Refractive-diffractive visual system for micro-display of LCOS

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Abstract **One head-mounted display visual system for computer entertainment and three-dimensional display of virtual-reality was achieved, which consists of a hybrid refractive-diffractive eyepiece and a relay reflector. It can be used in micro-display of liquid crystal on silicon (LCOS) diagonal of 18 mm. The whole system has better performance, with 60° field of view, 10 mm exit pupil, 23 mm eye relief, and reduces weight and size.**

Keywords: refractive-diffractive, micro-display, relay reflector.

Various kinds of flat panel display devices, such as liquid crystal display (LCD), field emission display (FED), thin film electroluminescent (TFEL), organic light emitting device (OLED), are developed rapidly with the development of photoelectron technologies. During the developing of flat panel display devices, different head-mounted display (HMD) systems with micro-display devices are also developed[1]. HMD has wide applications and a huge market, which can be used in military, industry production, simulating exercitation, entertainment, micro-technology, medical treatment and so on, so many countries in the world have given more attention to it. Due to the development of micro-display device with high resolution, the system transforms "helmet-mounted" display[2] into "head-mounted" display[3], the weight and size of the whole system are reduced considerably whether direct-view display or see-through display has a compact structure with micro-display device.

Modern HMDs require an optical system with wild field of view, big exit pupil and long eye relief. However, general all-refractive eyepieces, including conventional Erfle eyepiece, have too much weight and too big size with suitable Gaussian parameters required, which cannot fit to the HMD system. If diffractive surfaces are introduced into the optical system[4], optical design will have more functional parameters. They can not only improve the performance of the system, but also simplify the structure, reduce the weight and size. The first practical application of diffractive optics was in the area of infrared systems. One hybrid refractive-diffractive thermal weapon sight (TWS) was achieved in the middle of 1990s[5]. Thereafter, to research on diffractive element used in the optical system was given more attention. Wayne K. et al.[6] designed a 60° field-of-view eyepiece for night vision, with one diffractive surface, and compared it with another plastic aspheric element involved eyepiece. Two eyepieces have identical constraints on size and weight. They concluded that the eyepiece containing diffractive surface had better performances. Bunkenburg et al.[7] designed one eyepiece for HMD, which consists of diffractive surface and plastic aspheric elements. It can be used in 555—595 nm spectrum range with better performance than in the all-refrac- tive glass eyepiece. In this note we designed one hybrid refractive-diffractive eyepiece for HMD based on a conventional Erfle eyepiece, which can be used in a visible spectrum range. It satisfies the requirements of HMD system on field of view, exit pupil, and eye relief with lighter weight and smaller size.

The smaller the size of the micro-display device, the lower the cost. Now Spatia Light Inc. produces micro-display devices of liquid crystal on silicon (LCOS) diagonal of 25, 20, and 18 mm respectively. Micro Vue Inc. also produces LCOS diagonal of 18 mm. For a given field of view, the smaller size of micro-display device leads to selecting design forms that have shorter focal length. But generally, the eyepiece system with a shorter focal length cannot provide big enough exit pupil and eye relief. To solve this conflict, we combined the refractive-diffractive eyepiece with a relay reflector and achieved one visual system for HMD with LCOS diagonal of 18 mm.

1 Refractive-diffractive eyepiece design

HMDs with different applications have different requirements about field of view, exit pupil, and eye relief of optical systems. For applications in computer entertainment and three-dimensional display of virtual-reality, the optical systems should possess field of view more than 60°; the exit pupil should be more than 10 mm, though the diameter of the pupil of the eye is typically 3—5 mm, which allows for an eye swivel without causing vignetting and an effective eye relief more than 22 mm to accommodate users with eyeglasses.

For binocular HMDs, there are human factors to be considered. If the interocular distance (IOD) of the HMD does not equal the interpupillary distance (IPD) of the eye, the eyes' optics are not concentric with the system's optics, which is functionally equivalent to have prisms in front of the eyes, i.e. prismatic effect. In order to reduce the prismatic effect, the diameter of lens should be less than 46 mm. In addition, there is another match between accommodation demand and convergence demand of eyes. If the misalignment is too large, vision will be blurred or double. For acquiring one clear single vision, the distance of the virtual screen must be selected. Presently, most researches concluded that the image should lie at 1—2 m in front of eyes[8], namely, putting the image source at one suitable position inside the focal plane of the eyepiece, which can reduce the difficulties that one may encounter with matching the convergence demand to the accommodation demand and also may reduce the effect of user's IPD on convergence demand.

Conventional Erfle eyepiece is the most typical eyepiece, which consists of two cement-doublets and one double convex lens. The first cement-doublet and double convex lens share the optical power of the eyepiece, while the second cement-doublet plays roles in correcting field curvature and increasing eye relief. Fig. 1 shows the two-dimensional layout and performances of Erfle eyepiece. It has 30 mm focal length, 60° field of view, 10 mm exit pupil, and 20 mm eye relief. It can be known that the Gaussian parameters of the Erfle eyepiece satisfy the requirements of the HMD system. Nevertheless, the Erfle eyepiece has a glass length of 70 mm and an overall weight of 391 g. Apparently, it is too big and too heavy for an HMD system. Besides, the diameter of lens is about 50 mm, which cannot satisfy the requirement of binocular HMD system.

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

(1) Replace the cement-doublet near the exit pupil of the Erfle eyepiece with one double convex lens. Define both curvature radii and the back focal length as variables, and make optimization on the first-order feature, i.e. maintain the effective focal length unchanged.

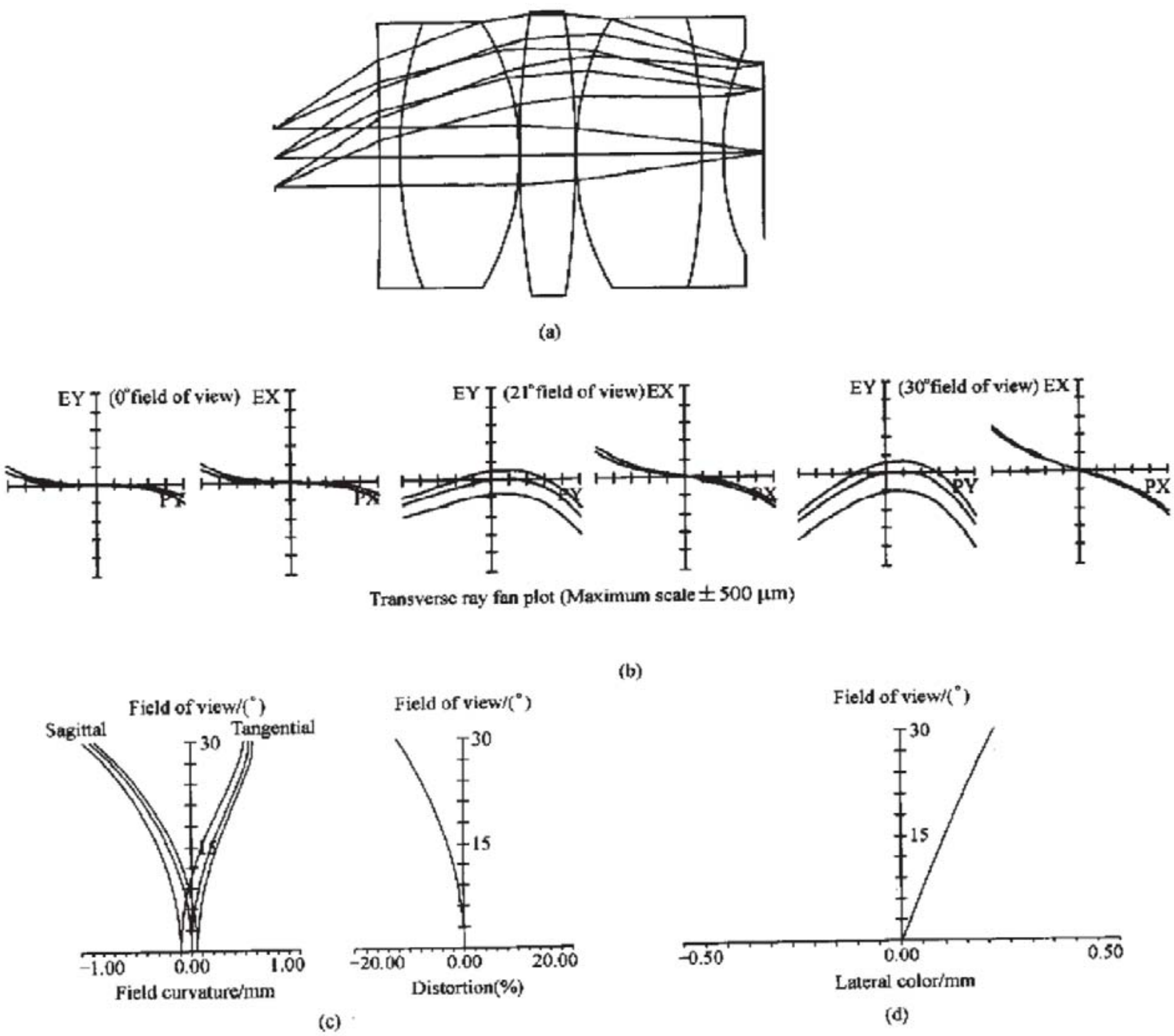

Fig. 1. Erfle eyepiece. (a) Two dimensional layout; (b) transverse ray fan aberration; (c) field curvature and distortion; (d) lateral color aberration.

(2) Replace another cement-doublet of Erfle eyepiece with one plane-convex lens. Similarly, define the curvature radius of convexity of plane-convex lens and the back focal length as variables and make optimization on the first-order feature.

(3) Choose the planar side of the plane-convex lens as diffractive surface, and make optimization on chromatic aberrations and monochromatic aberrations. Soft ware ZEMAX provides a diffractive surface with symmetrical phase polynomial, described as[9]

$$\varphi(r) = A_1 r^2 + A_2 r^4 + A_3 r^6 + \cdots, \tag{1}$$

where r is the normalized radial aperture coordinate. The first term is used to correct chromatic aberrations, while the other aspherical terms are used to correct high-order aberrations. In our design, only the first two terms are used. Firstly, we use the coefficient of the first term A_1 to correct chromatic aberrations. Then we define the coefficient of the second term A_2 as variable and make optimization with monochromatic aberrations introduced into the merit function of ZEMAX software. In this optimization, before defining the weights of the merit function, the balance between various aberrations and the required minimum line width of the diffractive surface should be taken into account.

All refractive elements of the eyepiece use the same ordinary K9 glass. Fig. 2 shows the two-dimensional lay-

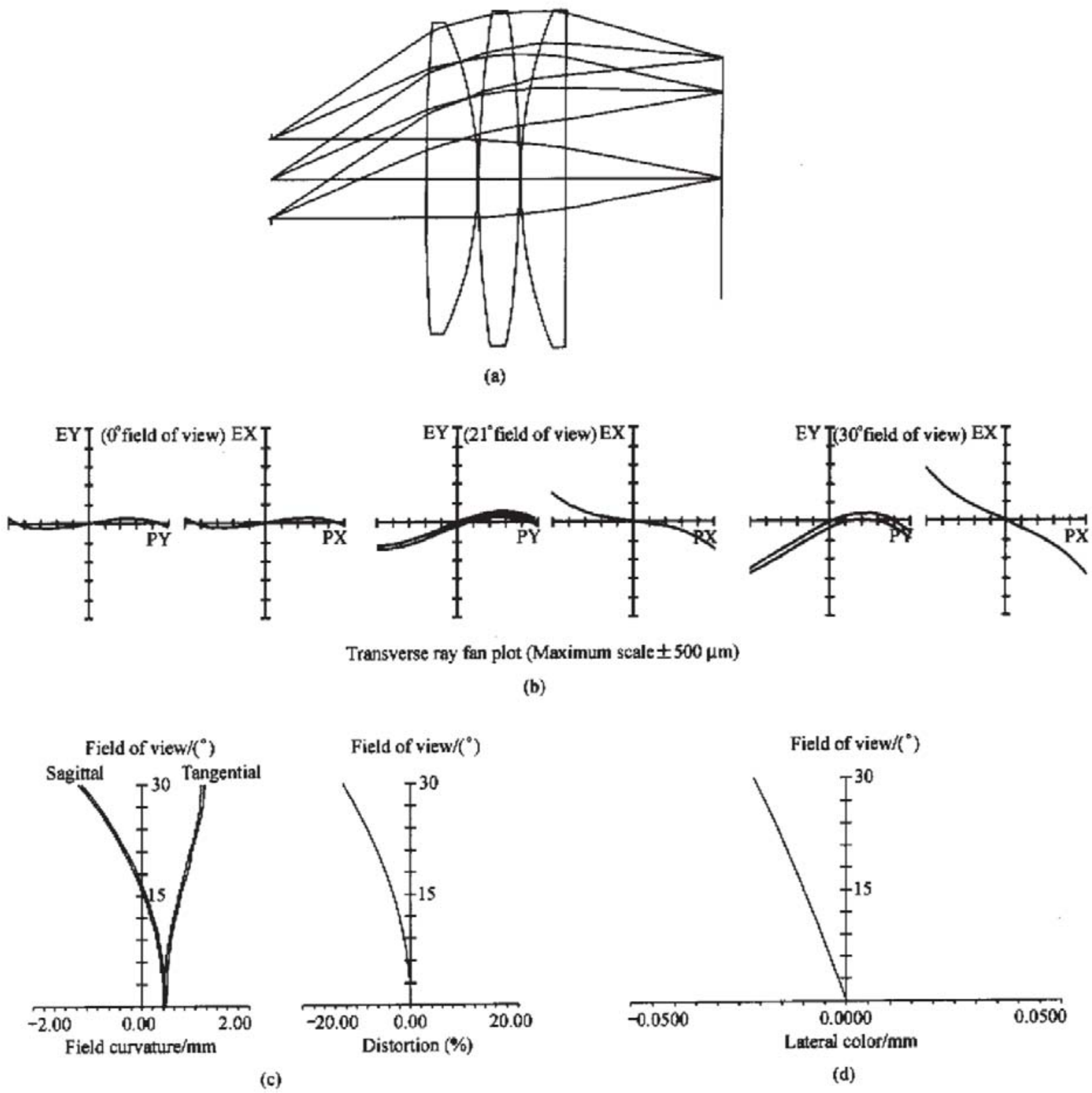

Fig. 2. Hybrid refractive-diffractive eyepiece. (a) Two dimensional layout; (b) transverse ray fan aberration; (c) field curvature and distortion; (d) lateral color aberration.

out and performances of the refractive-diffractive eyepiece. The hybrid eyepiece possesses the focal length of 30 mm, the field of view of 60°, the exit pupil of 10 mm, the eye relief of 23 mm, and the lens diameter of 43 mm, so the Gaussian parameters and the structure parameter satisfy the requirements of binocular HMD systems. Meanwhile, the glass length of the hybrid eyepiece is only 23 mm, the weight is only 50 g, reduced to 1/3 and 1/8 in comparison with the Erfle eyepiece, respectively. From aberration curves, it can be seen that the field curvature and the distortion of the refractive-diffractive eyepiece are almost equal to those of the Erfle eyepiece. However, the transverse ray fan aberration is reduced greatly, the maximum value is 32, 150, and 279 μm in zero, 0.7 and maximum field of view, respectively; but in identical field of views, the maximum value of that of Erfle eyepiece is 104, 308, and 420 μm, respectively. Chromatic aberrations are also corrected, the maximum lateral color aberration is 0.02 mm, dropped more than one order in magnitude compared with that of the Erfle eyepiece. So the refractive-diffractive eyepiece not only has a better performance, but also has a lighter and smaller structure.

2 Refractive-diffractive visual system for micro-display of LCOS

LCOS is a new kind of reflective micro-display device, which attracts a great deal attention in the area of micro-display, for the good performance merits and potential low price. LCOS in products are mostly less than 1 inch in diagonal. HMDs require that the eyepiece not only has a wild field of view, a big exit pupil, and a long eye relief, but also matches with the size of micro-display device. The micro-display device with a smaller size leads to requiring the eyepiece with a shorter focal length, for a given field of view. For example, if LCOS is 18 mm in diagonal, the focal length of the eyepiece required should be 18 mm with a 60° field of view. If we reduce the focal length simply, the exit pupil and the eye relief will decrease, otherwise, the structure and the aberrations of the system will become unacceptable. To solve the problem, we adopted one relay reflector, as a part of the whole visual system.

The relay reflector can make a suitable magnification of the image on LCOS, consequently, the amplificatory image can match with the sequential eyepiece. It can also provide enough space to place the illuminating light source. The relay reflector consists of one concave mirror and one half-transmitting planar mirror. The illuminating light source is over the half-transmitting mirror. Due to half-transmitting mirror, the brightness of image observed might decrease, however, it can provide the space to place the illuminating light source for reflective micro-display device. The concave mirror shares the optical power of the relay system, for enough magnification of the image on LCOS. The magnification is determined by the size of LCOS and the object linear field of the eyepiece required. Since we want to achieve the display of LCOS diagonal of 18 mm, the magnification of the relay system should be 1.7.

Connecting the relay reflector and above refractive-diffractive eyepiece by one field lens, we obtained the whole visual system for micro-display of LCOS diagonal of 18 mm. Fig. 3. shows the structure and performances of the whole system. The field lens lies near the focal plane of the eyepiece. It acts as the following functions: collect the light in the marginal field, reduce the aperture of the concave mirror, and drop the transverse ray fan aberration of the whole optical system. Form (b), (c), and (d) in fig. 3, we can see that the transverse ray fan aberration is less than 140 μm in zero field of view, and less than 550 μm in maximum field of view; the distortion is less than 12%; field curvature is less than 0.8 mm, which is well-pleasing for a 60° field of view. For the relay system has only reflective elements, the chromatic aberrations of the whole system are very small. So the visual system is suited for colored HMD especially.

3 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 a compact and light structure. The conventional all-refractive eyepiece can not satisfy all the requirements simultaneously. In this note we designed one refractive-diffractive eyepiece for HMDs based on a conventional Erfle eyepiece. The hybrid eyepiece has better performance with required field of view, exit pupil, and eye relief. The lens diameter also satisfies the requirement of binocular HMD. Moreover, its weight reduces to 1/8 and the total glass length reduces to 1/3, compared with Erfle eyepiece. In order to make the hybrid eyepiece match with LCOS diagonal of 18 mm, we adopted one relay reflector and achieved one visual system for HMD. The relay reflector can not only fulfil the matching between the image on micro-display device and the sequential eyepiece, but also provide the space to place the illuminating light source. The visual system can also be used in other micro-display with different sizes by changing the magnification of the relay reflector.

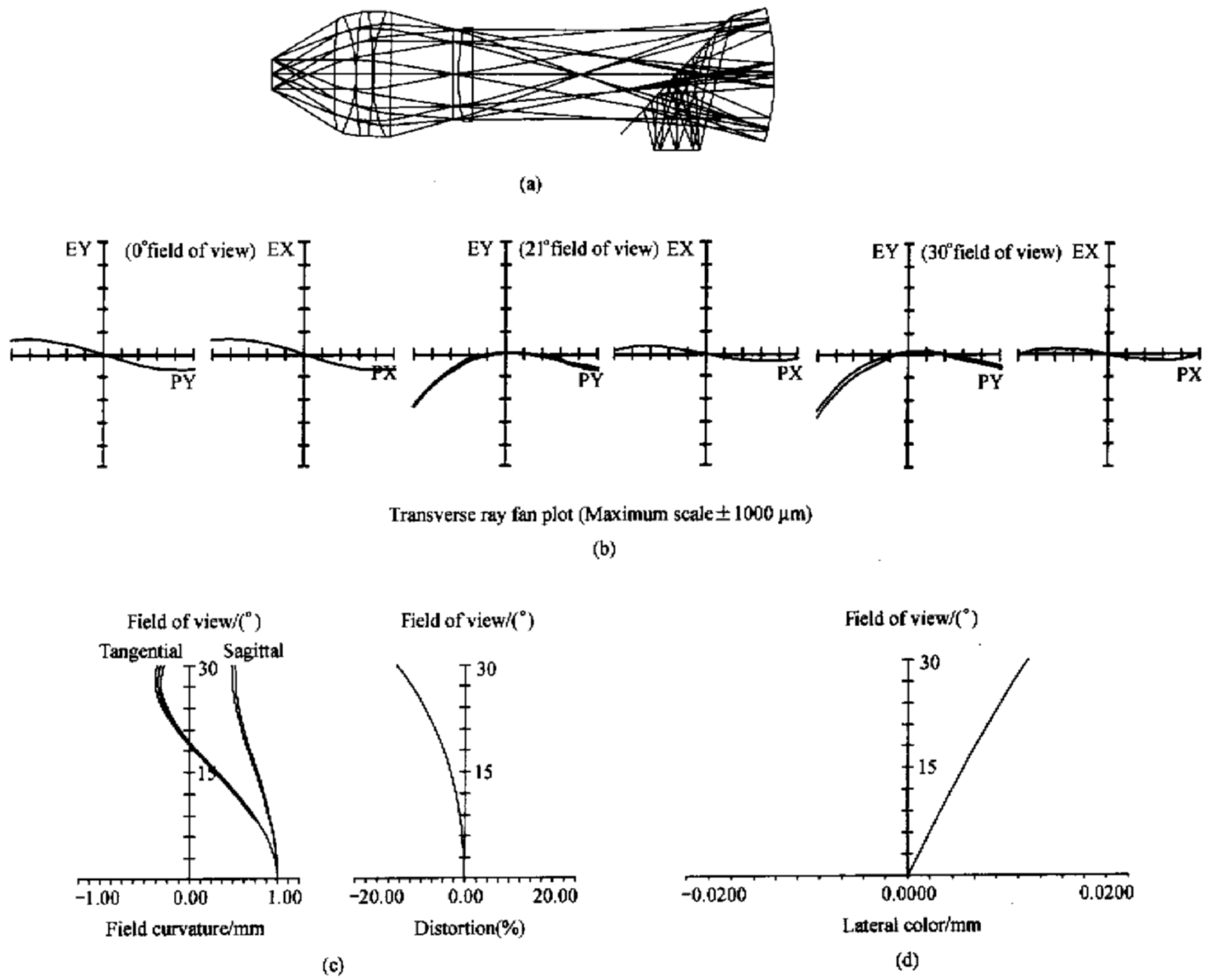

Fig. 3. The visual system for micro-display of LCOS. (a) The scheme of structure; (b) transverse ray fan aberration; (c) field curvature and distortion; (d) lateral color aberration.

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References

1. Frank, J. F., Selecting new miniature display technologies for head-mounted applications, Head-mounted Displays II, Proc. of the SPIE, 1997, 3058: 115.
2. Donald, J. R., Optical approaches to the helmet mounted display, Helmet-mounted Displays, Proc. of the SPIE, 1989, 1116: 14.
3. Frank, J. F., An update on optical systems for military head mounted displays, Helmet- and Head-mounted Displays IV, Proc. of the SPIE, 1999, 3689: 178.
4. Michael, D. M., Morris, G. M., Diffractive optics applied to eye-piece design, Appl. Opt., 1995, 34(14): 2452.
5. Pantazis, M., Visual Instrumentation, New York: McGraw-Hill, 1999, 338—340.
6. Wayne, K., Gary, B., Kumar, K. et al., Optical design comparison of 60° eyepieces: One with a diffractive surface and one with aspherics, Appl. Opt., 1997, 36(20): 4756.
7. Bunkenburg, J., Fritz, T. A., Innovative diffractive eyepiece for a helmet-mounted display, Novel Optical Systems Design and Optimization II, Proc. of the SPIE, 1998, 3430: 41.
8. Pantazis, M., Visual Instrumentation, New York: McGraw-Hill, 1999, 210—223.
9. Focus software, ZEMAX Optical Design Program User's Guide, Version 8.0, USA: Focus software, Inc., 1999. 176—177.

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