The Projection Lens Design for Holographic Waveguide Display with One-dimensional Exit Pupil Expansion

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ABSTRACT

In this study, a projection lens is designed with larger aperture in a reasonable size and combined with a 1D EPE structure of waveguides to construct a NED system, which DFOV achieved 30° and solved the problems of poor coupling efficiency and complicated process of 2D EPE.

1 Introduction

In modern life, more and more information is obtained and used through displays. Especially, head mounted display (HMD) and near-eye display (NED) provides the needs in traffic safety, education, and entertainment [1][2]. As the improvement of technology and the mature design of optical system, the demand of HMD for people tends to be lighter and smaller. To make the display system more functional, HMD is often combines with augmented reality (AR) [3][4][5]. There are many different kinds of NED and HMD. Among them, system based on it is more compact and more streamlined for the combination of optical waveguide.

For the structure of the optical waveguide, the use of diffractive elements as couplers provides compact and light weight in the overall system. In many diffractive elements, the volume holographic optical element (VHOE) is widely used.

In addition, field of view (FOV) is an important consideration for design an HMD system, it may affect the performance of the optical system. But, using VHOE as the coupler always need angle multiplexing and 2D EPE structure to improve the FOV of the image. Nevertheless, using more holographic optical elements (HOE) will decrease light efficiency.

To improve diffraction efficiency and avoid complicated manufacturing process of 2D EPE, this study purposed to design a rectangular projection lens which has larger aperture length in vertical direction to enhance the vertical field of view (VFOV) and combined with 1D EPE waveguide to reduce the horizontal size requirements of the projection lens, and set the exit pupil as close as possible to the waveguide. In this way, our design lens with 1D EPE holographic waveguide element can compose a compact HMD system with large FOV.

2 Specification and Optical Design

Considering the scale of adult head and the size of entire Near-Eye Display system, the reasonable specifications of our projection lens are as follows, the effective focal length (EFFL), f, is about 50 mm, the target diagonal FOV (DFOV) is 30° and the aperture diameter of lenses are approach to 28 mm.

According to this specification, we need a panel for 1.05", but it is uncommon. Therefore, using a mini projector to make an intermediate image could construct an image source of our designed projection lens.

Consequently, the optical design in this study is shown in Fig.1, which made by Paint 3D. First, using one mini projector to project an intermediate image on a diffuser, and it made the light more uniform and had larger divergence angle. Then, the intermediate image is imaged by our projection lens, and the infinity image is coupled into the waveguide by the in-coupling HOE. Finally, the image would be coupled out by the out-coupling HOE, and the user could see the images in front of the waveguide. And the holographic waveguide elements are composed of two symmetrical reflective linear gratings of in-coupling and out-coupling HOE.

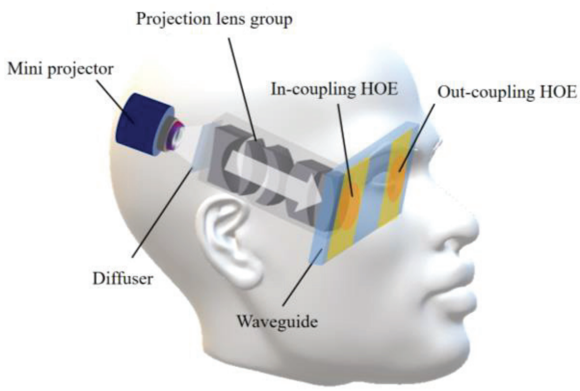

Fig.1 The Schematic of Optical Design for Near-Eye Display system

3 Simulation Result

In this study, the ray tracing simulation software Zemax is used to design the projection lens and analyze the image quality. Because of the projection lens should image the information at infinity, we set the collimation light from object surface entering the lens group to focus on the image surface initially. Ensuring that the image will be imaged at infinity, and then we reversed the lens group to observe the quality finally. The fields of view were set according to DFOV of 30° and keep the ratio of the final image at 16:9. The fields of simulation are set (0.00°,0.00°)and (±13.074°, ±7.354°).

In light of design procedures, the projection lens is designed with a general circular lens and selected spherical for simulation to reduce manufacturing costs. Then the lens will be shaped to rectangular in the future. After the optimization, the lens data of radius, thickness, air space, diameter of each surface and the material of each lens were shown in Table.1. All material of the lens was selected from common glass, and which second and third lens were fused as a cemented lens. The layout of the lens group is shown in Fig.2, and the EFFL is about 50.08 mm of this projection lens and the front focal length (FFL) is about 2.3 mm, total track length of lens (TOTR), the distance from surface1 to the image plane, is about 75.25 mm.

Table.1 The lens data of the projection lens after optimized

Surface	Radius	Thickness	Material	Semi-Dia
OBJECT	Infinity	Infinity	-	Infinity
1	Infinity	0.00	-	14.00
STOP	45.204	10.018	N-BK7	16.00
3	-98.484	4.894	-	16.00
4	-38.282	4.995	SF5	16.00
5	226.940	6.985	N-BK7	16.00
6	-36.318	2.964	-	16.00
7	25.329	6.192	N-BK7	16.00
8	28.238	14.257	-	16.00
9	30.276	5.927	N-BK7	16.00
10	Infinity	11.804	-	16.00
11	-20.949	4.957	SF5	16.00
12	221.069	2.257	-	16.00
13	Infinity	0.00	-	14.00
IMAGE	Infinity	-	-	13.559

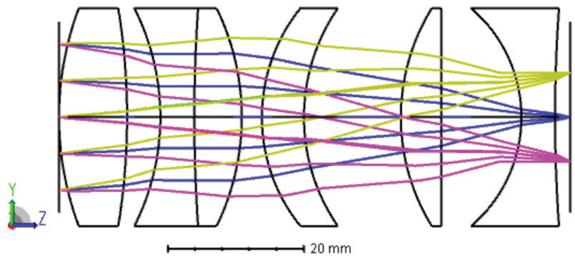

Fig.2 The layout of the projection lens in Y-Z plane

Considering the packing feasibility of the lens, the diameter of all optimized lens is increased to 32 mm which reserved 4 mm as the width of the frame and add the aperture with 28 mm for diameter at the front and rear of the lens group to observe the image quality in simulation. Then, the image quality is estimated according to the following parameters: Modulation transfer function (MTF), field curvature, distortion, footprint diagram, relative illumination and image simulation.

The MTF reflects the change in contrast at different spatial frequency, which is related to aberration and diffraction effects. In Fig.3, the curves indicate the MTF in the tangential and sagittal directions for each field, the MTF of all fields are reach more than 46.85 lp/mm at the contrast of 30% and the lens group can resolute the minimum pixel size is about 10.67 µm.

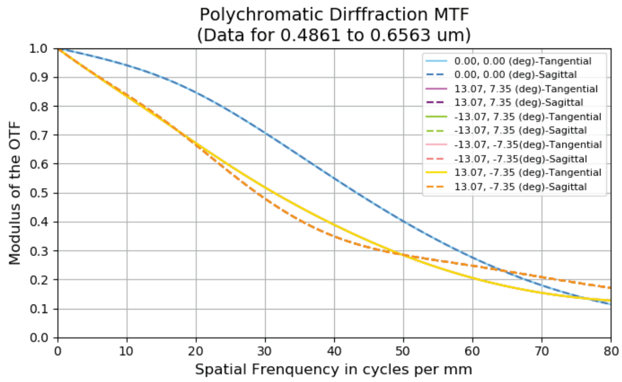

Fig.3 The MTF of the projection lens after optimized.

From the Fig.4, the largest tangential and sagittal field curvature are 0.148 mm appears in 0.00°, and the astigmatism maximum which appear at 10.2° is about 0.134 mm, both of them are under the human eye tolerance.

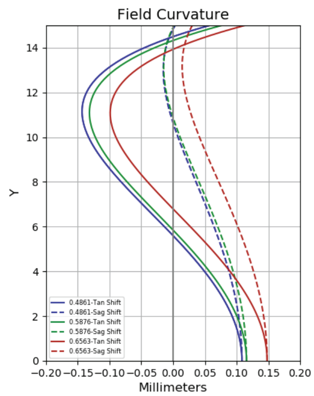

Fig.4 The field curvature of the projection lens

The distortion of the lens group is shown as Fig.5, the maximum distortion is 1.41% which belongs to pincushion distortion is small enough for human eyes.

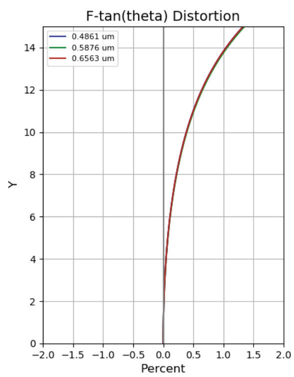

Fig.5 The distortion of the projection lens

And the footprint diagram is shown in Fig.6, the size of the image point aggregation, which affects the image quality and resolution, it also shows the object size about 13.43 mm of maximum radius which is match to our expected panel size 1.05”. As shown in Fig.7, the minimum illumination is 74% of the central field of view.

Finally, the lens group is reversed to observe the image simulation which is shown in Fig.8. The image simulation in Fig.8 is shown the demo picture which resolution is 1920×1080, and the field height is about 13.10 mm from footprint diagram.

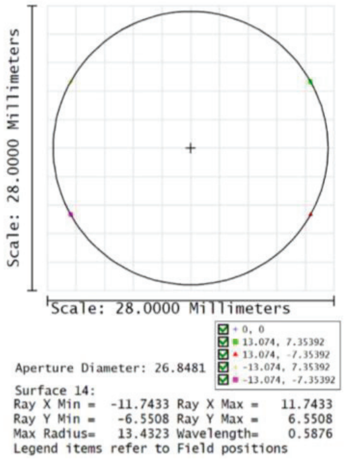

Fig.6 The footprint Diagram of the imaged surface

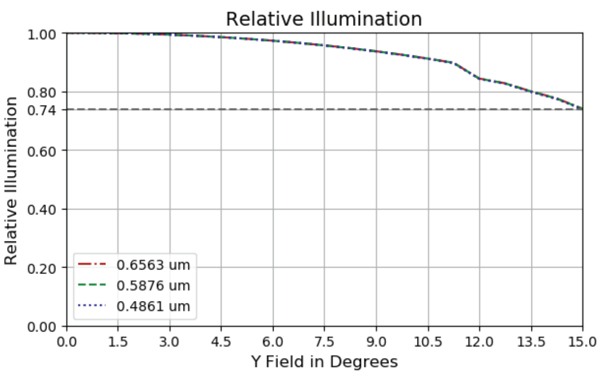

Fig.7 The relative illumination which simulated by add an ideal lens to focus the image

Fig.8 Image simulation about the demo picture which resolution is 1920×1080

4 Experimental results

4.1 Optical System Verification

After the projection lens be manufactured, we test the optical system on optical table and verify the effect of aperture size on VFOV, the actual architecture as shown in Fig.9 is used to validate the entire optical architecture. First, using one commercially available mini projector to form an intermediate image on diffuser, which is put on the front focus of the projection lens, then the image will be imaged at infinity, and be coupled into the waveguides, and passes through the waveguide by total internal reflection and then be coupled out of the waveguide by the output HOE and directing the final image to the observer.

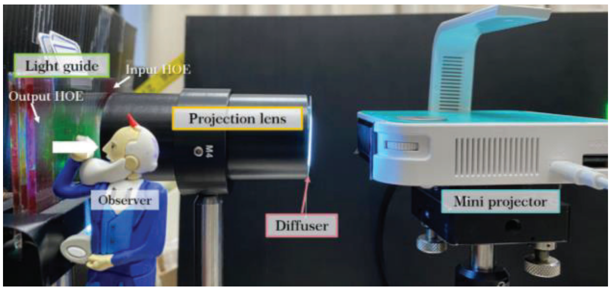

Fig.9 The optical system architecture of the NED system mounted on an optical table

Finally, the input information is shown as Fig.10. The image size of grid is 16:9, and the FOV is calculated by Eq.1.

$$\theta = 2\tan^{-1}\frac{H/2}{L} \dots\dots (1)$$

Where θ is FOV, H is the size of image per grid on the screen behind the waveguide and observer, L is the distance between observer and the screen. Which VFOV is about 2.53° per gird and HFOV is 3.38° per gird.

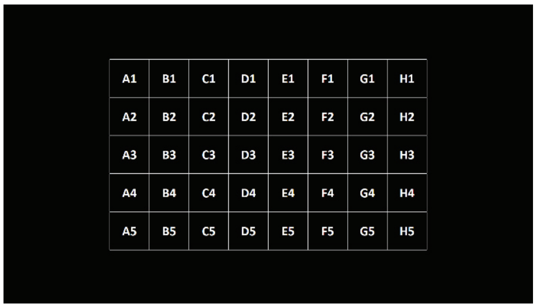

Fig.10 The image output by the mini projector

Then we attached different size of rectangular masks on the final surface of the lens to discuss the VFOV in different aperture size. There are three sizes of masks in vertical direction, which are 2.8 cm, 1 cm and 0.5 cm (mask1, mask2 and mask3), respectively. And width of all masks in horizontal direction are 1 cm. Among them, mask1 is match the projection lens of our design. The results with difference size masks are shown in Fig.11. We used column B as a comparison, the VFOV of mask1 has 6 grids about 15.18° , mask2 also has 6 grids about 15.18° and mask3 has 4 grids about 10.12°. As a result, the aperture size in the vertical direction has an effect on the VFOV under the 1D EPE system, the larger aperture size of projection lens is, the larger VFOV is. The experimental results confirm our design principle. However, there is no significant difference between the results of mask1 and mask2 because the vertical length of the input image is not large enough. Besides, the horizontal FOV (HFOV) and DFOV in Fig.11(a) is 27° and 30.97° which are achieving our target FOV.

(a)

(b)

(c)

Fig.11 The observing results of (a) mask1 (b) mask2 (c) mask3

4.2 Optical Mechanism Package

After observing on the optical table, we design the package to turn the overall optical system into a portable device which shown in Fig.12. Consider the limitations of waveguide placement, lens placement, and mini projectors, aiming at a portable near-eye display to design some component that conforms to this system. After the required acrylic size and style, using the vector graphics line editing software CorelDRAW to draw the required acrylic, then use a laser cutting machine, and finally combine all the acrylics. Total length of this device is about 23 cm, width is 5.4 cm and height is 6.1 cm. Let it can hold in hands and observe see-through images, which can see the image projected by computer and the actual scenery around ourselves at the same time.

Fig.12 The entity photo of HMD system after assembly

5 Discussion

In the future, the relationship between vertical length of the projection lens and VFOV can be further explored to find the required minimum height of the lens, so that the volume of the lens can be compacted under the required viewing angle. In addition, reducing the EFFL of the projection lens may also reduce the size of the system.

6 Conclusion

In this research, different masks are used to simulate the different aperture size of projection lens, and we prove the vertical height of lens will affect VFOV. Thus, we designed a projection lens with larger aperture in a reasonable size with diameter of 28 mm and made the exit pupil closed to the in-coupling HOE. Then, it with a 1D EPE structure of waveguides and with mini projector, we have successfully constructed a NED system. This system which is proposed in this study can replace the use of 2D EPE to solve the problems of light efficiency and complicated fabrication process.

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References

[1] Hua, H., Girardot, A., Gao, C., & Rolland, J. P, "Engineering of head-mounted projective displays." Applied Optics 39(22), 3814-3824 (2000).

[2] Cheng, D., Wang, Y., Hua, H., & Talha, M. M, "Design of an optical see-through head-mounted display with a low f-number and large field of view using a freeform prism." Applied optics 48(14), 2655-2668 (2009).

[3] Wen-Kai Lin, Wei-Ting Liu, Ying-Pin Tsai, Tsang-Hao Hsu, Bor-Shyh Lin, Fu-Li Hsiao, Wei-Chia Su, "Compact Helmet Display Based on Reflection Type Holograms." Laser Display and Lighting Conference (2017).

[4] Tomilin, M. G, "Head-mounted displays." Journal of Optical Technology 66(6), 528 (1999).

[5] Draper, C. T., Bigler, C. M., Mann, M. S., Sarma, K., & Blanche, P. A. "Holographic waveguide head-up display with 2-D pupil expansion and longitudinal image magnification." Applied optics, 58(5), A251-A257 (2019).