Slim Holographic Retina Display Based on Holographic Waveguide

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ABSTRACT

In this paper, we propose a slim system for holographic retina display on the basis of holographic waveguide and holographic optical elements (HOEs), promising in augmented reality (AR) system. By attaching the spatial light modulator (SLM) to the waveguide directly, we decrease the form factor of the AR system greatly.

1 INTRODUCTION

See-through near-eye display (NED) gives people an immersive experience in virtual world and allows prospective human-computer interaction in both virtual reality (VR) and augmented reality (AR) utilization. In particular, AR utilizing NED brings the virtual scenes directly to people's eyes, i.e., retina display. As a result, near-eye display in augmented reality system has been attracting more and more interest due to its diverse applications in military, healthcare, and entertainment areas during the last decades [1].

In order to provide as realistic three-dimensional (3D) scenes as possible, several factors should be taken into account in augmented reality using NED, including spatial resolution, occlusion, natural depth cues, wide field of view (FOV) as well as small form factor. Hence, a lot of researches considering these items have been implemented to promote the development of retina display systems [2-8]. The conventional NEDs tend to apply stereoscopic display with fixed focus to show two-dimensional (2D) images or 3D scenes by rendering parallax images in two eyes. However, stereoscopic display will result in the mismatch between convergence and accommodation, which may then cause severe visual fatigue [6]. Consequently, in recent years, there are some other technologies such as holographic display, volumetric display, light field display, and so on, being proposed to improve the vergence-accommodation conflict (VAC). Generally, among these different technologies, holographic display seems to be the hottest research direction on account of its effective elimination of VAC [9].

Holographic display employing liquid crystal on silicon (LCOS) spatial light modulators (SLMs) is most prevalent in recent years. To present 3D scenes with natural depth cues, the computer generated holograms (CGHs) are loaded on the SLM and the amplitude or the phase information will be modulated. Then, the accurate wave front of the objects to be displayed can be reconstructed and delivered like a “ghost image” to the observers’ eyes directly [8,10]. Thus, holographic display removes the VAC problem effectively.

In spite of various advantages of holographic display, its bulky optical setup and the restricted diffraction angle of SLMs [11] make it hard to be in widespread use in AR NED system. In other words, it is difficult to solve the trade-off between the small volume and the wide FOV. Recently, many researchers prefer to use holographic waveguide and holographic optical elements (HOEs) to balance this problem [1,3,6,7,12-14]. For example, in [3], a dual-focal waveguide NED with a compact structure and good depth cues is proposed. A group from Inha University designed a head mounted display employing two HOEs attached to a waveguide in 2015, promising a small form factor in NED system [13]. Besides, Jiasheng Xiao put forward a new achromatic surface microstructure for NED with his team in 2019 [7].

Holographic waveguides are lightweight, flexible and highly transparent, which is very attractive for NEDs. Meanwhile, according to the coupled wave theory [15], HOEs have the angular selectivity and the wavelength selectivity, which allows them to perform as optical elements only when the incident light has particular incident angle and wavelength, making them the excellent components for see-through displays. However, in the existing holographic waveguide-based NED scheme, the waveguide is externally connected to the SLM imaging system or other micro-display projection system, which makes the total volume of the optical system hard to be reduced. Hence, we designed a system to ameliorate this issue.

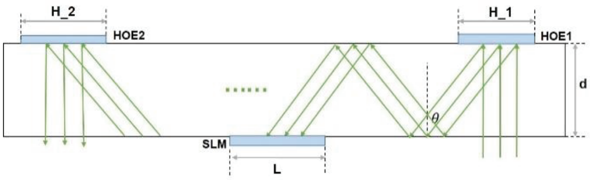
In this paper, we put forward a slim retina display system adopting the holographic waveguide with two HOEs and an a SLM attached to its two opposite sides, respectively. Section 2 describes our basic design scheme and emphasizes the key innovation. Then, Section 3 proves the effectiveness of the proposed design by presenting the experimental results. In general, this design benefits the development of AR NED applications, providing a new method to reduce the form factor.

2 METHOD

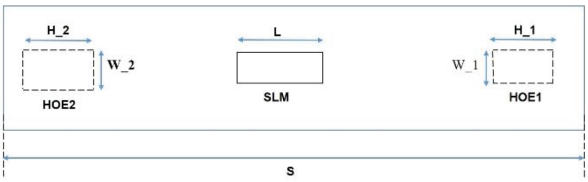
As mentioned above, holographic display is excellent for AR system because of its great ability to eliminate the

VAC. However, the necessity of employing optical instruments in projecting images and the narrow FOV caused by the limitation of SLM's diffraction angle make it not suitable for AR NED system. For that reason, we adopt holographic waveguide as well as HOEs, which are known as great optical elements for holographic display in AR NED system [13,14].

The basic structure is presented in Fig.1. Our design consists of a slab waveguide, two reflective volume holographic gratings (VHGs, i.e., HOEs) and a spatial light modulator. Fig.1(a) and Fig.1(b) represent the pictures of the designed structure of the holographic waveguide observing from two different views. As shown in Fig.1, the two HOEs are attached to the planar waveguide on the same side. At the same time, the SLM are adhered to the waveguide on the opposite side, resulting in the removal of restriction of small viewing angle in holographic display due to the fixed position between eyes and the SLM [12]. Besides, the in-coupler VHG is smaller than the out-coupler VHG to promise enough area of the exit pupil [14].



(a)



(b)

Fig. 1 Basic structure of proposed design. The widths and lengths of HOEs are W_1, W_2, H_1, H_2, respectively. Note that HOE2 is larger than HOE1 both in width and length. The parameter "d" and "S" represents the thickness and length of the waveguide. "L" means the SLM's length.

As Fig.1(a) shows, the light emitted from the light source is incident on the waveguide and extracted by HOE1 with the diffraction angle of θ. The light beam propagates in the waveguide by total internal reflection with the reflection angle θ, as well. In addition, the way by which the SLM is attached to the waveguide promises that the propagating light in the waveguide can illuminate the SLM directly. As a result, the CGHs loaded on the SLM can be modulated effectively. Then, the light is out-coupled by HOE2, finally reaching the observer's eyes through a lens, imaging on the retina. Furthermore, in case of more than one modulation on SLM, the following formula must be satisfied:

$$\mathrm{L} < 2\mathrm{d}\tan\theta \qquad (1)$$

Where L is the length of SLM, d is the thickness of the waveguide and θ is the total internal reflection angle.

By use of these optical elements, the form factor of the retina display system becomes more compact and the limitation of FOV is relaxed as well, balancing the trade-off well. Note that there have been a lot of similar waveguide-type AR NED systems [7,13,14]. However, none of them attached the SLM to the waveguide directly, so that is the strong point in this paper.

3 EXPERIMENT & RESULTS

In this section, the validity of the proposed compact design for holographic retina display system has been verified experimentally. In our optical experiment, the reflective volume gratings were recorded on the photopolymer to make the in-coupling and out-coupling HOEs. Those two HOEs were attached on the plat waveguide in advance, corresponding to a laser with the wavelength of 532nm. Fig.2 presents the 2D schematic diagram of our proposed retina display system and the real optical experiment setup is shown in Fig.3. As Fig.2 shows, HOE1 had a smaller area than HOE2. The distance between the two HOEs was about 80mm. In addition, the length, the width and the thickness of the waveguide was 120mm, 30mm, 5mm, respectively. The SLM (Smartvision Co., China, SLM-100) that we employed was a reflective phase-type LCOS SLM with the resolution of 1920×1080 and the pixel pitch of 6μm.

In addition, the polarizer was used to achieve the best effect of the SLM's modulation. The total internal reflection occurred after the light being diffracted by HOE1. There were 12 reflections between HOE1 and HOE2 with the reflection angle of 60° in all. Note that in the middle of the waveguide, the light exited and then irradiated onto the SLM. Accordingly, the CGHs loaded on the SLM would be modulated well, after which the light would be reflected into the waveguide again. Similar to [12], due to the oblique incidence of the light on SLM, we chose the Fourier hologram in the experiment to prevent being influenced by the potential strong inter-pixel cross-talk of the SLM. The traditional Gerchberg–Saxton (G-S) iterative algorithm were selected to obtain the phase-type hologram. For imaging, a lens with the focal length of 250mm was employed.

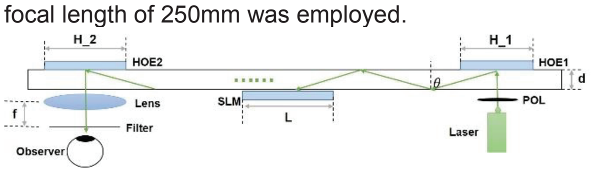


Fig. 2 Schematic diagram of optical experiment

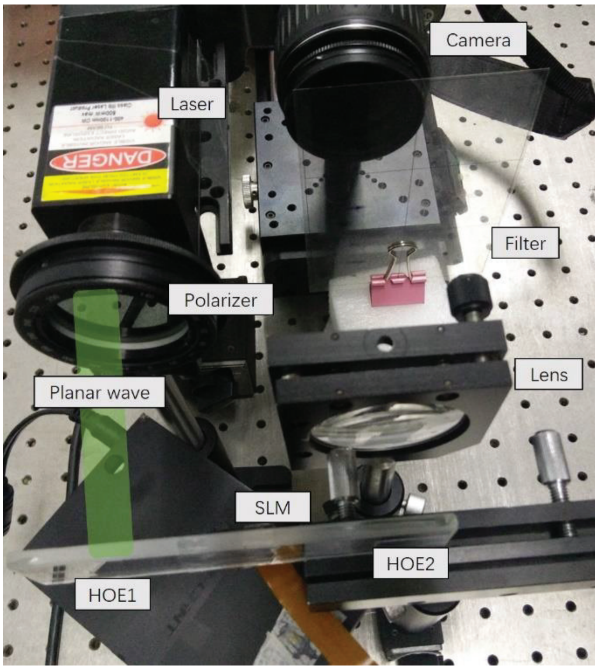


Fig.3 Setup of optical experiment

The result of the optical experiment presented in Fig.4 has verified the ability of our design to project virtual images to the observer's retina directly. The reconstructed image of the 'Dice' in Fig.4(a) was captured by the camera (Canon EOS700D). As Fig.4(b) shows, there was a dark dot in the middle of the reconstructed image which was resulted from the DC filter. In order to remove the zero-order DC noise, a DC filter which was made of black spot on a transparent film was put at the focal plane of the lens, resulting in a dark dot in the reconstructed image.

Although the result of the optical experiment has validated the meanings of the proposed system and proved it possible to be adopted in AR NED systems, the quality of the captured reconstructed image is not quite good, including many poor features. Due to the technological limitation in the fabrication of the HOEs and the way to attach the HOEs to the waveguide, there existed a lot of stray light in Fig.4(b). Moreover, the CGH that loaded on the SLM was a simple hologram obtained from G-S iterative algorithm without any improvement.

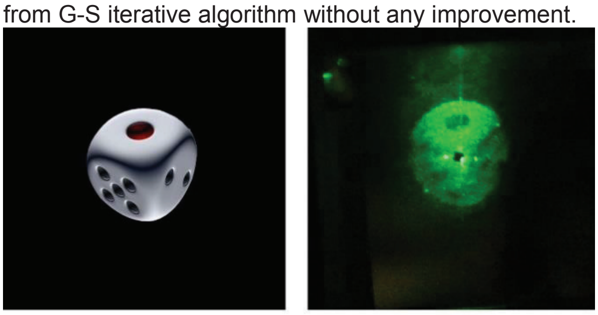


Fig.4 (a) Initial image 'Dice'; (b) Reconstructed image of (a) from the proposed structure

4 CONCLUSIONS

In this paper, we propose a slim structure for holographic retina display based on the holographic waveguide and holographic optical elements (HOEs), meaningful for AR NED systems. By attaching the spatial light modulator (SLM) to the waveguide directly, we decrease the form factor of the AR scheme greatly. The implemented optical experiments have proved the ability of the proposed design to display virtual images successfully.

However, in fact, the volume of the optical experimental setup in Fig.2 can be much smaller by changing the components attached on the waveguide. In our future work, we will attach the light source to the waveguide and make the out-coupling HOE act as both VHG and lens, further narrowing down the structure and making it more suitable for AR NED system. Besides, in order to achieve the virtual scenes with high quality, further research on improving algorithms and optical elements will be carried out to deal with the problems in image quality such as astigmatism, speckle noise, 0th-order diffraction light and so on.

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