Full-color lens-array holographic optical element for three-dimensional optical see-through augmented reality

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A novel system of optical see-through augmented reality (AR) is proposed by making use of a holographic optical element (HOE) with full-color and lens-array functions. The full-color lens-array HOE provides see-through property with three-dimensional (3D) virtual images, for it functions as a conventional lens array only for Bragg-matched lights. An HOE recording setup was built, and it recorded a 30 mm × 60 mm sized full-color lens-array HOE by using the techniques of spatial multiplexing for large-area recording and wavelength multiplexing for full-color imaging. The experimental results confirm that the suggested full-color lens-array HOE can provide the full-color 3D virtual images in the optical see-through AR system.

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Augmented reality (AR) is a technology that aims to provide a virtual image overlaid or superimposed onto a real-world scene through a display device [1]. AR has been actively studied so far and shown significant advancement in its research lately by virtue of the development of mobile devices, computer vision sciences, and display technologies [1–3]. There are two ways to display virtual images in AR by using a monitor-based display or an optical see-through display [2]. In monitor-based AR, sight of a user is blocked by the display device, and the real-world scene and the virtual image are provided by the display device. On the other hand, in the optical see-through AR, the user can perceive the real-world scene directly through the AR system while virtual images are overlaid on the physical world by a transparent screen or display. Since the optical see-through AR does not have drawbacks such as a low resolution of reality scene and a user disorientation compared to the monitor-based AR, it has been spotlighted more than the monitor-based AR recently, as in the case of Google Glass.

Most of the optical see-through AR system uses a half-mirror for an image combiner, which is an optical component where the virtual image is immerged into the real-world scene. Holographic optical element (HOE) is an alternative for the image combiner in the optical see-through AR [4,5]. HOE is a hologram that consists of diffraction gratings, which have optical functions of conventional optical elements, such as mirrors, lenses, and so on. The image combiner of HOE satisfies the see-through property without loss of brightness of real world scenes, which is essential for the optical see-through AR, because the HOE functions as the image combiner just for the Bragg-matched lights [6]. The image combiner using HOE also has the advantages of narrow thickness and low cost.

In spite of these recent interests and active research in the optical see-through AR, most of reported optical see-through AR systems provide 2D virtual images only, being unable to display three-dimensional (3D) virtual images. However, several research groups have recently presented optical see-through AR systems supporting 3D virtual images [7–10]. Takaki *et al.* adopted a super multiview (SMV) scheme [7], and Hong *et al.* used an integral floating display [8] to provide 3D virtual images in an optical see-through AR system. However, the former needs an imaging device of excessively high resolution to satisfy the SMV condition, and the latter requires complicated fabrication procedures to produce an image combiner. Furthermore, since both methods basically adopt conventional autostereoscopic 3D displays, they need additional optical systems in front of the imaging devices, and consequentially the total systems based on both methods are unavoidable bulky.

In this Letter, we propose a full-color 3D display on the basis of a projection-type integral imaging [11] for the optical see-through AR by making use of a full-color lens-array HOE as the image combiner. Principles of the lens-array HOE are introduced first, and then a recording scheme for the HOE having full-color and lens-array functions is described. Last, feasibility of the proposed system for displaying virtual 3D images in the optical see-through AR is verified by the experiments.

In the proposed AR system, the lens-array HOE plays a role of the image combiner. Principles of the lens-array HOE from recording and reconstruction perspective are depicted in Figs. 1(a) and 1(b), respectively. In the recording scheme of the volume hologram, an interference pattern formed by the plane-wave reference beam and the spherical-wave signal beam, containing properties of the conventional lens-array, is recorded into the holographic material in the form of a lens-array HOE. The recorded lens-array HOE reconstructs the duplicated wavefronts of the conventional lens-array when a displaying beam, identical to the reference beam in the recording scheme, is projected on the lens-array HOE.

There are several candidates for the holographic material, such as silver halide, photorefractive polymer,

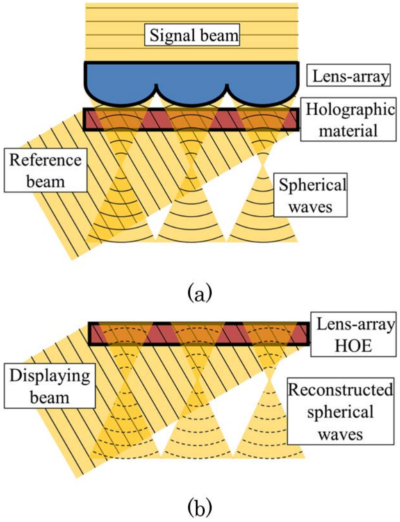


Fig. 1. Principles of (a) recording and (b) displaying for the lens-array HOE.

and photopolymer. Among them, a photopolymer film was used in this work because it has the advantage of wavelength multiplexing for a full-color recording and has an optically clear characteristic for the see-through property after hologram recording [12]. The photopolymer used in the experiments is provided from Bayer MaterialScience AG, and the thickness of the photopolymer is 14–18 μm.

As the image combiner, the proposed lens-array HOE recorded on the photopolymer can provide the virtual 3D images with the see-through condition nicely satisfying for the optical see-through AR system. As the lens-array HOE modulates only Bragg-matched lights from the imaging device, Bragg mismatched lights from the real world just pass through the lens-array HOE without feeling it as an optical element. Furthermore, to provide more realistic virtual images on the proposed AR system, we adopt the wavelength and spatial multiplexing techniques [13] in the recording procedure to display full-color virtual images and to record a large-sized lens-array HOE, respectively.

Figure 2(a) illustrates a schematic diagram of the experimental setup for recording the full-color lens-array HOE, and Fig. 2(b) shows a photograph of its experimental setup. The three laser beams of red (671 nm), green (532 nm), and blue (473 nm) are combined into a single beam path in a beam-combining part. The $\lambda/2$ wave plates located in the beam paths of the three lasers control the states of polarization. The power densities of the three lasers are adjusted by circular variable neutral density filters, and the exposure time of the combined single beam is determined by an electric shutter. The combined laser beam is expanded into a collimated plane wave by a spatial filter and a collimating lens in a beam-expanding part. In a recording part, the expanded beam is divided into the reference and signal beam paths through a beam splitter. A reflective hologram is preferable for wavelength multiplexing [6]. Therefore, we set the two beam paths to be incident on the photopolymer in opposite directions. A lens-array with 1 mm lens pitch and 3.3 mm focal length is located in the signal beam path,

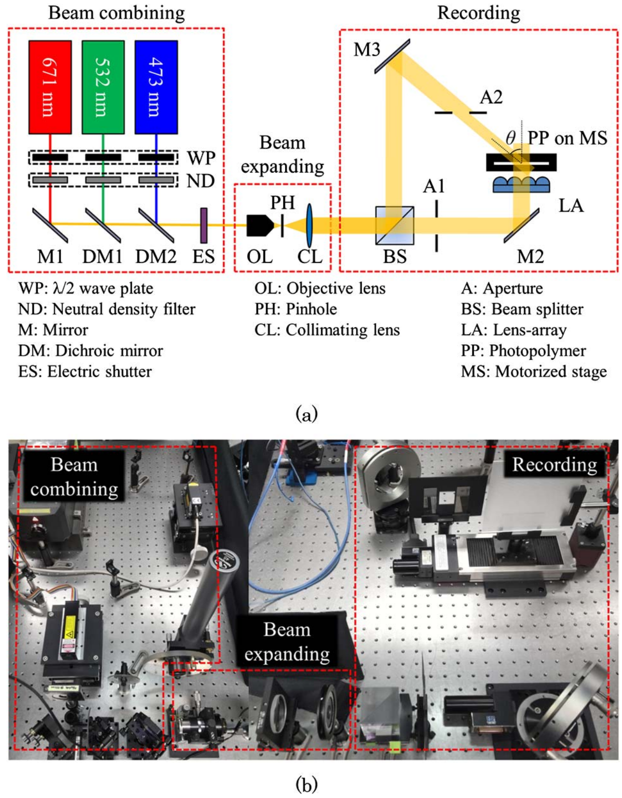


Fig. 2. Experimental setup for recording the full-color lens-array HOE: (a) schematic diagram and (b) photograph of its optical arrangement.

and the photopolymer mounted on a motorized stage is located at an intersecting position of the reference and signal beam paths. The signal beam is incident normal to the photopolymer, while the reference beam is projected with an incidence angle (θ) of 50° normal to the photopolymer. Two square apertures with a side length of 30 mm are located in both the beam paths for a precise alignment of the exposed area on the photopolymer. The size of recordable area on a fixed photopolymer is limited by the size of the square apertures. In order to enlarge the total recordable size of the photopolymer, we used a one-axis motorized linear stage for spatial multiplexing. In this setup, we recorded a 30 mm × 60 mm lens-array HOE by the spatial multiplexing with 30 mm horizontal translation of the one-axis motorized linear stage. To optimize the exposure condition for achieving similar magnitudes of diffraction efficiencies for the three wavelengths, we exposed the three lasers on the photopolymer simultaneously, while varying the power densities of the lasers individually. The full-color lens-array HOE to be used in the next displaying experiments was recorded on the exposure conditions of 51 mJ/cm^2 for 473 nm, 59 mJ/cm^2 for 532 nm, and 47 mJ/cm^2 for 671 nm.

The full-color lens-array HOE diffracts the collimated reference light into highly diverging diffracted light because it has a short focal length, and this makes it difficult to directly measure the diffracted lights from the lens-array HOE. Instead of measuring diffracted light rays, alternatively, transmittance and reflectance spectrums of the full-color lens-array HOE are measured to

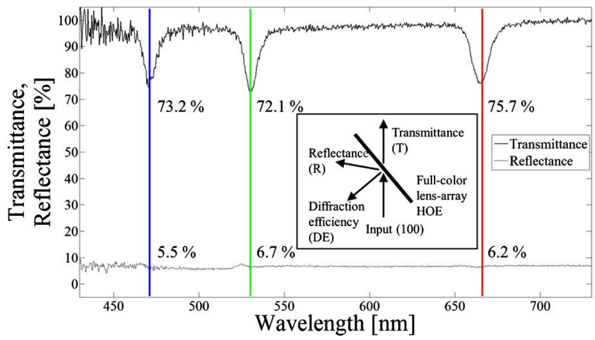


Fig. 3. Transmittance and reflectance of the recorded full-color lens-array HOE measured in the display experiments according to wavelengths. The inset describes the beam paths on the HOE for measuring the diffraction efficiency.

calculate the diffraction efficiencies within the visible range of the spectrum [14]. Since an image projector, which has broadband incoherent light source, is used to modulate and project images on the full-color lens-array HOE, we used a spectrometer (Ocean Optics, USB4000-VIS-NIR) with an incoherent white light source (Ocean Optics, HL-2000-FHSA) for measuring transmittance and reflectance spectrums of the full-color lens-array HOE. When absorption and scattering in the photopolymer are negligible, the diffraction efficiency (DE), in the unit of percentage (%), can be obtained by

$$DE = 100 - T - R, \tag{1}$$

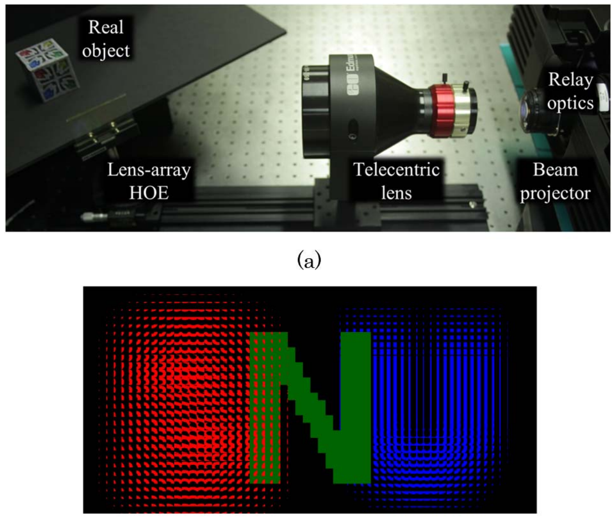
where T is the transmittance and R is the reflectance of the recorded full-color lens-array HOE, as described in the inset of Fig. 3.

T and R were observed by the spectrometer in our display experiments, and their measured curves are plotted along the wavelength in Fig. 3. The measured values of T, R, and DE for red, green, and blue are listed in Table 1. Recorded full-color lens-array HOE provides similar values of DE: 18.1%, 21.2%, and 21.3% for red, green, and blue colors, respectively.

Figure 4(a) shows a photograph of the experimental setup for displaying 3D virtual images in an optical see-through AR system using the proposed full-color lens-array HOE. A beam projector is used for an imaging device. Since we used the collimated reference beam in the recording setup, the imaging device for a display setup should also project collimated light on the full-color lens-array HOE to avoid the Bragg mismatch. To project the collimated images on the full-color lens-array HOE, a telecentric lens is used with the relay optics. However, if a diverging reference beam is used in the recording setup, the telecentric lens is not necessary, and a diverging angle of the projected image can be controlled by the relay optics. The full-color lens-array HOE is located in the path of the collimated light with an incidence angle of 50°, which is identical to that of the reference beam in the recording setup. To illustrate the see-through property of our proposed AR system, we locate a real object "cube" behind the full-color lens-array HOE.

Table 1. Measured Values of Transmittance, Reflectance, and Diffraction Efficiency for Red, Green, and Blue Colors Displayed by the Recorded Full-Color Lens-Array HOE

	Red (%)	Green (%)	Blue (%)
Transmittance (T)	75.7	72.1	73.2
Reflectance (R)	6.2	6.7	5.5
Diffraction efficiency (DE)	18.1	21.2	21.3



(a)

(b)

Fig. 4. (a) Experimental setup for displaying 3D virtual images in the proposed optical see-through AR system. (b) The elemental images for three characters (S, N, and U) projected on the lens-array HOE for 3D virtual imaging.

As the projection-type integral imaging is employed in the proposed method, elemental images should be projected on the full-color lens-array HOE to generate the 3D virtual images [15]. We used the computer-generated elemental images, which have 3D information of three characters, S, N, and U, as shown in Fig. 4(b). To demonstrate the color representation and the 3D imaging of the proposed system, each character of S, N, and U in the elemental images has the color information of red, green, and blue, and the depth information of +30, 0, and −30 mm, respectively.

Figure 5 shows the resultant see-through 3D virtual images captured in the display experiments from five different viewing points relative to the proposed optical see-through AR system. It is clearly confirmed in the experiments that the different perspective images captured from left, right, top, and bottom viewing points provide proper disparities among three characters: S, N, and U. The disparities among the virtual images shown in Fig. 5 provide a binocular disparity and give a 3D perception to the observer [16]. Further work could investigate the use of a lens-array HOE, which has a larger number of elemental lens HOEs, with smaller lens pitch in order to reconstruct 3D virtual images with higher ray density to satisfy an accommodation depth cue [17,18]. The real object cube is also clearly observed along with the 3D virtual images through the full-color lens-array HOE, which verifies that the proposed AR system provides the see-through property. The experimental results

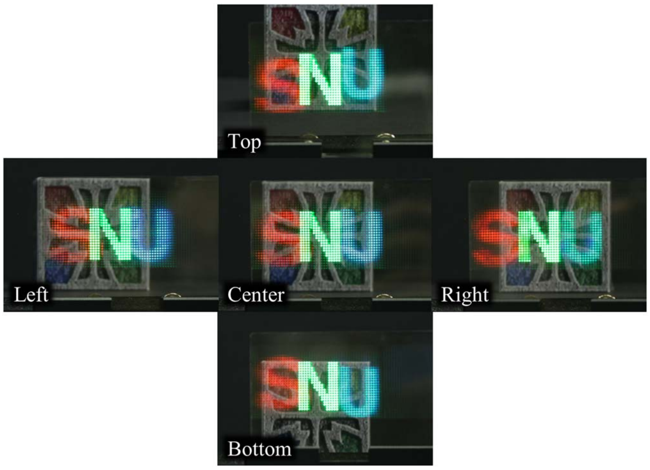


Fig. 5. Perspective see-through 3D virtual images of three characters (S, N, and U) with a real object cube for a background, which were captured from five different view positions in the display experiments.

support the validity of the proposed full-color lens-array HOE for a novel scheme applicable to the 3D optical see-through AR system.

In conclusion, a novel method for the 3D optical see-through AR system using the full-color lens-array HOE is proposed. We set the HOE recording setup, which can apply wavelength multiplexing and spatial multiplexing for full-color imaging and large-area recording, respectively. Experimental results for displaying the 3D virtual images in the proposed system reveal the feasibility of the 3D imaging with see-through and full-color properties, which are essential conditions for the 3D optical see-through AR system.

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