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Hybrid diffractive-refractive ultra-wide-angle eyepieces

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Abstract: Two kinds of hybrid diffractive-refractive ultra-wide-angle (70°) eyepieces are designed which are with considerably reduced apparent size and weight and with comparable or improved aberrations as compared with the conventional refractive countertype. The designing strategy including the consideration and the steps of the optimization, the most important specification of the diffractive efficiency, and the manufacture issues is presented. The structures and the performance merits of the designed systems are given in a comparison of the traditional Scidmore eyepiece. The designed eyepieces have potential applications in various kinds of modern head-mounted displays.

Key words: Hybrid diffractive-refractive system – computer-aided optical design – head-mounted display

1. Introduction

As the rapid development of different kinds of head-mounted display with micro-display devices, new designs of eyepieces are becoming of significance [1–3]. Although the requirements of the eyepieces are different for different applications, for instance military systems, medical instruments, entertainment systems and virtual-reality systems, there are common challenging design issues: a long eye relief, a large exit pupil, a wide field of view and a wide band of spectrum. In addition, a diameter limitation is required for binocular systems to accommodate a narrow interpupilary distance. Nevertheless, for comfortable requirement of users, the eyepiece should be smaller in size and lighter in weight. It is difficult for traditional eyepiece design to satisfy with above conditions, and diffractive optics has been introduced into today eyepiece design [4–7]. Particularly, Missing presented an hybrid diffractive-refractive wide-field (60°) eyepiece [8], based on traditional Erfle wide-angle eyepiece. His optical system consists of 3 elements, which is compared with 5 elements of Erfle eyepiece, with enhanced optical performance merits, and reduced weight and size.

Recently, the micro-display of Liquid Crystal on Silicon (LCOS) attracts a great deal attention in research and in industry, for the good performance merits and potential low price. LCOS is a kind of reflective micro-display, which needs enough working space to place the light source. With pure refractive eyepiece, such as Erfle wide-angle eyepiece and Scidmore ultra-wide-angle eyepiece, the working space is too small to set the light source. To solve this problem, an additional relay system is normally adopted, which makes the optical system larger and heavier. Also, as the development of the head-mounted display, more than 60° field of view of the optical system is required.

In this paper we design two kinds of diffractive-refractive hybrid ultra-wide angle (70°) eyepieces which consist of 4 elements with diffractive surfaces. The design process is as follows: firstly selecting a suitable Scidmore eyepiece with the focal length of 30 mm and the field of view of 70°; secondly replacing the first cemented-doublet lens with diffractive-refractive lens (or a refractive lens in the second design) and making an optimization; thirdly replacing the second cemented-doublet lens with another diffractive-refractive lens and making another optimization. The performance merits of the designed hybrid diffractive-refractive eyepieces are then compared with that of the conventional Scidmore eyepiece. The designed eyepieces meet the needs of 70° field of view head-mounted displays with the reflective micro-LCOS.

2. Design of the hybrid eyepiece with two diffractive surfaces

Scidmore eyepiece consists of 6 elements, two cemented-doublet lenses, a plane-convex lens and a convex lens as shown in fig. 1. All the positive elements are with the same kind of glass, and so the negative elements. Two convex lenses and the first cemented-doublet share the optical power of the eyepiece, while the second cemented-doublet plays a role of aberration

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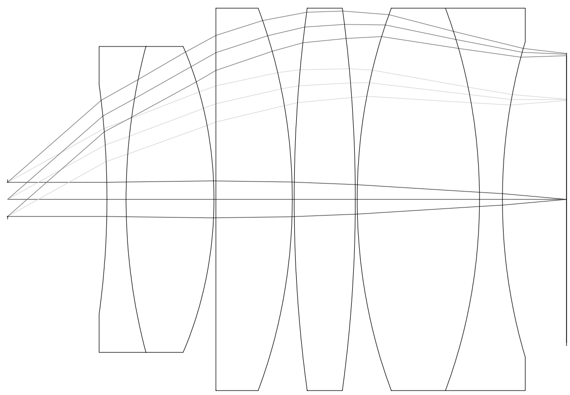

Figure 1. Scidmore ultra-wide angle eyepiece.

correction. The first cemented-doublet and the plane-convex lens form an achromatic system. In the design process of the diffractive-refractive eyepiece, we firstly replace the first cemented-doublet lens by a diffractive-refractive lens. This involves in an achromatic doublet design [5]. The distribution of the optical power of the first cemented-doublet and the plane-convex lens of the Scidmore eyepiece satisfies with the conditions:

$$\varphi_1 = \frac{V_1}{V_1 - V_2}\,\varphi \quad \text{and} \quad \varphi_2 + \varphi_3 = \frac{V_1}{V_2 - V_1}\,\varphi \tag{1}$$

where $\varphi = \varphi_1 + \varphi_2 + \varphi_3$ with φ_1, φ_2, φ_3 are the optical power of first, second and the third elements of the achromatic system, respectively; V_1 and V_2 are their respective Abbe numbers of the glasses. In our system $V_1 = 60.3$ and $V_2 = 33.8$, the distribution of the optical power is $\varphi_1:\varphi_2:\varphi_3 = 1.92:2.33:1$. This distribution makes the positive elements with larger curvatures. With the diffractive-refractive lens, the division of the optical power satisfies with the conditions:

$$\varphi_{\text{ref}} = \frac{V_{\text{ref}}}{V_{\text{ref}} - V_{\text{dif}}}\,\varphi \quad \text{and} \quad \varphi_{\text{dif}} = \frac{V_{\text{dif}}}{V_{\text{dif}} - V_{\text{ref}}}\,\varphi \tag{2}$$

where φ_{ref} and φ_{dif} are the optical powers of the refractive and the diffractive elements, respectively, V_{ref} and V_{dif} are their respective Abbe numbers. V_{dif} is a very small negative value ($V_{\text{dif}} = -3.45$). This makes the optical power of the refractive elements much smaller, even less than, but very near to, the total optical power of the achromatic system. The actually replacing procedure is as follows:

1) Replacing the cemented-doublet of the Scidmore eyepiece with a plane-convex lens, with the plane surface as the diffractive surface;
2) Making optimization on the first-order features of refractive surface and the diffractive surface simultaneously, with the effective focal length and the lateral color introduced into the merit functions;
3) Making optimization of the second-order feature of the diffractive surface with the transverse ray fan aberration and the distortion introduced into the merit functions. In this optimization, the balance between various aberrations and the required minimum feature size of the diffractive surface, which is related to the manufacturing issues, should be taken into account.

Software ZEMAX provides a diffractive surface with symmetrical phase polynomial [9], described as

$$\varphi(r) = A_1 r^2 + A_2 r^4 + A_3 r^6 + \cdots \tag{3}$$

where r is the normalized radial aperture coordinate related to normalization radius set in the program. The first term is used to correct chromatic aberrations (corresponding to the second replacing step), while the aspherical terms are used to correct high-order aberrations (corresponding to the third replacing step). The optimization is then a compromise between the lateral color reduction and the monochromatic aberration correction. It was found after above replacing that the eyepiece becomes smaller and lighter while the performance merits are comparable or improved as compared with the initial Scidmore eyepiece.

We then replace the second cemented-doublet by another diffractive-refractive lens with the similar three steps mentioned above. In the replacing process, however, the following fact should be taken into account: the second cemented-doublet of the Scidmore eyepiece plays roles not only the chromatic aberration correction but also the field curvature correction.

Fig. 2 shows the designed 70º field of view hybrid diffractive-refractive eyepiece with four refractive elements and two diffractive surfaces, and table 1 shows the performance merits of the designed eyepiece (row 4) in a comparison with the initial Scidmore eyepiece

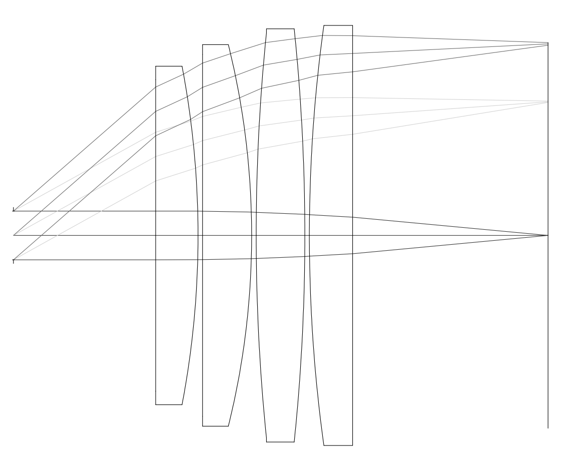

Figure 2. Hybrid diffractive-refractive ultra-wide angle eyepiece with two diffractive surfaces.

Table 1. The performance merits of the hybrid refractive-diffractive eyepieces in a comparison with the traditional Scidmore eyepiece. TRFA: Transverse ray fan aberration, AFC: Average field curvature.

Eyepiece Type	TRFA (μm)			Lateral Color (mm)	Distortion (%)	AFC (mm)
	0°	48°	70°			
Scidmore	8.3	178.9	275.1	0.21	13.3	0.67
Two Diffractive Surfaces	2.7	70.5	162.3	0.0017	15.6	0.17
Single Diffractive Surface	9.6	97.6	224.8	0.065	15.8	0.34

(row 3). It can be seen that the transverse ray fan aberration of the diffractive-refractive eyepiece is considerably reduced as compared with the Scidmore eyepiece. It drops from 8.3 μm to 2.7 μm, 178.9 μm to 70.5 μm, and 275.1 μm to 162.3 μm for 0°, 48° and 70° fields of view, respectively. The lateral color drops from 0.21 mm to 0.0017 mm, two-orders in magnitude improvement in a comparison of Scidmore eyepiece. The improvement is also in the average field curvature, which drops from 0.67 mm of the Scidmore eyepiece to 0.17 mm of the diffractive-refractive eyepiece. It can also be seen that the distortion of the diffractive-refractive system increases slightly (from 13.3% to 15.6%). This is because we set the weight of distortion in the merit functions smaller in the optimization process. As a matter of fact, the distortion aberration can be much smaller as if the weight of distortion of the merit functions is set larger in the optimization process. However, the transverse ray fan aberration becomes worse in this case. For the transverse ray fan aberration is more important than the distortion in a visual system, we pay more attention on it in the optimization.

Table 2 shows the reduced apparent size and weight (row 3) in a comparison with the initial Scidmore eyepiece (row 2). It can be seen that the size and the weight are reduced greatly. It drops by 30%, 18% and 81% for the total track, the diameter and the weight, respectively. Considering the designed eyepiece is for the use of head-mounted display, the great reduction in size and weight is of significance. Meantime, the working space increases from 9.6 mm of the Scidmore eyepiece to 21.4 mm, which is beneficial for the arrangement of light source for reflective micro-display devices.

Table 2. The structure parameters of the hybrid refractive-diffractive eyepieces in a comparison with the traditional Scidmore eyepiece.

Eyepiece Type	Total Track (mm)	Weight (10–3 Kg)	Diameter (mm)	Working Space (mm)
Scidmore	83.4	188.2	22.8	9.6
Two Diffractive Surfaces	58.6	35.8	18.6	21.4
Single Diffractive Surface	58.7	39.3	18.6	21.3

3. Design of the hybrid eyepiece with single diffractive surfaces

Although the designed diffractive-refractive eyepiece is smaller and lighter, and possesses satisfactory performance merits, it has two main drawbacks. First, one of the diffractive surface is on the eye side, which needs an environmental protection. Second, the diffraction efficiency of the system is the product of the diffraction efficiencies of two diffractive elements, which reduces the effective light power and reduces the contrast of the desired image. For these reasons we improve the system with only one diffractive surface. The design procedure is as follows: firstly, replacing the first cemented-doublet of the Scidmore eyepiece with a single lens and making optimization with the curvatures of two surfaces of the new lens as variables to maintain the effective focal length; secondly, replacing the second cemented-doublet of the Scidmore eyepiece with a diffractive-refractive element. The second procedure takes the same three steps as described in section 2. The designed hybrid diffractive-refractive eyepiece with single diffractive surface is shown in Fig. 3.

Table 1 also shows the performance merits of the designed eyepiece with single diffractive surface (row 5). It can be seen that the transverse ray fan aberration, the lateral color, the field curvature and the distortion increase in a certain degree as compared with the first designed system (two diffractive surfaces). However the aberrations are still better than that of the Scidmore eyepiece except for the distortion. The slightly increased distortion is because we set the

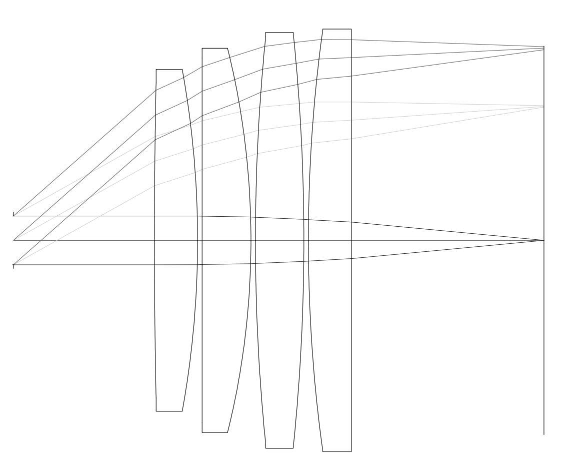

Figure 3. Hybrid diffractive-refractive ultra-wide angle eyepiece with single diffractive surface.

weight factor of the distortion in the merit functions smaller in the optimization, which we have explained in section 2. Table 2 also shows the apparent size, the weight of the eyepiece and the working space with single diffractive surface (row 4), which are almost the same as the first design sample.

4. Fabrication issues of the diffractive elements

In the above hybrid diffractive-refractive eyepiece design, we adopted ZEMAX software, and the phase polynomial is described by equation (3). When only first two terms exist, which is the case in our designs, the ring number of the diffractive elements n is given by:

$$-2\pi n = A_1 r^2 + A_2 r^4 . \quad (4)$$

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

$$r_n = \sqrt{\frac{-A_1 - \sqrt{A_1^2 - 8\pi n A_2}}{2A_2}} \quad (5)$$

The maximum number of the rings is given by:

$$n_{\max} = \mathrm{Int}\left|\frac{A_1 r_0^2 + A_2 r_0^4}{2\pi}\right| \quad (6)$$

where r_0 is the normalized radial aperture of the diffractive element, and Int denotes the integration operation. Suppose the diffractive element is manufactured with eight etching levels. The depth of each level is given by:

$$d = \frac{\lambda_d}{8(n-1)} \quad (7)$$

where n is the refractive index of the material and λ_d is the center wavelength in air. In our design the adopted visible wavelengths are λ_f = 486 nm, λ_d = 588 nm, λ_c = 656 nm, respectively. For the first diffractive surface of the first design, the normalization radius is 19.2 mm. The coefficients A_1 and A_2 are –1353.4 and –293.8, respectively. The actual radius of the diffractive surface is 15 mm. According to eqs. (4) to (6) the normalized radial aperture is 0.78, and the total ring number is 149. When the etching level is eight, the minimum feature size is 5.6 μm. For the second diffractive surface, the normalization radius is 24.0 mm. The coefficients A_1 and A_2 are –5324.3 and 1563.1, respectively. The actual radius of the diffractive surface is 18.6 mm. Then the normalized radial aperture is also 0.78, and the total ring number is 419. When the etching level is eight, the minimum feature size is 3.5 μm. For the diffractive surface of the second design, the normalization radius is 24.0 mm. The coefficients A_1 and A_2 are –5394.4 and 2247.5, respectively. The actual radius of the diffractive surface is 18.6 mm. The normalized radial aperture is 0.78, and the total ring number is 387. When the etching level is eight, the minimum feature size is 4.1 μm. The minimum feature size of 5.3 μm, 3.5 μm and 4.1 μm are quite large for manufacturing.

5. Conclusions

We have presented the designing considerations and procedures of hybrid diffractive-refractive ultra-wide-angle eyepieces, one is with two diffractive surfaces and another is with single diffractive surface. It has been shown that the hybrid systems offer considerable reduction in the apparent size, weight and number of elements, which is of significance in the applications of modern head-mounted display, while the performance merits are improved or comparable as compared with the conventional countertype. In the design, the balance between aberrations, the minimum feature size of the diffractive element, and the diffraction efficiency should be taken into account. For the diffractive elements possess inherently strong color correcting and wave front shaping ability, the improvements in lateral color and field aberration of the hybrid diffractive-refractive system are particularly notable. The diffraction efficiency of the diffractive elements is the first important specification, for the high-order diffractions normally yield undesirable multiple images, which reduce the contrast in the desired image. To enhance the diffraction efficiency so as to improve the image quality, the hybrid system with single diffractive surface and with larger minimum feature size is preferable. It is no doubt that the designed eyepieces have potential applications in various kinds of modern head-mounted displays.

Reference

[1] Ferrin FJ: Current issues in helmet mounted display systems for military applications. Proc. SPIE **3362** (1998) 71–79

[2] Frank JF: An update on optical system for military head mounted displays. Proc. SPIE **3689** (1999) 178–185

[3] Bunkenburg J, Feritz TA: Innovative diffractive eyepiece for helmet-mounted display. Proc. SPIE **3430** (1998) 41–49

[4] Stone T, George N: Hybrid diffractive-refractive lenses and achromats. Appl. Opt. **27** (1988) 2960–2971

[5] Wood AP: Design of infrared hybrid refractive-diffractive lenses. Appl. Opt. **31** (1992) 2253–2258

[6] Swanson GI, Veldkamp WB: Infrared applications of diffractive optical elements. Proc. SPIE **885** (1988) 22–32

[7] Knapp W, Blough G, Khajurivala K, Michaels R, Tatian B, Volk B: Optical design comparison of 60º eyepiece: one with a diffractive surface and one with aspherics. Appl. Opt. **36** (1997) 4756–4760

[8] Missing MD, Morris GM: Diffractive optics applied to eyepiece design. Appl. Opt. **34** (1995) 2452–2461

[9] Focus software. ZEMAX Optical Design Program User's Guide, Version 8.0., pp. 176–177. Focus Software, Inc., USA 1999