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Digital holographic display with two-dimensional and three-dimensional convertible feature by high speed switchable diffuser

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Abstract

Digital holographic display with a two-dimensional (2D) and three-dimensional (3D) convertible feature is proposed. The 2D and 3D convertible feature is implemented by a high speed switchable diffuser. In a 3D display mode, 3D images are displayed by the principle of the digital holography with a coherent surface light source. An electrically controlled switchable diffuser changes the coherent light into a scattered surface light to display 2D images in a 2D display mode. The displayed image on a spatial light modulator for 2D and 3D display modes is in synchronizes with the status of the diffuser, diffuse or clear, which is electrically controlled by a personal computer. The experimental results show that the proposed method is capable of displaying 2D images and 3D digital hologram convertibly.

Introduction

Digital holographic display can reconstruct the complete wave field containing both intensity and phase information from three-dimensional (3D) objects. Since a hologram can record whole information of light, the holographic display is the only method that can provide all the depth cues to the human visual system. While analog holograms are already commercialized, the digital holographic displays are still at the research stage due to limitations of electronic devices necessary for recording and displaying holograms [1].

One of the most significant limitation for displaying digital hologram is a space-bandwidth product problem. Spatial light modulator (SLM) is commonly used for a display device in the digital holographic display. Figure 1 shows a one-dimensional schematic diagram of an SLM for the digital holographic display, where the SLM has *the* number of pixels, M, with the pixel pitch of p and λ is the wavelength of the laser. In this case, a screen size is proportional to *pM,* and a diffraction angle of the holographic display is defined as $\theta = 2\sin^{-1}(\lambda/2p)$ [2]. When the pixel pitch is reduced to increase the viewing angle, the screen size will become smaller. The relation between the screen size (space) and viewing angle (bandwidth) is in inverse proportion. As a result, the screen size and viewing angle of the digital holographic display cannot be increased at the same time [3].

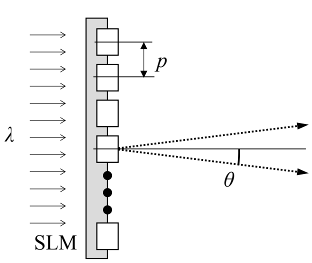


Figure 1. Schematic diagram of SLM and its space-bandwidth product limitation for digital holographic display.

One way to overcome the space-bandwidth product problem in the digital holographic display is a holographic projection system [4-7]. Figure 2 shows the principles of holographic projection system, where q, d and w are a reimaged pixel pitch, an observing distance and a width of a viewing window, respectively. The SLM and diffracted light emanating from it are imaged at the reimaged SLM plane by the first lens placed after the SLM. Relay optics can be located after the first lens to magnify the image. However, it is not depicted in the figure for the simplicity. By placing the field lens at the reimaged SLM plane, the holographic projection system converges diffracted light from the SLM into a viewing window which is formed at the observer's eye location. The observer can see the enlarged hologram through the holographic projection system because all the information of diffracted light from the SLM is transmitted to observer's eye. Although this system can enlarge observable screen size of the digital holographic display, it has a drawback that the observable position is limited by the size of the viewing window which is defined as $w = d\lambda/p$.

Though the holographic projection system can enlarge the screen size, the digital holographic display still has a narrow observable area. Furthermore, up to now, most of digital holographic display only can reconstruct a simple 3D object that has no background image because of the limited amount of information that an SLM can express. The observers may feel inconvenient when watching the digital holographic display because of these limitations.

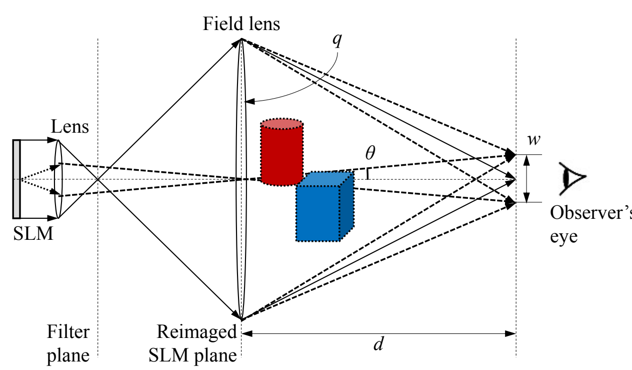


Figure 2. Principles of holographic projection system with viewing window.

2D and 3D convertible display has been actively researched in the field of stereoscopic and autostereoscopic display [8-10]. Most of 3D TVs already have the 2D and 3D convertible feature, and several 2D and 3D conversion methods are reported for autostereoscopic 3D displays such as lenticular and integral imaging displays. The concept of 2D and 3D convertible display is illustrated in Fig. 3. 2D mode and 3D mode of the display can be selected by the observer. This technology can be a stepping stone to penetrate the 3D display technologies into the commercial market.

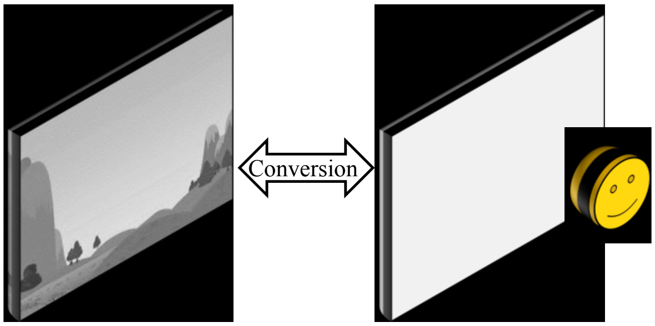


Figure 3. Concept of two-dimensional and three-dimensional convertible holographic display based on flat panel spatial light modulator.

The 2D and 3D convertibility is also important for the digital holographic display not only for the commercialization but also for overcoming the aforementioned limitations. However, 2D and 3D convertible display based on the digital holographic display has not been actively researched yet.

In this paper, we propose a digital holographic display with the 2D and 3D convertible feature by switching scattering and coherent properties of the light source.

2D and 3D convertible holographic display using switchable diffuser

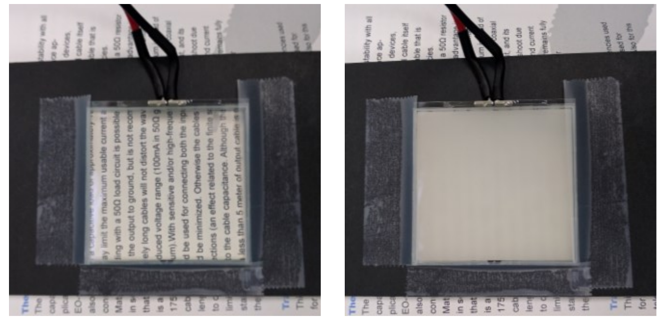
A display for reproducing 2D images such as a liquid crystal display (LCD) displays 2D images by using the SLM for amplitude modulation and a backlight unit emitting scattering surface light. The digital holographic displays, on the other hand, represent 3D images by illuminating coherent and collimated light on a hologram image displayed on the phase or amplitude modulating SLM. Therefore, 2D and 3D display mode can be selectively switched by changing scattering and coherent properties of the light source.

In this section, a method for controlling scattering and coherence properties of a light source by using the switchable diffuser will be described for implementing 2D and 3D convertible display based on the digital holographic display.

Controlling scattering and coherent properties of light source by switchable diffuser

Switchable diffuser is an optical film that can electrically controls its transparency. Polymer dispersed liquid crystal (PDLC) and polymer stabilized cholesteric textured liquid crystal (PSCTLC) are well-known switchable diffusers. Both materials become a clear states when a certain voltage is applied, and it changes to light-scattering state when the applied voltage is disconnected. Therefore, the switchable diffuser acts as a transparent film or diffusive screen in its clear and light-scattering states respectively [11, 12].

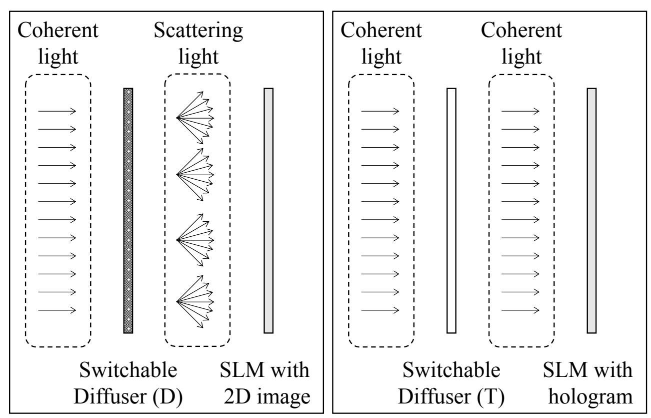
PSCTLC (FSD, LCTech, Sweden) is used for the switchable diffuser in the experiments to implement the proposed method. It has a clear aperture of 2 inch square, opening and closing times are less than 7 and 9 ms respectively. The clear state exhibits over 83% transmittance while the light-scattering state effectively diffuses light in the whole visible range. Clear and light-scattering states of the PSCTLC is shown in Fig. 4(a) and (b) respectively. It is clearly shown in the figure that the PSCTLC act properly as the switchable diffuser.



(a) (b)

Figure 4. PSCTLC used as switchable diffuser: (a) transparent and (b) diffusive states.

Figure 5 illustrates the concept of the proposed method to control the scattering and coherent properties of the light source by using the switchable diffuser. The properties of the light source determine the 2D and 3D display modes. The 2D and 3D display modes are shown in Fig. 5(a) and (b) respectively. In both cases, the collimated coherent light sources are illuminating the SLM and the switchable diffuser is located in front of the SLM. Therefore, the collimated coherent light incident to the switchable diffuser before it is modulated by the SLM. When the switchable diffuser is in the light-scattering state, the coherent light is scattered by the diffusive screen and turned into the scattering light. It is the 2D display mode, shown in Fig. 5(a), when this scattering light illuminates the SLM with a 2D image. In the 3D display mode, on the other hand, the switchable diffuser is in the clear state and the collimated coherent light still remains its coherency after passes through the switchable diffuser. The 3D images will be displayed when this coherent light illuminates a hologram image on the SLM as shown in Fig. 5(b).



(a) (b)

Figure 5. Principles of proposed 2D/3D convertible holographic display by switchable diffuser: (a) 2D and (b) 3D display modes.

States of the switchable diffuser and displayed images on the SLM should be controlled as a pair. The pair of the clear state and 2D image, and another pair of the light-scattering state and hologram image should be synchronized for the 2D or 3D display modes respectively. In the proposed method, each controlling pair for the 2D and 3D modes are switched by a trigger signal. The state of the switchable diffuser and the uploaded images on the SLM are electrically synchronized with the trigger signal by a personal computer. Figure 6 shows the timing control for the switchable diffuser and SLM by the trigger signal.

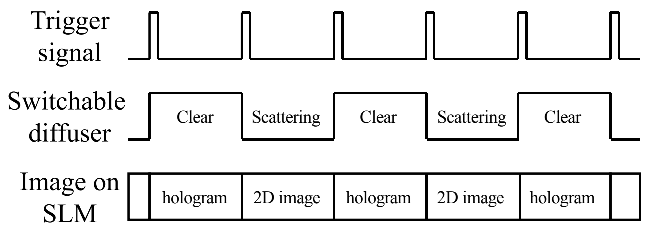


Figure 6. Timing used to drive switchable diffuser and SLM with trigger signal for 2D and 3D mode of proposed system.

Experiments

Hologram contents generation for 3D display mode

A hologram image for 3D display mode in the proposed method is made by computer generated hologram (CGH) technique based on Fresnel diffraction theory [2, 13]. Optical field on the SLM plane which is propagated from objects on a virtual 3D scene can be calculated by the CGH method. The calculated CGH has complex values that contains both amplitude and phase information of the objects. However, only the real part are encoded from the calculated CGH because the amplitude modulating SLM is used in the experiments.

The 3D scene recorded on the CGH is shown in Fig. 7. It has two plane objects, a cone and cubic, which are located at 50 mm and 200 mm far from the SLM plane respectively.

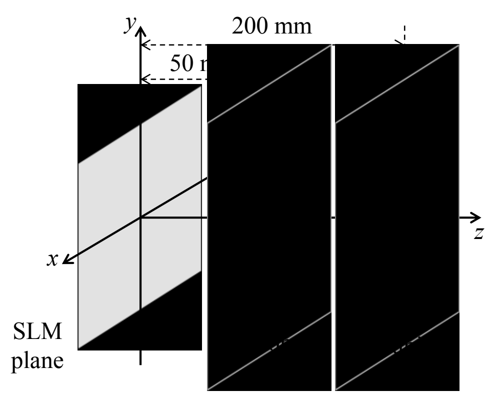


Figure 7. 3D scene with two plane objects for CGH calculation.

Experimental setup for 2D and 3D convertible holographic display

The test-bed system is implemented to verify the feasibility of the proposed 2D and 3D convertible digital holographic display. Figure 8(a) shows a schematic diagram of an experimental setup. It has a cascaded layer structure which is consist of a field lens for forming the viewing window, the PSCTLC as a switchable diffuser, and the LCD as a SLM for the amplitude modulation. The coherent surface light is converged by the field lens and diffracted by the hologram loaded on the SLM. The diffracted light, depicted as a dotted line, forms the viewing window at the observing point. An iris is located at the viewing window plane to filter out noises such as undiffracted and high order diffracted signals. The switchable diffuser is located between the field lens and SLM to switch scattering and coherent states of the illuminated light. A DSLR camera is used for capturing 2D or 3D hologram images displayed on the proposed system.

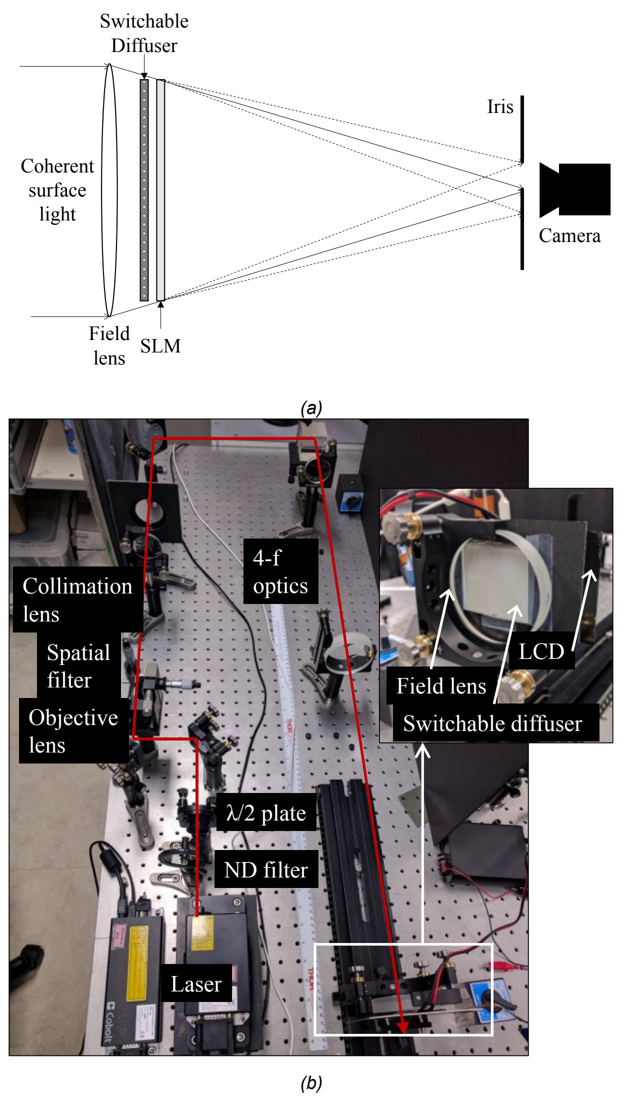


Figure 8. (a) Schematic diagram and (b) captured image of experimental setup for feasibility test of proposed method.

A captured image of experimental arrangements for the feasibility test of the proposed method is shown in Fig. 8(b). A diode-pumped solid-state (DPSS) laser with wavelength of 660 nm is used for the coherent light source. A variable neutral density (ND) filter and λ/2 wave plate are located in front of the laser to control a power density and polarization state of the laser beam respectively. A coherent surface light is generated by expanding the laser beam using a spatial filter with a high NA objective lens and a collimation lens. Since the PSCTLC that we used for the switchable diffuser has shape of 2 inch sized square, the collimated beam need to be expanded again by a 4-f optics located on the beam path. After two step of the beam expansion, a 3 inch circular shaped coherent surface light is formed and incident into a cascaded layer of the field lens, switchable diffuser, and SLM which are shown in the enlarged inset figure. The field lens for generating the viewing window of the holographic projection scheme has a focal length of 500 mm. A transparent type LCD is used as the SLM for the amplitude modulation. The LCD has a resolution of 2560 by 1440 and a pixel pitch of 46.7 µm. Active region on the SLM is limited by the size of the switchable diffuser to the area of 1000 by 1000 pixels in the experiments. In the system, the switchable diffuser and SLM are electrically controlled by a personal computer.

Experimental results

Figure 9 (a) show a 2D image for the 2D display mode. Depth and texture information of the two objects, cone and cube, is numerically calculated and encoded into the hologram image as explained in the previous section. The amplitude hologram used for 3D display mode is shown in Fig. 9(b). Both images have a same size of 1000 by 1000 pixels.

(a) *(b)*

Figure 9. Displayed images on SLM for (a) 2D and (b) 3D display modes.

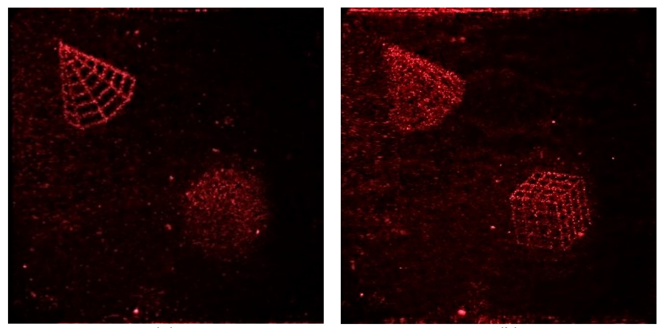
2D and 3D hologram images display on 2D and 3D display modes of the proposed method are captured by the DSLR camera placed on the viewing window plane. Figure 10 and 11 are the captured resultant 2D and 3D images, respectively, from the 2D and 3D display mode of the experimental setup shown in Fig. 8. In the case of the 2D mode, uploaded 2D image shown in Fig. 9(a) is properly displayed on the SLM with scattered backlight by the light-scattering state of the switchable diffuser. The 3D hologram images displayed on the 3D mode are also verified by the captured images at different focuses on the object cone and cube shown in Fig. 11(a) and (b) respectively. The feasibility of the proposed 2D and 3D convertible method in the digital holographic display is clearly verified by these experimental results.

Conclusion

The digital holographic display with the 2D and 3D convertible feature by using the switchable diffuser is proposed. In the 3D display mode, 3D images are displayed by the principle of the digital holography with a coherent surface light source. An electrically controlled switchable diffuser changes the coherent light into a scattered surface light to display 2D images in the 2D display mode. As a result, mono-color 2 inch sized 2D and 3D images are convertibly displayed. Experimental results for selectively displaying 2D and 3D images in the proposed system reveal the feasibility of 2D and 3D convertible display based on the digital holographic display.

Additional studies are required for the temporal multiplexing including the synchronization process between the 2D and 3D display modes for simultaneous display of hologram 3D images on the 2D background image.

Figure 10.Experimental results of 2D display modes.



(a) *(b)*

Figure 11.Experimental results of 3D display mode: focused on (a) cone and (b) cube objects.

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