Ghost Analysis in Thin and Lightweight Head-Mounted Displays with Holographic Optics

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Keywords: head-mounted displays, polarized laser backlight, virtual reality, ghost, holographic optics.

ABSTRACT

To improve the image quality of thin and lightweight head-mounted displays with hologram optics and polarized laser backlight liquid crystal displays, we analyzed ghosts of the fabricated benchtop prototype. The ghosts are caused by the reflections on the surfaces of quarter waveplates and holographic optical element. Based on the analysis, we obtained a clear image by suppressing surface reflections.

1 Introduction

In the metaverse, head-mounted displays (HMDs) for virtual reality (VR) play a crucial role. People will wear HMDs for a long time. Large and heavy HMDs are stressful.

Recently, a class of display designs combining holographic optics, directional backlighting, laser illumination, and polarization-based optical folding to provide thin and lightweight HMDs for VR was proposed [1,2].

The polarization-based optical folding, or "pancake" optics, can reduce the size of HMDs [3]. However, current pancake optics rely on curved optical parts of solid glass or plastic, which has limited designs to goggles-like form factors.

In the study, polarization-based optical folding and holographic optics were combined. Holographic optics can provide arbitrary deflection of light from a thin flat surface, but they require wavelength and angle sensitivities. It was stated that a spectral bandwidth of 0.1 nm to 1 nm is required for optimal performance. This spectrum is much narrower than that of conventional displays, such as LED backlight LCD or OLED panels. It can be achieved using a laser backlight LCD. The laser backlight LCD can also achieve a wide color gamut, such as BT. 2020. However, there are challenges. The light efficiencies of "pancake" optics and a laser backlight are low.

Recently, we proposed combining polarization-based optical folding, holographic optics, and polarized laser backlight LCDs to reduce the power of thin and lightweight HMDs [3]. The polarized laser backlight enhances the light efficiency of the laser backlight LCD [4]. We fabricated a benchtop prototype and confirmed the feasibility.

In pancake optics, ghost is known that causes image quality degradation. Ghost can be categorized into two types. The one is surface reflection ghost and another one is polarization ghost. Inside the "pancake" optics, there are several components and air interfaces. Reflection at an unwished interface will occur and enter the pupil. On the other hand, polarization ghosts come from non-ideal polarization components such as axis shift of quarter waveplate [2]. During the fabrication of the bench top prototype, we investigated and solved the ghost issue as it uses the pancake optics.

In this report, we discuss the analysis of the ghost in the benchtop prototype, which has "pancake" optics with holographic optics.

2 HMDs with Holographic Optics

In conventional HMDs, a bulk lens is used to generate a virtual image of an LCD. The lens is set apart from an LCD to create a large virtual image, and the bulk lens is thick. Thus, conventional HMDs need a thickness as shown in Fig. 1(a).

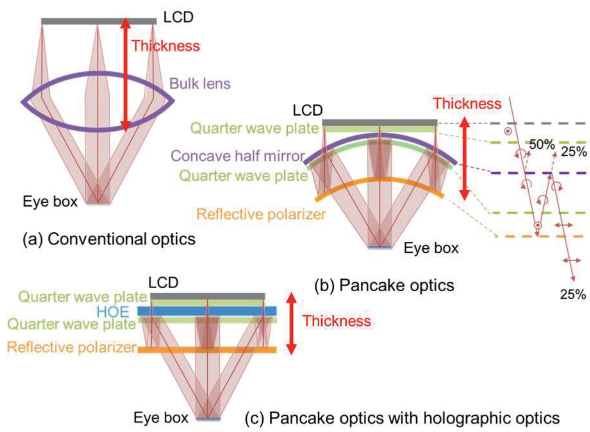


Figure 1. Pancake optics with holographic optics.

To reduce the thickness, polarization-based optical folding, or "pancake" optics was proposed. Figure 1(b) shows the basic concept of pancake optics. A gap is created between a concave half mirror and a reflective polarizer. The concave half mirror reflects 50% and transmits 50% of incident light. The reflective polarizer reflects light from one linear polarization while transmitting the orthogonal polarization. Quarter-wave plates are placed on an LCD and inside the gap.

In the pancake optics, light transverses as follows.

The first quarter-wave plate on the LCD converts parallel linear polarized light from an LCD to counterclockwise circular polarized light. The second quarter-wave plate converts the counterclockwise circular polarized light back to the parallel linear polarized light. The reflective polarizer reflects this linear polarized light, which is then converted to counterclockwise circular polarized light by the second quarter-wave plate. Then, the concave half mirror reflects half of the counterclockwise circular polarized light. The polarization of the reflected light is clockwise circular. Thus, the second quarter-wave converts it to orthogonal linear polarization and it passes through the reflective polarizer.

In the pancake optics, light traverses the length of the gap three times while occupying only the physical space of one gap length. This enables the LCD to be placed closer to the optics than in conventional optics. However, since the light transmits the concave half mirror twice and loses half of the light each time, the overall light efficiency is 25%.

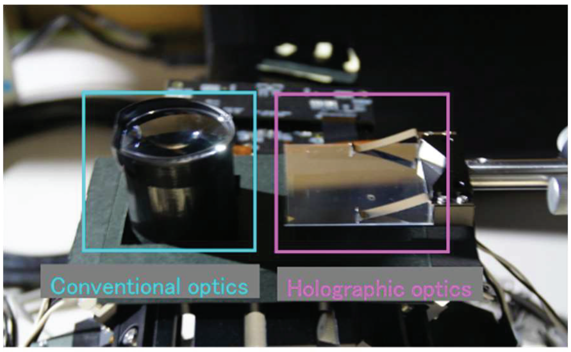
As shown in Fig. 1(c), the thickness due to bulk optics can be reduced by combining polarization-based optical folding and holographic optics, All the focusing power is performed by holographic optical elements (HOEs) rather than bulk optics. An HOE replaces the concave half mirror. HOEs consist of thin,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

In this way, HMDs with holographic optics reduce the thickness significantly. However, pancake optics sacrifice the efficiency, and holographic optics require a laser backlight whose efficiency is low. To improve the efficiency, we have applied a polarized laser backlight that enhances the light efficiency of a laser backlight LCD.

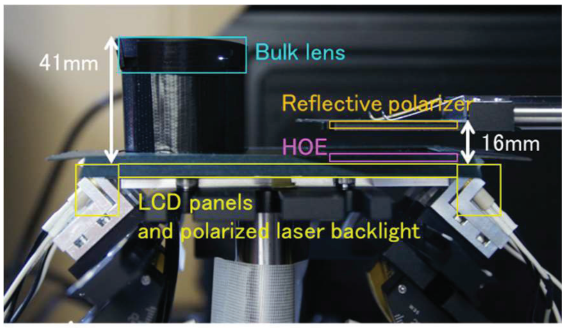
To confirm the feasibility of thin and lightweight HMDs with polarized laser backlight and holographic optics, we fabricated a monochrome prototype.

Figure 2(a) and (b) show the oblique and side views of the prototype, respectively. On the left LCD panel, we placed a conventional bulk lens, and on the right LCD panel, we used the pancake optics with holographic optics. The polarized laser backlight for both LCD panels was identical. The thickness of an LCD panel and backlight was 3 mm except the laser diodes aligned at the edge of the light guide plates. We used conventional laser diode with 9 mm diameter. The pancake optics with holographic optics consist of a quarter-wave plate, an HOE, a quarter wave plate, and a reflective polarizer on the LCD in this order. The distance between the LCD surface and the top of the bulk lens was 41 mm, while the distance between the LCD surface and the top surface was only 16 mm. The thickness was reduced significantly. The weight was also reduced by replacing the bulk lens with a flat HOE film.

As shown in Fig. 3, a volume phase hologram was recorded in the HOE using two-beam interference. Photopolymer film was irradiated using a object beam and a reference beam from each side. The object beam was created using the same bulk lens as in the prototype. A green laser with 532 nm wavelength was used for recording so that the prototype operated only for green. When the green light impinges onto the HOE, it operates as a concave mirror and reflected light converges on the focus. In the polarized laser backlight, green laser diodes with 530 nm wavelength were used.



(a) Oblique view



(b) Side view

Figure 2. Fabricated benchtop prototype.

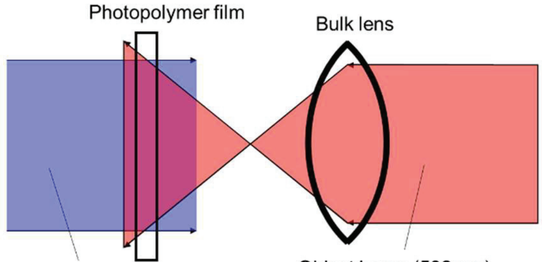
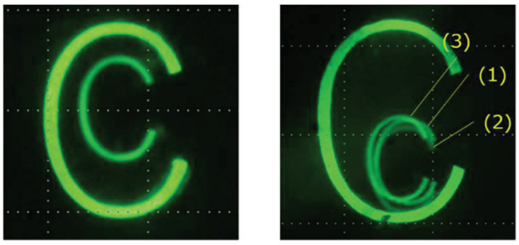


Figure 3. HOE fabrication.

3 Experiments

We observed the virtual image of the prototype when a letter “C” is displayed on an LCD panel. Figure 4(a) show the virtual image of prototype when it was observed from the normal direction. The desired magnified image and the ghost were observed. The size of the ghost was close to that of the image of “C” on the LCD panel. To investigate the ghost, it was observed from an oblique direction. The results are shown in Fig. 4(b). The ghost is divided into three images: ghost (1), (2), and (3). It is presumed that the ghosts occur by three different causes.

To clarify the causes of these ghosts, we observed the images with anti-reflection (AR) film attached on surfaces (A), (B), and (C) as shown in Fig. 5.



(a) From normal direction. (b) From oblique direction.

Figure 4. Observed images of the prototype.

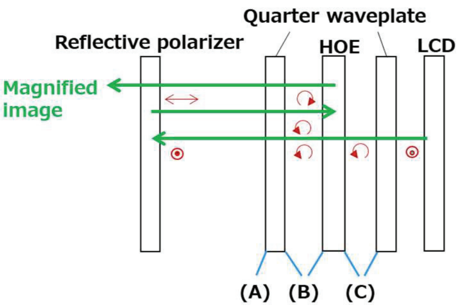
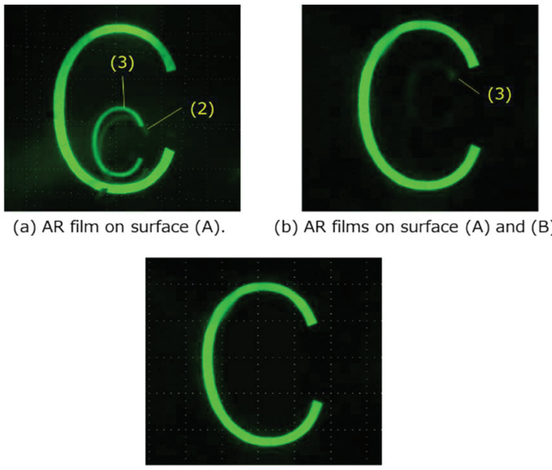


Figure 5. The attached surfaces of AR film.

4 Results and Discussions

Figure 6 (a) shows the observed image when AR film was attached on surface (A). Ghost (1) disappeared while ghost (2) and (3) still existed. Figure 6 (b) shows the observed image when AR films were attached on surfaces (A) and (B). Ghost (1) and (2) disappeared while ghost (3) still existed. Figure 6(c) shows the observed image when AR films were attached on surfaces (A), (B), and (C). All ghosts disappeared and only magnified image was observed.

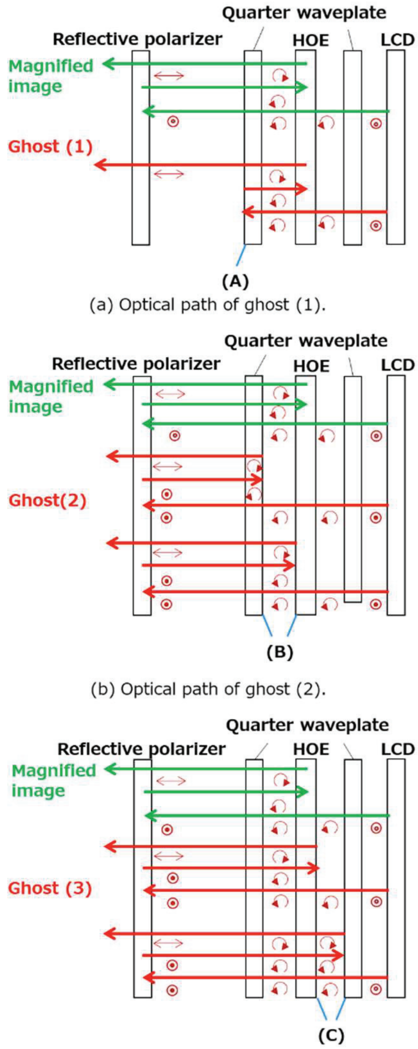
From these results, it is considered that these ghosts are generated by the following three optical paths as shown in Figs. 7 (a), (b), and (c). Ghost (1) is caused by the reflection on surface (A) before reaching the reflective polarizer as shown in Fig. 7 (a). The optical length between the LCD panel and HOE is shorter than desired optical path. Therefore, the image of ghost (1) is smaller than the designed virtual image. Ghost (2) is caused by the reflection on surface (B). The light is not reflected by the HOE as shown in Fig. 7 (b). Therefore, the image is not magnified and the image of ghost (2) is almost the same size as that of an original image on the LCD panel. Ghost (3) is caused by the reflection on surface (C). The light is not reflected by the HOE as shown in Fig. 7 (c). Therefore, the image is not magnified, either. The image of ghost (3) is also almost the same size as that of an original image on the LCD panel.



(a) AR film on surface (A). (b) AR films on surface (A) and (B).

(c) AR films on surface (A), (B) and (C).

Figure 6. Observed image when AR films were attached.



(a) Optical path of ghost (1).

(b) Optical path of ghost (2).

(c) Optical path of ghost (3).

Figure 7. Optical path of Ghost.

Based on the above analysis, we suppressed the ghost in the prototype. Figure 8(a) and (b) show the virtual images of LCDs through developed holographic optics, and conventional optics, respectively (see Fig. 2). A clear virtual image with the same magnification as that through conventional optics was observed through developed holographic optics. We did not observe any ghost.

5 Conclusion

We analyzed the ghost of the fabricated bench prototype of a head-mounted display with holographic optics and a polarized laser backlight. We observed the ghost whose size is smaller than that of a desired virtual image. Based on the analysis, we found that three ghosts were overlapped with almost the same sizes. The ghosts of our prototype are caused by the surface reflections at the quarter waveplates and HOE. We realized a clear virtual image without a ghost in the developed prototype by suppressing the surface reflection of the quarter wave plates and HOE.

6 References

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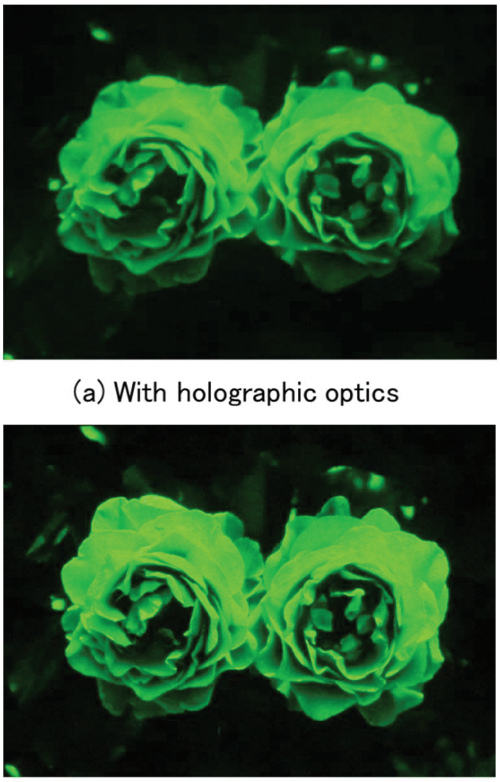

(b) With bulk lens

Figure 8. Observed virtual images without ghost.