

Additional file for

Integral Imaging Near-eye 3D Display Using a Nanoimprint Metalens Array

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Section S1. Simulation results of nanopillar gratings

In order to give a complete picture to compare different nanoimprint adhesive materials, a parameter sweep of the complex transmission coefficient in the plane of nanopillar diameter and refractive index n is shown in Fig. S1(a) and S1(d). A plane wave is normally incident onto the nanopillar gratings from the top of the air. It can be seen that if the nanoimprint material with a low refractive index is used, the transmission of the gratings with different diameters is relatively high, but the coverage range of the phase interval is relatively small. When using the high-refractive-index material, the phase coverage range is larger, and the transmission can still maintain a high level for the gratings with a small diameter but is relatively reduced for the large-diameter gratings. In particular, when the refractive index is greater than 1.9, the transmission is reduced more. Although one can increase the thickness of the nanopillars to further improve the coverage of the phase interval, a high depth-width ratio of the nanopillars will considerably increase the difficulty of the nanoimprint process. Generally, we choose the nanoimprint adhesive material with the refractive index of 1.9.

On the other side, there is always a residual layer of nanoimprint adhesive between the substrate and the nanopillars in the nanoimprint process. In order to investigate the effects of the residual layer thickness on the gratings, a parameter sweep of the complex transmission coefficient in the plane of nanopillar diameter and residual thickness h is also shown in Fig. S1(b) and S1(e). It can be seen from the phase diagram in Fig. S1(b) that the phase changes with the thickness in sync; hence, the change of the residual thickness does not affect the coverage of the phase interval. Meanwhile, with the increase of the residual thickness, the transmission of the grating changes little. Therefore, the thickness of the residual layer here has little influence on the effect of grating in manipulating the light field. Fig. S1(c) shows the phase curves in different cases, where all three curves are shifted to the origin for comparison. When the refractive index is 1.9, the coverage range of the phase interval can reach π , while it can only cover 0.4π when the refractive index is 1.5. Besides, the thickness of the residual layer does not affect the phase coverage, comparing the result in $h=0$ to that in $h=1000$ nm. Fig. S1(f) shows the corresponding transmission curve. In the case of a low refractive index, the transmission remains high, while in the case of a high refractive index, the transmission of large-diameter grating is low. Similarly, the residual thickness has little effect on the transmission.

Section S2. Fabrication of silicon master mold for metalens array

The silicon master mold shown in Fig. S2 is achieved by a top-down nanofabrication process. First, the negative electron-beam resist (HSQ) is spin-coated on a 4-inch-diameter silicon wafer. The metalens patterns are then defined in the high-resolution HSQ by an EBL system (EBPG5000 ES, Vistec) at 100 KV and subsequently developed by the Tetramethylammonium hydroxide (TMAH) for about 120 seconds. Next, the inductively coupled plasma (ICP) etching (PlasmaPro System100 ICP180, Oxford Instrument) using HBr gas is applied to etch a 500-nm-thick silicon layer. Finally, the residual resist is removed by the wet etching with the hydrofluoric acid solution, and hence the silicon nanopillars are patterned as the desired master mold of the metalens array.

Section S3. Nanoimprint fabrication of metalens array

First, as shown in Fig. S3(a), the silicon master mold is cleaned with absolute ethanol and nitrogen, and treated with an anti-sticking agent. To avoid the residual material leaving on the master mold during the working stamp creation, the contact angle of the silicon master mold should be greater than 90° . Then, according to the type of nanoimprint resists selected, it is necessary to choose an appropriate material to make the working stamp. The materials (such as PDMS) are spin-coated onto the master mold and cured with the UV light in the process of creating the working stamp, as shown in Fig. S3(b). Meanwhile, the flatness and the thickness of the working stamp, and the time of UV curing are also needed to be carefully controlled. In Fig. S3(c), the working stamp is demoulded, and then the inverse structures of the master mold are generated on the working stamp, as shown in Fig. S3(d).

Next, spin-coat the nanoimprint resists (IOC-133, Inkron) onto the silica substrate, as shown in Fig. S3(e). As the time and rotation speed during the spin-coating will affect the thickness of the residual resist layer at the bottom of the nanoimprint structure, fine regulating is always needed. The tackifier (Primer, Germanlitho) to increase adhesion is added between the silica substrate and the nanoimprint resists. After that, as shown in Fig. S3(f), press the working stamp down on the nanoimprint resist, and cure the nanoimprint resist with UV light. In the nanoimprint process, the parameters (such as the pressure, the waiting time before and after exposure, and the exposure time, etc.) usually rely on the type of nanoimprint resists and the target nanoimprint structure, etc. Hence, to ensure the quality of the final nanoimprint sample, the most suitable parameter values must be selected carefully. Using the nanoimprint device (UniPrinter, Germanlitho), the entire nanoimprint process can be conveniently monitored and adjusted. Finally, as shown in Fig. S3(g) and S3(h), the working stamp is demoulded, and the desired structure of the metalens array is obtained on the cured nanoimprint resists layer.

Section S4. Measurement setup for characterizing the performances of metalens array

As shown in Fig. S4, the laser source is generated by a supercontinuous laser (Fianium WL-SC480-20-PP) and filtered by a narrow-band filter (Fianium LLTF-VIS2-HP-FDS-SM). Since the spot size of laser is too small to cover the metalens array completely and uniformly, we use a beam expander (GCO-2503) to expand the spot size and make sure that the incident light illuminates uniformly on the metalens array as much as possible. An attenuator (GCO-07M) is used to adjust the intensity of light. The metalens array is placed on a high-precision (~ 20 nm stepping precision) motorized three-axis translation stage (Newport 9063-XYZ-PPP-M), which is used to scan the field distributions. The surface of the metalens array is set as the $z=0$ plane, and the light propagates along the positive direction of z . The microscopic imaging system behind the metalens array consists of a $5\times$ objective lens (Olympus MPlanFLN5xBD), a tube lens (Thorlabs ITL200) and a CCD detector (HAMAMATSU C11440-22CU). The magnification between the image pixel of CCD and the actual physical scale is measured by a calibration ruler ahead. The surface of the metalens array and the focal plane can be found by moving the sample back and forth in the z -direction using the translation stage. By scanning the field intensity images in different z -planes with high precision, the field intensity distributions of the metalens array can be obtained.

Section S5. Dispersion characteristic of metalens array

Fig. S5(a-c) show the intensity distributions of a single metalens in the metalens array in the yz plane at the wavelengths of 463 nm, 547 nm and 617 nm, respectively, while Fig. S5(d) shows the intensity distributions of the central axis along the z-direction at different wavelengths. It can be seen that the focal points of the metalens are different at different wavelengths with obvious dispersion characteristics. For this metalens, the focal length is about 6.9 mm at 463 nm while the focal depth is 361 μm . At 547 nm, the focal length is approximately 5.8 mm, the focal depth is 402 μm , and the corresponding numerical aperture is about 0.05. At 617 nm, the focal length is about 5.2 mm, and the focal depth is 465 μm . Therefore, the focal length of the metalens complies with the designed focal length, but the metalens dispersion is relatively severe, which may affect the multicolor imaging.

Fig. S6 shows the intensity distribution of the focal plane's light field, the focal spot's transversal intensity distribution along the x-direction, and the corresponding MTF curve of a single metalens at different wavelengths. It can be seen that the focal spot size does not change much at different wavelengths. The FWHM of the focal spot half-height width at 463 nm is 6.4 μm , that at 547 nm is 6.6 μm , and that at 617 nm is 6.6 μm . One can find that the cut-off frequency at different wavelengths is about 150 lp/mm. The dashed lines in the MTF curves give the MTF diffraction limit lines. Since the metalens in the metalens array has a square aperture, the aperture used in the calculation of the diffraction limit is the diagonal of the metalens instead of the side length. Thus, the calculated MTF diffraction limit is generally higher than the actual MTF curve of the metalens. Here, the results show that the focusing performance of the metalens is still close to the diffraction limit. In addition to the light field intensity distributions, we also measured the transmittance and focusing efficiencies of the metalens array at different wavelengths. At 463 nm, 547 nm and 617 nm, the transmittance values of the metalens array are 59%, 67% and 76%, respectively, and the focusing efficiencies are 35%, 26% and 23%, respectively.

Note that ordinary metalens arrays do have a severe dispersion problem; however, many solutions have been proposed in recent years. On the component design, by designing specific nanopillars in the metalens, achromatic can be realized, just as the broadband achromatic metalens array work (Ref. [22]) before and also the work of RGB-achromatic metalenses (Ref. [39,43]). On the algorithm side, chromatic aberration can be corrected to a certain extent by means of computational imaging. For meta-II display, by separately pre-correcting the film source in different color channels, the chromatic aberration can be alleviated to a certain extent. On the nanofabrication process, the realization of achromatic metalens needs improvements in the nanoimprint process, as the designed nanopillars with much smaller linewidth are involved. In general, to realize the full-color meta-II display by the large-area achromatic metalens arrays is still a worth studying challenges.

Section S6. Comparison of eyebox size in metalens arrays with different F-numbers

To indicate the eyebox sizes corresponding to our current system and a metalens array with a small F-number, we also designed a metalens array with a smaller F-number and carried out optical simulation to compare their eyeboxes. Note that the focal length and the F-number of our current metalens array at 547 nm are 5.8mm and 12.6, respectively. In our metalens design with a small F-number, we set the focal length to be 1 mm, so its F-number is 2.2. Fig. S10(a) shows the intensity distributions of the small F-number metalens in the yz plane at the wavelengths of 547 nm, while Fig. S10(b) shows the intensity distributions of the central axis along the z-direction. It can be seen that the focal length is 997 μm at 547 nm while the focal depth is 20 μm . Therefore, the focal length of the metalens is in accordance with the designed focal length. Fig. S10(c) shows the focal plane's light field; Fig. S10(d) shows the focal spot's transversal intensity distribution along the x-direction. The focal spot's full width at half maximum is 1.3 μm at 547 nm.

Fig. S11 shows the eyebox simulation with LightTools. Fig. S11.(a-e) give perceived images of our prepared metalens array when the eye moves from left to right (eye relief: 21 mm). Due to the small size of the eyebox in this situation, we set a circular plane with a radius of 1mm to represent the eye and move it continuously. Fig. S11. (b) and (d) correspond to several critical positions during the movement. When the eye shifts to a position where crosstalk appears or the image is incomplete, we consider the position out of the eyebox. Therefore, the simulated eyebox is $1\text{ mm} + 0.5\text{ mm} \times 2 = 2\text{ mm}$. Fig. S11.(f-j) provide the results corresponding to the metalens array with the small f-number. The eye size is 4 mm, with an eye relief of 21 mm. Similarly, Fig. S11. (g) and (i) show perceived images at several critical positions. The incomplete images are obtained when the eye shifts more than 2.2 mm. Thus, the simulated eyebox, in this case, is 8.4 mm.

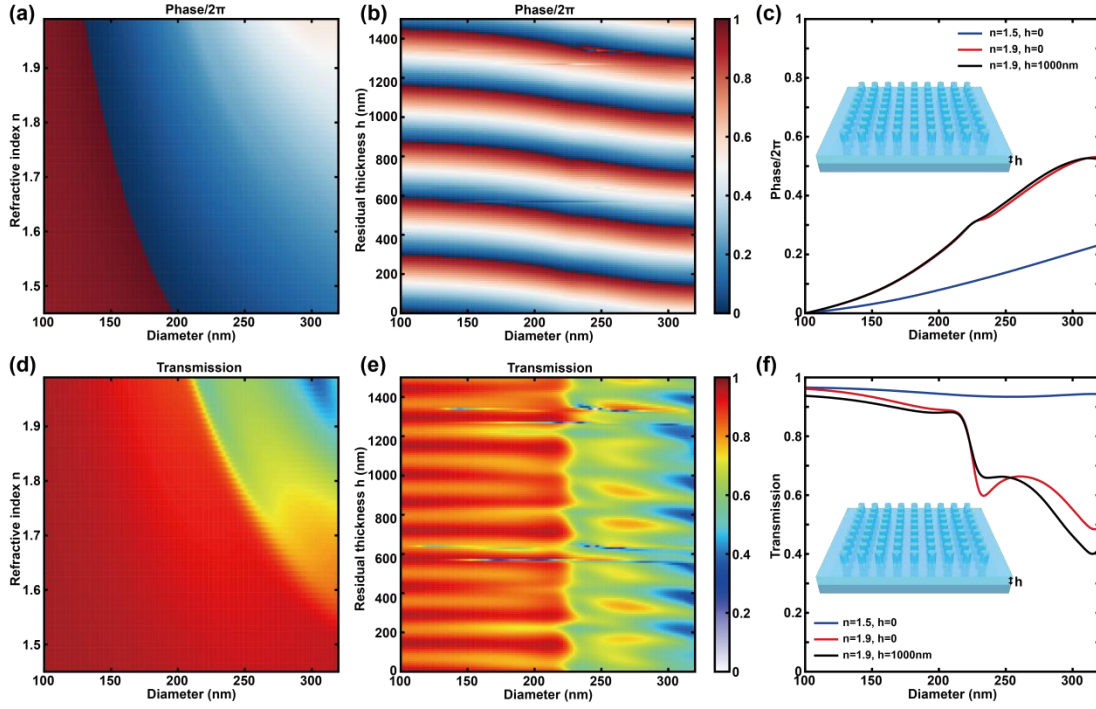


Fig. S1. Simulation results of the nanopillar gratings at the wavelength of 547 nm. (a) Normalized phase and (d) transmission as a function of the nanopillar diameter and the refractive index n . (b) Normalized phase and (e) transmission as a function of the nanopillar diameter and the residual thickness h . (c) The phase profiles in the cases of (i) $n=1.5$, $h=0$; (ii) $n=1.9$, $h=0$; and (iii) $n=1.9$, $h=1000\text{nm}$. The phase curves are manually shifted to the original point for comparison. (f) The corresponding transmission profiles in the cases of (i), (ii) and (iii).

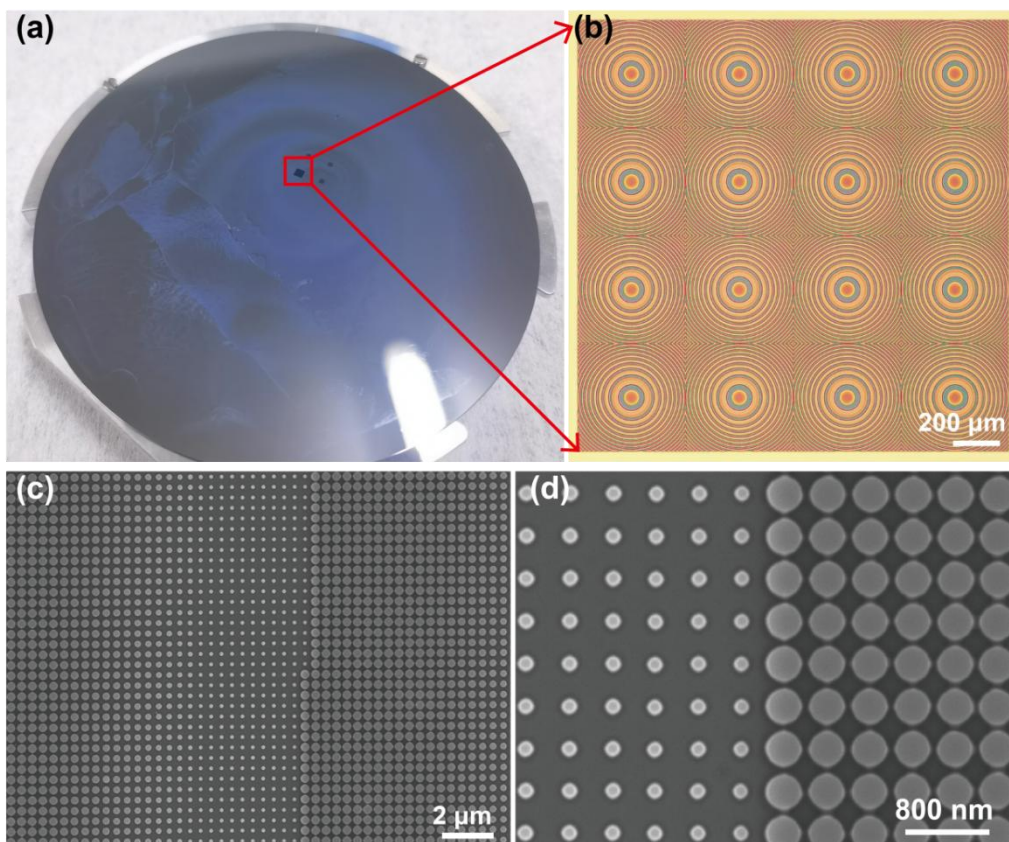


Fig. S2. Optical and SEM images of the silicon master mold of metalens array. (a) Optical photo of the silicon master mold. (b) The microscope photo. (c,d) Top-view SEM images of a portion of the silicon master mold.

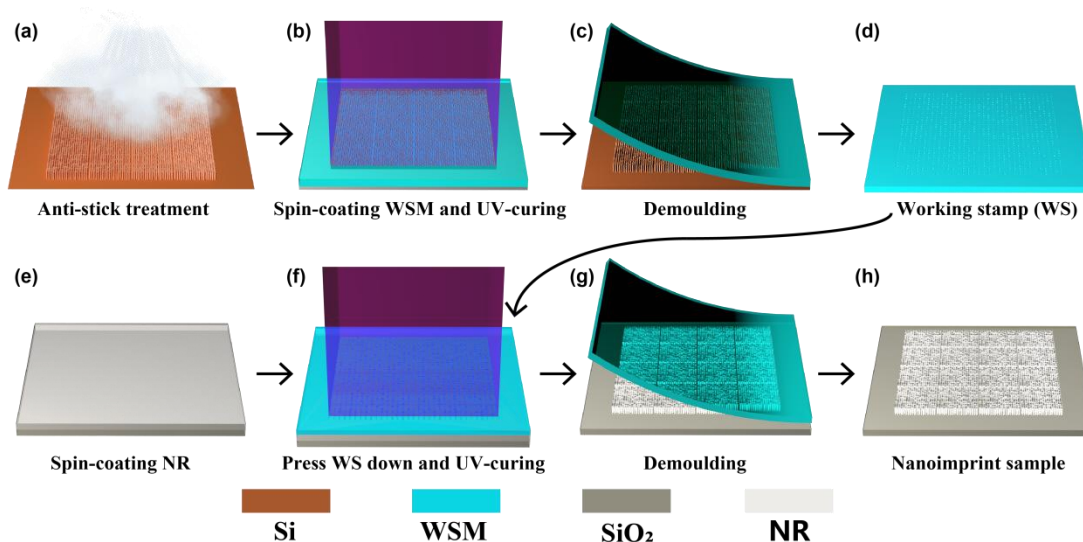


Fig. S3. Schematic illustration of nanoimprint fabrication of metalens array. WSM: working stamp material; NR: nanoimprint resists.

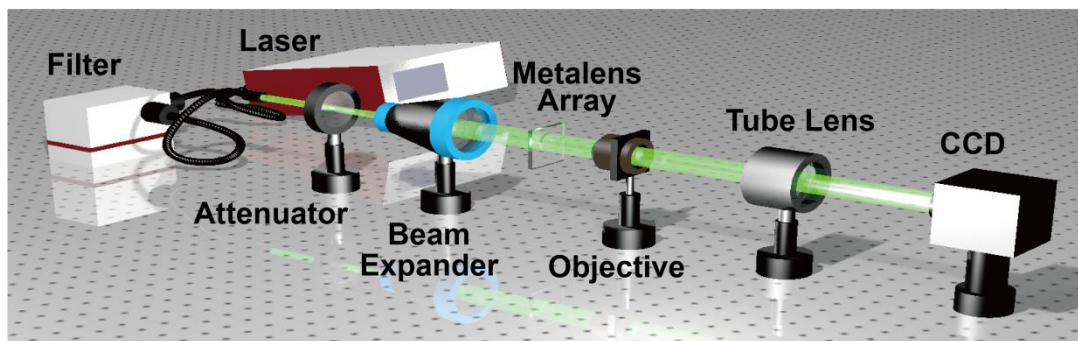


Fig. S4. Measurement setup for characterizing the performances of metalens array.

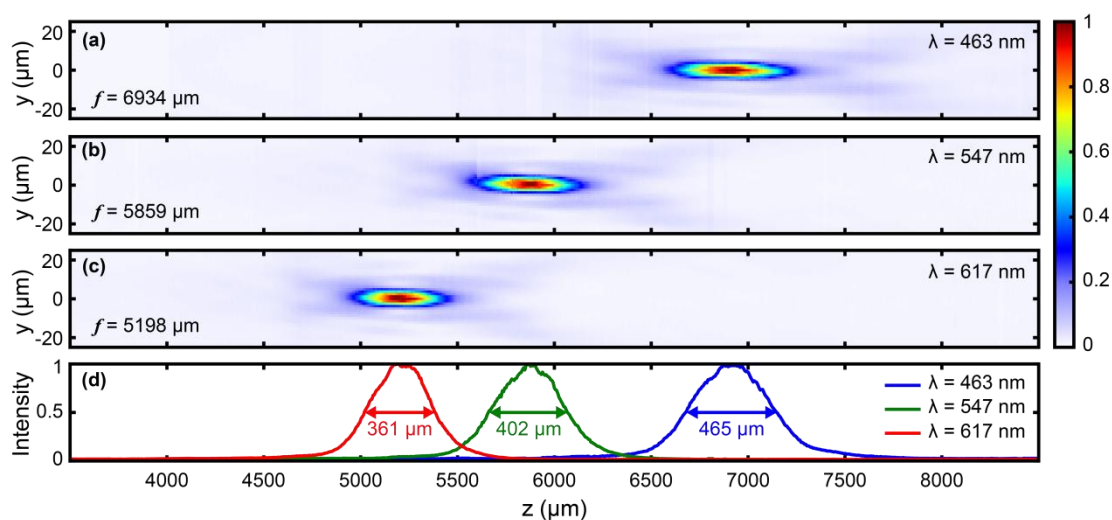


Fig. S5. Measured intensity distributions in the yz plane of a single metalens. Normalized measured intensity distributions at 463 nm (a), 547 nm (b), and 617 nm (c). The z -direction cross sections of light intensity at all three wavelengths are shown in (d).

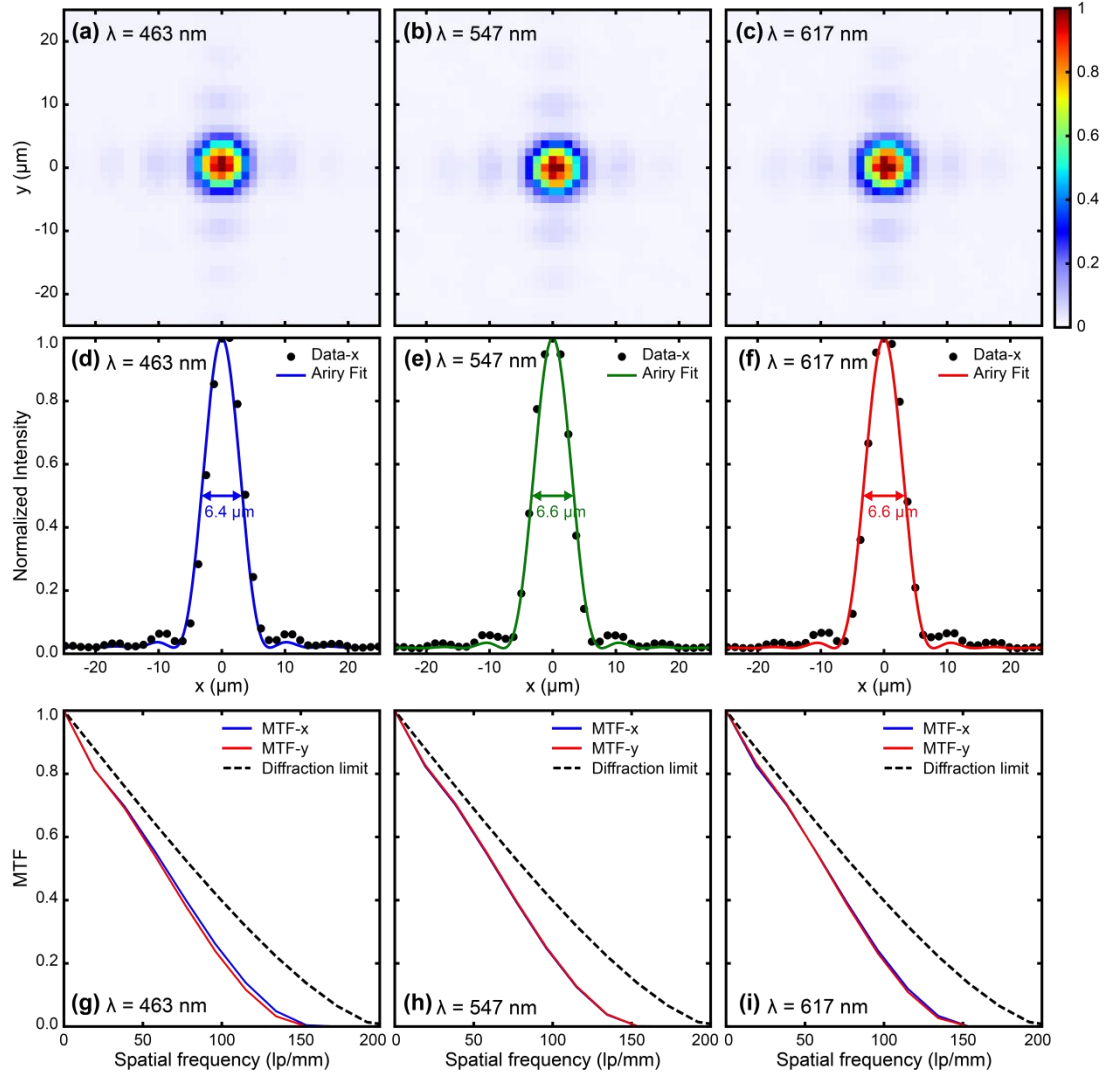


Fig. S6. Measured intensity distributions in the focal planes of a single metalens. Normalized measured intensity distributions at 463 nm (a), 547 nm (b), and 617 nm (c). (d-f) show the x-direction cross sections of (a-c). (g-i) show the corresponding MTF lines.

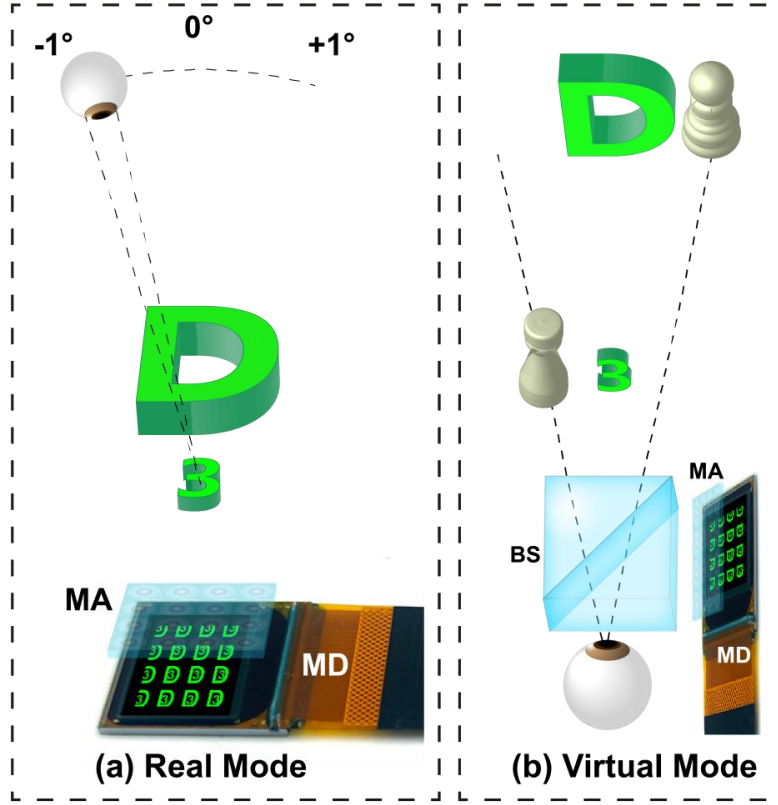


Fig. S7. Optical path diagrams for the 3D II display. (a) On the real mode. (b) On the virtual mode. MA: metalens array; MD: micro-display; BS: beam splitter.

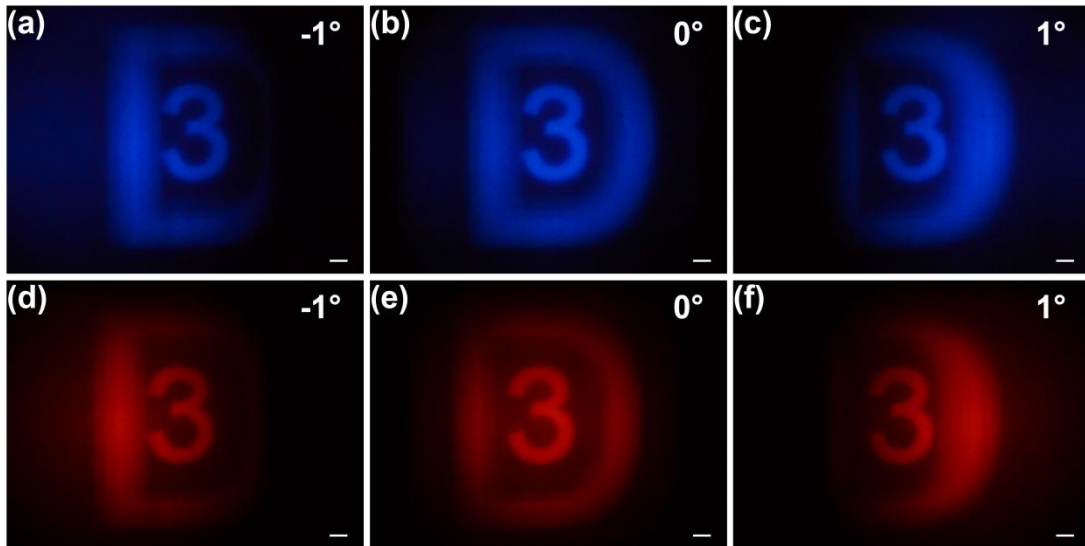


Fig. S8. Experimental results of the 3D parallax effect. (a-c) The result of the 3D parallax effect in the meta-II system on the real mode under the blue light. (d-f) The result under the red light.

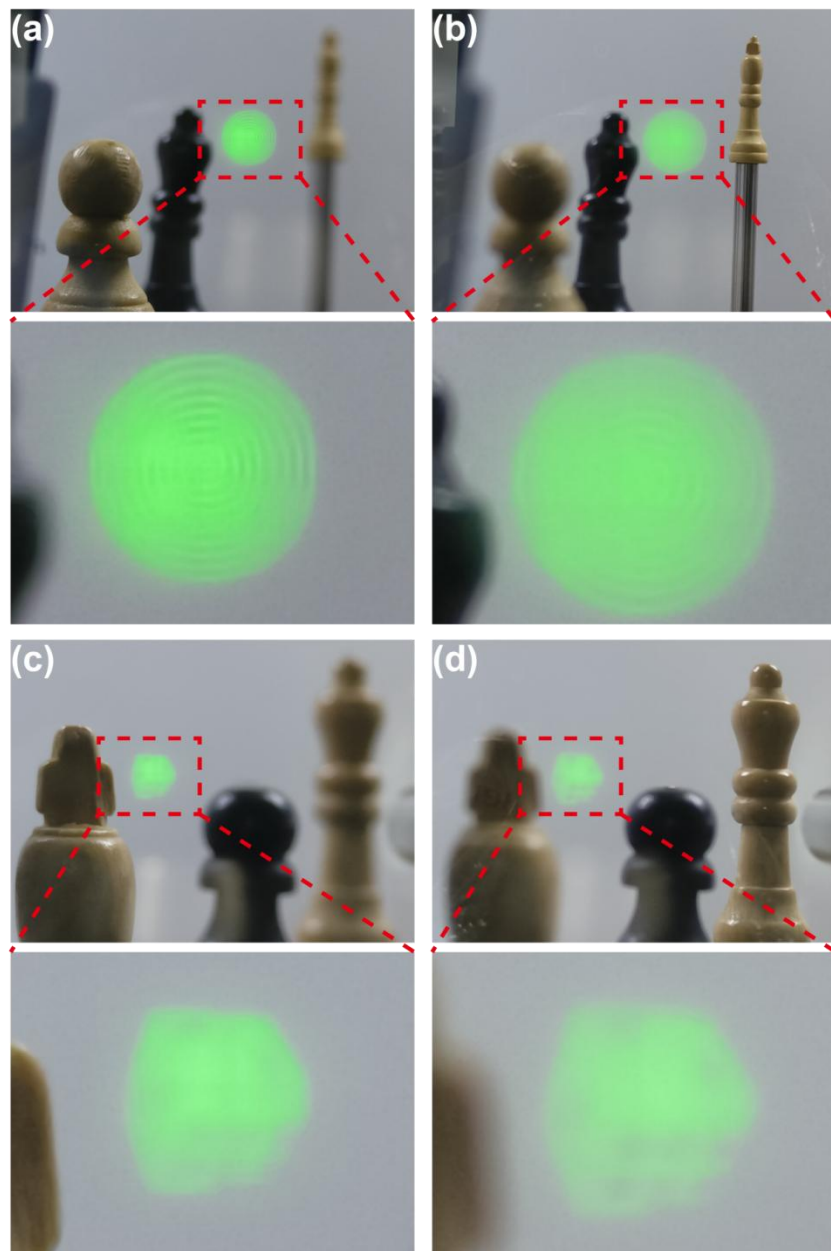


Fig. S9. The defocusing AR effects of the meta-II NED system. The defocusing AR effects are shown on the virtual mode under a bright background using the meta-II NED system. (a) The image captured in the depth plane of the yellow chess piece “Pawn” in front on the pattern case of ring. The bottom with red frame is the partial enlarged detail. (b) The image captured in the depth plane of the rear yellow chess piece “King” on the case of ring. (c) The image captured in the depth plane of the yellow chess piece “King” in front on the case of dice. (d) The image captured in the depth plane of the rear yellow chess piece “Queen” on the case of dice.

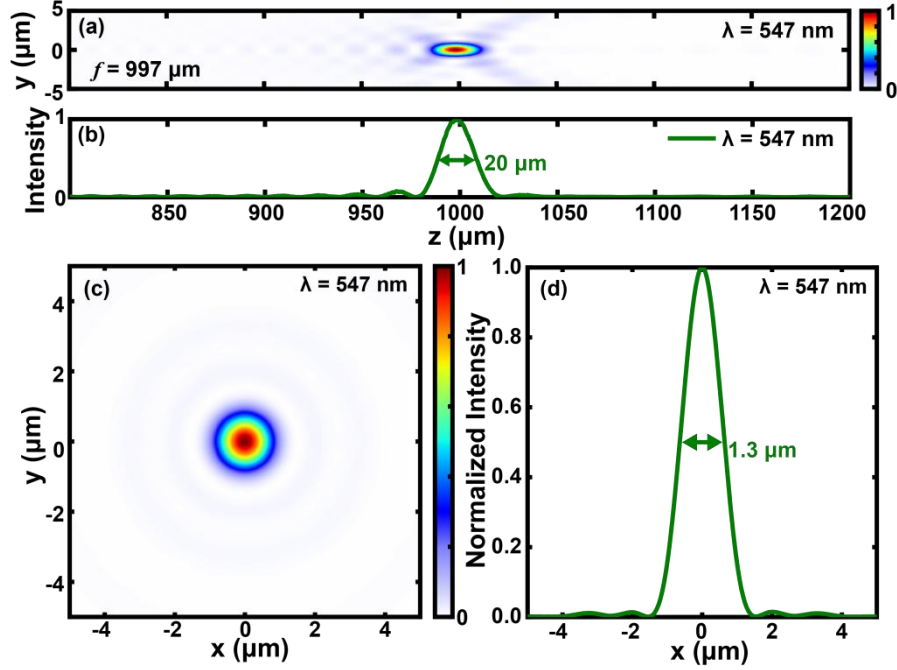


Fig. S10. Simulated results of a small F-number metalens array (focal length: 1mm, F-number: 2.2). (a) Simulated intensity distribution in the yz plane at 547 nm. The z-direction cross section of light intensity is shown in (b). (c) Simulated intensity distributions in the focal plane at 547 nm. (d) shows the x-direction cross section of (c).

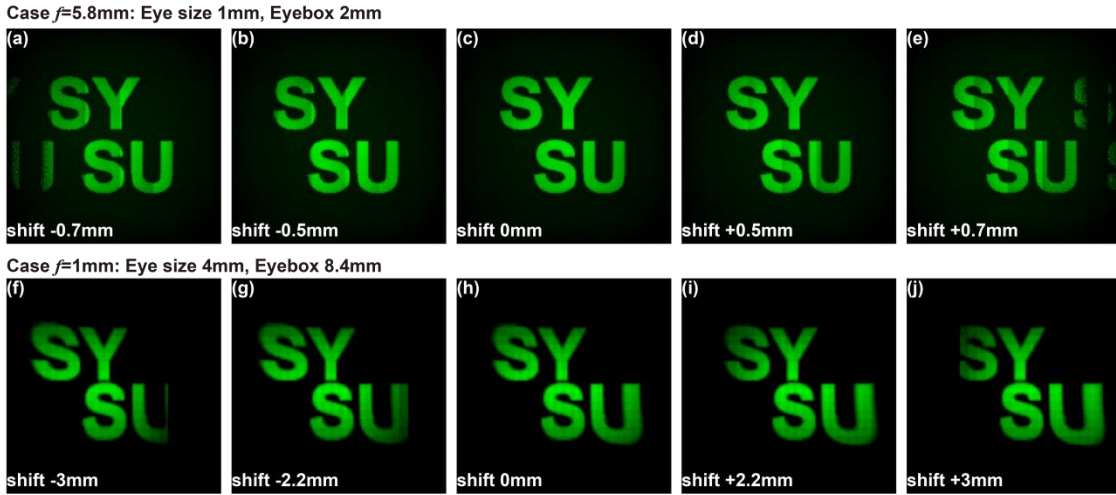


Fig. S11. The eyebox size simulations of different F-number metalens arrays. (a-e) The receiving results of our current metalens array (focal length: 5.8mm, F-number: 12.6) when the eye moves from left to right. The eye size is 1mm, the eye relief is 21mm, and the simulated eyebox is 2mm. (f-j) The receiving results of the small f-number metalens array (focal length: 1mm, F-number: 2.2) when the eye moves from left to right. The eye size is 4mm, the eye relief is 21 mm, and the simulated eyebox is 8.4mm.

Movie S1.

The results of 3D parallax effect under the green light.

Movie S2.

The results of 3D parallax effect under the blue light.

Movie S3.

The results of 3D parallax effect under the red light.

Movie S4.

The results of AR effect under the green light.

Movie S5.

The results of AR effect under the blue light.

Movie S6.

The results of AR effect under the red light.