Large-Scale Huygens’ Metasurfaces for Holographic 3D Near-Eye Displays

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Novel display technologies aim at providing users with increasingly immersive experiences. It is a long-sought dream to generate three-dimensional (3D) scenes with high resolution and continuous depth, which can be overlaid with the real world. Current attempts, however, fail in providing either truly 3D information, or large viewing area and angle, strongly limiting the user immersion. Here, a proof-of-concept solution for this problem is developed. A compact holographic 3D near-eye display with a large exit pupil of 10 mm × 8.66 mm is realized. The 3D image is generated from a highly transparent Huygens’ metasurface hologram with large (>108) pixel count and subwavelength pixels, fabricated via deep-ultraviolet immersion photolithography on 300 mm glass wafers. High-quality virtual 3D scenes with ~50k active data points and continuous depth ranging from 0.5 to 2 m, overlaid with the real world and easily viewed by naked eye are experimentally demonstrated. A new design method for holographic near-eye displays is introduced that is able to provide both parallax and accommodation cues, solving the vergence–accommodation conflict existing in current 3D displays. Additionally, the complementary metal oxide semiconductor (CMOS) compatible, industry-grade fabrication technology employed opens new avenues for the large-scale, mass manufacturing of metasurfaces.

1. Introduction

Driven by the advances in mobile computing and an increasing desire from the general public to try more immersive visual experiences, near-eye 3D displays have emerged as a subject of intense study, with the particular focus on their applications in both virtual reality (VR) and augmented reality (AR). Aiming to show users the virtual scenes that imitate the real world, most of the commercial near-eye 3D display products generate 3D images with parallax cues realized by providing two sets of images, each corresponding to the separated perspective position of our two eyes. With the neural processing of the brain, the user reconstructs the scene and perceives the objects as 3D. However, a common limitation of most of these products is that they can only provide one virtual display depth, irrespective of the distance from the virtual object to the user. Therefore, when the user tries to focus on virtual objects that are supposed to be at different distances in the scene but finds a single focal distance for all of them, he or she experiences visual confusion and fatigue, particularly during prolonged usage. This phenomenon is called vergence–accommodation conflict.

Several technologies, such as multiple focal planes,[1] variable focal planes,[2,3] light field,[4,5] and holographic displays,[6–8] and retinal projection[9] have been introduced to alleviate or solve this problem. Among these, 3D holographic displays are considered to be the ultimate solution, as they intrinsically create real 3D objects, with full, continuous depth of view.[10] So far, most attempts to generate 3D digital holographic displays have used spatial light modulators[11,12] (such as Digital Micromirror Devices or Liquid-Crystal on Silicon) as the key enabling technology. The main limitation of these devices, however, is their large pixel size (>3.5 μm), which translates into a small first order diffraction angle and a rather large higher-order diffraction noise. Consequently, in order to filter out this noise and to enlarge the limited viewing angle to a practical range, the optics for this type of display becomes bulky and cumbersome.

Recently, a new class of devices allowing wave-front manipulation with ultrasmall pixels has emerged. The so-called metasurfaces are typically a single layer of metallic or high-index dielectric nanostructures, called nanoantennas, that can manipulate the phase, amplitude, and polarization of an incident light beam at subwavelength scales.[11–13] Compared to traditional diffractive optical elements, the subwavelength nature of these nanoantennas makes it possible for metasurface-based optical
components to eliminate any higher order diffraction, thus greatly increasing the diffraction angle and the efficiency of the first order.\textsuperscript{[16]} On top of that, the unique amplitude, phase, and polarization manipulation mechanisms provide more freedom to integrate multiple functions into a single element. In this regard, various optical functions had been demonstrated using metasurfaces, such as lensing,\textsuperscript{[17–20]} electromagnetic Brewster effect,\textsuperscript{[25]} beam bending,\textsuperscript{[26–29]} steering\textsuperscript{[30–32]} and splitting\textsuperscript{[33,34]} vortex beam generation,\textsuperscript{[26,35]} multifunction metasurface,\textsuperscript{[36]} holograms,\textsuperscript{[33,37,38]} and many others.

Thanks to the subwavelength size of its nanoantenna constituents, metasurface-based 3D holographic display holds promise of large viewing angle and high efficiency, with potentially very simple optics. However, so far this potential has not been fully exploited in previous works using metasurface holograms for display applications. Most of them, in fact, used simple 2D pictures as the image source.\textsuperscript{[38–45]} The reconstruction, in these cases, was either projected on a physical screen or required a microscope to be viewed. On the other hand, those works that demonstrated full 3D reconstruction did so using a very small aperture. Thus, in these works, a microscope, or an image sensor,\textsuperscript{[44,45]} had to be used to capture the 3D nature of the reconstructed objects, which prevented their direct visualization by naked eye. To achieve a high-performance virtual 3D image with a large eye box, one should increase the aperture of metasurface hologram, which can increase the display device’s etendue. It is the product of the diffraction angle and display device area, and it is constant for a fixed display device. The eyepiece cannot increase it, but only can play some trade-off between the viewing angle and the eye box. In order to enlarge the aperture size of metasurface holograms, photolithography and nanoimprint are the two most promising fabrication techniques.\textsuperscript{[14]} Indeed, using either, large area metasurfaces\textsuperscript{[46–48]} and even 2D metasurface holograms\textsuperscript{[49]} have been demonstrated.

For the future display applications, not only static but also dynamic control of wave fronts with metasurfaces will be required. In recent years, different approaches to that have been explored, including electrically tunable metasurface-based spatial light modulators. In this regard, some progress has been recently achieved using liquid crystals to dynamically tune resonant dielectric nanoantennas, aiming to realize novel spatial light modulators with a large pixel count and sub-micrometer pixel pitch in fully functional devices.\textsuperscript{[30]} Another promising approach is modulating the phase of sub-micrometer pixels through charge injection at the interface between ITO and dielectric materials such as hafnium oxide/aluminum oxide under a metallic nanoantenna.\textsuperscript{[10,51]} In the future, this type of devices can be used as dynamic spatial light modulators to encode computer-generated holograms (CGH) for 3D displays or other arbitrary wave front manipulation applications.

In this work, we explore the potential applicability of the metasurface approach for the 3D holographic near-eye display applications. Our work can be treated as a necessary step toward ultimate 3D displays with high resolution and full depth cues. To do so, we demonstrate a large-scale (4 mm × 4 mm with 11 000 ×11 000 pixel count) static hologram fabricated using 12 in. deep-ultraviolet (deep-UV) immersion photolithography on a glass wafer. Using properly design optics, the final display has a large exit pupil of 10 mm × 8.66 mm, able to render a virtual 3D scene with ~50k active data points and continuous depth ranging from 0.5 to 2 m overlaid with the real world in AR fashion. We show that images with full depth cues can be directly viewed along with the real scene by naked eyes, representing, to the best of our knowledge, the first demonstration of this kind of devices based on metasurfaces.

2. Results and Discussion

2.1. Near-Eye Display with a Metasurface Hologram

An ideal near-eye display should provide compact outlook and virtual 3D scene with a high-resolution. In AR, digital virtual information should blend in with the real world (Figure 1a), which implies that the projected scenes from the display should have depth information. Figure 1b,c illustrates the ideal AR experience. When the user focuses near, the optical axis of both eyes converges to meet on the interested position, and the crystalline lens will also be adjusted to focus on the same position. The convergence function is achieved by rotating the eye ball, and the accommodation can be adjusted by controlling the muscle around the crystalline lens. The virtual scene along with any real objects in near area will become simultaneously in-focus. At the same time, any virtual and real objects in the scene that are in the far area will be simultaneously blurred due to defocusing. The opposite would hold if the user would focus on some object far away and, therefore, ideally, the display should be able to generate virtual images with continuous depths.

When a metasurface hologram is used as the image source of a near-eye display device, some special considerations are needed for the design of the optics. Figure 1d,e provides schematic illustrations of a general immersive and optical see-through near-eye display system with a metasurface hologram as the image source. When the metasurface hologram is illuminated with a coherent light source, a 3D holographic image can be generated in front of the metasurface hologram. Human eye cannot focus on the reconstructed 3D scene due to the small distance from the holographic images to the eye, thus, the images cannot be viewed clearly by naked eye. In order to allow the viewer to view the reconstructed 3D images, an eyepiece is needed to image the 3D information of the near image source far away. This eyepiece images the active area of the metasurface to a region around the eye pupil, forming a viewing window that is usually called exit pupil (or eye box). This is the area inside which the user can view the whole virtual 3D image. Figure 1d,e shows two general scenarios of near eye displays using a transmissive metasurface hologram as the image source for VR and AR applications, respectively. In the VR case (Figure 1d), one eyepiece can be designed to image the reconstructed 3D object in front of the viewer while blocking the real-world path. For AR applications (Figure 1e), a transparent optical combiner needs to be included in the eyepiece, typically a beam splitter or a waveguide. The eyepiece can image the virtual scene far away and allow the light from the real-world pass through the eyepiece simultaneously. With the help of the eyepiece, the depth of 3D objects generated directly by the metasurface hologram can be expanded to cover the full range from near to far distances and, thus, a virtual scene with continuous depths can be displayed along with the real world.
The design of the eyepiece for metasurface hologram based near-eye display is different from that of traditional near-eye displays. The display device (i.e., the metasurface hologram) and the 3D image directly reconstructed by the display device are not in the same depth. The imaging performance of both the display device and the reconstructed 3D image along with the eyebox should be optimized when designing near-eye displays using metasurface holograms as the image source. Within the exit pupil, the user should completely observe the 3D scene reconstructed by the metasurface hologram. Thus, the metasurface hologram and the exit pupil should be set in the object–image conjugate relationship under the function of the eyepiece (Figure S1, Supporting Information). To obtain virtual objects ranging from the nearest distance to far away, real images should be reconstructed directly by the metasurface hologram, and the position of the real images should be set within the focal length of the eyepiece, which thus can be viewed as virtual images in front of the eye (Figure S2, Supporting Information). The relationship between the focal length of the eyepiece and other design parameters, including the generated holographic depth and the overall optical length is provided in Figure 1f,g. To make the system compact, the overall optical length should be kept as small as possible. On the other hand, large generated holographic depth is better to provide the user with a good feeling of depth. Thus, when choosing the focal length of the eyepiece, the volume occupied by the reconstructed 3D image should be considered.

### 2.2. Design and Performance of the Metasurface Hologram

Following the general design principle for holographic 3D near-eye display proposed above, a compact near-eye display setup has been designed. For the experimental proof of concept demonstration, a 4 mm × 4 mm metasurface hologram with pixel count of 11 000 × 11 000 is used as the source of the 3D image. In near-eye displays, a large exit pupil is typically preferred, as it offers better tolerance for users with different interpupillary distances and also allows swiveling within the eye sockets without vignetting or loss of image. As the human pupil size is typically ∼2–8 mm, the exit pupil should be larger than this size. In our case, we choose to set a minimum size as large as 10 mm. To achieve this, a 2.5x magnification ratio of the hologram area is chosen in design, which can satisfy the exit pupil requirement. The desired reconstructed holographic 3D scene consists of three objects: the A*STAR logo, a dice and the Nanyang Technological University (NTU) logo, comprising more than 50k total active data points. In
Figure 2. System schematic and design of the metasurface hologram. a) Illustration of the setup of the optical see-through near-eye display system using a transmissive metasurface hologram. b) Spatial position relationship between the reconstructed 3D images and the hologram metasurface. The function of the eyepiece should be considered to provide correct 3D scene from near area to far distance. c) Schematic illustration of a unit cell of the Huygens' metasurface hologram. d–f) Simulated results for regular Huygens' metasurfaces comprising silicon nanodisks of different diameters, with the height of 100 nm and the period of 360 nm embedded into a homogeneous medium with refractive index of 1.5. The color maps indicate: (d) the phase shift of the transmitted wave in \( \pi \) units and (e) the transmittance. (f) The transmission and phase shift as a function of the nanodisks diameter for a metasurface illuminated by a plane wave at the operational wavelength of 680 nm. The scene, the object positions are set from 0.5 m (for the A*STAR logo) all the way to 2 m (for the NTU logo) away from the eye (0.5 diopter to 2 diopter) when viewing with the designed eyepiece. Considering the rendering image depth and optical size (see Figure 1f,g), an eyepiece with a focal length of 50 mm is designed. Moreover, to avoid the possible zeroth order diffraction of the hologram and/or any portion of incident light that may pass outside the hologram, both the axis of illumination and the metasurface are tilted off-axis by 30° with respect to the eyepiece. Figure 2a gives the complete system configuration, consisting of a laser illumination, a beam expander, a beam splitter, a concave mirror and the metasurface hologram. Here, the beam splitter and the concave mirror together act as an optical see-through eyepiece, which projects the virtual image and let light from the real world pass into the user’s eye simultaneously. With this system, the exit pupil with a total size of 10 mm \( \times \) 8.66 mm is achieved.

The phase map of the metasurface hologram is computed using the coherent ray tracing algorithm, which can provide 3D reconstruction\(^{[32]}\) in high quality and is widely employed to produce CGH. It treats the 3D objects as a collection of point sources with randomly distributed initial phases. A complex hologram is formed by summing up the complex field distributions of the point sources at the designed hologram plane. The phase hologram can then be obtained from the complex one by simply retaining the phase information and setting the amplitude to unity. It is important to note that, when calculating the hologram, the object–image relationship imposed by the presence of the eyepiece and the 30° off-axis tilt is taken into account to determine the location of these objects in the CGH calculation. The positional relationship between the objects point clouds and the hologram is shown in Figure 2b. After calculating the hologram, the information is encoded into the metasurface using the correspondence between the meta-atom geometries and the phase of the transmitted light, as detailed below.

The considered metasurface consists of a square lattice of amorphous silicon nanodisks with a constant period \( P = 360 \) nm and height \( h = 100 \) nm and varying diameters, \( D \), standing on top of a glass substrate and embedded in a poly(methyl methacrylate) (PMMA) polymer matrix that acts as an index-matching medium with the substrate (Figure 2c). The measured refractive index and absorption coefficient of amorphous silicon is shown in Figure S3 of the Supporting Information for different wavelengths. Refractive index of glass and PMMA polymer is set to 1.49 and absorption coefficient to zero for the simulation. The size of the disks is chosen so that in some of them two resonances, namely, electric dipole (ED) and magnetic dipole (MD), are excited in the disks at the operation wavelength of interest (680 nm). This wavelength is chosen as it not only falls in the visible spectrum, but also has a slightly lower absorbance than other wavelengths within the visible range and allows higher transmission. In lossless wavelength range, when these two resonances are tuned, via aspect ratio of the disks,\(^{[33,34]}\) so that they overlap spectrally, it is possible to achieve full \( 2\pi \) phase modulation of a transmitted plane wave, while keeping near-unity transmission.\(^{[28,43,55,56]}\) The
former is enabled by the doubly resonant characteristics of the structures, while the latter is enabled by the realization of the so called first Kerker’s condition, leading to strong inhibition of the backward scattering, and caused by the destructive directional interference of ED and MD. The phase as well as the amplitude modulation of a plane wave transmitted through the metasurface as a function of the wavelength (in the range from 500 to 800 nm) and the nanodisk diameters are shown in Figure 2d,e. They were simulated using a commercial finite-difference time-domain (FDTD) software (Lumerical FDTD). From the phase map obtained we can see that in the range from 650 to ∼700 nm, 2π phase coverage can be achieved. From the transmission map, we can clearly see that the two resonance peaks are separated at disk diameters ∼280 nm, and start to move toward each other with the decrease of disk diameters and finally overlap together at disk diameters ∼225 nm and wavelength ∼680 nm. At this point, high transmission ∼0.6 is achieved. While for purely lossless dielectrics the transmission should be unity, the non-negligible absorption of silicon in this wavelength region prevents this, and a nonunity, but high transmission is obtained. The two resonances then start to split (partially overlap) again with the decrease of the disk diameter, and transmission drops accordingly. The phase shift and transmission values at wavelength of 680 nm as a function of the nanodisk diameters are shown in Figure 2f. From there, 8 phase levels with constant phase steps of π/4 are retrieved and used to map the phase hologram, and the corresponding silicon disk diameters are 163, 184, 195, 203, 209, 215, 223, and 250 nm, respectively. The difference of the transmission at different geometry will decrease the diffraction efficiency and contrast of the reconstructed image from the hologram. Note that, since the period P of the metasurface is much smaller than the designed operation wavelength λ, according to the diffraction formula (Equation (1)), only the first order diffraction will be present for light reconstructed from the hologram fabricated based on this metasurface, while the high order (n > 1) diffractions are prohibited

\[ P \cdot \sin \theta = n \lambda \] (1)

This feature makes the reconstruction optics simple. While for hologram reconstruction with traditional spatial light modulator, due to the large pixel size, the view angle is limited and high order diffraction makes it difficult to reconstruct the hologram with a simple optics, a complex and bulky system is needed to remove the high order diffraction and enlarge the view angles.

The metasurface fabrication is done on a 300 mm glass wafer using deep-UV immersion photolithography, a CMOS-compatible process that allows fabrication of large area metasurfaces, as well as their mass replication (see Figure 3a,b). The detailed fabrication procedure is described in the Experimental Section and Figure S4 (Supporting Information). To test the hologram diffraction efficiency and transmission, a supercontinuum

Figure 3. Performance of the metasurface hologram. a) Photograph of the metasurface hologram sample along with a ruler. b) SEM images of the fabricated sample from top view. c) The diffraction efficiency for zeroth order, real image, and virtual image as a function of the wavelength (normalized to transmitted light). d) The total transmission of the metasurface hologram sample as a function of wavelength. e,f) Reconstructed virtual 3D images at the wavelength of 728 nm captured by the camera when focused at the depths corresponding to (e) the A*STAR logo and (f) the NTU logo (the logos are reproduced with permission from A*STAR and NTU, respectively). In (e), the A*STAR logo becomes sharp, while the NTU logo appears blurred due to the defocusing. An opposite situation holds in (f).
laser is used as a light source to illuminate the hologram. In order to cover the whole area of the hologram, the laser beam is expanded with a beam expander before it impinges onto the metasurface hologram. The transmitted holographic image is collected by a condenser lens with high numerical aperture and measured in the wavelength range from 500 to 800 nm in steps of 2 nm. Optical efficiencies of the real image, the virtual image and the zeroth order diffraction are shown in Figure 3c. A highest efficiency of above 80% (normalized to transmitted light) is achieved at the wavelength of 728 nm, accompanied with a very strong suppression of the zeroth order (<10%) and a slight contribution from the virtual image. Note that this optimum wavelength is redshifted with respect to the designed wavelength. We believe that this deviation may be due to a variation in the optical parameters of the material, caused by the deposition conditions, as well as size deviations from the design (see Figure S4, Supporting Information). While it can be optimized in the future, in the current sample it has an influence on the total transmission (Figure 3d), leading to its drop to ~20% at the wavelength of the highest diffraction efficiency.

2.3. Performance of the Near-Eye Displays Using the Metasurface Hologram

A prototype of a holographic 3D near-eye display based on the designed parameters mentioned above was set up using the designed metasurface hologram as the image source (see Figure S5, Supporting Information). Since, after the spectral shift observed in the experiment, the wavelength for the best diffraction efficiency cannot be easily observed by a human eye or captured by a normal camera (which filters out light at wavelengths above 700 nm), a monochromatic 16-bit scientific CMOS camera (PCO. edge 5.5, PCO AG) with a wavelength coverage from 300 to 1100 nm was used to capture the display performance at the best-efficiency wavelength. In this case, we first characterize it in a VR setting, which can be obtained by simply blocking the real-world optical path. In the setup, the focal position of the camera can be controlled to focus at different depths. The performance of the holographic display at the wavelength of 728 nm is shown in Figure 3e,f. Due to the depth information of the generated objects, when the camera focuses on the near region, the A*STAR logo and the letters inside it are clear, while the NTU logo is blurred owing to defocusing. Conversely, when focusing far away, the NTU logo becomes sharper and the A*STAR logo blurs. This indicates real 3D image reconstruction from our metasurface hologram with full depth cues. One should note, however, the presence of a slight background noise along with the reconstructed virtual images. We believe it to be mainly generated by the coherent speckle noise, which, as discussed in previous works, may arise from the resonant scattering on the metasurface.

From the efficiency curve in Figure 3c, another peak in the visible range can be observed, at the wavelength of 544 nm. Note, however, that the actual total transmission for this nonoptimized case is actually quite low. Nevertheless, it is interesting to realize that, from the analysis of the phase shift and transmission values at this wavelength (Figure 2d,e), it turns out that the previous, 8-phase-level metasurface designed for 680 nm, actually acts as a binary hologram at 544 nm. Indeed, for binary holograms, the diffraction efficiency of real and virtual images should be close to each other, as it is the case here (see the measured data in Figure 3c). Since, despite the total low transmission at this wavelength, the efficiency values are reasonable, and they work at a wavelength for which a human eye is particularly sensitive, we decide to mimic a human eye by placing a simple visible light camera at the position of the exit pupil. As the wavelength of the light source is changed to 544 nm, the position of the eyepiece has also to be adjusted, due to the depth difference for different wavelengths. Figure 4a,b shows the virtual information displayed by the system, as captured when the camera is focused at 0.5 m (2 diopter) and 2 m (0.5 diopter) depth, respectively. The generated 3D images are very clear with depth cues, and they can be directly observed by human eyes. To analyze the display performance, the image contrast (defined as the quotient of image and background grayscale) can reach over 7. That is to say, the image signal is much higher that the speckle noise background, and the user can easily observe the virtual image with a high quality. To further verify the proposed near-eye display method, we move to AR configuration, in which the real-world path is unobstructed. In this situation, one toy plane model and one toy car model act as reference objects to measure the integration with the virtual images generated by the prototype. We locate them, respectively, at the distance of 50 cm and 2 m away from the exit pupil of our near-eye display. Figure 4c,d gives the augmented information displayed, as captured when the camera is focused at 0.5 m (2 diopter) and 2 m (0.5 diopter) depth, respectively (see also Movie S1 of the Supporting Information to visualize the continuous change of focus at the depths ranging from 0.2 to 3 m). The performance has been shown for one display channel in this work, which can verify the accommodation function. Similar to the structure of most near-eye displays, left and right channels can be separated, and another structure with different parallax can be duplicated to realize complete vergence and accommodation perception. As can be seen in Figure 4c, when the camera focuses near, both the A*STAR logo and the toy plane model become simultaneously in focus (see lower panels for sharpness details), while both farther virtual and real objects (the NTU logo and the toy car model) become blurred. The situation is exactly reversed (NTU and the toy car are in focus, the A*STAR logo and the toy plane are blurred) when the camera focuses far away, ultimately implying that the present solution can indeed solve the vergence–accommodation conflict issue. For completeness, generated images at different wavelengths ranging from 530 to 600 nm have been captured using exactly the same setup and different source wavelengths (see Note S2 and Figure S6, Supporting Information).

3. Conclusions

In summary, we have proposed and developed a proof-of-concept solution for holographic 3D near-eye display using a large-scale transmissive metasurface hologram as the image source. This demonstration is based on a large-scale static metasurface device fabricated using deep-UV immersion photolithography. This CMOS-compatible, industry-grade fabrication technology allows realization of high-resolution, large area metasurface devices in a completely scalable way, which opens new venues in applications beyond holography, such as flat lenses and complex beam
generation. Equipped with electrically addressable features, this metasurface-based device may rise as an alternative to current display solutions, opening new avenues for research, as they enable the realization of continuous depths, which can be viewed directly with naked eye. The proposed approach can solve the visual confusion and fatigue problem in consumer products, ultimately making long-term usage of mobile AR/VR applications possible. This might help to push the adoption of near-eye displays, called to replace smartphones in the consumer electronics market, and even go beyond them, opening potential applications in education, medicine, or engineering, to mention some.

4. Experimental Section

Metasurface Hologram Fabrication: A 100 nm thick amorphous silicon film was deposited on a 12 in. glass wafer with plasma enhanced chemical vapor deposition. The refractive index and absorption coefficient of the film were measured by ellipsometry and further used in the simulations. Following that, the pattern of the designed dielectric metasurface hologram was generated via deep ultraviolet (193 nm ArF) immersion lithography. After resist development and critical dimension inspection, the wafer was then diced into small pieces with one copy of hologram on each piece. In this way, the processing parameters were fine-tuned and they were characterized individually. The pattern was then transferred from the photoresist to the amorphous silicon layer by reactive ion etching with fluorine chemistry, which was a pseudo Bosch process using SF6 and C4F8 gases,[58] followed by resist removal via oxygen plasma and wet cleaning process. Finally, samples were planarized by spin-coating of PMMA A5 resist (MicroChem Inc.; speed: 1000 rpm; time 60 s).

Characterization and Measurements: Scanning electron microscopes (Hitachi SU8220) was used to capture the size and morphology of the nanostructures. To measure the diffractive efficiency of the metasurface hologram, a supercontinuum source (SuperK EXTREME, NKT Photonics) and multiwavelength filter (SuperK SELECT, NKT Photonics) were used as the light source. An optical power meter (Thorlabs PM320E Model Console + S120C Detector) was utilized to measure the power of the incident light, the real image, the virtual image, and the zeroth order. An infrared camera (PCOedge 5.5, PCO AG) and a single lens reflex camera (Canon EOS 80D with a standard lens of EF-S 18–135 mm) were used at the position of the exit pupil to capture the display performance with the continuous depth. These two cameras were employed for infrared and visible light, respectively.

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.

Author Contributions
W.S. and X.L. contributed equally to this work. W.S., X.L., R.P.-D., Y.Z., and A.I.K. conceived the idea and designed the experiments. S.L., D.L., R.P.-D., K.H.L., and Q.L. performed the design, optimization, and fabrication of the metasurface. W.S., X.L., S.L., R.P.-D., Y.Z., and A.I.K. cowrote the paper. All authors contributed to the results analysis and discussions.

Data Availability Statement
All authors contributed to the results and discussions.

Research data are not shared.

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