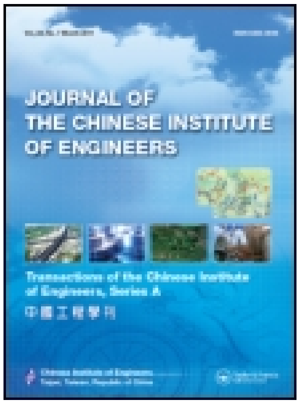

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The research is aimed at designing an optimized head-mounted-display (HMD) system equipped with two 0.26-inch Liquid Crystal on Silicon display elements for imaging. In order to form an image at a distinct-vision distance of 250 mm, the eyepiece system features 17-times magnification, a 15.63-mm focal length and a 15° field of view. Using the resolution of the human eye as the evaluation standard, we analyze the diminution of aberration and the increase of modulation transfer function, giving the HMD system high resolution as the finishing touches.

Keywords: LCOS; eyepiece system; head-mounted-display

1. Introduction

In 1960s, Ivan E. Sutherland developed the first head-mounted-display (HMD) by using a Cathode Ray tube (CRT), focusing optical system and a computer image generator to control monitor display signals generated by head turning (Melzer and Moffitt 1997, Girolamo, 2001). Since 1970, the military of the United States has applied HMD system to military equipment.

Not until Thin Film Transistor-Liquid Crystal Display (TFT-LCD) began to be used in HMD, did the weight of HMD equipment decrease much because HMD had always been mainly composed of a CRT unit, which had made the systems large and heavy. In spite of the short 50-year HMD development history, many display-related technologies have been developed. Moreover, because the maturity of the technologies and the low cost of the parts have solved the problems of low resolution and high price of TFT-LCD, the prices and sizes of HMD systems have been going down. Therefore, HMD systems are, now, not only applied to military affairs but also to entertainment, medicine and education (Mordekhai 1998). In the process of miniaturizing TFT-LCD display elements, high resolution cannot be maintained. To achieve high resolution and small size, Liquid Crystal on Silicon (LCoS), whose aperture ratio, brightness, and contrast ratio are better than those of TFT-LCD, is used for displays. This study has focused on an LCOS-type HMD design with an optimized eyepiece system. Because eyepiece systems affect image quality directly, the aberrations before and after the optimization are to be analyzed. Additionally, in order to ensure that the HMD presents a high-quality image, we evaluate how well the eyepiece matches the resolution of the human eye.

2. Theories of HMD optical system and the-resolution-of-the-human-eye analysis

The eyepiece system in an HMD system is used to enlarge the image from the LCoS, which, then, forms image on retinas. Thus, the design of the eyepiece system decides image qualities. Figure 1 shows that the object y is magnified to y'. The magnification calculated by object distance (l) and image distance (l') is expressed as in Equation (1). Focal length (f), magnification (M), object distance (l), and image distance (l') of eyepiece system are calculated by Equations (1)–(3). The proper distance between the eyepiece and the eyes can be set as 5 mm (Rosen 1965, Fedorova and Fedorova 1980, Laikin, 2006). HHMD-F320B manufactured by Oculon Optoelectronics Inc. was used as the main system structure in this study as shown in Figure 2, and the side view of the optical system is depicted as shown in Figure 3. To improve

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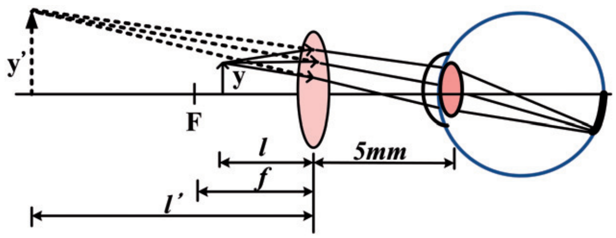

Figure 1. Object image magnified by eyepiece system.

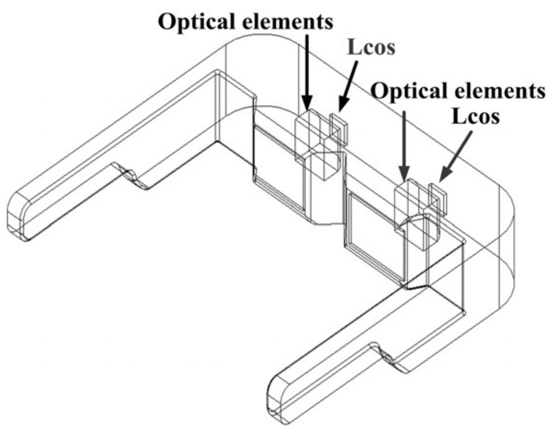

Figure 2. HMD-F320B system structure.

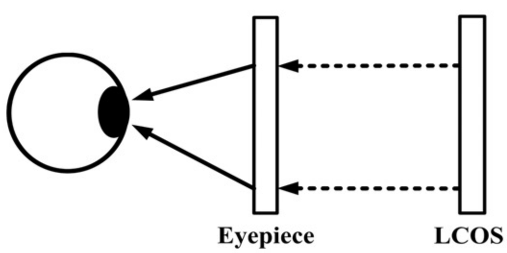

Figure 3. Side view of HMD optical system.

the eyepiece system, we will simulate and optimize it for increasing its resolution.

$$\mathrm{M} = \frac{l'}{l} \tag{1}$$

$$l = \left(\frac{1}{M} - 1\right) f \tag{2}$$

$$l' = (1 - M) f \tag{3}$$

To decide whether the image quality meets the needs of the human eye, this optical system was evaluated by standards matching the resolution of the human eye. On the standard of spatial frequency resolution of modulation transfer function (MTF), the number of recognizable black and white lines within 1 mm decides the largest effective spatial frequency (Lin *et al*. 1989, Smith 1990). From Weymouth (1958), we know that the minimum resolution of the human eye on the optic axis is 1 minute of angle (MOA), and the half-view angle of the HMD we have designed is 12°, which equates to four MOA. As shown in Figure 4, after being refracted, the *d* between the two points form an angle θ and a 1-MOA image on the retina. Equation (4) is used to calculate the minimum value *d*, which is 250 mm away from the eyeball. After the calculation, we know that the minimum *d*, when it forms a 1-MOA image on the retina, is 0.0727 mm. That is to say that when the formed image on the retina becomes 4 MOA, *d* increases to 0.2909 mm. Then, we substitute spatial frequency into Equation (5), obtaining 6.88 lp/mm and 1.72lp/mm at 1 MOA and 4 MOA, respectively (Toet and Levi 1992, Lyons and Mouroulis 1996). Consequently, the highest recognizable spatial frequency of the human eye at 1 MOA is 6.88 lp/mm.

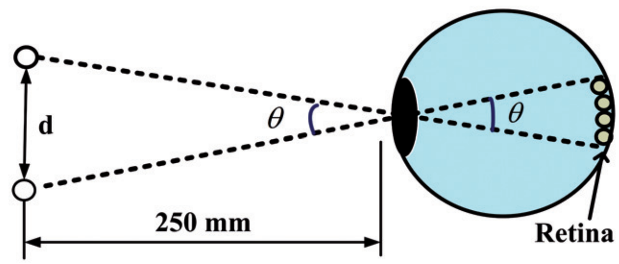

Figure 4. Illustration of human eyes resolution.

$$d = \frac{1}{60} \times \frac{\pi}{180} \times 250 \tag{4}$$

$$\text{Spatial frequency} = \frac{1}{2 \times \text{minimum width recognizable by the human eye}} \times (\text{lp/mm}) \tag{5}$$

3. Simulation and optimization of the optical system

This study is aimed at designing a 0.26-inch LCoS HMD eyepiece that can make the LCoS image form at 250 mm away from viewer's eyes, so that a magnified virtual image can be obtained. The specifications of an eyepiece using United States Patent US 2002/0180662 (Ko *et al*. 2002) are exhibited in Table 1, and the lens data of Patent U6,349,004 (Robert et al. 2002) in Table 2.

First, the eyepiece information meeting our demand most is inputted into optical simulation software, ZEMAX, and the specifications, such as focal length, object distance, object height, magnification, and field of view, are used later. The image quality of different fields of view will be analyzed and optimized, respectively, through ZEMAX.

The optimization process, the merit function in Zemax, is used to optimize the optics system. This optimization algorithm will be calculated by damped least squares. The terms of the optimization process must be limited properly. According to the system design shown above, the focal distance and magnification in the system are limited to fixed values by EFFL, PMAG calculation. Every element of thickness and gap will be limited and finely adjusted by optimizing units of DISG, CTGT, CTLT, MNCA, MXCA, MNCG, and MXCG, and DIMX, MTFT, and MTFS are to limited the MTF and aberration values. In addition, in order to complete the optical structure, four height fields are created to examine whether the optimized optics system fits the needed fields' angles and whether the aberration values conform to the normal standard values. Information on the optimized lens's surface is presented in Table 3. The lens layout is depicted in Figure 5.

Table 1. Specifications of eyepiece.

Focal length	15.63 mm
Field of view	15°
f/#	5
Magnification	17

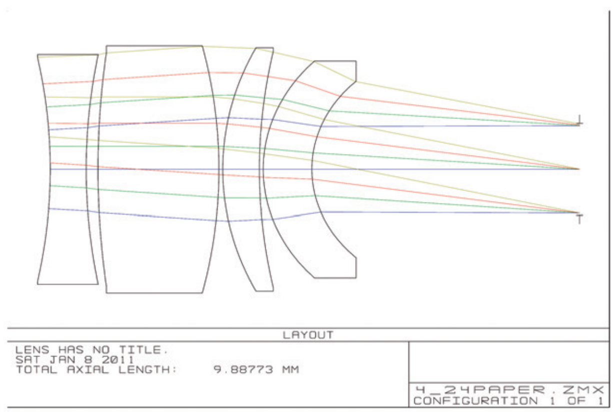

Figure 5. Lens layout after optimization.

Table 2. The lens data of Patent U6,349,004.

Surf	Type	Radius (mm)	Thickness (mm)	Glass	Semi-diameter (mm)
OBJ	Standard	Infinity	Infinity		Infinity
STO	Standard	Infinity	25		3
2	Standard	138.360	1.5	SF6	9.240
3	Standard	35.727	6	S-LAH66	9.496
4	Standard	−37.727	0.25		9.869
5	Standard	22.273	6	S-LAH66	9.822
6	Standard	−64.982	1.5	SF6	9.164
7	Standard	33.977	17.292		8.492
IMA	Standard	Infinity			5.760

Table 3. Lens data after optimization.

Surf	Type	Radius (mm)	Thickness (mm)	Glass	Semi-diameter (mm)
OBJ	Standard	Infinity	13.620893		3.3
1	Standard	−12.084342	0.672562	PBH11W	2.382395
2	Standard	13.436513	0.219753		2.441298
3	Standard	19.656936	2.259069	S-LAH66	2.480546
4	Standard	−11.261793	0.072059		2.626897
5	Standard	5.710609	0.684486	S-LAH66	2.585325
6	Standard	12.299569	0.070827		2.507805
7	Standard	3.248581	0.908974	SF6	2.304424
8	Standard	2.534030	5		1.872174
STO	Standard	Infinity	−256.328392		0.975241
IMA	Standard	Infinity			56.525008

This study set manufacturing errors including the lens thickness and the air gap distance. The MTF performance was used as the merit function in the tolerance process. Figure 6 shows the manufacturing errors of the MTF at 6.88 lp/mm based on the manufacturing error. The plot suggests that the MTF degradation at a given −0.02 manufacturing error is −3.12%, −4.49%, −2.91%, and −2.0% at the four real image heights from 0 to 56.3 mm, which is acceptable for our system.

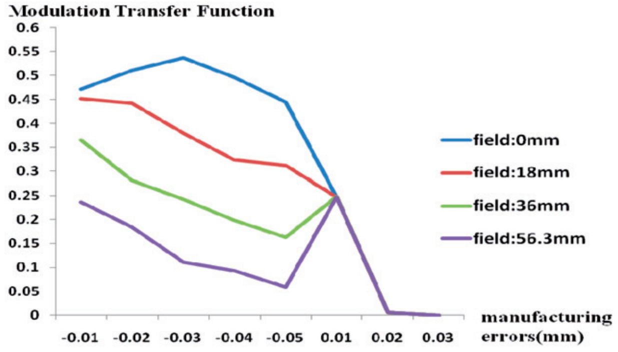

Figure 6. The manufacturing errors for the MTF tolerance.

4. Result and discussion

Figure 7 shows the structure of the lens system after optimization. '1' is image position, '2' exhibits LCoS image element position, '3' depicts eyepiece system, and '4' shows the position of viewer's eye. The magnification principle can be interpreted clearly from the layout.

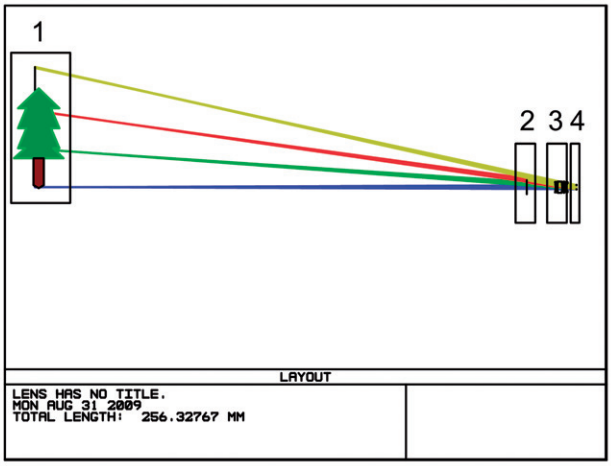

Figure 7. System layout after the optimization.

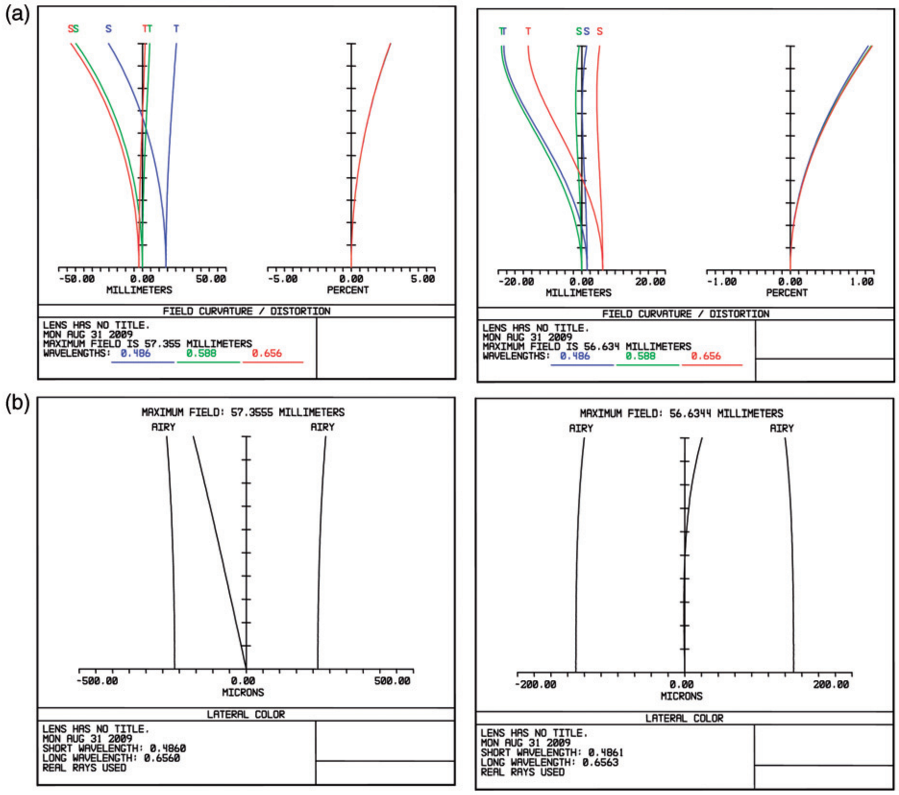

Figure 8. (a) Field curvature and distortion and (b) transverse chromatic aberration before and after optimization.

Field curvature, distortion, and transverse chromatic aberration before and after optimization are depicted in Figure 8 and sorted in Table 4. The transverse chromatic aberration and the field curvature decrease from −158.28 μm and 39.73 mm to −18.19 μm and 15.73 mm, respectively. The distortion is reduced from 34% to 0.96%. As the result shows, system aberrations can be greatly lessened via the optimization.

Figure 9 shows the relation between the MTF and the field. The MTF differences between the tangential surface and the agittal surface of the eyepiece system are small. If the MTF differences were greater than 10%, the aberrations would lead to aberration problem. Our system design has no such problems.

The simulation result shown in Figure 10 tells whether the MTF matches the needs of the human eye. We have obtained the highest spatial frequency 6.88 lp/mm from previous calculations. Human eyes cannot discern an image when its spatial frequency is higher than 6.88 lp/mm. MTF values before and after optimization are sorted in Table 5. The greater the MTF value, the higher the image resolution. Before the optimization, the MTF value at 1 MOA was only 0.09, and after the optimization, the MTF value has increased to above 0.3. Photoreceptor cells within the range of 1 MOA on the retina are the most sensitive, and after the optimization, the resolution at 1 MOA appears higher, which greatly improves the quality of the eyepiece system. Moreover, the MTF values at 2, 3, and 4 MOA reach above 0.66, making human eyes see images more distinctly.

Good image quality can be acquired through simulation. Long focal lengths between 20 and 30 mm are normally used in HMD optical systems (Zhao *et al.* 2007, Zhang and Hua 2008). However, in order to shorten the length of the system, the focal length 15.625 mm is adopted in the research. For the sake of light weight and miniaturization, plastics are used as the material of the eyepiece system.

Table 4. Aberrations comparison before and after optimization.

	Transverse chromatic aberration (μm)	Field curvature (mm)	Distortion (%)
Before	−158.28	−39.73	2.34
After	−18.19	−15.73	0.96

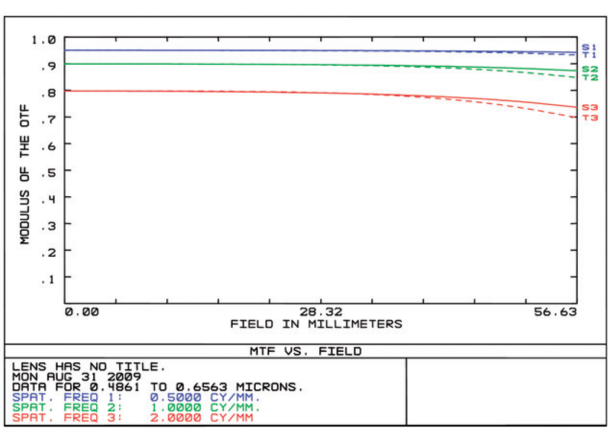

Figure 9. MTF vs. field after optimization.

5. Conclusions

HMD systems have been commonly applied in the optical industry recently. Their handiness and

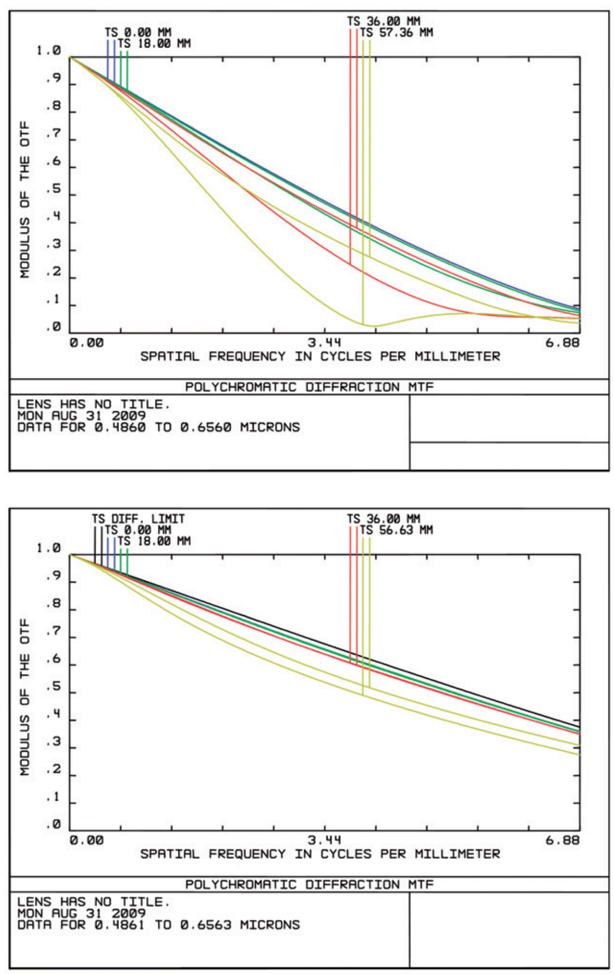

Figure 10. MTF values before and after optimization.

Table 5. Corresponding values of human eyes resolution and the MTF.

Human eyes resolution	Field	Spatial frequency (lp/mm)	MTF value before optimization	MTF value after optimization	Diffraction limit
One minute angle	0°	6.88	0.09	0.36	0.38
Two minute angles	5°	3.44	0.44	0.66	0.66
Three minute angles	8°	2.29	0.53	0.75	0.77
Four minute angles	12°	1.72	0.56	0.74	0.83

resolution are worth improving. This study is aimed at optimizing the eyepiece system and finding the human eye's greatest tolerance toward the system. As this study shows, the MTF at 1 MOA increases from 0.09 to 0.36 after optimization. Additionally, to achieve high resolution, field curvature, distortions, and transverse chromatic aberrations have been reduced. Short focal length shortens the length of the whole system, and plastics reduce the weight of the HMD. Therefore, using diffraction elements on the surface of the lens to thin lens thickness and to achieve better resolution will be an important issue in the near future (Zhao *et al*. 2004).

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