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A Practical See-Through Head Mounted Display Using a Holographic Optical Element

Ichiro KASAI*, Yasushi TANIJIRI, Takeshi ENDO and Hiroaki UEDA
Optics Technology Division, Minolta Co., Ltd., 1-2, Sakura-Machi, Takatsuki, Osaka, 569-8503 Japan

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This paper describes a practical method for design and fabrication of holographic optical elements (HOEs) as off-axis imaging optics. The authors have designed and fabricated a compact glass-like and see-through display using HOE and a total internal reflection prism. Observers can see through the display because wavelength selectivity of the HOE provides high transparency. Wave front of the HOE is designed by commercial software, though the actual fabrication method is not provided. The authors propose a practical method to fabricate HOEs, which can be applied to a wide range of imaging optics.

Key words: holographic optical element, head mounted display, off-axis optics, wearable computer, see-through display

1. Introduction

See-through type head mounted displays (HMDs) have been reported. One of the conventional optics to combine a displayed virtual image and a real image from the scene in front of the observer is a half mirror.[1] The half mirror not only reduces brightness of both virtual and real images by half but also requires a large optical path to combine the two images. See-through displays using Maxwellian view are also reported.[2] Maxwellian view display should be illuminated by a point light source such as a laser to prevent blurring of the image. The light source and the exit pupil should be conjugate, so that the exit pupil has essentially no area. Another see-through type display uses a pair of prisms that has asymmetrical or free-form surface. Optics used in this type has negligible loss of brightness because total internal reflection in the prism is applied, but the thickness is rather large.[3]

Holographic optical elements (HOEs) are well known for their useful function of wavelength selectivity and wave front reproduction. HOEs are used for head up displays as image combiner using the function of wavelength selectivity. Although other functions of wave front reproduction are not used, conventional systems require additional optics for imaging and/or correcting aberrations.

2. Optical Layout

A simple optical layout of HMD using an HOE is shown in Fig. 1. It comprises an imaging source that is usually a liquid crystal display (LCD) and an HOE that is recorded by an interference pattern of a converging beam and a parallel beam as shown in Fig. 2. The HOE combines the displayed image with a real scene, without reducing brightness of the virtual image and little loss of real image for its wavelength selectivity. Figure 3 shows the typical transmission spectrum of the reflection hologram. The profile shows the inverse of a narrow bandpass filter. Steep absorption of the green region is caused by diffraction of the hologram, but broad absorption of the red region is caused by absorption of the material. The spectrum from the image source corresponding to the bottom of the green in the figure is diffracted by the HOE to be displayed as a virtual image. Image quality: resolution, distortion and brightness is inadequate, however, it is difficult to correct aberrations by only one optics in such a steep angle layout. Diffraction efficiency of the HOE is not sufficient in this layout because the diffraction angle between the incident beam and the diffracted beam is large. Surface reflection loss is not negligible because the incident angle to the HOE is also large. Edge illuminating method is efficient to reduce the surface reflection loss but it comes greater color dispersion and has the disadvantage of reducing color aberration.[4]

Size, aberration and number of optical components are always a trade-off in optical design. The authors designed the optical layout of the display regarding the thickness of the optics as most important and found the simple optical layout shown in Fig. 4.[5] It comprises a light emitting diode (LED) as a light source, a condenser lens, an LCD and a prism on which an HOE is attached. The radiated light illuminates a transmission LCD through a condenser lens. The beam refracts into a prism from surface A. Next, the beam undergoes total internal reflection on surface B followed by total internal reflection on surface C followed again by total internal reflection on surface B. Finally, the beam reaches the HOE to be diffracted and guided to the exit pupil where it is magnified as a virtual image through prism surface B. The incident angles on surfaces B and C except the last path on B are designed so that the beam makes total internal reflection. Note that the HOE has a slanted angle to the optical axis. Clearly the HOE should possess asymmetric power to cancel the distortion caused by this de-centered optics.

The imaging function should have an asymmetric lens power to cancel aberrations and distortion of the total optical system so that the observer can see the virtual image correctly without additional optics.

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*E-mail: kasai@optec.minolta.co.jp

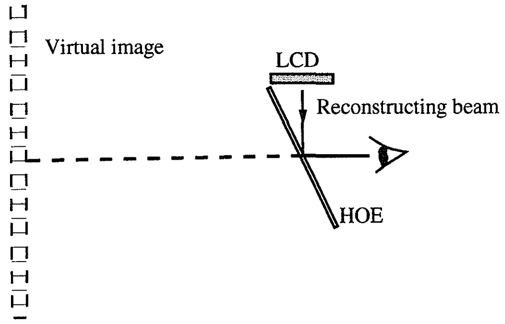

Fig. 1. Exposing optical layout of HOE.

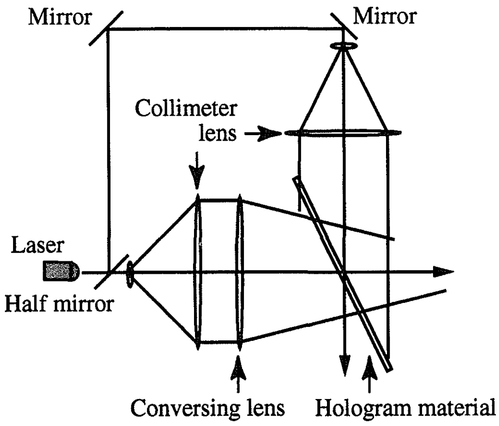

Fig. 2. Principle of HMD with HOE.

3. Design of the Holographic Element

A computer generated hologram is easily defined and calculated by recent fast computers if it is a surface hologram; it can be made by an electron beam drawing machine. A volume hologram that has narrow wavelength selectivity which is the essential function for see-through displays, however, must be fabricated by two-beam interference method. How to design and fabricate exposing optics that generates the desired wave front for the interference pattern is the key issue. The designing procedure of the HOE and the exposing optics is described below.

The first step is the design of the total optics including the HOE in use to optimize the conditions of image resolution and distortion, considering a thin prism, an LCD and so on. In this paper, "in use" means the condition in which the HOE is reconstructed by the beam from the image source and the observer can see the displayed image properly. Variables are set on the phase distribution function, position, de-centering and tilt of the HOE surface after determining the prism size. The two-dimensional phase distribution on the holographic surface is very complex for correcting aberration and distortion. The distribution is described by an X–Y polynomial expression, but never directly gives any information on how to design the exposing optics. The wave front needs to be rotationally asymmetric and aspheric to correct the aberrations properly.

The second step is the design of the exposing optics to produce the above required HOE. Generally, each beam comes from a spatial filtering pinhole with spherical wave front at recording a reflection hologram, but the wave fronts should be rotationally asymmetric and aspherical to correct the aberration and distortion of the off-axis optics. The schematic layout of the designed optics is shown in Fig. 5. This layout is conjugate to the layout in use because it is difficult to generate the desired beam through the prism. Birefringence in the acrylic prism might affect the contrast of the interference pattern when the beam goes through a long optical path. Thus the exposing optics can be considered as the optics that converges a light from a point light source to another point through the HOE. In other words, designing the exposing optics is equivalent to getting the phase distribution function that satisfies the desired performance for each optics in use and at exposing. Note that the point light source and the observer's pupil should be on the same point. It is obvious that maximum diffraction efficiency is obtained when the reconstruction light comes from the same point which the expos-

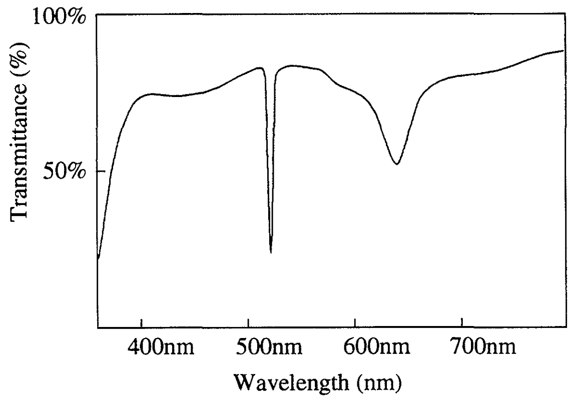

Fig. 3. Transmission spectrum of HOE.

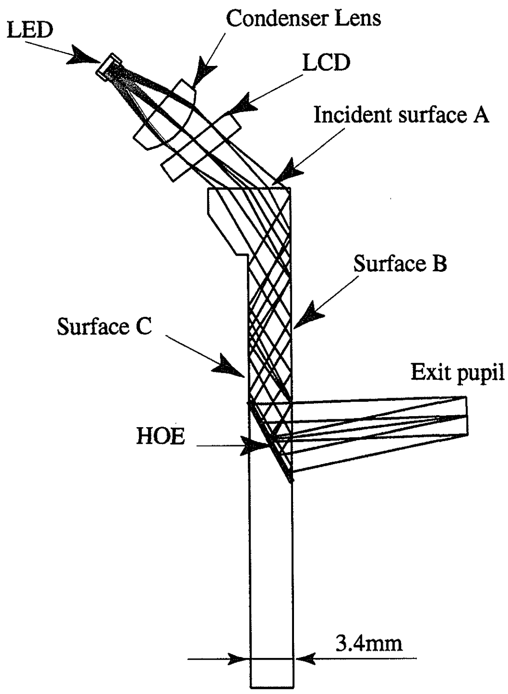

Fig. 4. Optical layout of the experimental HMD.

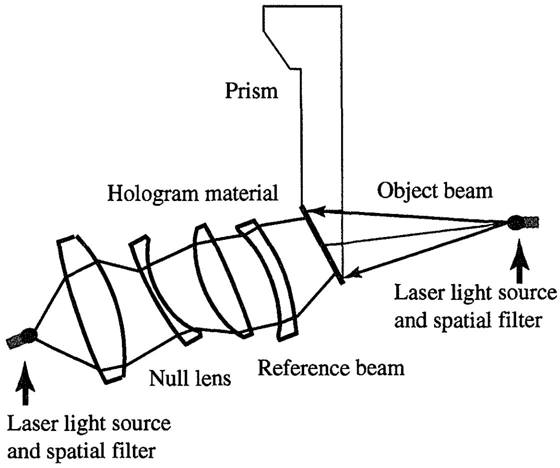

Fig. 5. Exposing optical layout of the experimental HOE.

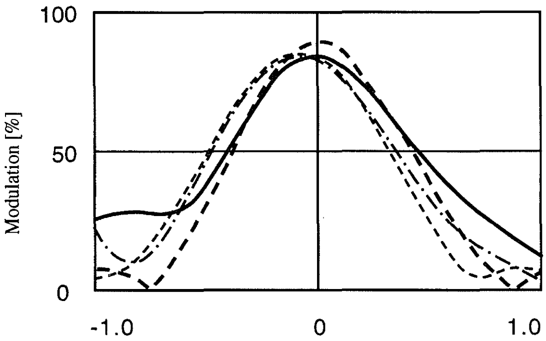

Fig. 6. Modulation transfer functions of the HMD. ——, Center (Y); – – –, Center (X); — · —, Corner (Y); · · · · · ·, Corner (X).

ing light came from. Locating the pupil and the light source as described above means that enough brightness can be obtained over the entire displayed area. Considering the pupil of the observer, the system can be extended easily to enlarge the field of view and pupil size. Also, note that the condenser optics designed in this step cannot make a complete point image in a strict sense because it has aberrations to some degree.

The last step of the procedure is to revise the exposing optics. The remaining aberrations mentioned above lead to deterioration of image quality if they are used. To obtain a well-corrected image, the optics should be revised by ray tracing. It takes much time to trace all the light rays that reach the local points of the HOE surface. However, using the ray tracing method the phase shift distribution function at a local point of the holographic surface can be defined as an interference pattern produced by two point light sources.

Using this procedure, we successfully designed the exposing optics shown in Fig. 5, consisting of several spherical lenses that are arranged in an off-axis layout to correct the aberrations and distortion. Figure 6 shows the MTF (modulation transfer functions) plotted by defocusing at the spatial frequency of 16 cycles/mm. Modulations at the center and the corner of the displayed image are plotted by the solid and broken lines respectively. Horizontal and vertical fields of view

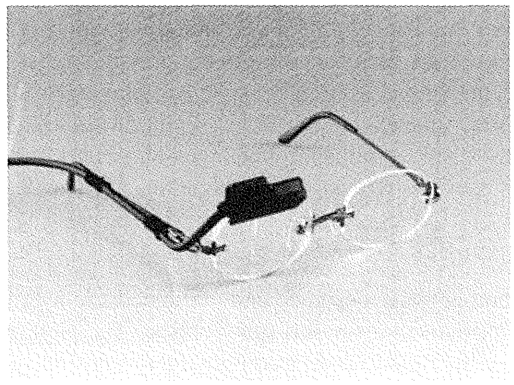

Fig. 7. Prototype of HMD.

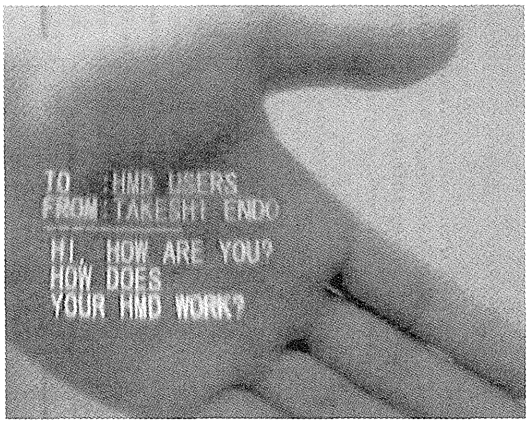

Fig. 8. Virtual and see-through image.

(FOV) are 27 deg and 10 deg respectively, while the pupil is 3 mm diagonal. The thickness of the prism is 3.4 mm, which can be reduced to 2 mm if 7 deg of the vertical FOV is accepted at the same angular resolution.

4. Experiments

The HOE is recorded as a refractive index modulation throughout the holographic material by exposing two wave fronts opposite each other, as shown in Fig. 5. All the optics are laid out on an air insulated table. The light source is a Nd:YVO4 laser (SHG, rambda is 532 nm). An LED that has the emission peak of wavelength at 520 nm is selected for the reconstruction light source considering the wavelength shift of the HOE. It is known that holographic material shrinks to some degree after exposure and processing and the wavelength peak of diffraction efficiency becomes shorter. Photo polymer that was used in this experiment shrinks around 2% which corresponds to the wavelength change of 532 nm to 520 nm.

The prism having the HOE on a surface is assembled with an LCD, an LED and housing to a display unit. The LCD has a 0.25 inch diagonal with resolution of 320 $\times$ 240 pixels (QVGA). Though HOE has 27 by 10 deg of FOV, a commercial LCD has an aspect ratio of 4 to 3. The LCD is laid out in the center of the FOV, which limits the FOV of the actual virtual image 13.4 by 10 deg.

Finally, the display unit is assembled with an acrylic plate having a hollow corresponding to the prism. Figure 7 shows an overview of the prototype display. Total weight of the display is only 25 g excluding cables. Figure 8 shows an example of the displayed image. Displayed characters and a hand through the glass type display are both clearly visible.

5. Conclusions

The authors have designed and fabricated a reflection HOE in a thin prism as a small display optics. The HOE has two characteristic functions, as a combiner and a positive powered mirror. We have made positive use of the aberration correcting function of the HOE. The prototype described in this paper is a monochrome display, but a color display using multi-color HOE and three LEDs can be made by the same principal. The design method proposed in this paper is available practically for many kinds of optics. The compact lightweight display we propose is highly suitable for mobile or wearable appliances.

References

1) Y. Ohta and H. Tamura: *Mixed Reality* (Ohmsya, Tokyo, 1999) p. 31.
2) G. Westheimer: Vision Res. **6** (1966) 669.
3) S. Yamazaki, K. Inoghchi, Y. Saito, H. Morishima and N. Taniguchi: Proc. SPIE **3639** (1999) 453.
4) H. Ueda, E. Shimizu and T. Kubota: Opt. Eng. **37** (1998) 241.
5) I. Kasai, Y. Tanijiri, T. Endo and H. Ueda: *Proceedings of the 2nd International Conference on Optical Design and Fabrication (ODF2000)* (2000) p. 117.