Aberration Improvement in Thin and Lightweight Head-Mounted Displays Using Holographic Optics and Polarized Laser Backlight

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ABSTRACT

This paper proposes aberration improvement technology for thin and lightweight head-mounted displays with holographic optics and polarized laser backlights. The MTF is improved by adding lens functionality to both the HOE and reflective polarizer. We also discuss realizing high ppd with large low-ppi panels because holographic optics remain thin regardless of the panel size.

1 Introduction

With the growing demand for immersive experiences in virtual environments, head-mounted displays (HMDs) have become increasingly important. Users seek prolonged engagement; however, conventional HMD devices are bulky and heavy, thereby causing discomfort. Recently, thin and lightweight HMDs that employ holographic optics and laser backlights have been proposed [1–4]. These systems employ polarization-based optical folding, referred to as pancake optics, with holographic optical elements (HOEs) to reduce the size of the device [5].

Conventional pancake optics rely on curved glass or plastic components, which results in thick and heavy designs. In contrast, HOEs can deflect light from a thin plane, offering sufficient lens functionality with minimal thickness and weight. However, with pancake optics, light passes through a half-mirror twice; thus, the light loses half its intensity each time, thereby limiting efficiency to 25%.

In addition, HOEs require laser illumination due to their high wavelength sensitivity, requiring a spectral bandwidth below 1 nm [6], which is much narrower than that of OLED or LCDs with LED backlights. Laser diodes are less efficient than LEDs; thus, they pose challenges in terms of power and brightness. To address this issue, we developed an LCD with a polarized laser backlight using a zero–zero birefringence polymer in the light guide plate. Unlike conventional backlights, which lose half of the unpolarized light at the polarizer, the polarized laser backlights emit linearly polarized light, thereby doubling the transmission efficiency. By applying the zero–zero birefringence polymer, our design achieves 88% polarization, significantly improving LCD performance [3,4,7].

In a previous report [4], we constructed an HMD device using a polarized laser backlight and pancake optics comprising a lens-function HOE and a flat reflective polarizer. HMDs require a wide field of view (FOV), and this introduces optical aberrations. Typically, multiple lenses are employed to correct such distortions; however, our earlier prototypes [3,4] exhibited aberrations because the lens functionality was limited to the HOE. In the current study, we attempt to address the occurrence of aberrations by integrating the lens functionality into both the reflective polarizer and the HOE.

2 Pancake optics with holographic optics

In a conventional HMD device, a thick bulk lens is placed apart from the LCD to generate a large virtual image, which results in significant device thickness (Fig. 1(a)). Therefore, pancake optics have been proposed (Fig. 1(b)) to reduce the device thickness. This configuration includes a concave half-mirror and a reflective polarizer separated by a gap, with quarter-wave plates positioned on the LCD and within the gap. Here, the concave half-mirror reflects 50% of the incident light and transmits the remaining light, and the reflective polarizer reflects one linear polarization and transmits the orthogonal polarization.

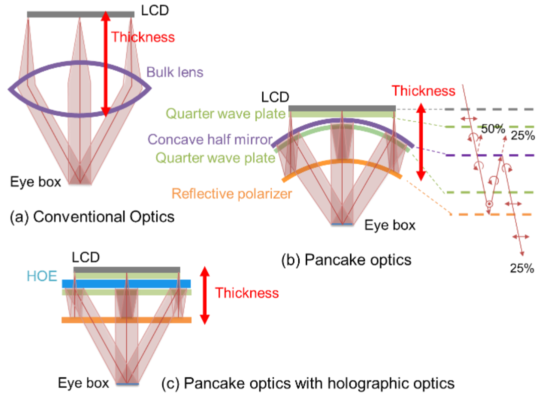


Fig. 1 Pancake optics with holographic optics

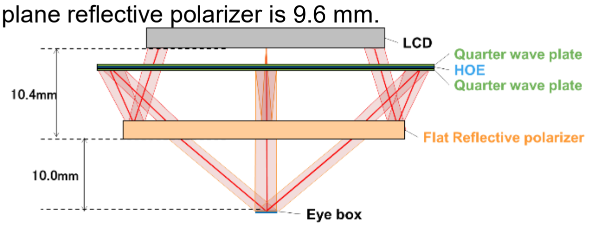
The light from the LCD undergoes multiple polarization conversions and reflections. As a result, the light traverses the gap three times while occupying only a single gap length, which enables a thinner optical path. While the light efficiency is limited to 25% due to the double transmission through the half-mirror, the pancake optics is commonly adopted because device thickness can be significantly reduced.

To further reduce the thickness, the concave half-mirror can be replaced with an HOE (Fig. 1(c)). HOEs are thin, flat films that can focus light, thereby facilitating compact and lightweight HMD designs without bulky optical components.

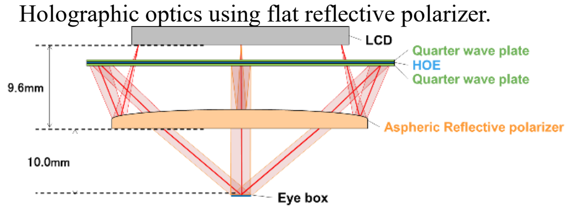
3 Pancake optics with holographic optics incorporating aberration improvement

Fig. 2(a) shows our previously proposed holographic optics design [4], which employs a flat reflective polarizer and assigns lens functionality solely to the HOE. This system comprises a quarter-wave plate, HOE, an additional quarter-wave plate, and a flat reflective polarizer on the LCD. With an eye relief of 10 mm, the distance from the LCD to the plane reflective polarizer is 10.4 mm.

To address this issue, we developed holographic optics with the lens functionality distributed across both the HOE and the reflective polarizer. Fig. 2(b) shows the updated design, which employs an aspheric reflective polarizer. Here, the HOE is designed to refocus light reflected from the polarizer, bonded to the aspheric surface, back to the eye box. In this design, the distance from the LCD to the plane reflective polarizer is 9.6 mm.



(a) Holographic optics using flat reflective polarizer.

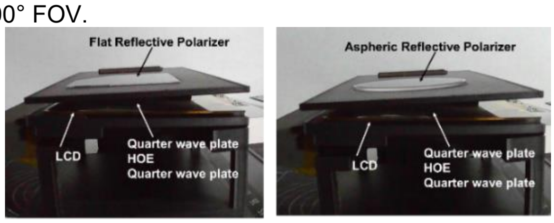


(b) Holographic optics using aspheric reflective polarizer.

Fig. 2 Holographic optics

4 Experiment and results

Fig. 3(a) shows the previous prototype with a flat reflective polarizer, while Fig. 3(b) presents the developed prototype with a curved reflective polarizer. Both the previous and developed prototypes employ HOEs fabricated with RGB laser exposure. The laser Backlight (Green: 528nm) was used in both prototypes to evaluate the aberration as a proof of principle. In addition, each prototype supports a ±50° FOV, which is equivalent to a 100° FOV.



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

Fig. 3 Fabricated prototype of holographic optics and polarized laser backlight for HMDs

To evaluate the aberrations in the lens systems, we captured sagittal and tangential blur images caused by aberration. Fig. 4 shows the experimental configuration. In this evaluation, a horizontal bar containing two types of green-striped patterns, i.e., sagittal and tangential, was displayed on the LCD. Each stripe represented 5-line pairs per degree (lp/deg), equivalent to 10 pixels per degree (ppd), with one line pair comprising a green line and a black line. In addition, the eye relief was fixed at 10 mm.

We employed a wide-FOV webcam positioned at the pupil location to capture the magnified horizontal bar through holographic optics with either a flat or aspheric reflective polarizer. This webcam has a resolution of 2 megapixels and an FOV of approximately 120°. This configuration facilitated an effective assessment of the image quality and aberration performance of the previous and developed prototypes.

The aperture diameter of the webcam employed in this evaluation was approximately 3 mm, which is similar to the aperture diameter in the human pupil. The captured image had a sagittal and tangential blur because of aberrations. Fig. 5 shows the captured images with the FOV scale added post-capture. Here, the 0° mark corresponds to the center of the webcam.

Fig. 5(a) shows the sagittal blur. The previous prototype resolved up to 10°, and the developed prototype achieved a resolution up to 50°. Fig. 5(b) shows the tangential blur. Here, the previous prototype resolved up to 10°, and the developed prototype reached approximately 30°. These results demonstrate an improvement in terms of the peripheral aberrations due to the incorporation of the lens functionality into both the reflective polarizer and the HOE.

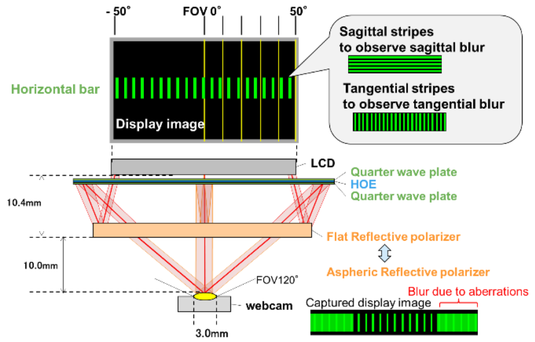
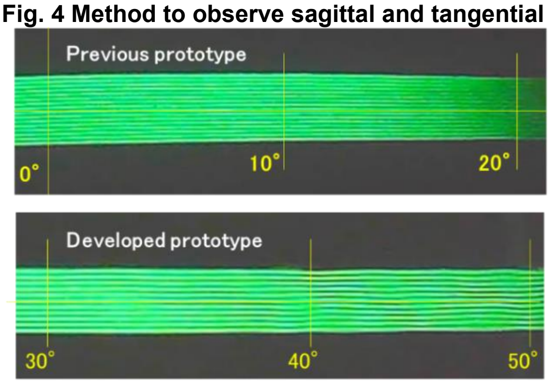
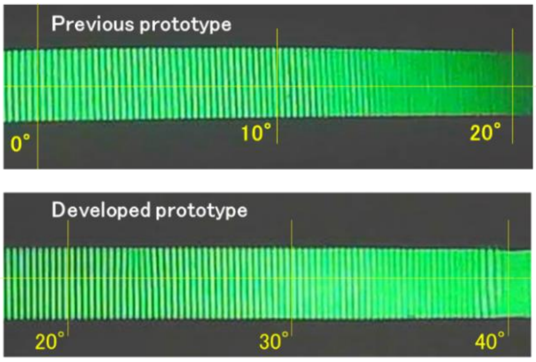


Fig. 4 Method to observe sagittal and tangential blur



(a) Sagittal blur.



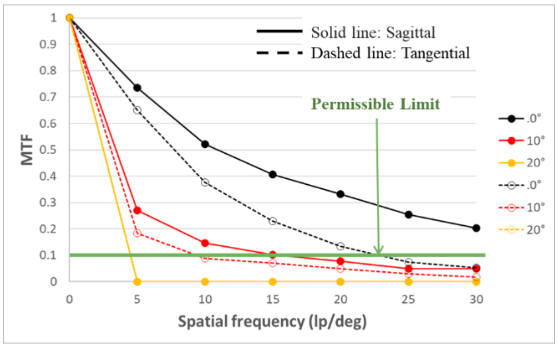
(b) Tangential blur.

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

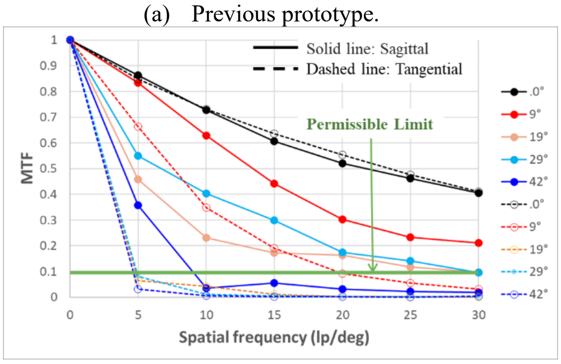
Recent HMDs typically offer a resolution of 20 ppd, equivalent to 10 lp/deg [8]; however, resolutions up to 60 ppd (30 lp/deg) are required to match the visual acuity of an individual with 20/20 vision. Thus, the optical systems in HMDs should be evaluated up to 60 ppd. The LCD employed in the developed prototype cannot display images at this resolution.

To assess aberrations quantitatively, we measured the modulation transfer function (MTF) using the ImageMaster Lab VR (Trioptics Japan Co., Ltd.) measurement system with the detector positioned at the pupil location (similar to the webcam configuration). To evaluate the MTF beyond the LCD's resolution limit, we fabricated a resolution test target with 4 μm crossed slits placed at FOV positions of approximately 0°, 10°, 20°, 30°, and 40°. This slit size corresponds to resolutions beyond 30 lp/deg. In this evaluation, the measurements were performed with an eye relief of 10 mm and polarized laser backlight (528 nm).

Fig. 6 shows the MTF results, where the solid lines represent the sagittal orientation, and the dashed lines represent the tangential orientation. Here, to define a permissible limit for the MTF in the aberration evaluation, we compared qualitative and quantitative results using 5 lp/deg test patterns. As shown in Fig. 5, the previous prototype resolved the sagittal and tangential patterns up to 10° FOV in the qualitative observations. Correspondingly, Fig. 6(a) shows that the MTF values for 5 lp/deg remain greater than 0.2 up to 10°, supporting this resolution. For the developed prototype, the sagittal and tangential resolutions extended to 50° and 30° FOV (Fig. 5), respectively. As shown in Fig. 6(b), the MTF values for 5 lp/deg approached 0.1 at these angles. Based on this correlation, we defined an MTF value of 0.1 as the permissible limit for the resolution. In Fig. 6(a), the previous prototype exhibits MTF values of zero beyond 20° FOV, and in Fig. 6(b), the developed prototype maintains MTF values greater than 0.1 up to 20° at 30 lp/deg and up to 30° at 10 lp/deg, representing significant improvements in peripheral aberrations.



(a) Previous prototype.



(b) Developed prototype.

Fig. 6 MTF evaluation results

5 Future prospects

To investigate the feasibility of achieving higher resolutions and a wider FOV in future HMD devices, we analyzed the relationship between the pixel density and panel size. Fig. 7 shows the relationship between pixel density and panel width. Here, the black line represents 20 ppd at 100° FOV, and the blue and green lines correspond to 40 and 60 ppd, respectively. In addition, the white circle indicates the panel employed in this study. To achieve 60 ppd at 100° FOV for VR, over 4860 ppi is required. However, a panel width of 60 mm (considering an interpupillary distance of 65 mm) enables 60 ppd when using a 2500 ppi panel. This density has already been demonstrated at the development stage [9].

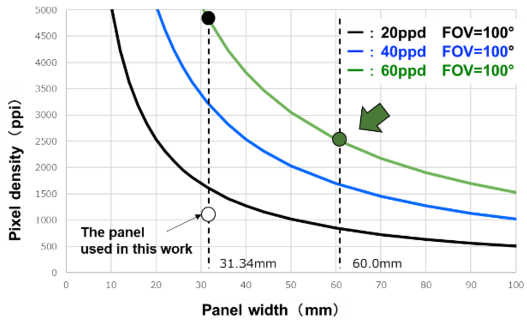
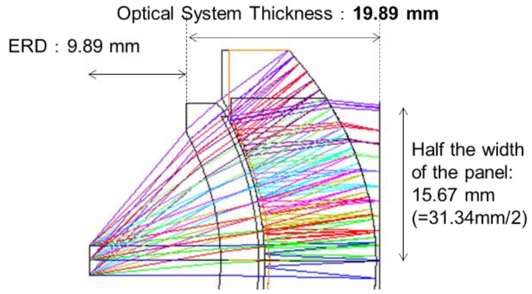
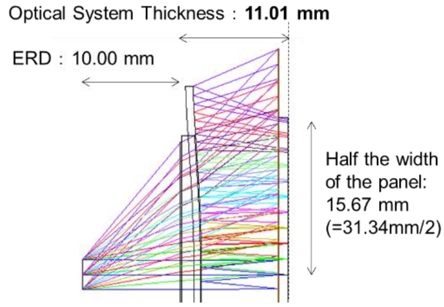


Fig. 7 Relationship between pixel density and panel width

Fig. 8(a) and Fig. 8(b) show the simulation results of the optical system with conventional pancake optics and the developed holographic optics, respectively. Here, both were simulated under the same conditions, i.e., 15.67 mm, which is half the width of the panel, and 100° FOV. We found that the conventional system required nearly twice the thickness.



(a) Pancake optics.



(b) Holographic optics.

Fig. 8 Simulation results of the optical system

Fig. 9 shows the relationship between the thickness of the optical system and half the width of the panel (assuming proportional scaling). Here, the black line represents the conventional pancake optics, and the blue line represents the developed holographic optics. Simulation points from Fig. 8 are also plotted. To achieve 60 ppd at 100° FOV, the developed optics require a thickness of 20 mm with 60 mm, which is panel width, equivalent to the thickness needed for 15 mm, which is half the width of the panel in conventional optics. This suggests that thin, lightweight HMD devices are feasible even with larger panels with lower density.

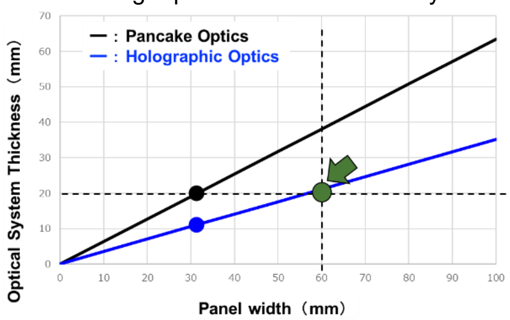


Fig. 9 Relationship between optical system thickness and panel width

6 Conclusion

We developed a prototype HMD that combines a polarized laser backlight with holographic optics to achieve a thin and lightweight design.

The holographic optics described in this paper demonstrated improved aberration performance compared with the previous design, thereby confirming the effectiveness of incorporating lens functionality into both the HOE and the reflective polarizer.

In this study, a quantitative evaluation was performed using MTF measurements, and we improved the resolve up to 20° and 30° FOV by using holographic optics at 60 and 20 ppd, respectivity.

These results demonstrate that incorporating lens functionality into both the HOE and the reflective polarizer significantly improves the peripheral aberration performance in holographic optics.

We have also demonstrated the potential to realize thin and lightweight HMDs with 60 ppd and 100° FOV using holographic optics and large panels with 2500 ppi.

7 Acknowledgements

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