**INP2-2**
***Invited***

# Holographic Contact Lens Display

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Keywords: Smart contact lens, contact lens display, AR, holography

## ABSTRACT

*The holographic technique is used to realize contact lens displays. Hologram patterns are displayed on a display device embedded in a contact lens and three-dimensional (3D) images are produced apart from eyes so that eyes can focus on the 3D images. Phase-only holograms are displayed to enable the see-through function.*

## 1 Introduction

Augmented reality (AR) devices have the potential to replace smartphones. Recently, the developments of AR head-mounted displays and AR glasses have been accelerated. The contact lens display [1, 2] is an ultimate AR device because it provides clear vision without any obstacles. The contact lens display can also be used for the enhancement of human vision. The smart contact lenses for health monitoring have also been developed [3, 4]. However, there are many issues to be solved to realize the contact lens displays. We have adopted the holographic technique to address the image formation problem [5]. The use of holographic technique enables the production of visual information at the same distances as real objects.

## 2 Principle

When a display device is embedded in a contact lens, as shown in Fig. 1(a), the lens of the eye cannot focus on the display screen due to its close proximity to the eye. To address this problem, previous techniques have added micro optical elements to all display pixels and cancel the lens power of the eyes, as shown in Fig. 1(b) [1, 6]. In this study, we propose the use of the holographic technique to enable the eyes to naturally focus on the produced images. As shown in Fig. 1(c), a display device embedded in a contact lens displays hologram patterns, which generate a wavefront emitted from three-dimensional (3D) images located far from the eyes. Thus, the eyes can focus on the 3D images.

Figure 2 illustrates the optical system of the holographic contact lens display. The thin laser backlight employing a holographic optical element (HOE) emits horizontally polarized laser light to illuminate the phase-only spatial light modulator (SLM) which displays phase-only holograms, i.e., transparent holograms. The phase-only SLM modulates the phase of the horizontally polarized light. The polarizer transmits the vertically polarized light from the outer scene, which is not modulated by the SLM. Because of the wavelength selectivity of the HOE, the HOE backlight has high transmittance for light from the outer scene. The phase-only SLM also has high transmittance because it does not modulate the amplitude of light.

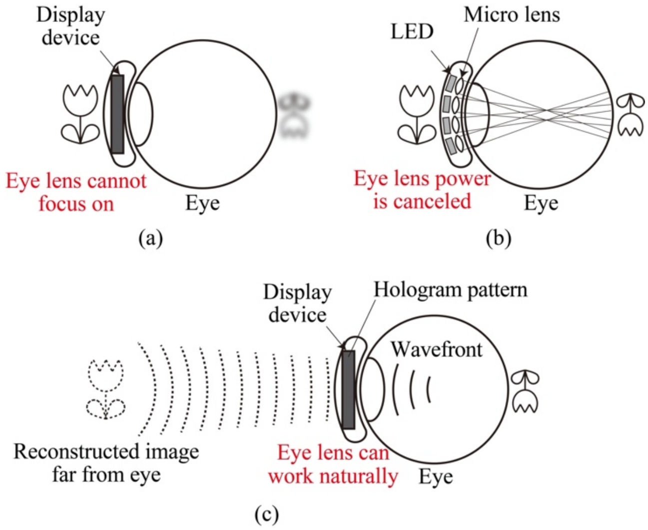



**Fig. 1 Concept of holographic contact lens display: (a) problem, (b) conventional solution, and (c) proposed technique**

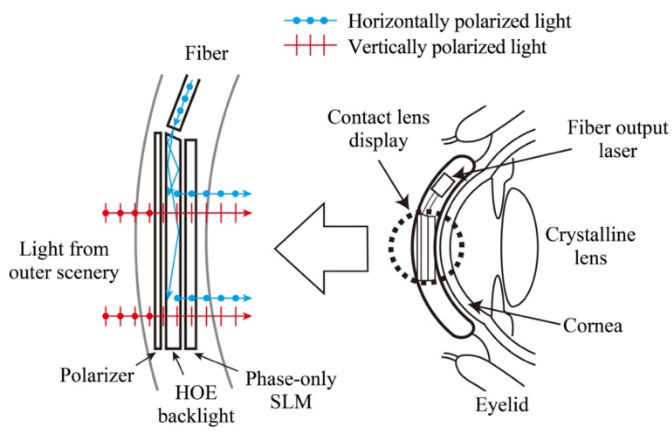



**Fig. 2 Structure of holographic contact lens display**

## 3 Experimental Verification

The proposed technique was verified using a bench-top experimental system. A transmission-type twisted nematic liquid-crystal SLM (TN-SLM) was used as the phase-only SLM. A photopolymer was used as the HOE material for the laser backlight. Figure 4 shows the constructed experimental system. Because the TN-SLM modulates the phase of circularly polarized light, a quarter-wave plate (QWP) was inserted in the experimental system.

Figure 8(a) shows the retinal image obtained when the reconstructed image (characters “ar”) was produced at a distance 1,500 mm from the TN-SLM, and Fig. 8(b) shows the retinal image obtained when the reconstructed image (characters “AR”) was produced at a distance of 2,000 mm. Two real objects, a toy deer and toy car, were placed at distances of 1,500 mm and 2,000 mm, respectively. The two objects were observed through the experimental system. In Fig. 8(a), the focus of the camera was at a distance of 1,500 mm, so both the characters “ar” and the toy deer were observed without blur. In Fig. 8(b), the focus of the camera was at a distance of 2,000 mm, so the characters “AR” and the toy car were observed without blur.

## 4 Miniaturization of devices

The possibility is discussed of implementing the proposed optical system into contact lenses. Particularly, the thicknesses of the optical devices are considered because typical contact lenses can have a thickness of as little as approximately 0.1 ~ 0.2 mm.

When a liquid-crystal SLM is used for the phase modulation, it comprises a liquid-crystal layer and transparent electrodes. The liquid-crystal layer for the phase modulation is several microns thick, and the transparent electrodes have a thickness of less than one micron. The implementation of the liquid-crystal display in the contact lens was demonstrated in [2]. Thus, the phase-only SLM could be implemented in contact lenses.

The photopolymer is several microns thick. The use of multiple total internal reflection inside the waveguide enables a thin backlight. Recently, waveguides used for AR glasses that are ~1 mm thick and several tens of millimeters long have been developed. The scaling law can be applied because the total internal reflection is used. As the length of the waveguide used for the proposed optical system is several millimeters, a waveguide with a thickness of ~0.1 mm might be possible as a result of a simple consideration.

The typical thickness of the polaroid polarizer used for liquid-crystal displays is approximately 30 μm. When the wire-grid polarizer is used, the thickness is several microns. Therefore, the polarizer can be incorporated into contact lenses.

Regardless of whether the edge-emitting laser diodes or the vertical-cavity surface-emitting lasers are used, their thicknesses can be made to be less than 0.1 mm. They can, therefore, be incorporated into contact lenses. The integration of LEDs into contact lenses was demonstrated in [1, 7, 8].

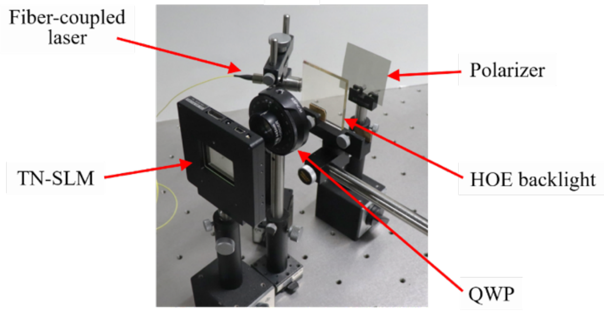
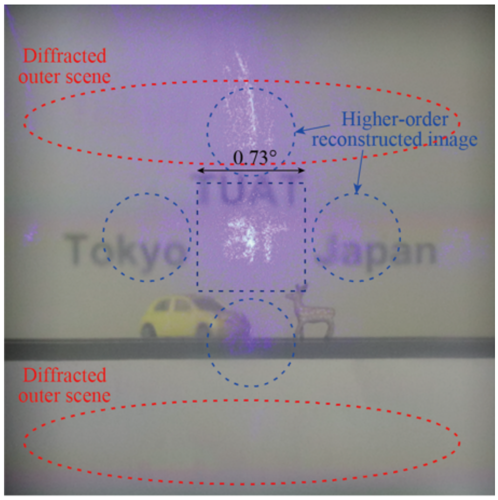



**Fig. 3 Constructed bench-top experimental system**




(a)


(b)

**Fig. 4 Captured see-through images: focus at (a) 1,500 mm, and (b) 2,000 mm**

## 5 Conclusions

The image formation technique for the contact lens displays using transparent holograms and its experimental verification are explained.

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