SUPPLEMENTARY MATERIAL

Decimeter-depth and polarization addressable color 3D meta-holography

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5 pages, 4 figures S1-S4

S1: Error diffusion at any point on holographic plane

When the amplitude information of the complex amplitude hologram is directly removed, each pixel will produce an error, as shown in Eq. (S1):

$$E(x_u, y_v) = T(x_u, y_v) - P(x_u, y_v) \ , \tag{S1}$$

where $T(x_u, y_v)$ is the complex amplitude pixel value of any point (x_u, y_v) on the holographic plane, $P(x_u, y_v)$ is the pure phase pixel value of the point after the amplitude information is discarded, and $E(x_u, y_v)$ is the generated error. By using the error diffusion algorithm [1-2], each pixel is scanned line by line, and the error of each pixel is diffused to the pixels that have not been scanned according to a certain proportion. When the scanning is carried out from top to bottom and from left to right, the error diffusion results of complex amplitude pixel values at any point on the holographic plane are shown in Fig. S1, where k_{mn} is the weight of each position, $\sum_m \sum_n k_{mn} = 1$.

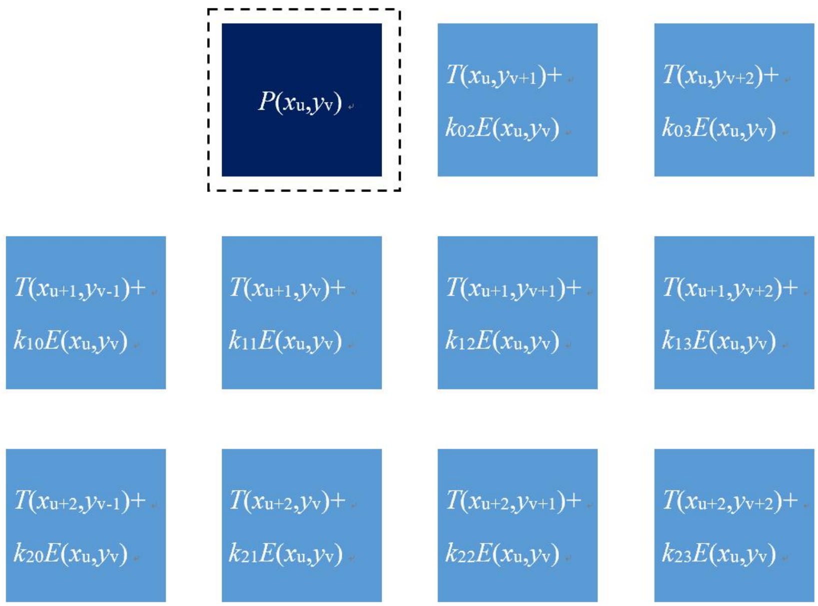

Figure S1 Schematic diagram of the error diffusion at any point on holographic plane.

S2: Depth setting principle and simulation of the hologram

Due to the substantial memory requirements of theoretical full-wave simulations, it is extremely challenging to perform full-wave simulations of the large-scale metasurface. Therefore, the holographic phase is preliminarily simulated by wave optics method, and the holographic 3D reconstruction experiment is verified by spatial light modulator (SLM). As a result, the depth range for holographic 3D reconstruction of metasurface can be obtained, as shown in Fig. S2.

The selected 3D object consists of two letters, “N” and “U” located at different depth planes. The depth of letter “N” is 3 mm, while the depth of letter “U” ranges from 10 mm to 100 mm with a 1 mm interval. Figs. 2S a-d present the simulated reconstruction results of the hologram with a pixel pitch of 0.3 μm and a size of 1500 μm×1500 μm when the depth of letter “U” varies. The pixel pitch and size of the simulated group are consistent with the meta-hologram. In order to verify the accuracy of the simulation based on wave optics, experiments are conducted using the SLM. While the hologram size remaining the same, the pixel pitch of the hologram is changed to 3.74 μm to accommodate the SLM. Figs. 2S e-h present the simulated reconstruction results of the hologram with a pixel pitch of 3.74 μm and a size of 1500 μm×1500 μm, as the depth of the letter "U" varies. Additionally, optical experiments are conducted based on the hologram corresponding to Figs. 2S e-h, and the validation results are shown in Figs. 2S i-l. It can be observed that the three groups of simulation and optical experimental results exhibit consistent performance at different depths.

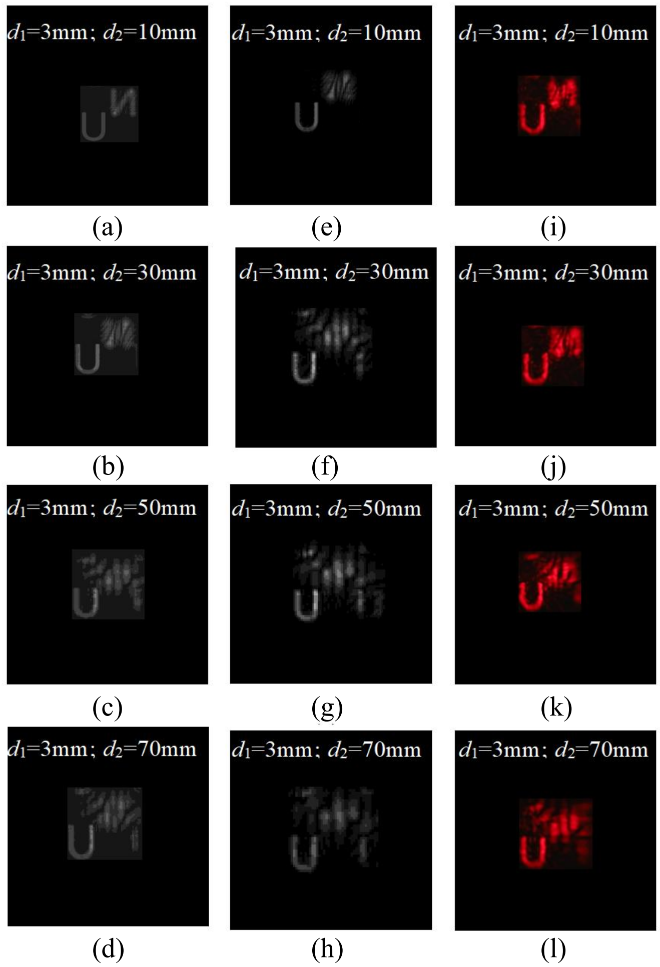

Figure S2 Simulation and optical reconstruction results of the holograms with different depths. a-d Simulation results of holograms with different depths when the pixel pitch is 0.3 μm and the size is 1500 μm×1500 μm. **e-h** Simulation results of holograms with different depths when the pixel pitch is 3.74 μm and the size is 1500 μm×1500 μm. **i-l** Optical results of holograms with different depths when the pixel pitch is 3.74 μm and the size is 1500 μm×1500 μm.

S3: Multi-layer holographic reconstruction results

Our proposed meta-holographic display technology offers continuous depth and a large depth of field, making it applicable to multi-layered meta-holographic reconstruction rather than being limited to only two layers, as shown in Fig. S3. The 3D object consists of "leaves", "sun", "butterfly", and "umbrella" located at different depth planes. The depths of the “leaves”, “sun”, “butterfly” and “umbrella” are 4 mm, 14 mm, 24 mm and 34 mm, respectively. As observed, all four objects can be reconstructed with high quality on their respective depth planes.

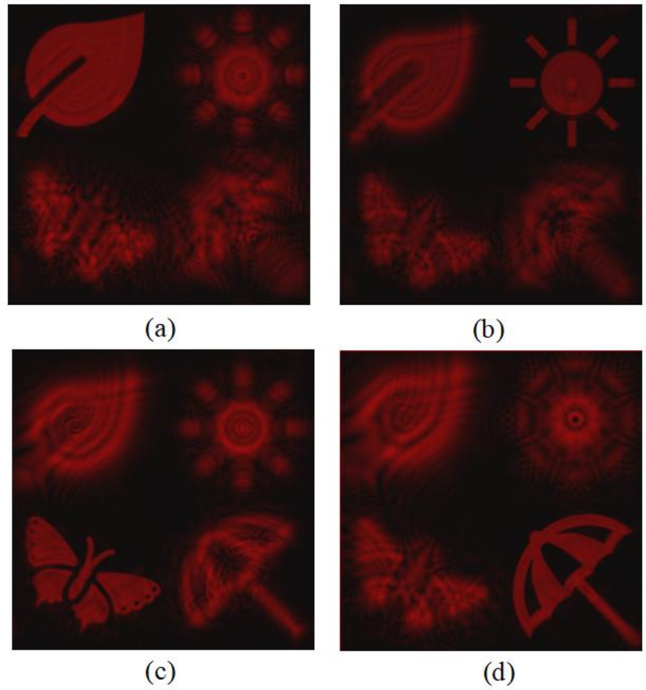

Figure S3 a-d Multi-layer holographic reconstruction results when focusing on 4 mm, 14 mm, 24 mm and 34 mm.

The hologram generated by our proposed method contains all the information of the 3D object at each point, which is different from the calculation method of the 2D multi-object holograms. Tomographic algorithm including Fresnel algorithm and angular spectrum algorithm is a plane-to-plane diffraction propagation calculation method. In holographic reconstruction, the light field along the z-axis near the target reconstruction depth can be regarded as the target reconstruction field with added additional phase factor. Therefore, the out-of-focus blurred light field of the object can still be captured in a long distance, which leads to the problem of crosstalk. In our paper, it can also be seen from the simulation results that with the increase of the depth of the letter “U”, the letter “N” will become more and more blurred, but its blurred diffraction image still exists, thus contributing to the crosstalk.

Currently, the most direct way to solve the crosstalk problem is to superimpose an additional diffraction phase during the meta-hologram generation, and once it is correctly focused at the target depth, the holographic diffraction filed is allowed to diffract quickly later. In future, we will further study this approach to find a solution to eliminate crosstalk and achieve natural and realistic in-focus and out-of-focus effects without damaging the quality of holographic reconstruction images.

S4: Color meta-holographic reconstruction

The meta-hologram based on the angular spectrum diffraction has no problems of positional chromatic aberration and magnification chromatic aberration in holographic reconstruction. However, there are concerns about axial chromatic aberration. When the meta-hologram is irradiated with mismatched wavelengths, the axial displacement is directly proportional to the reconstruction distance and also depends on the wavelengths:

$$z_r = \frac{\lambda_0}{\lambda_r} z \,, \tag{S1}$$

where λ_0 is the predetermined incident light wavelength, z is the predetermined focal depth, λ_r is the actual incident light wavelength, and z_r is the real focal depth when illuminating the hologram with a laser of wavelength λ_r.

When the meta-hologram is illuminated by RGB composite light sources, the gap between RGB holographic images with a depth of 3 mm is very small, and white holographic reconstruction result can be obtained at this position. However, the gap between RGB holographic images with a depth of 70 mm is about 30 mm, which makes it challenging to achieve high-quality white holographic reconstruction, as shown in Fig. S4. Therefore, the proposed algorithm can only realize white holographic reconstruction at close range. The introduction of RGB color reconstruction results in our paper aims to prove that the designed metasurface shows a good diffraction efficiency in all three RGB wavelength bands, and there is no magnification chromatic aberration and position chromatic aberration. In the future, if we want to eliminate axial chromatic aberration, we can consider coding three independent holograms and compensating chromatic aberration in advance, which is also our future research work.

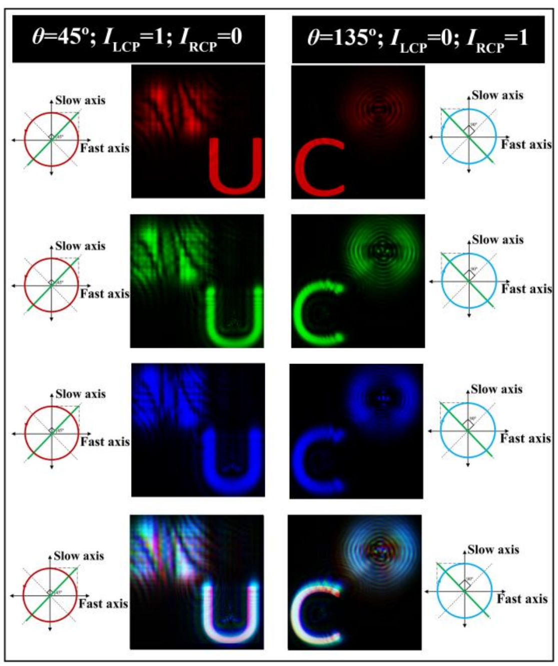

Figure S4 Simulation results of the meta-hologram at 70 mm depth.

References

1. Tsang, P. W. M. et al. Novel method for converting digital Fresnel hologram to phase-only hologram based on bidirectional error diffusion. Opt. Express **21**, 23680-23686 (2013).
2. Min, K. et al. Quality enhancement of binary-encoded amplitude holograms by using error diffusion. Opt. Express **28**, 38140-38154 (2020).