Chromatic near-eye display with double-layer holographic waveguide configuration

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ABSTRACT

A double-layer holographic waveguide, which is made from the acrylate photopolymers, is proposed for the see-through augmented reality. The most significant contribution is the integration of ocular lenses into the waveguides. The waveguide design, imaging principle, optical simulations, and fabrication methods are introduced. In our experiments, a prototype with a diagonal field of view of 30° is demonstrated. Compared to other multi-layer waveguides, our solution could offer a more compact form factor, which is essential for wearable devices.

Keywords: augmented reality, near-eye display, holographic waveguide, acrylate photopolymer

1. INTRODUCTION

Recently, many researchers have studied the holographic waveguide structures [1–8], whose in-coupling and out-coupling optical elements are the reflection volume holographic grating (VHG) with mirror symmetry. Both of the in-coupling and out-coupling VHGs are laminated on the both surfaces of waveguide. The image exited from the microdisplay is firstly collimated by the collimation optical system, then diffracted into the waveguide, and finally enters the human eye [9]. The field of view (FOV) of the holographic waveguide configuration is dependent on the collimation optical system and the angular bandwidth of VHGs [2]. However, the wavelength and angle selectivity of VHGs is so high that limits the FOV of the holographic waveguide display system, which ranges from 10° to 20° [4,5]. For many years, the scientists have been seeking various solutions to increase the FOV, which is a key problem of the holographic waveguide display. Mukawa *et al.* (Sony) found that when the incidence axis closes to the grating vector, the Bragg selectivity of VHGs would become weaker, which can increase the FOV to some extent [1]. Han *et al.* (Beijing Institute of Technology) proposed and simulated a holographic waveguide using freeform lens as the in-coupling optical elements, and three reflective VHGs with different grating slanted angles and grating period arranged along the x-axis were used as the out-coupling optical elements, in order to realize splicing the horizontal FOV to reach 18° [10]. Similarly, Yu *et al.* (Zhejiang University) proposed a holographic waveguide structure, whose both in-coupling and out-coupling optical elements are space-variant reflection VHGs [11]. The experiment result shows that the horizontal FOV can be expended to 20°, the vertical FOV can be expanded to 6°. Wu *et al.* (Shanghai Jiao Tong University) investigated the multiplexed VHG structure to expand the angular bandwidth, which even has five different grating periods and slanted angles [2]. However, this will be a big challenge to the refractive index modulation of holographic materials and exposure process, when recording five different VHGs with high diffraction efficiency at the same time [12]. In this paper, instead of using the grating as the out-coupler, a holographic lens will be adopted in the out-coupling region.

2. DOUBLE-LAYER WAVEGUIDE

2.1 Proposed configuration

In the proposed double-layer waveguide configuration, reflective red (R) + green (G) and blue (B) VHGs are used as the in-couplers of the waveguide, while reflective R+G and B holographic volume lenses (HVLs) are used as the out-couplers, as shown in Fig. 1. The input full-color images pass through the collimation lens into enlarged inverted real images, then the enlarged images are diffracted into the waveguides by the reflective VHGs and propagate to the reflective HVLs on

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the out-coupling region of the waveguides through the total inner reflections. Finally, magnified virtual images will be formed by the HVLs.

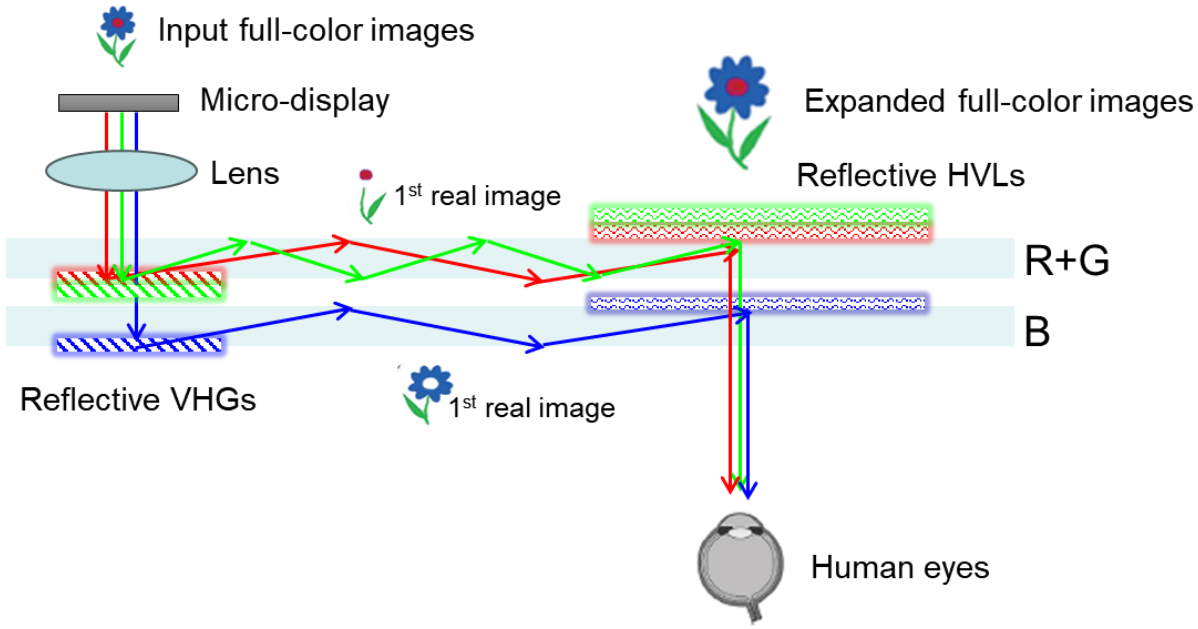


Fig. 1. Diagram of the proposed chromatic double-layer holographic waveguide configuration. VHG: volume holographic grating; HVL: holographic volume lens.

2.2 Imaging principle

Fig. 2 illustrates the imaging principle of the simplified optical path of our waveguide near-eye display. The original image y emitting from the microdisplay is firstly transformed as an inverted magnified image y′ when passing through the lens 1 (L1). Then, the inverted magnified image y′ is changed as the upright expanded virtual image y″, which can be observed at the distance x‴.

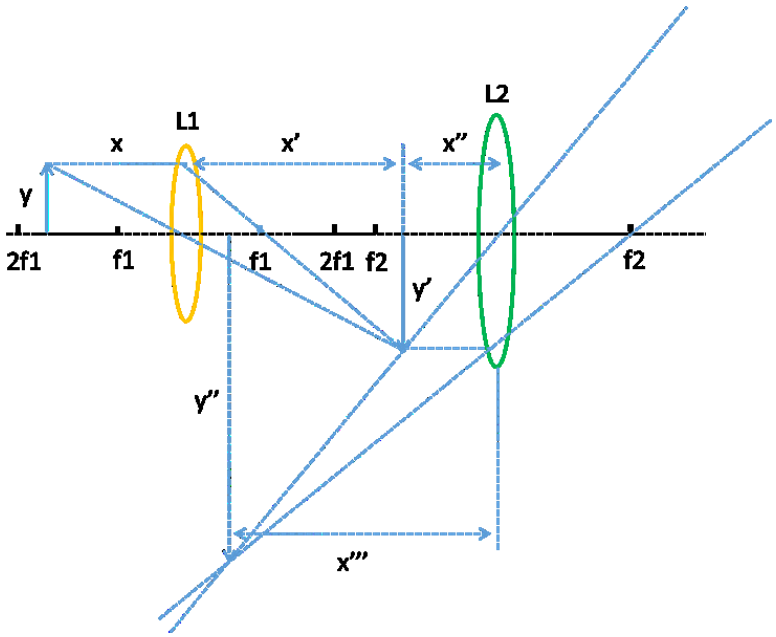


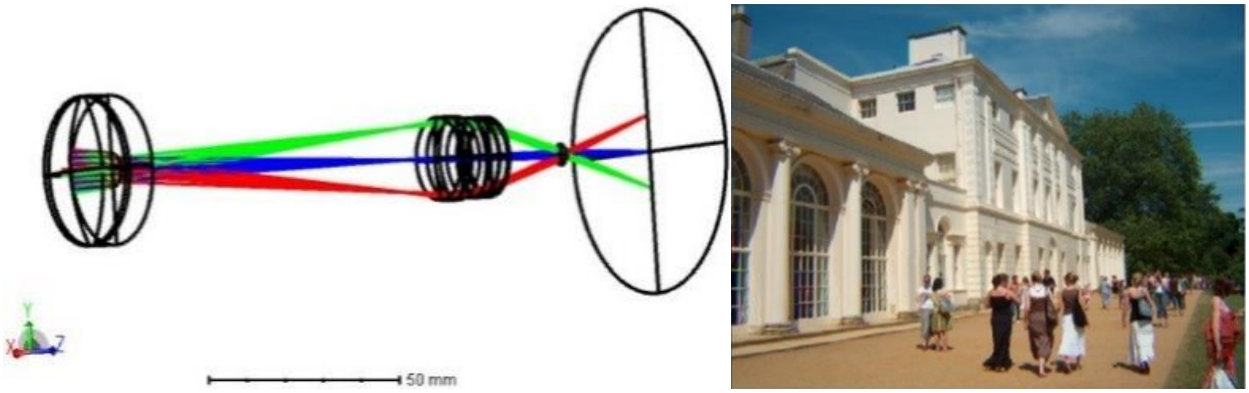
Fig. 2. Imaging principle of the simplified optical path of our waveguide display.

2.3 Optical simulation

Fig. 3(a) and Fig. 3(b) show the ray tracing diagram and the simulated image, respectively, which are obtained from the Ansys Zemax OpticStudio. Despite that the ocular lens or eyepiece is in fact a holographic lens, it is treated as a conventional lens because the Zemax is best at simulating the geometric optics. The detailed parameters of the object lens and ocular lens are provided in Table 1. The lens material is Schott K10. The refractive index at 639/532/457 nm is 1.4993/1.5043/1.5102. The diagonal FOV is 30°.

Table 1. Optical parameters of the object lens and ocular lens.

Parameter	Object lens	Ocular lens
Material	Schott K10	Schott K10
Refractive index at 639/532/457 nm	1.4993/1.5043/1.5102	1.4993/1.5043/1.5102
f1 (mm)	100	25
f2 (mm)	100	20
Diameter (mm)	40	40
FOV (degree)	30	30



(a) (b)

Fig. 3. (a) Ray tracing diagram, and (b) simulated imaging results.

3. EXPERIMETNAL RESULTS

3.1 Fabrication process

To substantiate our design, we fabricated the reflective VHGs and HVLs with the acrylate photopolymer and the interference exposure method [6,7]. The optical setup for exposure is plotted in Fig. 4. The R+G and B layers are recorded with the solid state lasers of 639/532/457 nm, respectively. The RGB laser beam separately passed and combined through the mirror M1 and dichromatic mirrors DM1 and DM2, then entered the spatial filter SF after reflecting form the mirror M2. The combined laser beam was expanded by SF, then collimated by the lens L. The size and shape of collimating beams can be adjusted with the aperture A. The polarization splitting prism is used to divide into two beams. The half wave plate H4 is used to ensure the polarization states of the two beams are both s-polarization light. The exposure dosages for the R+G VHGs and HVLs were both set as 200 mJ/cm^2, the blue VHGs and HVLs were set as 25 mJ/cm^2. Then the recorded R+G and B holographic plates should be placed for 5 minutes in the dark room to ensure enough time for the dark reaction. After the dark reaction, the photo-initiators in the holographic plate are consumed. For fixing the periodic structure of the HOEs that has formed, the 10 minutes baking at 100 °C temperature and 5 minutes of ultraviolet (UV) flood curing process should be added. After the post-treatment process, the diffraction efficiency of the prepared R+G and B VHGs and HVLs can all reach 90%. Finally, the fabricated R+G holographic waveguide and blue waveguide are laminated together by the UV curing adhesive. To avoid the crosstalk, the R+G and B layers were kept apart with spacers for ensuring an air gap of 50 μm.

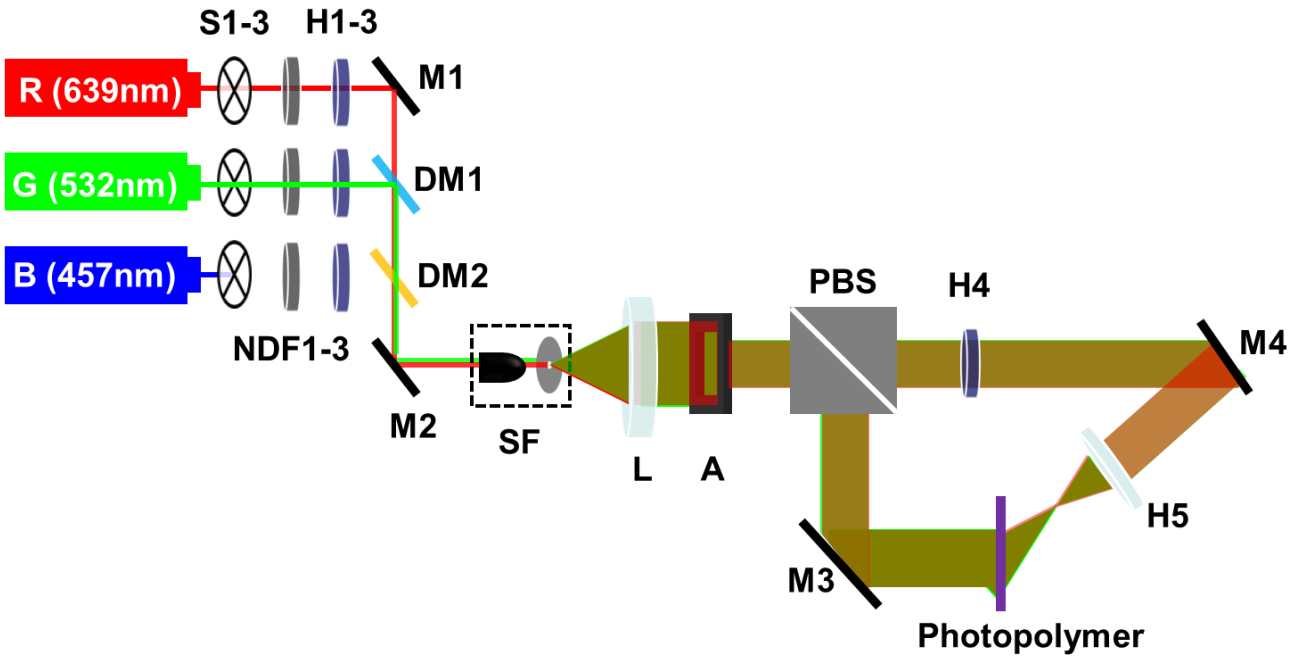
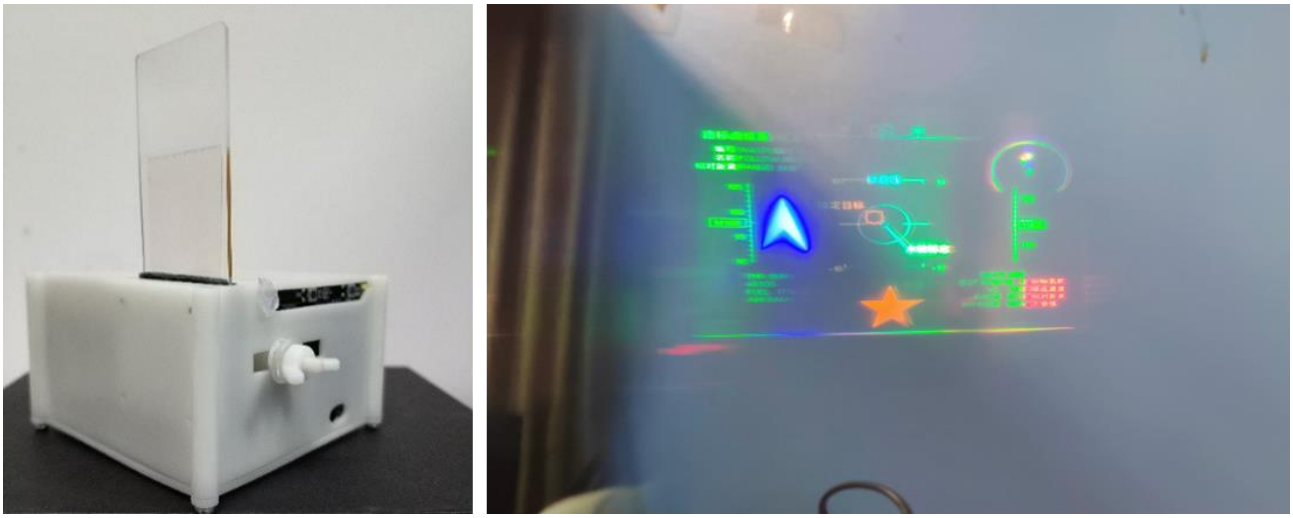


Fig. 4. Laser interference exposure method for fabricating R+G and B holographic waveguides. S: shutter; NDF: neutral density filter; H: half wave plate; M: mirror; DM: dielectric mirror; SF: spatial filter; L: lens; A: aperture; PBS: polarization beam splitter.

3.2 Prototype

To prove the feasibility of the proposed chromatic double-layer holographic waveguide, we fabricated a near-eye display prototype, as shown in Fig. 5(a). A fixture structure was designed to combine the double-layer waveguides at the exit pupil position of the liquid crystal on silicon (LCoS) microdisplay, where the in-coupling grating areas are precisely overlapped. In the out-coupling region of the waveguide, observers can see the images projected from the LCoS. The actual displayed images at the view point of the waveguide are captured by a fixed-focus camera. During the capture, the camera lens was positioned 18 mm away from the out-coupling HVL. The full-color images can be correctly displayed, as shown in Fig. 5(b). The black background in the original image becomes transparent in the displayed virtual image, allowing observers to see the surrounding environment unobstructed through the waveguide, as shown in Fig. 6.



(a) (b)

Fig. 5. Photos of the (a) fabricated prototype and (b) full-color images.

(a) (b) (c)

Fig. 6. Monochromatic images of (a) letter A, (b) letter B, and (c) letter C.

4. CONCLUSIONS

A chromatic double-layer holographic waveguide featuring the acrylate photopolymer has been investigated. The integration of the holographic ocular lens into the waveguide allows to further reduce the system size and weight. In our experiments, a prototype with a diagonal FOV of 30° is demonstrated. Compared to other multi-layer waveguides [13–16], our solution could offer a more compact form factor, which is essential for wearable devices. Compared to the liquid crystal-based holographic materials [17–21], the acrylate has the advantages of high sensitivity, low haze, low cost, better durability, *etc*.

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