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Simple 40° head-mounted display

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Abstract: A simple 40° eyepiece matched with the micro-display device is designed. It consists of two elements, including a binary surface and an aspheric surface. With satisfactory performance, the eyepiece can be used in display with a SXGA resolution sized 1.1 inches diagonal. Because no other relay system is needed, the HMD system could be made more compact with much less weight.

Key words: Head-mounted display – hybrid refractive-diffractive – binary surface – aspheric surface

1. Introduction

For potential applications, head-mounted displays (HMD) are being given more and more attentions. They can be used in military, industry, surgery, virtual-reality, entertainment, and so on. The requirements on optical system are different for different applications [1, 2]. But there are some common, including a long eye relief, a large exit pupil and good performance over a wide spectral range. Besides, the HMD should be small and light for comfortable use. For binocular HMD, there is another human factor to be considered. Because the inter-pupillary distance of adult person generally is at range of 50–74 mm, the diameter of lens should be less than 46 mm, in order to insure that the interocular distance of HMD can be adjusted to accommodate with the interpupillary distance of the eye. So an additional limitation on the diameter of the optical system is required. In traditional eyepieces design, cemented doublets or cemented triplets are generally introduced to correct chromatic aberrations, as well as field curvature. So the system often has a bulky volume and a heavy weight with a complicated structure. The diameters of lenses are also often too big for binocular HMD.

Diffractive elements introduced into the conventional system could add freedoms and variables for design; they not only can improve the performance of system, but also can simplify the structure. The first practical application of diffractive optics was in the area of infrared systems. One hybrid refractive-diffractive Thermal Weapon Sight (TWS) was achieved on the middle of 1990s [3]. Thereafter, Wayne K., Bunkenburg, Fritz, and Missing etc. have researched the diffractive element used in optical system respectively [4, 5, 6]. We have designed one hybrid refractive-diffractive 40° eyepiece for HMD [7], which consists of two elements, including one binary optical surface. The effective focal length is 50 mm, and the image size is 35.4 mm. For all kinds of flat panel devices, such as liquid crystal on silicon (LCOS), the dimensions of commercially available are 0.7 inches, 0.9 inches and 1.1 inches diagonal, so the above hybrid eyepiece can't be used in micro-display directly. Thereupon we introduced one reflective relay system to achieve the matching between micro-display device and the eyepiece. But the introduction of the relay system would inevitably increase the weight and the volume of the HMD package, as well as the difficulty of system mounting. In this paper, we presented a hybrid refractive-diffractive eyepiece with an aspheric surface. It can be used directly in micro-display sized 1.1 inches diagonal. The new hybrid eyepiece has a 10 mm exit pupil and a 25 mm eye relief, the weight of which is only 16 g. With the satisfying performances, the hybrid eyepiece can make the HMD package more compact with much less weight.

2. Design of the hybrid refractive-diffractive eyepiece for micro-display

Though modern HMD with different applications has different requirements about field of view, exit pupil, and eye relief, generally the optical system should possesses an exit pupil more than 10 mm, which allows for an eye swivel without causing vignette [8]; and an effective eye relief more than 22 mm to accommodate users with eyeglasses. So we designed our eyepiece with a 10 mm exit pupil and a 25 mm eye relief.

We selected a modification of the conventional 40° Kellner eyepiece shown in fig. 1 as our designing original structure [9], which consists of one positive lens and

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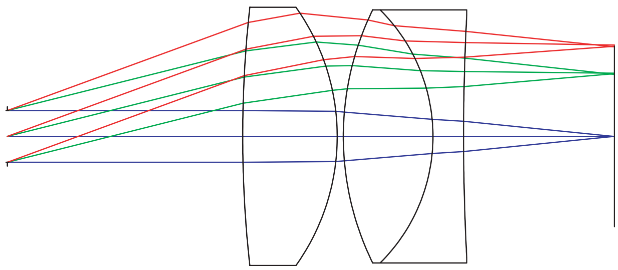

Fig. 1. The layout of a modification of traditional Kellner eyepiece.

one cemented doublet. By making focal length to scale lens for enough exit pupil, the result is that it has a 50 mm effective focal length with a 10 mm exit pupil, and the image size is 35.4 mm. Apparently, for achieving one eyepiece matched with current micro-display devices, we need to strengthen the power of the system.

First, replace the cemented doublet of Kellner eyepiece with one plano-convex lens setting the plane near to the image surface, select SK5 as materials, and choose the convex surface as the binary surface. Defining all curvature radii and back focal length as variables, optimize the system to have an enhanced power. In the course, the power taking on for each surface should be reasonably distributed so as to acquire better aberrations balance. When the effective focal length of the system equal to about 39 mm, the image size is 1.1 inches diagonal.

Following, adjust the eye relief to be 25 mm, and optimize the system on the first order feature, i.e. keep the effective focal length from changing. Then utilize variables of the binary surface to correct the chromatic aberrations and monochromatic aberrations. Considering the minimum line width of the binary surface and the balance among different aberrations set the merit functions with appropriate weights.

For further improvement of the performance of the hybrid eyepiece, we introduced an aspheric surface on the first surface (near to the exit pupil) of the first element. In view of the shape of the binary surface is identical to the even aspheric surface type, the odd aspheric surface is more effective for aberrations compensation. The sag of the binary surface is given by the following expression [10], in which there are only even powers of the radial coordinate

$$Z = \frac{cr^2}{1+\sqrt{1-(1+k)\,c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \dots \quad (1)$$

Equation (2) shows the sag of the odd aspheric surface [10], which includes both even and odd powers of the radial coordinate

$$Z = \frac{cr^2}{1+\sqrt{1-(1+k)\,c^2r^2}} + \beta_1 r^1 + \beta_2 r^2 + \beta_3 r^3 + \beta_4 r^4 + \beta_5 r^5 + \dots \quad (2)$$

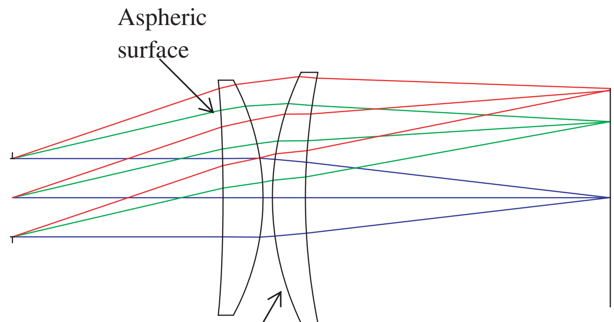

Fig. 2. The layout of the eyepiece matched with the micro-display device sized 1.1 inches diagonal.

In optimization, we used the coefficients of polynomial terms on the 3, 5, 7th powers of r in eq. (2). The results show that performances of the system are improved effectively, due to the introduction of the odd aspheric surface.

The layout of the hybrid eyepiece with an aspheric surface is shown in fig. 2. It has a 10 mm exit pupil and a 25 mm eye relief with a 40° field of view. The effective focal length is 39 mm, and the image size is 1.1 inches diagonal. The whole structure is very compact and simplified, the diameter of the lens is about 32 mm and the weight is only 16 g, which are compared with our previous design where the diameter is 39.2 mm and the weight is 31.5 g.

Fig. 3a), b), c) gives the aberrations curves respectively. From a), we can see that the transverse ray aberrations in zero and 0.7 fields of view are very small, both less than 100 μm, the maximum value in marginal field of view is 283 μm. From b), the maximum distortion is 5%, which is allowable for a 40° field of view; and the maximum field curvature is 0.8 mm. The field curvature of an eyepiece is best evaluated in diopters of defocusing at the eye. Using the newtonian imaging equation, we can get the corresponding field curvature is 0.5D. From c), we can know that the lateral color is less than 0.02 mm. All of them show that the performance of the hybrid eyepiece is satisfactory.

In fig. 4, we present the MTF curves in 0° and 14° fields of view. Like most eyepieces, the MTF of this hybrid eyepiece at largest field of view is poor. But we can see that the MTF at 0° is excellent, the maximum spatial frequency at which the MTF is greater than 0.3 is 56 cycles/mm. This value corresponds to a resolution of 112 pixels/mm, or of 0.8 minutes of arc, which is higher than the result of our previous design (1.5 minutes of arc) in which we adopt a reflective relay system to achieve the matching between the eyepiece and micro-display device [7]. So the hybrid eyepiece can be better used in HMD with a SXGA resolution.

Moreover, with a smaller image size, the hybrid eyepiece can directly match with a micro-display de-

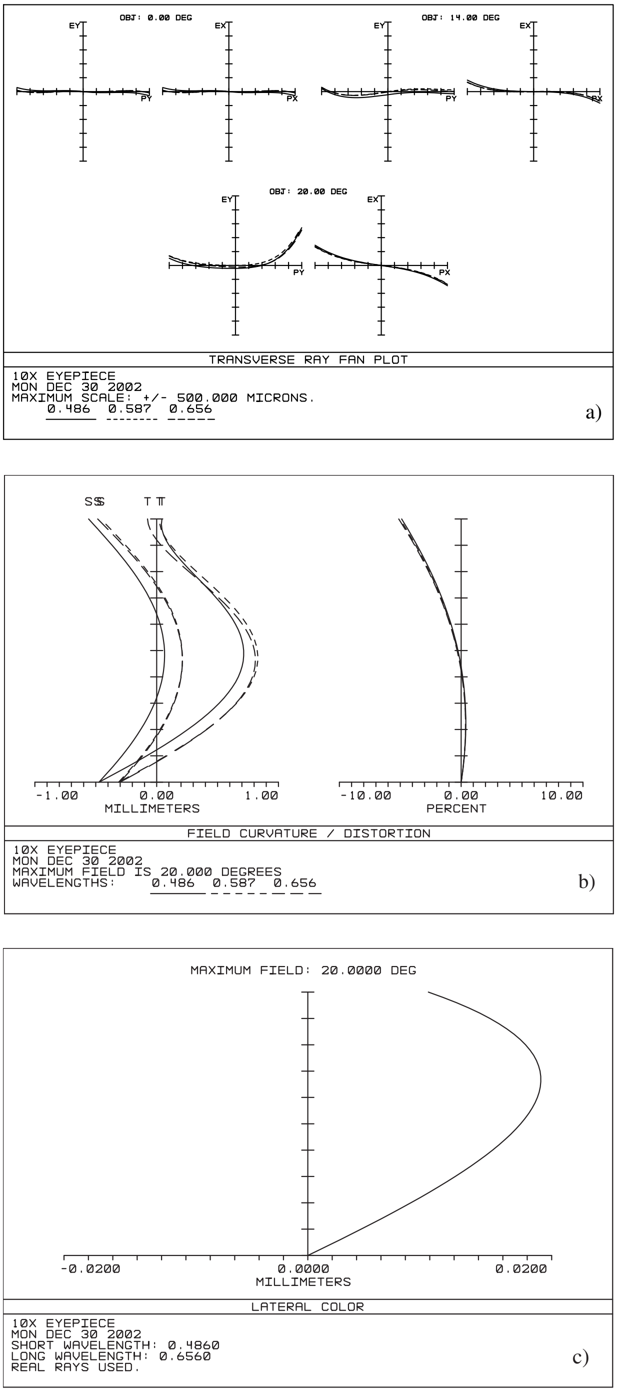

Fig. 3. Aberrations curves of the hybrid eyepiece in fig. 2. a) Transverse ray aberrations; b) field curvature and distortion; c) lateral color.

vice sized 1.1 inches diagonal. Because of without relay system, the HMD system can be made more compact with less weight. Compared with our system with a relay reflector previous designed [7], the hybrid eyepiece with an aspheric surface is more suitable for HMD.

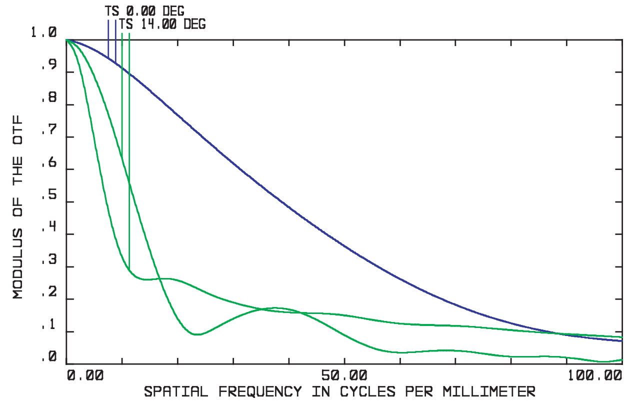

Fig. 4. The modulation transfer function (MTF) curves of the eyepiece in fig. 2.

3. Conclusions

We presented one simple 40° eyepiece for micro-display, which consists of two elements, including a binary surface and an aspheric surface. It can directly match with the micro-display device sized 1.1 inches diagonal. With satisfactory performances, it can be well used in display with a SXGA resolution. The weight is only 16 g, accompanying a 10 mm exit pupil and a 25 mm eye relief. Without relay system, the HMD system can be made more compact in size and light in weight. So this hybrid eyepiece would have much more predominance in HMD.

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