Retinal Projection Near-Eye Displays with Huygens’ Metasurfaces

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Most of current commercial near-eye 3D displays use traditional stereoscopic approach to generate the 3D information. A well-known issue for this type of technology is the vergence and accommodation conflict, which leads to visual confusion and fatigue for the viewer. To address this problem, a proof-of-concept solution based on retinal projection technology has been developed to provide accommodation-free virtual images by using a small aperture (360μm × 360μm) transparent Huygens’ metasurface hologram as the display device. The virtual image is generated using a visible laser illuminating a metasurface hologram, which is then directly projected onto the retina using an optical see-through eyepiece. Using this concept, we experimentally demonstrate a compact and wearable near-eye display of light weight (~50g, including spectacle frames, light source and battery) creating accommodation-free images (clear ranging from 0.5m to 2m), overlaid with the real world and directly viewed by naked eye. To do so, we introduce a new design method for retinal projection near-eye displays that, inherently, is able to solve the vergence-accommodation conflict using a small aperture Huygens’ metasurface hologram.
1. Introduction

Miniaturized, compact and lightweight mobile displays are triggering the fast development of wearable computing, near-eye and head-mounted displays, both in virtual reality (VR) and augmented reality (AR) applications. Most commercial products provide only one focal plane, and thus the crystalline lens should accommodate to focus on a fix given depth for the user to obtain a clear view of the virtual image. When the eye of the user focuses on other depth planes, the virtual image becomes blurred. To provide three-dimensional sense, two sets of images with parallax cues are then projected into the two eyes. This binocular disparity leads to the rotation of the eyes, bringing the visual axes inward or outward to intersect at the corresponding depth in the 3D scene. In natural vision, these two stimuli, eye rotation and crystalline focusing, corresponding to vergence and accommodation, are highly correlated and occur simultaneously. In contrast, a conflict between them exists in near-eye displays where a single focal depth is provided, which results in visual confusion and fatigue. This phenomenon is called vergence accommodation conflict (VAC).

Several technologies have been developed to address the VAC issue. They attempt to generate discrete or continuous depths in front of human eyes and range from creating multiple focal planes \cite{1-2} to the use of light fields \cite{3-4} and holographic displays \cite{5-6}. Among these methods, the holographic display method has been treated as the ultimate one where we can directly observe the 3D scene with both amplitude and phase information. Within these years, holographic methods and near-eye displays can be combined, and the light wavefront of the virtual image is often controlled by SLMs \cite{7-8}. In the first several works, the optical display setup should be built on the optical bench, with the limited spatial resolution of the virtual image. Thanks to the optimization of the system \cite{9-10} and the introduction of the neural network \cite{11-13}, part of the system can be compact and the spatial resolution has been improved. Due to the remarkable progress, more intentions from both academia and industry have been paid within these two years. Still, to our best knowledge, compact optical see-through holographic displays which can be viewed by the naked eye have not been reported. Nevertheless, holographic near-eye displays, when viewed by the naked eye within a relatively large eye box, still suffer from low resolution, because many pixels contribute to the depth information. Moreover, due to étendue conservation \cite{14}, the product of the field of view and exit pupil in near-eye displays will be no more than that of the diffraction angle and effective aperture of the SLM. The étendue of SLMs (limit of the diffraction angle and effective aperture) commonly used in holographic

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displays is often very small, and cannot achieve a large field of view and a large eye box simultaneously. This problem also restricts the development of holographic near-eye displays. Additionally, to obtain a vivid scene with a high resolution, large amounts of data should be transferred, processed, stored and displayed, which requires advances in various technological domains. This means that there is still a long way to go before achieving the ultimate solution for our daily life. Retinal projection near-eye display providing an accommodation-free virtual image is another approach which can both maintain the resolution and solve the VAC problem [15-17]. With this approach, beams emitted from each pixel of spatial light modulators (SLMs) (such as Liquid Crystal Display, Digital Micromirror Devices or Liquid-Crystal on Silicon) will converge at the center of the viewer’s pupil using an eyepiece, and is then directly projected onto the retina without triggering the accommodation function of the crystalline lens. With the help of eye-tracking method, the eye box can be extended during the usage. While the size of current SLMs, normally several centimeters in diagonal, is too large compared to human’s eye pupil (~2 to 8mm). This makes it difficult to meet the accommodation free requirement with simple optics. A special illumination structure should be designed to limit the beam angle emitting from the pixels of SLM, which can ensure a small size of convergence aperture on the viewer’s pupil. Therefore, a complex and bulky system is required to provide retinal projection images with these devices, which limits its potential application in near eye displays. Another type of retina projection uses a two-axis scanner and a collimated thin laser beam to directly draw an image onto the viewer’s retina by raster scanning. Although the system can be smaller, a malfunctioning of the scanning system can lead to retinal damage by the continuous illumination of the laser beam. Therefore, it will be ideal and safer for retinal projection if an image instead of a laser spot can be projected onto the retina with a small form factor display system.

Recently, a new class of flat optical elements composed of artificially fabricated subwavelength nanostructures, which are called metasurfaces, have been proposed and developed. The phase, amplitude, and polarization of an incident light beam can be manipulated by metasurfaces at subwavelength scales [18-21]. With the help of the subwavelength structures, the diffraction angle and the efficiency of the first order can be greatly increased, and multiple different functions can be integrated with more freedom into a single device. In this regard, metasurfaces have been successfully demonstrated for many optical applications, including lensing [22-29], holograms [30-35], beam bending and steering devices [36-41], multifunctional devices [42], vortex beam generation [43], and many others, reaching comparable performance as traditional optical components.
Their capability to manipulate the phase of incident light with subwavelength pixel sizes makes metasurfaces an ideal candidate for holographic displays by promising a large diffraction angle, high diffraction efficiency, elimination of the high-order diffraction and a display system with simple reconstruction optics. Indeed, in recent years, various metasurface holograms have been demonstrated [30-35], for both 2D and 3D display applications. It should be noted that most of them were fabricated with electron beam lithography (EBL), which allows only limited aperture sizes in the range of several hundreds of microns. In this case, if a 2D image is used as the image source, normally the reconstruction is in the projection mode and a screen is needed to capture the reconstruction or a microscope is required to view it. In the case of a source providing a 3D scene, in most cases a microscope had to be used to view the reconstructed image, due to the limited aperture of the hologram.

With the development of virtual reality and augmented reality, especially the concept of metauniverse, a light-weighted and compact display device with high performance is required. Due to its strong capability of dispersion engineering and multiple optical functions integrated into a single subwavelength thick layer device, the metasurface could act as compact optical components in near-eye displays. It can be a light-weighted achromatic lens [44-45], and it also can be used as a key component in designing the eyepiece, such as freeform plus metasurface [46] or metasurface-based waveguide [47]. Moreover, the on-chip metasurface waveguide display [48], and compact see-through eyepiece with an anisotropic response [49] have also been reported. Another application of metasurface in the near-eye display is to be an image source. Only recently the first case of a naked-eye-viewable 3D hologram in near eye display configuration, obtained with large aperture metasurfaces fabricated using photolithography has been reported [31]. However, a dynamic tunable full $2\pi$ phase control metasurface is desired for 3D holographic display application. Various material system (phase change materials, semiconductors, transparent conductive oxides, liquid crystals, etc.) and stimuli (thermal, electrical and optical) have been explored for tunable metasurfaces [50]. For display application, in particular, electrically tunable metasurface based spatial light modulators working in the visible wavelength range is preferred [40,51-54]. In the future, this type of devices can be used in displays as dynamic spatial light modulators to encode computer-generated holograms (CGH). For current 3D display methods with continuous depth cues, however, a huge number of pixels should contribute to the depth and spatial resolution. On the other hand, the retinal projection method decreases the resolution requirements, providing a potential viable solution for 3D displays in the near future.
In this work, we show that a small aperture metasurface hologram may provide a good opportunity to achieve accommodation-free display with retinal projection by using very simple optics. As mentioned above, a retinal projection near-eye display using current display devices (such as LCD, DMD, and LCoS) often results in a bulky system. Thanks to the principle of metasurface hologram, this type of image source can provide a high-resolution virtual image by a small active display area. Thus, a retinal projection near-eye display using a metasurface hologram as an image source will be much more compact compared with the traditional approaches. Based on this consideration, we design and experimentally demonstrate a compact near eye display system using a transmissive Huygens’ metasurface hologram as the image source and an optical see-through eyepiece. A static metasurface hologram with a small aperture has been used to demonstrate the proposed retinal projection near-eye display. The potential ability of metasurface hologram as an image source for near-eye displays can be explored. The virtual image can be directly projected on the human retina overlaid with the real world in an augmented reality fashion. Images can be directly viewed along with the real scene by naked eyes which provides a compact solution to the VAC problem in near-eye displays.

2. Results

2.1. Retinal projection near-eye display with a metasurface hologram

In most commercial near-eye displays, an eyepiece is used to magnify the image generated by display devices and form a virtual image appearing at a fixed distance from the eye. Different from the immersive displays such as those used in VR, an optical see-through display (such as those for AR/MR applications) requires an optical combiner, which can overlay the virtual images along with the real world \[55-57\]. Typically, this is achieved using diffractive optical waveguides or beam-splitters. In most cases, only one virtual depth can be generated. As explained before, ciliary muscles change the refractive power of the crystalline lens minimizing the amount of blur for the corresponding depth of the scene. When the user perceives virtual 3D objects with parallax images corresponding to different depths away from the clear depth plane, there will be a disparity between the eye movement and the crystalline accommodation, creating the VAC issue. A retinal projection near-eye display is a useful approach to provide accommodation-free virtual images, which can solve the VAC problem \[58-59\]. As shown in Figure 1a, the display device (here, a metasurface one) along with the illumination source emits light beams to form the required image. An optical see-through eyepiece should be applied to
make the light beams converge from the display device, forming a convergence aperture at the
center of the viewer’s pupil. These beams with the virtual information will then pass through
the eyeball and will be directly projected onto the retina. Ideally, the size of this convergence
aperture should be much smaller than that of eye pupil, so that the focus change of the
crystalline lens does not influence the clarity of the virtual images on the retina.
The design of an eyepiece for retinal projection using a metasurface hologram as an image
source is different from that of traditional near-eye displays, because, for the former, the display
device (i.e. the metasurface) and the generated holographic image are not at the same depth.

**Figure 1**b and **Figure 1**c show a general scenario of retinal projection near eye displays using
a transmissive metasurface hologram as the image source for AR applications. To allow the
viewer to observe the reconstructed image from the metasurface, an eyepiece can be designed
to make the light beam with the information of the generated holographic image from
metasurface hologram converge into the eye pupil and then project it onto the retina. As follows
from the object-image relationship of the eyepiece, the virtual image of the generated
holographic object will be in front of the eye. Making the size of the convergence aperture much
smaller than the size of eye pupil one can enlarge the depth of field of the virtual images,
creating an accommodation-free system. For AR applications, a transparent optical combiner
needs to be included in the eyepiece, typically a beam splitter or a waveguide, such that the
light from the real-world can pass through the eyepiece and be focused onto the retina by the
crystalline lens, allowing the user to receive simultaneously the virtual and real information.

As mentioned above, during the design process, the position and the size of the convergence
aperture should be optimized along with the performance of the virtual image. In particular, the
metasurface hologram and the convergence aperture should follow the object-image conjugate
relationship under the function of the eyepiece (Supplementary Note 1). According to this
principle, the convergence aperture position and size should be designed according to the user’s
pupil. As the human pupil size is typically ~2 to 8mm, the aperture size should be much smaller
than that. Since the size of the convergence aperture cannot be negligible in actual systems, the
whole optical length of the system will be determined by the aperture size, the metasurface size
and the focal length of the eyepiece (**Figure 1**d). The depth of field is the accommodation zone
in which we can observe the virtual image clearly. The relationship between the depth of field
and the virtual image position, along with different aperture size is provided in **Figure 1**c. As
we observe the real scene from 4 diopter (250mm, least distance of distinct vision of normal
human eye) to 0 diopter (infinite distance) in daily life, the virtual objects should be set at
appropriate distance in front of human eye. Thus, 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. To make the system compact, the overall optical length should be kept as small as possible, while trying to make the depth of field cover as much of the accommodation zone as possible.

2.2. Design and performance of the metasurface hologram

Following the general design principle described in the previous section, a compact and wearable near-eye display for retinal projection was designed and fabricated. For the proof-of-concept demonstration, a 360μm × 360μm metasurface hologram with pixel count of 1000 × 1000 (i.e. the pixel size of 360nm × 360nm) is used as the source of the holographic image. Considering the rendering image depth and optical size, an eyepiece with a focal length of 30.6mm is designed, with an aperture size coinciding with that of the metasurface, which is much smaller than the eye pupil. We select the Merlion symbol as the holographic image, which is reconstructed as a virtual image 1 meter (1 diopter) away from the human eye and is clearly viewable from near to far-away. To make the system compact, the eyepiece consists of only two components, one beam-splitting prism (25.4mm × 25.4mm) and one plano-convex lens (with a radius of 75.8mm and the convex side being coated with Aluminum film as a mirror). Moreover, both the axis of laser illumination and the display device are tilted by 45 degrees with respect to principal axis of the eyepiece to prevent the possible zeroth order diffraction and direct transmission of incident light from entering the field of view. Figure 2a. gives the final system layout, consisting of the laser source, the optical see-through eyepiece (beam splitter + concave mirror), and the metasurface hologram. Here, the eyepiece makes the light converge from the metasurface to the human pupil, projecting the virtual image onto the retina along with the real-world scene.

As mentioned above, the positions of the display device and the generated holographic image should be outside and inside the focal length of the eyepiece, respectively. The positional relationship between the point cloud comprising the Merlion symbol and the metasurface hologram is shown in Figure 2b. While various algorithms can be used to calculate computer-generated holograms (CGH), here we compute a point-cloud-based phase type hologram using a coherent ray tracing approach [60]. The complex hologram is formed by summing up the complex field distributions at the metasurface plane from point sources forming the Merlion symbol. After the sum, the amplitude information is discarded and only the phase information is retained and discretized into 8 phase levels with constant π/4 steps. The phase distribution at
the hologram plane is then mapped into the corresponding nanoantennas forming the metasurface hologram. The nanoantenna used here are amorphous silicon disks of equal height \((h = 100\text{nm})\) and varying diameters arranged in a square lattice with constant period \((P = 360\text{nm})\) forming the so-called Huygens’ dielectric metasurface \([61, 38, 36]\). This type of metasurfaces is non-sensitive to polarization of incident light, and thus, no polarizer or analyzer is required in designing the system, which can make the display more compact. The phase modulation is achieved by the diameter variation, which results in the fine tuning of the spectral positions of the optical resonances supported by the Si nanodisks. As is well-known, this type of resonant dielectric nanoparticles presents electric dipole (ED) and magnetic dipole (MD) resonances as the lowest-order optical modes \([20]\). When the induced dipole moments associated with these resonances have the same amplitude and phase, the backward scattering from the nanoantennas can be suppressed (a situation known as the first Kerker’s condition \([62-64]\)), resulting in a near-unity transmission through the metasurface. Moreover, when this dipole overlap happens at the maxima of the resonances, a full \(2\pi\) phase retardation around the resonant frequency can be observed. These nanoantennas, having zero back-scattering and doubly-resonant character, act like a perfect Huygens’ secondary source, which gives the name to this type of metasurfaces. \([65, 61, 38, 36]\)

The simulated phase modulation and transmission maps of the metasurface for wavelengths ranging from 500nm to 800nm and nanodisk diameter ranging from 150nm to 300nm are shown in Figure 2c and Figure 2d respectively. The maps were obtained with a commercial finite difference time domain (FDTD) simulation software (Lumerical). From these transmission maps, one can see the typical spectrum of ED and MD resonances excited in the nanodisk at different wavelengths at a larger diameter with a normal incident and collimated light beam, and there are two dips at long and short wavelengths sides in the spectrum, corresponding to the ED and MD respectively. With the decrease of nanodisk diameter, the ED and MD dips in the spectrum move toward each other, and finally merge at a diameter size of around 230 nm and a wavelength of 650 nm, at which condition the transmission can be higher than 40%. The first Kerker condition can be met, that is to say, the ED and MD resonances are excited in the nanodisk simultaneously and interference constructively, the forward scattering is enhanced and full phase modulation can be achieved. From the phase modulation map we can see that in the range of 610nm to around 670nm, \(2\pi\) phase coverage can be achieved for diameters ranging from 180nm to 240nm. On the other hand, from the transmission map one can see that high transmission values can be achieved for all nanodisk diameters for an operating wavelength around 650nm. Figure 2e shows the phase shift and transmission values at this wavelength as
a function of the nanodisk diameters, from which the 8 phase levels used to map the phase
hologram (in equal steps of π/4) are chosen. As the pixel size of the hologram (period of the
metasurface) is smaller than the operation wavelength, all high-order diffraction will be
suppressed and only the first order present.

The metasurface is fabricated by depositing 100nm thick amorphous silicon thin film on a
10mm x 10mm fused quartz substrate with inductively coupled plasma chemical vapor
deposition (ICP-CVD) method and patterned with electron-beam lithography and subsequently
etched with a reactive ion etching process. Detailed fabrication is described in the Methods
section. The diffraction efficiency of the hologram is measured with a supercontinuum laser as
the light source to illuminate the hologram. The reconstructed holographic image is collected
by a condenser lens and measured in the wavelength range from 500 nm to 800 nm in step of
2nm (see Methods for details). A scanning electron microscope (SEM) image of the
metasurface hologram and optical diffraction efficiencies of the reconstructed image are shown
in Figure 2f. The efficiency is calculated by dividing the measured power diffracted to the
holographic image by the incident light power. The highest diffraction efficiency, around 17.2%,
is achieved at the wavelength of 650nm, which matches quite well with the designed operation
wavelength of the metasurface. We attribute the moderate efficiency achieved to inter-particle
coupling, which causes a deviation of the experimental phase values from the simulated ones.
In the simulations, the phase values are retrieved from uniform nanoantenna arrays, in which
periodic boundary conditions are assumed during the calculation. In the real metasurface
hologram, adjacent meta-atoms are usually dissimilar, which may cause the deviation of the
phase values and the drop of the final diffraction efficiency.

2.3 Performance of the near-eye displays using the metasurface hologram

Based on the design parameters described in previous sections, a prototype of a holographic
near-eye display was set up with the fabricated metasurface hologram as the display device. To
make the system easy to wear, a spectacle frame was designed and manufactured (by 3D
printing method) to hold the battery, the laser source, the eyepiece, the metasurface hologram
and the optical attenuator (Figure 3a). Here, a button cell (Panasonic CR2032 3V) is used to
power the laser source and an optical attenuator is included to reduce the intensity of the light
projected into the retina to protect the eye. The final retinal projection near-eye display
prototype is provided in Figure 3b, along with a scale ruler and the photograph of the
metasurface hologram sample.
Figure 3c and Figure 3d show the augmented information displayed by the system along with the real world, as captured when the camera is focused at 0.5m (2 diopter) and 2m (0.5 diopter) depth, respectively, (see also Supplementary Movie 1 to visualize the continuous change of focus at the depths ranging from 0.2m to 3m). One magic cube and one toy plane act as the nearer and farther real world reference objects respectively, to show the different focusing of the camera and the performance of virtual image (Merlion model, see Figure S4a) generated by the prototype. As can be seen in Figure 3c, when the camera focuses nearby, the magic cube becomes in focus, while the farther real objects (toy plane) become blurred. On the other hand, in Figure 3d, when the camera focuses far away, the toy plane becomes clear while the near real object (magic cube) is blurred. During the focusing process of camera, the sharpness of the virtual image stays the same, demonstrating that the virtual image is projected directly onto the sensor without the accommodation provided by the camera (or eye), and thus that the present solution can solve the vergence - accommodation conflict issue existing in traditional near-eye displays. The image quality for performance is not well enough, it is mainly due to the speckle noise caused by the temporal and spatial coherence of the collimated laser beam used to shine the hologram and the initial random phases imposed on the holographic image during the calculation process. In fact, many approaches have been proposed to reduce it, such as averaging the speckle noise using high-speed refreshing multiple holograms, double phase encoding [9], and camera-in-the-loop neural network algorithm [11]. These techniques can be introduced to improve the image quality when a dynamic metasurface based spatial light modulator is available in the near future. For completeness, virtual images at other wavelengths away from the designed one have been captured along with the real world (simply changing the source wavelength) and are shown in Supplementary Figure S5. Moreover, another fabricated metasurface hologram with a different pattern, corresponding to an “orchid” (Figure S4b), was used as a metasurface hologram in the developed system. The results are shown in Supplementary Figure S6. This demonstrates that dynamic accommodation-free virtual image can be generated by changing the CGH on the metasurface hologram when tunable metasurface-based spatial light modulators are available in the near future. Forming a dynamic eye box would also be possible with a tunable device, which will make the device more practical by working with an eye tracking system.

3. Conclusion
In summary, we have proposed and demonstrated a proof-of-concept solution for accommodation-free near-eye display including a transmissive metasurface hologram as the image source. Virtual images can be generated by modulating the illumination light on the metasurface hologram, and an eyepiece is utilized to project the image onto the human retina. The developed method can ultimately solve the vergence-accommodation conflict problem with a compact and light-weight system, promoting the development of mobile VR/AR products that might replace smart phones in the consumer electronics market in the near future and that might also find wide applications in education, medicine, engineering and beyond.

4. Method

Metasurface hologram fabrication: A layer of 100 nm thick amorphous silicon was deposited by inductively coupled plasma chemical vapor deposition method onto a fused-quartz substrate (1.0mm thick, 10 mm by 10 mm). A layer of hydrogen silsesquioxane (HSQ) resist was then spun onto the sample followed by baking on the hotplate at 180 °C for 3 minutes, and then it was coated by another layer of e-spacer, to prevent the charging by the electron-beam lithography (EBL). The calculated pattern of the hologram was then generated and written on the sample using EBL. The sample was developed in tetramethylammonium hydroxide (TMAH, 25%) solution for 30 seconds and rinsed with iso-propanol, water and blown dried with a nitrogen gun. The fidelity of the pattern was then checked using an SEM. Following that, the sample was etched by reactive ion etching (HBr chemistry). The pattern was imaged under an SEM again to confirm the result of the etching. Thereafter, another layer of undiluted polymethyl methacrylate (PMMA A8, Microchem) was spun onto the sample (1000 rpm, 45 seconds) to achieve index matching with the substrate.

Characterization and measurements: Scanning electron microscopes (Hitachi SU8220) is used to characterize the size and morphology of the metasurface. The diffractive efficiency of the metasurface hologram is measured with a supercontinuum source (SuperK EXTREME, NKT Photonics) and multi-wavelength filter (SuperK SELECT, NKT Photonics) as the light source. An optical power meter (Thorlabs PM320E Model Console + S120C Detector) is utilized to measure the power of the incident light and the reconstructed real image. A single lens reflex camera (SONY alpha 6000, with a standard lens of FE35mm F1.8) is used at the exit pupil to evaluate the display performance. A collimated laser beam emitted from the light source incident to the metasurface hologram normally, in order to meet the requirement of Huygens metasurface condition. The beam size is controlled with a 300µm pin hole in order to cover the
hologram (360 µm × 360 µm) appropriately. The incident light intensity is measured after the pin hole and before the hologram. The first-order diffraction, corresponding to the reconstructed image which entered the eyepiece for retinal projection, is measured with the aid of a condensed lens to guarantee that the light correctly collected by the photodetector of the power meter. The diffraction efficiency is calculated as the ratio of the first order diffraction intensity to the incident light intensity.

Supporting Information

Figure S1 Schematic and specific parameters of a retinal projection near-eye display using a metasurface hologram as the image source.

Figure S2 Schematic of the depth of field in a retinal projection near-eye display.

Figure S3 The spectral profile of the laser source used in compact near-eye display.

Figure S4 Models used in the developed near-eye displays.

Figure S5 Display performance at different wavelengths.

Figure S6 Display performance of the developed system using another metasurface hologram at different wavelengths.

Supplementary Note 1. Design considerations and analysis for retinal projection near-eye display using a metasurface hologram as the image source

Supplementary Movie 1. Display performance for the Merlion model with the continuous change of focus from near to far distances.

Supplementary Movie 2. Display performance for the Orchid model with the continuous change of focus from near to far distances.

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designed the optical system, calculated the hologram and characterize the display performance. X.L., S.L., M.P. and E.L. performed the design, optimization, and fabrication and characterization of the metasurface. W.S., X.L., Y.Z., R.P.D, and A.I.K. cowrote the paper. All authors contributed to the results analysis and discussions.

Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

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References


**Figure 1.** General illustration of retinal projection near-eye displays using a metasurface hologram. **a,** Artistic illustration of the retinal projection near-eye display. **b,** Schematics of the general retinal projection optical see-through near-eye display systems using a transmissive metasurface hologram. **c,** An enlarged image form (b) to show the arrangement of the illumination, metasurface, and the generated holographic image. **d,** Dependence of the optical length on the aperture size. **e,** Dependence of the depth of field on the virtual image position.
Figure 2. System schematic and design of the metasurface hologram. a, Illustration of the setup of the retinal projection near-eye display system using a transmissive metasurface hologram. b, Spatial position relation between the reconstructed holographic image and the hologram metasurface. The optical see-through eyepiece will image the holographic image at the appropriate position with a large depth of field. c-e, Simulated results for regular arrays of 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: c, the phase shift of the transmitted wave in π units and d the transmittance. e, The transmission and phase shift as a function of the nanodisks diameter for arrays illuminated by a plane wave at the operational wavelength of 650 nm. The 8 particular diameters spanning the 2π phase range in equal (π/4) steps are chosen to map the hologram. f, The diffraction efficiency for holographic image as a function of the wavelength along with the scanning electron microscope (SEM) images of the fabricated metasurface sample (inset).
Figure. 3. Performance of the near-eye display prototype. **a**, Illustration of the mechanical structure of the near-eye display prototype along with a human head model. **b**, Photograph of the near-eye display prototype with a metasurface hologram sample along with a scale ruler. Virtual image along with the real-world image captured by the camera when: **c**, it is focused at 2 diopters (0.5m away), the nearer real reference object, a magic cube and **d**, it is focused at 0.5 diopters (2m away), the farther real reference object, a toy plane. In this case, both real objects (magic cube, toy plane) and virtual objects (Merlion model) coexist in the same scene. The sharpness of the holographic image (Merlion model) stays the same when the camera focuses at different depths.
A compact augmented-reality near-eye display method with the virtual image directly projected to retina is introduced and demonstrated using a metasurface hologram as the image source.

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Retinal Projection Near-Eye Displays with Huygens’ Metasurfaces

ToC figure
Supporting Information

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Supporting Information

**Figure S1** Schematic and specific parameters of a retinal projection near-eye display using a metasurface hologram as the image source.

**Figure S2** Schematic of the depth of field in a retinal projection near-eye display.

**Figure S3** The spectral profile of the laser source used in compact near-eye display.

**Figure S4** Models used in the developed near-eye displays.

**Figure S5** Display performance at different wavelengths.

**Figure S6** Display performance of the developed system using another metasurface hologram at different wavelengths.

Supplementary Note 1. Design considerations and analysis for retinal projection near-eye display using a metasurface hologram as the image source

Supplementary Movie 1. Display performance for the Merlion model with the continuous change of focus from near to far distances.

Supplementary Movie 2. Display performance for the Orchid model with the continuous change of focus from near to far distances.
Supplementary Note 1. Design considerations and analysis for retinal projection near-eye display set up using a metasurface hologram as the image source.

![Diagram of retinal projection near-eye display set up using a metasurface hologram](image)

Figure S1. Schematic and specific parameters of a retinal projection near-eye display using a metasurface hologram as the image source.

In order to project the reconstructed holographic image onto the retina, the positions of the metasurface hologram and the convergence aperture should follow the object-image conjugate relationship of the eyepiece. To provide an accommodation-free image onto the user’s retina, the size of the convergence aperture should be set much smaller than that of human’s pupil. Supposing the diameter of human’s pupil is set as $D$, and the size of the metasurface is set as $M$. The size of the convergence aperture is set as $\beta$ times the size of the metasurface ($\beta$ can be less than 1, if $M$ is close to $D$). Then, the overall length ($OL$) of the system from the metasurface to the eye pupil, the distance ($L$) between the eyepiece and the metasurface, the eye relief ($L'$), the magnification ratio $\beta$, and the focal length ($f$) of the eyepiece shown in Figure S1 can be related as below \(^1\):

\[ OL = (\beta + 1)^2 \frac{f}{\beta} \]  
\[ L = (\beta + 1) \frac{f}{\beta} \]  

\(^{(s1)}\)

\(^{(s2)}\)
Figure S2. Schematic of the depth of field in a retinal projection near-eye display.

Supposing the virtual image is located at the distance $I_p$ in front of the user, and $\alpha$ is the minimum resolution angle of the human eye, the distance of the front boundary of the depth of field $F_p$ can be given as follows.

$$F_p = I_p \cdot \frac{D}{D + \alpha I_p}$$  \hspace{1cm} (s3)

If the angle of the eye pupil facing the virtual image point ($D/I_p$) is smaller than $\alpha$, the rear boundary of the depth of field $R_p$ is infinity. If not, it can be given as follows:

$$R_p = I_p \cdot \frac{D}{D - \alpha I_p}$$  \hspace{1cm} (s4)
Figure S3. The spectral profile of the laser source used in the compact near-eye display.

It can be powered by a 3V button cell and emit a collimated light with the central wavelength of 655nm and FMHW of 3nm;
Figure S4. Models used in the developed near-eye displays. To generate virtual images in the near-eye displays along with the real world. Two models have been employed, including a merlion model (a) and an orchid model (b).
Figure S5. Display performance at different wavelengths. Virtual images captured along with the real world by the camera when a-c it is focused at 2 diopters (0.5m) and d-f it is focused at 0.5 diopters (2m) away from the eye at the wavelengths of 473 nm (a&d), 532 nm (b&e), and 580nm (c&f). The sharpness of holographic image (Merlion model) stays the same when the camera focuses at different depths.
Figure S6. Display performance of the developed system using another metasurface hologram at different wavelengths. Virtual images captured along with the real world by the camera when (a-c) it is focused at 2 diopters (0.5m) and (d-f) it is focused at 0.5 diopters (2m) away from the eye at the wavelengths of 620 nm (a&d), 530 nm (b&e), and 590nm(c&f). Similar to the results in Figure S4, the sharpness of holographic image (Orchid model) stays the same when the camera focuses at different depths.

Supplementary References