Aberration Improvement for Head-Mounted Displays with Holographic Optics and Polarized Laser Backlight

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Abstract

This paper presents an aberration improvement technology for thin, lightweight head-mounted displays with holographic optics and polarized laser backlights. To improve aberration, we incorporate aspheric lens functionality into a reflective polarizer and the holographic optical element functioning as a flat lens. A fabricated prototype shows an improvement in the measured modulation transfer function.

Author Keywords

LCD; polarized laser backlight; wide color gamut; BT.2020; virtual reality; head-mounted display; holographic optics.

1. Introduction

The metaverse is attracting significant attention, with head-mounted displays (HMDs) playing a crucial role. People wish to enjoy the metaverse for extended periods, but the bulky, heavy bodies of HMDs cause discomfort. In recent years, thin, lightweight HMDs using holographic optics and laser backlights have been proposed [1-4]. These holographic optics consist of polarization-based optical folding with holographic optical element (HOE). Polarization-based optical folding, or pancake optics, can reduce the size of HMDs [5]. Current pancake optics rely on curved optical components made of solid glass or plastic, resulting in thick, heavy designs. However, HOEs can deflect light arbitrarily from a thin plane and thus provide lens functionality with a nearly negligible thickness and weight.

However, pancake optics face significant challenges. In this technology, light passes through a half-mirror twice, and half of the light is lost each time, so light efficiency cannot exceed 25%.

Holographic optics require laser illumination because HOEs are highly sensitive to wavelength. A spectral bandwidth of less than 1 nm is required for optimal performance [6]. This is significantly narrower than the wavelengths used in conventional displays, such as OLED panels and LCDs with LED backlights. The efficiency of the laser diodes used for laser illumination is lower than that of the LEDs used in conventional LCDs. To maintain HMD performance in terms of power consumption and brightness, we developed an LCD with an efficient laser backlight using a no-birefringent polymer called zero–zero-birefringence polymer in the light guide plate. In conventional backlights, half of the unpolarized light is absorbed by a polarizer. Polarized laser backlights emit linearly polarized light, resulting in an ideal transmission rate that is twice as high. Therefore, the polarized laser backlight can make the LCD panel highly efficient. Our polarized laser backlight can emit linearly polarized light with 88% polarization by applying the zero–zero-birefringence polymer to the light guide plate [3,4,7].

In a previous report [4], we constructed an HMD using a polarized laser backlight with pancake optics consisting of a holographic element with lens functionality and a flat reflective polarizer. VR HMDs require a large field of view (FOV), and aberrations become an issue in optical systems with large FOVs.

In general, aberrations are improved by combining multiple lenses. However, in our previous prototypes [3,4], aberrations were present because only the HOE was equipped with lens functionality.

In this study, we aimed to improve aberrations by integrating lens functionality into both the reflective polarizer and the HOE.

2. Pancake optics with holographic optics

In a conventional HMD, a thick bulk lens is set apart from an LCD to generate a large virtual image of the LCD. Thus, conventional HMDs need a certain thickness, as shown in Figure 1(a).

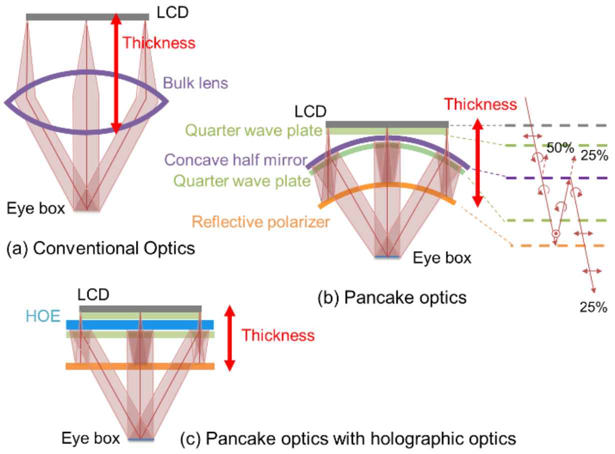

Figure 1. Pancake optics with holographic optics.

The use of pancake optics is proposed to reduce the thickness. Figure 1(b) shows the basic concept of pancake optics. A gap separates a concave half-mirror and a reflective polarizer. The concave half-mirror reflects 50% of the incident light and transmits the other 50%. The reflective polarizer reflects the light from one linear polarization while transmitting the light from the orthogonal polarization. Quarter-wave plates are placed on the LCD and in the gap.

In pancake optics, light traverses as follows. The quarter-wave plate on the LCD converts parallel linearly polarized light from the LCD into counterclockwise circularly polarized light. The second quarter-wave plate converts the counterclockwise circularly polarized light back into parallel linearly polarized light. The reflective polarizer reflects this linearly polarized light, which is then converted into counterclockwise circularly polarized light by the second quarter-wave plate. Then, the concave half-mirror reflects half of the counterclockwise circularly polarized light. The reflected light is clockwise circularly polarized. Thus, the second quarter-wave converts it into orthogonal linear polarization, and it passes through the reflective polarizer.

In pancake optics, light traverses the length of the gap three

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times while occupying the physical space of only one gap length. This enables the LCD to be placed closer to the optics than in conventional optics. However, because light passes through the concave half-mirror twice and is halved each time, the overall light efficiency is 25%.

In this way, the use of pancake optics can reduce thickness. However, the concave half-mirror still occupies some thickness.

As shown in Figure 1(c), the thickness due to the bulk optics can be reduced by combining polarization-based optical folding and holographic optics. Focusing is entirely performed by the HOEs rather than bulk optics. An HOE replaces the concave half-mirror. As HOEs consist of thin, flat films of negligible thickness and weight, thin, lightweight HMDs are achievable.

3. Pancake optics with holographic optics incorporating aberration improvement

Figure 2(a) shows our previously proposed holographic optics [4]. It uses a flat reflective polarizer and assigns lens functionality solely to the HOE. The pancake optics with holographic optics consist of a quarter-wave plate, an HOE, a quarter-wave plate, and a flat reflective polarizer on the LCD, in this order. With an eye relief distance of 10 mm, the distance from the LCD surface to the plane reflective polarizer was 10.4 mm. We have made the previously prototype with flat refractive polarizer (Figure 3(a)). Using this previous prototype, we confirmed that the aberrations occur in the large-FOV areas of the virtual image.

We attempt to solve this problem by developing holographic optics with lens functionality (specifically in the HOE and reflective polarizer) to improve aberration.

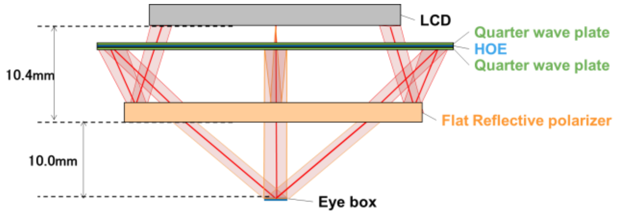
Figure 2(b) shows the developed holographic optics. It uses an aspheric reflective polarizer and assigns lens functionality to both the HOE and the polarizer. The HOE is designed such that the light reflected from the reflective polarizer, which is bonded to an aspheric surface, passes back through the aspheric lens to be focused at the eye box. With an eye relief distance of 10 mm, the distance from the LCD surface to the plane reflective polarizer was 9.6 mm. Figure 3(b) shows the prototype which we developed holographic optics with curved reflective polarizer.

In the developed prototype, the HOE fabricated using exposure optics with red, green, and blue lasers was used. We found the chromatic aberration in both prototypes. We chose simple exposure optics for proof-of-principle purposes. We designed them for green illumination (528 nm) rather than using three sets (red, green, and blue) of exposure optics. In the following discussion, evaluation was performed with green (528 nm) illumination.

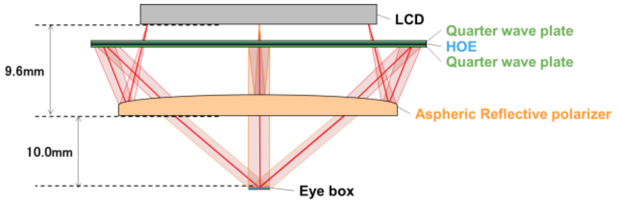
Both the previous and developed prototypes were designed to have a ±50° FOV, which is equivalent to a 100° FOV.

4. Experiment and results

To evaluate aberrations of our lens systems, we must capture the sagittal and tangential blur image due to aberration. Figure 4 shows our experiment system to capture the image. We displayed on LCD horizontal bar which is included stripes and we use 2 kinds of straps. One is sagittal stripe; another is tangential stripe. Each stripe was equivalent to 5-line pairs per degree (lp/deg), corresponding to 10 pixels per degree (ppd). One line pair consists of one white line and one black line. Horizonal bar with stripes were displayed in green. The eye relief distance was kept 10 mm. We captured a horizontal bar magnified by holographic optics with a flat (or aspheric) reflective polarizer using a wide-FOV webcam located at the pupil position. The webcam has a resolution of 2 megapixels and an FOV of approximately 120°.

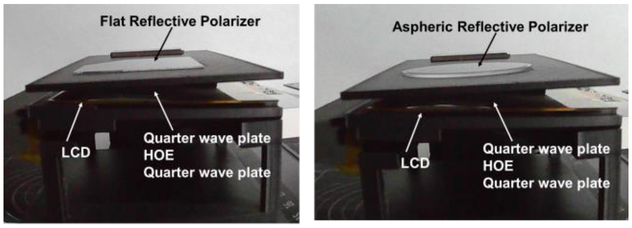


(a) Holographic optics using flat reflective polarizer.



(b) Holographic optics using aspheric reflective polarizer.

Figure 2. Holographic optics.



(a) Previous prototype. (b) Developed prototype.

Figure 3. Fabricated prototype of holographic optics and polarized laser backlight for HMD.

Its aperture diameter was approximately 3 mm, it is similar to that of the human pupil. The captured image had sagittal (tangential) blur because of aberrations. The captured images are shown in Figure 5. The FOV scale was added later. The 0° mark corresponds to the center of the webcam. Figure 5(a) shows the sagittal blur. The previous prototype resolved up to 10°, whereas the developed prototype resolved up to 50°. Figure 5(b) shows the tangential blur. The previous prototype resolved up to 10°, and the developed prototype resolved up to approximately 30°. These results show the significant improvement of peripheral aberrations by the incorporation of lens functionality into the reflective polarizer in addition to the HOE.

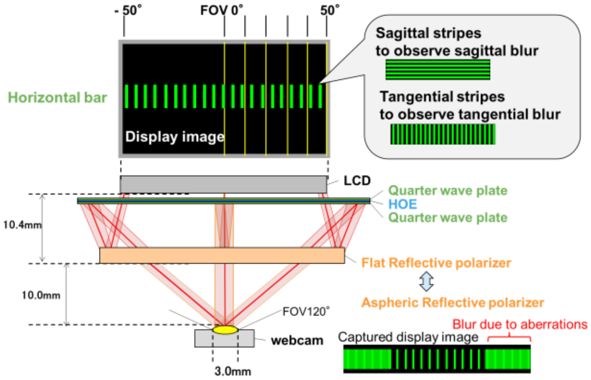
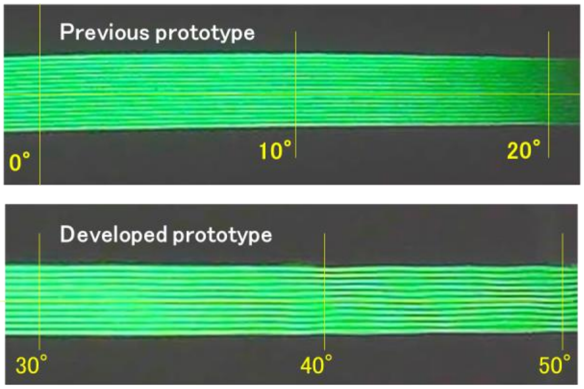
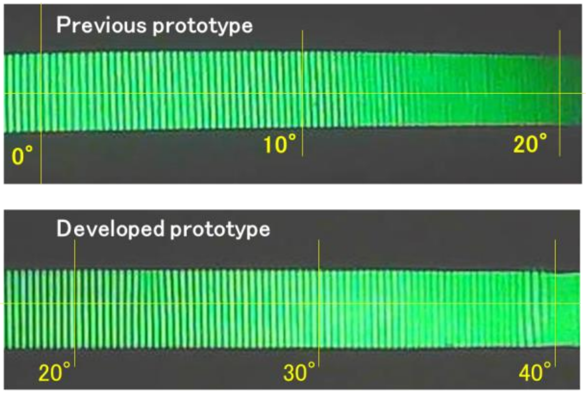


Figure 4. The method for observing sagittal and tangential blur using the previous (or developed) HMD.



(a) Sagittal blur.



(b) Tangential blur.

Figure 5. Sagittal and tangential blur in previous and developed HMDs.

Recently, HMDs typically have a resolution of 20 ppd [8], which is equivalent to 10 lp/deg. But HMDs require resolutions is known up to 60 ppd (equivalent to 30 lp/deg), which is resolvable by a person with 20/20 vision. Therefore, the optics used in HMDs should be evaluated up to 60 ppd. However, the LCD used in our developed prototype cannot display an image with 60 ppd.

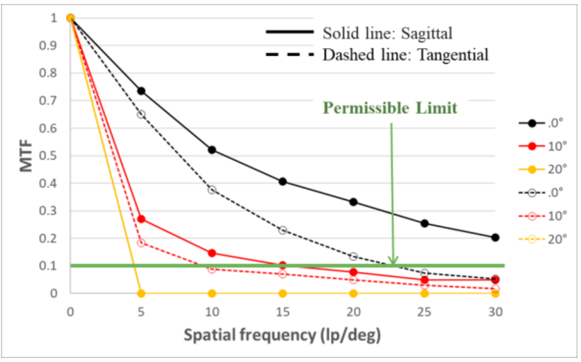
To assess aberrations quantitatively, we measured the modulation transfer function (MTF) using ImageMaster Lab VR (Trioptics Japan Co., Ltd.). The detector of this measurement device is positioned at the pupil position same as webcam. To measure the MTF at a resolution beyond the display limit of the LCD, we fabricated a resolution test target with crossed slits with a 4 μm width at positions corresponding to FOVs of approximately 0°, 10°, 20°, 30°, and 40° and placed it at the panel position. A 4 μm slit was chosen as the size to evaluate resolutions greater than 30 lp/deg. In MTF evaluation, the eye relief distance was set to the design value of 10 mm, and the backlight only produced green light (528 nm). Figure 6 shows the MTF evaluation results of the previous and developed prototypes. The solid line represents the MTF value in the sagittal orientation, and the dashed line represents the MTF value in the tangential orientation. Figure 6(a) shows the MTF results of the previous prototype as a function of spatial frequency. The MTF values of the previous prototype were 0 at FOVs greater than 20°. Figure 6(b) shows the MTF results of the developed prototype as a function of spatial frequency.

In the following discussion, the image was assumed to be resolvable at MTF values exceeding 0.1 as permissible limit (see figure 6). At 30 lp/deg, which is equivalent to 60 ppd, the image of the previous prototype could only be resolved at the 0° FOV, whereas that of the developed prototype could be resolved up to the 20° FOV.

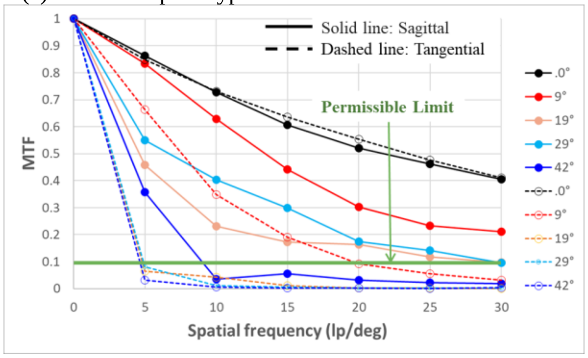
At 10 lp/deg, which is equivalent to 20 ppd, the image of the previous prototype could be resolved up to only the 10° FOV, whereas that of the developed prototype could be resolved up to the 30° FOV.

Therefore, the peripheral aberrations of the developed prototype were considerably improved compared with those of the previous prototype.

Figure 7 shows enlarged virtual images of the developed prototypes. The image was clear because aberration was improved.



(a) Previous prototype.



(b) Developed prototype.

Figure 6. MTF evaluation results.

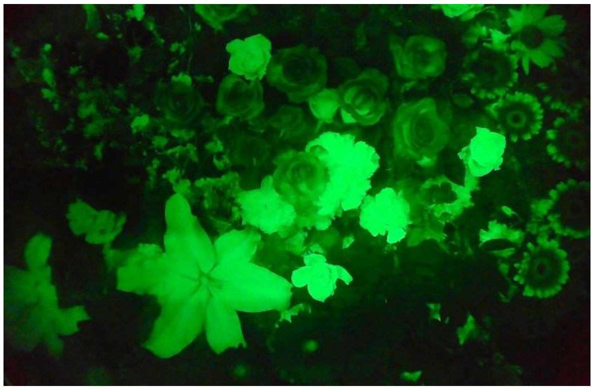


Figure 7. Photograph of natural image on developed prototype.

5. The additional effect of aspheric refractive polarizer

Using aspheric refractive polarizer and HOE, the panel size might be smaller than current optical system. We evaluated the relationship between the FOV and object height as LCD size. We use enough size LCD panel and display grid pattern instead of panel size. Figure 8 shows the FOV vs grid position on the LCD (object height). The relation FOV and position is represented half of the screen. The black line is the previous prototype, and the orange line is the developed prototype. In the previous prototype, a 50° FOV was obtained at a 22 mm object height, whereas in the developed prototype, this was obtained at a 17 mm object height. At the same pixel density, the object height corresponds to the number of pixels. Therefore, Figure 8 indicates that the developed holographic optics realized the same FOV with a smaller number of pixels than those of the previous prototype.

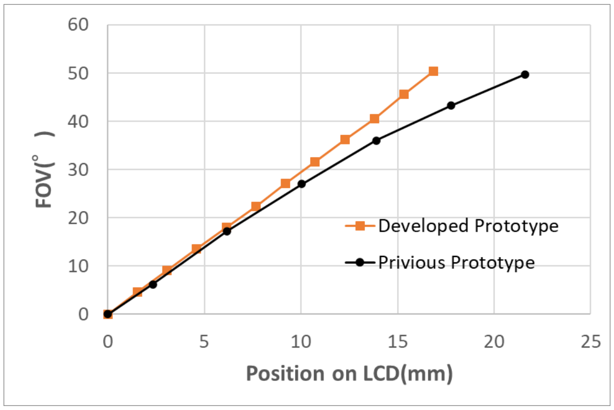


Figure 8. Evaluation of FOV.

6. Conclusion

We developed holographic optics with lens functionality incorporated into the reflective polarizer in addition to the HOE to confirm that aberrations are improved.

We observed sagittal or tangential aberrations by displaying sagittal and tangential stripes corresponding to 5 lp/deg within the horizontal bar on the LCD. It was confirmed that the developed prototype resolves images over a larger FOV compared to the previous prototype.

We also evaluated the MTF to assess the aberrations quantitatively. The MTF result of the developed holographic optics can be resolved up to FOVs of 20° and 30° at 60 and 20 ppd, respectively. In contrast, the MTF result of the previous holographic optics can only be resolved at FOVs of 0° and up to 10° at 60 and 20 ppd, respectively.

And we checked photograph of the natural image on developed prototype. We could confirm the image was clear all the way to the edge.

Thus, aberrations are improved in the developed holographic optics.

Developed holographic optics could achieve smaller object height (17 mm) than previous one (22mm) to realize 50° FOV. Therefore, the developed holographic optics realize the same FOV with fewer pixels than the previous holographic optics when using LCDs with the same pixel density.

This paper presents the improvement of aberrations by incorporating an aspherical reflective polarizer into the holographic optics. This technology is expected to enable the realization of thin and lightweight HMDs.

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