is 25.6 μm. Because of multi-order-diffraction of the diffractive element, the contrast in desired image could be reduced. Increasing etching levels can get high diffraction efficiency. When the number of etching levels is eight, a diffraction efficiency of 95% can be obtained [10]. In this way, the minimum characteristic size of diffractive surface is 3.2 μm, which can be made by modern technology.

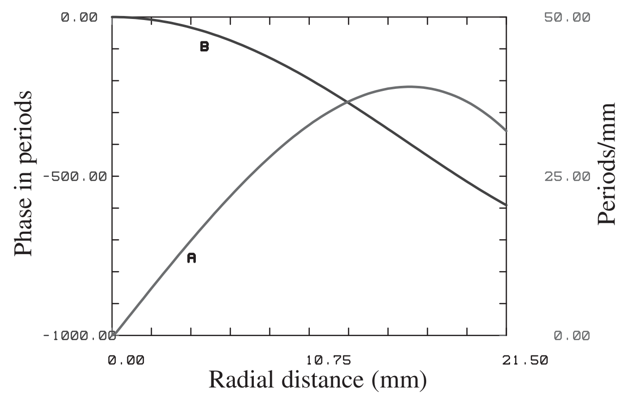

Fig. 2. Phase and line frequency vs. aperture of the binary surface.

3. The optical imaging system for HMD with LCOS

If we apply the hybrid eyepiece in HMD with micro-display of LCOS, there will exist two problems: one is the space placing the illuminating light source, for LCOS is a kind reflective display device; the other is the matching between the eyepiece system and the size of LCOS. Under a given field of view, if the size of micro-display device is smaller, the focal length of matched optical system should be shorter. For instance, under the FOV of 60°, the focal length of the optical system should be about 18 mm for LCOS diagonal of 18 mm. So above hybrid eyepiece can't match with it. If we make scale on focal length simply, the exit pupil and the eye relief will be decreased, or the structure and the aberrations of the system will become unacceptable. In order to solve these conflicts, we adopted a relay system. The relay system can make a suitable magnification in order to achieve the matching between the micro-display device and the wide-angle eyepiece. On the other hand, the relay system can also provide space to place the illuminating light source.

The relay system consists of one concave mirror and one polarization beam splitter (PBS), plus two quarter-wave plates and one polarizer, as shown in fig. 3. The concave mirror shares the optical power of the relay system, for enough magnification of the image on LCOS. The PBS transmits the illuminating light to

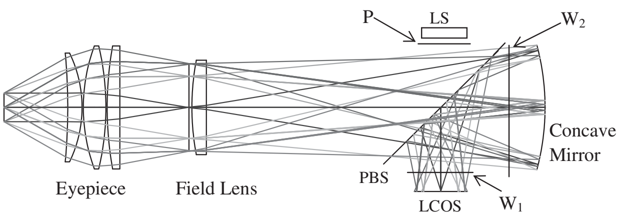

Fig. 3. The schematic of the optical system used in HMD with LCOS. P: Polarizer; PBS: Polarization beam splitter; W_1, W_2: Quarter-wave plate; LS: Light source.

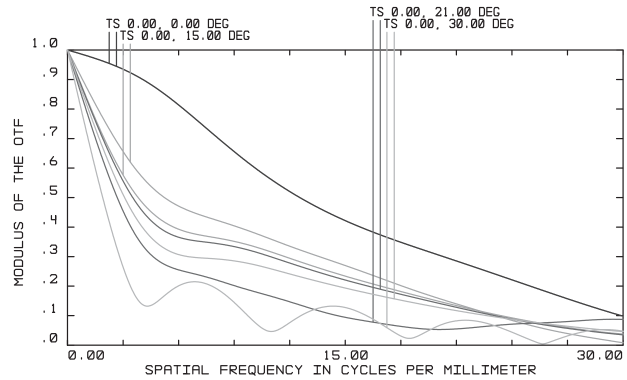

Fig. 4. The modulation transfer function (MTF) of the optical system for micro-display of LCOS.

LCOS, on the other hand, it reflects the image on LCOS to the concave mirror. Light from source is polarized firstly, then into the PBS, so the light after polarizer is nearly all transmitted, which avoiding the decrease of contrast effectively.

Connecting the relay system and the hybrid refractive-diffractive eyepiece by one field lens, we obtained the whole optical system of HMD with LCOS. Fig. 3 shows the sketch of the whole optical system. It can be used in display of 18mm-diagonal LCOS. The field lens lies near the focal plane of the eyepiece, which can collect light in marginal field and reduce the aperture of the concave mirror. Fig. 4 shows the modulation transfer function (MTF) plots of the whole optical system in zero, 0.5, 0.7, and full field of view. If LCOS diagonal of 18 mm has a 4:3 horizontal-to-vertical aspect ratio and a VGA (640×480) resolution, we get the system's cut-off frequency to be 22 cycles/mm. These figures in fig. 4 show that, the MTF in lager field of view, like most wide-angle eyepiece system, is quite poor. But in zero and mid-field of view, the actual system is capable of resolving spatial frequency above the required level (MTF > 0.2).

4. Conclusion

Modern HMDs not only require the eyepiece with a wide field of view, a big exit pupil, and a long eye relief, but also require the whole system with compact and light structure. Although the conventional pure refractive eyepiece can provide a wide field of view, a big exit pupil, and a long eye relief simultaneously, the structure of the optical system is too bulky and too heavy for HMD. In this paper, we designed one hybrid refractive-diffractive eyepiece based on Erfle eyepiece, which consists of three elements and one diffractive surface. It possesses good performance and has a 60° FOV, a 10 mm exit pupil, and a 22 mm eye relief. More importantly, compared with the Erfle eyepiece, its weight reduces to 1/7 and the total track reduces to 2/3. It is no doubt that the hybrid refractive-diffractive eyepiece can be better used in HMD. Then we applied the hybrid eyepiece in micro-display of LCOS, by using one relay system. The relay system achieves the matching between the micro-display device and the eyepiece, and provides the space to place the illuminating light source for LCOS. The whole optical system can be used in display of 18 mm-diagonal LCOS with a VGA resolution.

This research is partially supported by National Nature and Science Foundation of China (number 60277021), and United Academy of Nankai University and Tianjin University.

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