Optical Metasurface-Based Holographic Stereogram

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Holographic stereography providing binocular depth cues is one of the most promising technologies for 3D displays. However, conventional holographic stereograms based on micrometer-scale pixels suffer from multiple diffraction orders and narrow viewing angles. Optical metasurfaces with sub-wavelength-scale features have recently been leading amongst the state-of-the-art technologies in 3D holograms but employing only monocular depth cues. Here, a novel method is presented based on optical metasurfaces for obtaining a binocular holographic stereopsis. The demonstrated optical metasurface is an ensemble of several hologram pieces, which produce the different 2D projections of the target 3D structure depending on the observation direction, and displays the holographic stereogram of $25 \times 25 \times 25 \, \mu \text{m}^3$ over a wide viewing angle of more than $\pm 30^\circ$. A Gerchberg–Saxton algorithm modified with a spatial Fourier filter calculates the phase and amplitude distribution of meta-atoms. The results will open avenues to advanced eyeglasses-free 3D displays that can provide rich and well-defined depth cues.
The propagation profile of the scalar field verifies the performance of the spatial Fourier filter in the modified GS algorithm. In Figure 2b,c, we examined the creation of a $30 \times 30 \mu m^2$ holographic image at an angle of $-30^\circ$ relative to the vertical direction and in the image plane $50 \mu m$ above the plane of the hologram. The hologram measures $50 \times 50 \mu m^2$ and consists of $200 \times 200$ pixels. Each pixel, of which the amplitude and phase are given by the GS algorithm, acts as a point source of the scalar field. The hologram generated by the ordinary GS algorithm exhibits the widely divergent propagation of the scalar field up to $\sim 70^\circ$ (Figure 2b). On the other hand, the modified GS algorithm successfully provides a directionally propagating holographic wavefront with a narrow divergence angle of $10^\circ$ (Figure 2c). The bandwidth of the spatial Fourier filter determines the divergence angle.

We designed seven different hologram pieces of which the amplitude and phase distributions reconstructed the alphabets from “A” to “G” (Figure 3a,b). The amplitude and phase of the hologram pixel were modulated with two (binary) and eight steps, respectively. The modified GS algorithm allowed us to obtain the directionally propagating holographic wavefronts at different angles from $-30^\circ$ to $+30^\circ$ with a step of $10^\circ$ in the $xz$ plane (Figure 3c). Here, the light wavelength was 680 nm and the hologram pixel size was $250 \times 250 \, \mu m^2$. As shown in the insets of Figure 3c, each designed hologram pieces generated high-quality holographic images on the image plane. The phase distribution governed the propagation direction and divergence of the wavefront; the faster the spatial modulation of the phase, the larger the propagation angle. Such a fast spatial modulation of the phase as to generate the holographic wavefront propagating at a large angle requires the arrangement of several components within the wavelength scale or even less, which the metasurface can indeed realize. The binary amplitude distribution mainly followed the shape of the targeted object. The Fourier transform of the amplitude and phase distribution quantitatively evaluated the propagation of the holographic wavefront in terms of the in-plane momentum (Figure S2, Supporting Information). The center and width of the distribution of the spatial Fourier transform exactly corresponded to the direction and divergence of the holographic wavefront, respectively. According to the Fourier transform, the intensity of the background radiation was suppressed down to the order of $10^{-2}$ on average, compared to that of the holographic radiation within the divergence angle.

The integration of hologram pieces, whose wavefronts propagated directionally, allowed to display different holographic images depending on the observation angle ($\theta$). We combined the seven holograms in Figure 3a,b into a hologram of $107 \times 50 \, \mu m^2$ (Figure 3d,e). To display all directionally-propagating holographic images in the same area of the image plane, we arranged the hologram pieces along the $x$-axis with the formula $x = -h \tan \theta$. Here, the height ($h$) of the image plane from the hologram plane was $50 \mu m$. The hologram pieces partially overlapped each other and, due to the tangent function, the degree of overlap of the hologram pieces was higher in the center region than the border region. In the overlapping region, the phase of the resulting hologram was given as the linear sum of those of the hologram pieces, and the amplitude followed the OR operation of the Boolean algebra. Figure 3e exhibits the position-dependent behavior of the spatial phase modulation; the closer the position to the center, the lower the spatial frequency.
The scalar field profile in Figure 3f verified the convergence of the holographic wavefronts in the targeted area (30 × 30 μm²) of the image plane (the red dashed line). The intensity of the scalar field was quite uniform over the angular region except for the outermost angles, −30° and 30°. Related to the degree of overlap of the hologram pieces, the central region of the assembled hologram supported several propagation angles, but the border region supported only the outermost angle.

We experimentally demonstrated the hologram by generating the angle-dependent holographic images. Figure 4a shows the optical microscopy of the fabricated metasurface of which the amplitude and phase distribution was as designed in Figure 3d,e. We employed inverted V-shaped nanoantennas as the elements of the metasurface (Figure 4b). The inverted V-shaped nanoantennas were formed in a 30-nm-thick Au film on the quartz substrate. Depending on its geometry, the V-shaped nanoantenna manipulates the phase and amplitude of the cross-polarized transmitted light.[18] We chose a combination of eight V-shaped nanoantennas, which supported the phase shifts over 2π with a step of π/4 while keeping the transmitted amplitude nearly constant (Figure S3, Supporting Information). The center-to-center distance between two neighboring nanoantennas was set to 250 nm corresponding to the pixel size of the hologram. The generated holographic stereogram was observed by a goniometer-based measurement setup (Figure 4c). A compact optical microscope scanned the holographic images depending on the observation angle θ. A 680-nm laser linearly-polarized along the x-axis was incident on the metasurface and holographic images of the polarization along the y-axis were acquired by a linear polarizer and a complementary metal–oxide–semiconductor (CMOS) camera.

Figure 4d shows the demonstrated angle-dependent holographic images over a wide viewing angle of ±30° by the metasurface. The reconstructed alphabet images appeared at the same position on the image plane 50 μm apart from the metasurface plane. The spatial Fourier filter of the modified GS algorithm successfully suppressed the cross-talk between the holographic images. Figure 4e shows the calculated holographic images from the amplitude and phase distributions of Figure 3d,e. Considering the oblique view in the experiments, we reduced the width of the holographic images, calculated initially on the image plane parallel to the metasurface, by the cosine of the observation angle. We examined the degree of linear correlation between the experimental and calculated images employing the Pearson correlation coefficient (See the Experimental Section). The seven pairs of experimental and calculated results showed a high correlation coefficient from 0.76 to 0.92. We noted that the V-shaped nanoantenna exhibited anisotropic radiation of the transmitted light, while the point source in the GS algorithm had the ideal spherical radiation distribution. Based on the previous results, further consideration of the radiation distribution of the meta-atom would raise the quality of the computer-generated holography one step further. The quality of the demonstrated holographic images could also be improved by increasing the number of participating hologram pixels per image. While each holographic images of the insets in Figure 3c employed 40 000 pixels, the holographic images in Figure 4d,e were constructed by 12 229 pixels on average because of the overlapping of the hologram pieces. We also note that more precise modulation of the amplitude and phase of the meta-atoms can enhance the quality of the holographic images. The creation of holographic images large enough to be seen with the naked eye will require the use of numerous meta-atoms and a great improvement of image quality, including speckle denoising, which is the advantage of metasurfaces. The planar resolution of holographic images (Δx) is determined by the well-known Abbe diffraction limit considering the divergence angle (α) of the wavefront: $\Delta x = \frac{\lambda}{2} \sin(\alpha/2)$. 

Figure 2. Modified Gerchberg-Saxton algorithm. a) Flowchart of the modified GS algorithm. We employed a spatial Fourier filter to manipulate the direction and divergence of holographic wavefront propagation (Figure S1, Supporting Information). Insets, an example target image (character “A”) and the amplitude and phase distribution of calculated scalar fields at the image and hologram planes. b,c) Profile of the calculated scalar field on the xz-plane: b) The hologram obtained by the ordinary GS algorithm exhibited the widely divergent propagation of the scalar field. The spatial Fourier filter embedded in the modified GS algorithm enabled the design of a hologram which generated a directionally propagating wavefront. Here, the propagation and divergence angles were set to −30° and 10°, respectively. The image plane (the red dashed line) was 50 μm above the hologram (the white bar). The sizes of the hologram and its pixel were 50 × 50 μm² and 250 × 250 nm², respectively, and the size of the holographic image was 30 × 30 μm².
Figure 3. Design and combination of hologram pieces. a,b) Profiles of the calculated amplitude and phase distributions of hologram piece. Seven hologram pieces, which generated the different holographic images (alphabet characters from “A” to “G”) at the angles between −30° to +30° with a step of 10°, were designed. The amplitude and phase were modulated with two and eight steps, respectively. Scale bar, 20 µm. c) Profiles of the calculated scalar fields on the xz-plane. The scalar field from the hologram piece propagated with a divergence angle of 10° and generated a holographic image on the image plane (the red dashed line) 50 µm above the hologram piece (the white bar). Scale bar, 100 µm. Insets, the calculated holographic images that each hologram pieces reconstructed on the image plane. Scale bar, 20 µm. d–f) Calculated amplitude, phase, and scalar field profiles of the combination of hologram pieces.
In this study, with respect to the divergence angle of the wavefront of 10°, the planar resolution is \( \approx 3.9 \) µm.

The generation of multiple, angle-dependent holographic images enabled us to perform the holographic stereogram of a 3D object. We rendered a 3D structure consisting of three rods in a volume of \( 25 \times 25 \times 25 \) µm\(^3\) (Figure 5a). The three rods were located at different depths: the upper, middle, and lower rods were respectively at -12.5, 0, and +12.5 µm on the z-axis relative to the center of the target structure. Like before, we calculated the phase distribution of the binary amplitude hologram and fabricated a metasurface (Figure 5b,c). The metasurface hologram consisted of eleven hologram pieces which generated the 2D projections of the target 3D structure depending on the observation angle along the meridian parallel to the x-axis. Figure 5d shows the rendered perspective projections at the observation angle from -30° to +30° with a step of 10°. We noted that when a person observes an object at a distance of \( \approx 35 \) cm, the angular difference between the views of both eyes is \( \approx 10° \). The projected images of the three rods also contained two monocular depth cues, relative size, and motion parallax. The upper rod farther away had a smaller size on the projected 2D image than the lower rod. Also, the upper (lower) rod farther away (closer to) the observer moved to the right (left) direction relative to the center of the target structure, as the observation angle changed from negative to positive. In addition, the parallel upper and lower rods formed a vanishing point in the perspective projection.

Figure 5e,f shows the calculated and experimental holographic stereogram images. The metasurface successfully created 2D holographic stereogram images of similar brightness, as rendered, over the angular range of interest. In fact, because we employed eleven hologram pieces, the metasurface hologram was able to generate a holographic image at eleven angles from -50° to +50° (Figure S4, Supporting Information). However, as described previously, the brightness of the holographic image, depending on the degree of overlapping of the hologram pieces, increased as the observation angle increased (Figure S5, Supporting Information). We noted that the brightness of the holographic images can be controlled effectively by manipulating the amplitude and far-field distribution of the transmitted radiation of the meta-atom. The measured cross-polarized transmittance of the metasurface over the angular range of \( \pm 50° \) was \( \approx 3.5\% \), which can be further enhanced by increasing the density of meta-atoms\[^{38} \] or employing low-loss dielectric meta-atoms.\[^{21,37} \]

We analyzed the signal-to-background ratio to examine the contrast of holographic images (Figure S6, Supporting information). The signal-to-background ratio was from 11.2 to 14.2 dB in experiments (from 15.7 to 17.3 dB in calculations): The holographic images in experiments are \( \approx 17 \) times on average brighter than the background. When the left and right eyes see two slightly different stereo images, retinal disparity provides a binocular depth cue. In Figure 5g, we present six anaglyph images with red (left eye) and cyan (right eye) colors created by pairing two adjacent holographic images of Figure 5f. Typical red-cyan anaglyph glasses can be used to view the images in 3D. Although a microscope was used to observe the micrometer-scale holographic stereogram in this study, the metasurface of the millimeter-scale or larger enables a person to perceive the 3D structure directly with only both naked eyes. Our metasurface-based method is naturally applicable for generating holographic stereograms at arbitrary 2D solid angles and making the ideal 3D display. The depth resolution of binocular stereogram depends on not only the quality of the generated holographic images but also the angular resolution of the imaging system.\[^{38,39} \]

Considering that our setup has an angular resolution of \( \approx 0.1 \) arcsec and a working distance of 25 mm, the depth resolution in experiments was \( \approx 3.7 \) µm (See the Experimental Section). We also successfully demonstrated the holographic stereogram of a wire-framed cube (Figure S7, Supporting information).

In summary, we demonstrated that optical metasurface-based holographic stereograms are capable of creating the perception of a 3D object at a wide viewing angle. The modified GS algorithm employing the spatial Fourier filter allowed to
effectively calculate the amplitude and phase distribution for the directionally propagating wavefront with the desired divergence angle. The metasurface hologram consists of several hologram pieces which display the angle-dependent 2D projections of the target 3D structure without cross-talk. Employing the inverted V-shaped nanoantennas, we modulated the amplitude and phase of the transmitted light with two and eight steps, respectively. The quality of the demonstrated holographic stereograms was already high enough to form the anaglyph images but can be further improved by increasing the number of the meta-atoms and modulating their phases and amplitudes with finer steps. We thus anticipate that the millimeter-scale metasurface containing numerous, diverse meta-atoms will be able to produce high-quality eyeglasses-free holographic stereograms. Eventually, high-performance optical metasurfaces will pave the way for the demonstration of the ideal 3D display, both for stereoscopy (binocular) and for all monocular cues at the same time.

Experimental Section

A 30-nm-thick Au film was deposited on the quartz substrate using electron beam evaporation. The inverted V-shaped nanoantennas were fabricated by conventional electron beam lithography using a 130-nm-thick polymethyl methacrylate (PMMA) 950 C2 layer. To avoid the charging effect during the electron beam lithography, an additional layer of a conductive polymer (Spacer 300z) was coated and rinsed it with deionized water before the development process. The patterns were developed using a 1:3 methyl isobutyl ketone (MIBK):isopropyl alcohol (IPA) solution at room temperature. The Ar ion milling process formed the inverted V-shaped antenna, and then the O2 plasma treatment removed the PMMA layer. In measurements, a diode laser (Sacher Lasertechnik, lynx-150-0680-025-NG) illuminated the metasurface from the backside and a complementary metal–oxide–semiconductor (CMOS) camera (Thorlabs, DCC3260M) recorded the demonstrated holographic images. The bulk lenses (L1 and L2 in Figure 4c) had a focal length of 25 and 200 mm, respectively.

The Pearson correlation coefficient $R$ was calculated as follows

$$ R = \frac{\sum_{m,n} (A_{mn} - \langle A \rangle)(B_{mn} - \langle B \rangle)}{\sqrt{\sum_{m,n} (A_{mn} - \langle A \rangle)^2 \sum_{m,n} (B_{mn} - \langle B \rangle)^2}}. $$

Here, $A_{mn}$ and $B_{mn}$ were respectively the intensity of the calculated and measured holographic images at the sample pixel point ($x_m, y_n$) indexed with m and n. $\langle A \rangle$ and $\langle B \rangle$ were the average of $A_{mn}$ and $B_{mn}$ over the image area of interest. The depth resolution ($\Delta Z$) of binocular stereogram is given as

$$ \Delta Z = \frac{f}{f + 2D \cdot \Delta \theta}. $$

Here, $f$ and $D \Delta \theta$ are the baseline and angular resolution of the binocular imaging system, respectively, and $Z$ is the distance of the imaging system from the holographic images.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

computer-generated holograms, holographic stereograms, meta-atoms, optical metasurfaces

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