

Supplementary Information for

Discontinuous Orbital Angular Momentum Metasurface Holography

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Supplementary Note 1: Security enhancement of discontinuous OAM holography compared to conventional OAM holography.

Although conventional OAM holography significantly enhances security compared to polarization-encrypted holography, it remains vulnerable to brute-force attacks using randomly incident integer-OAM vortex beams that can fully decode encrypted information. In stark contrast, our discontinuous OAM holography imposes dual-decryption prerequisites: simultaneous acquisition of both topological charge (TC) combination and azimuthal phase distribution for successful image reconstruction.

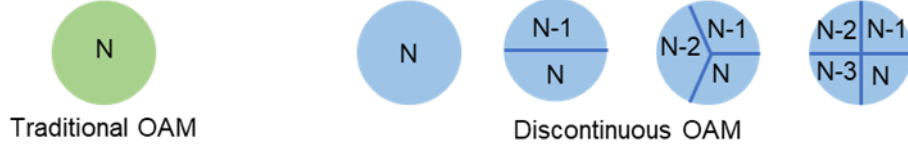


Fig. S1. The number of multiplexing possibilities of conventional OAM and discontinuous OAM modes formed by N topological charges.

As a proof of concept, to quantitatively compare the information security of conventional and discontinuous OAM holography, we use $N = 300$ (with TC ranging from -150 to 150) as an example. The commercialized SLM (model: HOLOEYE PLUTO-2.1-NIR-135) generates vortex beams with a refresh rate of 70 ms. For conventional OAM holography, decoding the information requires inputting 300 distinct OAM modes, which takes only 21 seconds in total. However, for discontinuous OAM holography, the azimuthal partitioning is uncertain. Assuming only four equal partitions (1/2/3/4), the total number of possible combinations is calculated as:

$$N + N * (N - 1) + N * (N - 1) * (N - 2) + N * (N - 1) * (N - 2) * (N - 3) \quad (S1)$$

With 300 TCs, this results in 7965808800 possible configurations, requiring 6454 days—or approximately 17.7 years—to decode by using the commercialized SLM with the same refresh rate of 70 ms. This doesn't even account for the effects of TC mismatches during rotation. Therefore, our discontinuous OAM holography offers a security enhancement of at least 7 orders of magnitude compared to traditional OAM holographic encryption.

Supplementary Note 2: Electric field distribution of discontinuous OAM beam.

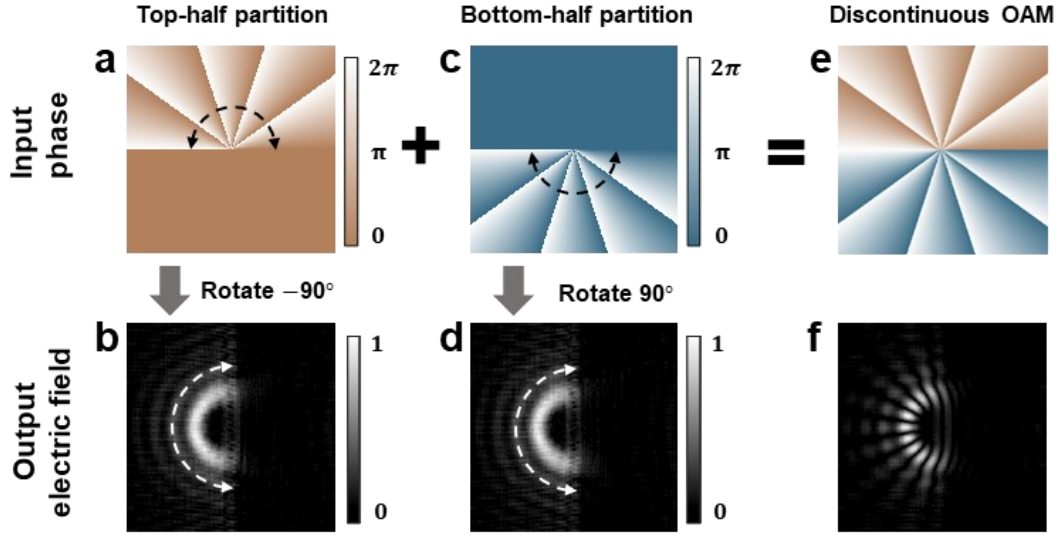


Fig. S2. Input phase and output electric field distribution of a dual-partition discontinuous OAM. (a) The phase distribution of the top-half partition with a negative TC. (b) The corresponding output electric field distribution undergoes a rotation angle of -90° relative to the input phase distribution. (c) The phase distribution of the bottom-half partition with a positive TC. (d) The corresponding output electric field distribution undergoes a rotation angle of 90° relative to the input phase distribution. (e) The combination of the two partitions creates a dual-partition discontinuous OAM. (f) The corresponding output electric field distribution exhibits a “petal-like” pattern due to the interference between the two partitions.

To investigate the optical properties of discontinuous OAM at different rotation angles, we first theoretically calculate the electric field distribution of the discontinuous OAM beam. As a proof of concept, we use a dual-partition discontinuous OAM with opposite TC distributions as shown in Fig. S2. For discontinuous OAM, each partition can be considered as a partially blocked spiral phase plate. The phase of one partition is written as,

$$V_l(\rho, \varphi) = \begin{cases} e^{-il\varphi}, & 0 < \varphi < \pi \\ 0, & \pi < \varphi < 2\pi \end{cases} \quad (\text{S2})$$

where ρ and φ are the radial distance and azimuth of the polar coordinates in the input plane. l is the TC of one partition.

The Fraunhofer diffraction pattern in the focal plane of a lens produced by this phase pattern is given by,

$$E(r, \phi) = C \int_0^R \rho d\rho \int_0^{2\pi} d\varphi V_l(\rho, \varphi) e^{-i(kr\rho/f)\cos(\varphi-\phi)} \quad (\text{S3})$$

where the variables r and ϕ are polar coordinates in the output plane, $k = 2\pi/\lambda$ is the wavevector, f is the focal length of lens, C is a constant.

Each partition of the discontinuous OAM can be considered as a partially blocked

spiral phase plate, which will produce a partial vortex output pattern that is rotated by 90° relative to the input according to the Fraunhofer diffraction theory. The sign of the 90° rotation depends on the sign of the TC. For a phase plate with negative TC in the angular $[0, \pi]$ range as shown in Fig. S2a, the output E of the half pattern OAM can be written as,

$$E(r, \varphi) = C \int_0^R \rho d\rho \int_0^{2\pi} d\varphi * e^{-il\varphi} * e^{-i\left(\frac{kr\rho}{f}\right)\cos(\varphi-\phi)}, \quad 0 < \varphi < \pi \quad (\text{S4})$$

$$E(r, \varphi) = e^{-il(\varphi+\frac{\pi}{2})} C \int_0^R J_m(kr\rho/f) \rho d\rho, \quad 0 < \varphi < \pi \quad (\text{S5})$$

$J(\cdot)$ is the Bessel function. From Eq. S5, it can be seen that the output electric field is rotated counterclockwise by $\frac{\pi}{2}$ (i.e. -90°) relative to the original phase distribution and then is distributed in the region of $[\frac{\pi}{2}, \frac{3\pi}{2}]$. The electric field intensity on the opposite side is zero as shown in Fig. S2b. By performing the coordinate transformation of $\phi = \varphi + \frac{\pi}{2}$, Eq. 3 can be rewritten as:

$$E\left(r, \phi - \frac{\pi}{2}\right) = \begin{cases} e^{-il\phi} C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho, & \frac{\pi}{2} < \phi < \frac{3\pi}{2} \\ 0, & -\frac{\pi}{2} < \phi < \frac{\pi}{2} \end{cases} \quad (\text{S6})$$

For the bottom-half partition as shown in Fig. S2c, the phase distribution spans the angular range of $[\pi, 2\pi]$ with a positive TC. The phase of this part is written as,

$$V_l(\rho, \varphi) = \begin{cases} 0, & 0 < \varphi < \pi \\ e^{il\varphi}, & \pi < \varphi < 2\pi \end{cases} \quad (\text{S7})$$

The electric field distribution is given by:

$$E(r, \varphi) = e^{-il(\varphi-\frac{\pi}{2})} C \int_0^R J_m(kr\rho/f) \rho d\rho, \quad \pi < \varphi < 2\pi \quad (\text{S8})$$

From Eq. S8, it can be seen that the output electric field is rotated clockwise by $\frac{\pi}{2}$ (i.e. 90°) relative to the original phase distribution and then is distributed in the region of $[\frac{\pi}{2}, \frac{3\pi}{2}]$ as shown in Fig. S2d. By performing the coordinate transformation of $\phi = \varphi - \frac{\pi}{2}$, Eq. 8 can be rewritten as:

$$E\left(r, \phi + \frac{\pi}{2}\right) = \begin{cases} 0, & -\frac{\pi}{2} < \phi < \frac{\pi}{2} \\ e^{-il\phi} C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho, & \frac{\pi}{2} < \phi < \frac{3\pi}{2} \end{cases} \quad (\text{S9})$$

Therefore, for the full dual-partition discontinuous OAM as shown in Fig. S2e, the electric field distribution is the superposition of both partitions, occupying the same $[\frac{\pi}{2}, \frac{3\pi}{2}]$ range as shown in Fig. S2f. The electric field distribution in range $[-\frac{\pi}{2}, \frac{\pi}{2}]$ is 0, while the electric field distribution in range $[\frac{\pi}{2}, \frac{3\pi}{2}]$ is the sum of both partitions:

$$\begin{aligned}
E(r, \phi) &= e^{il\phi} C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho + e^{-il\phi} C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho \\
&= (e^{il\phi} + e^{-il\phi}) C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho \\
&= (\cos(l\phi) + i\sin(l\phi) + \cos(-l\phi) + i\sin(-l\phi)) C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho \\
&= 2\cos(l\phi) C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho \tag{S10}
\end{aligned}$$

The final electric field distribution of discontinuous OAM can be expressed as,

$$E\left(r, \phi + \frac{\pi}{2}\right) = \begin{cases} 0, & -\frac{\pi}{2} < \phi < \frac{\pi}{2} \\ 2\cos(l\phi) C \int_0^R J_m\left(\frac{kr\rho}{f}\right) \rho d\rho, & \frac{\pi}{2} < \phi < \frac{3\pi}{2} \end{cases} \tag{S11}$$

It can be seen that the electric field distribution of the dual-partition discontinuous OAM is related to function $\cos(l\phi)$. By plotting $\cos(l\phi)$ as shown in Fig. S3, we can observe ten zeros in the range of $\phi = \left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$, corresponding to ten dark areas with zero intensity in the electric field distribution, resulting in a “petal-like” field distribution as shown in Fig. S2f.

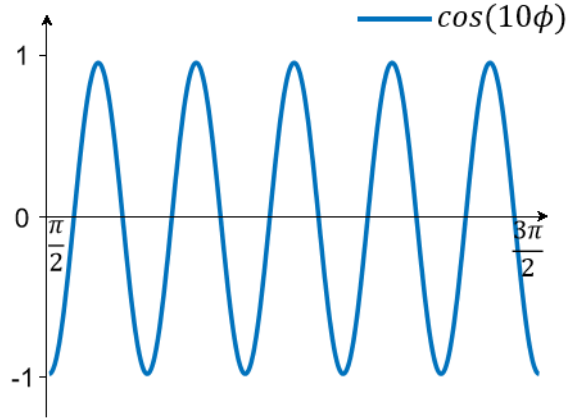


Fig. S3. Electric field distribution of the dual-partition discontinuous OAM is related to function $\cos(l\phi)$.

Supplementary Note 3: Self-orthogonality analysis of discontinuous OAM at different rotation angles.

The orthogonality of the two beams can be determined by integrating the normalized inner product H of the two vortex beams in the angular direction. Assuming that the field distributions of any two beams are u_1 and u_2 , their corresponding normalized fields u_{n1} and u_{n2} can be described as:

$$u_{n1} = \frac{u_1}{\sqrt{\int_0^{2\pi} u_1^2 d\varphi}} \quad (\text{S12})$$

$$u_{n2} = \frac{u_2}{\sqrt{\int_0^{2\pi} u_2^2 d\varphi}} \quad (\text{S13})$$

where φ represents the azimuth angle of the beam. Therefore, the inner product H can be written as:

$$H = \int_0^{2\pi} u_{n1} * u_{n2} d\varphi \quad (\text{S14})$$

In Mode 1 as shown in the main text Fig. 1c, the inner product of the two beams (denoted as H_1) approaches zero, indicating complete orthogonality. Since the orthogonality and inner product are inversely related, their relationship can be expressed as:

$$O = 1 - H \quad (\text{S15})$$

For Mode 1, the orthogonality is 1. For Mode 2, the orthogonality is 0.5, which lies between 0 and 1, indicating that the two beams are neither orthogonal nor parallel due to their partial overlap as shown in Fig. 1d of the main text.

Supplementary Note 4: Orthogonality analysis between conventional OAM holography and discontinuous OAM holography.

We quantitatively calculate the inner product between the incident light and encoded beams to distinguish between conventional constant OAM holography and the proposed discontinuous OAM holography. For both types of holography, the incident OAM must have the opposite TC compared to the encoded OAM in order to decode the holography. In traditional OAM holography, the inner product between the incident decoding OAM and the encoded beam remains zero regardless of the incident beam's rotational angle as shown in Fig. S4a, indicating perfect orthogonality across all rotation angles. Consequently, the decoded image exhibits little signal-to-noise ratio (SNR) variation during rotation. In contrast, the discontinuous OAM holography demonstrates azimuth-dependent orthogonality. As the incident beam rotates, the inner product gradually increases, indicating that the orthogonality is reduced, leading to progressively increasing SNR as depicted in Fig. S4b. This dynamic orthogonality can enhance cryptographic security by requiring precise azimuth alignment for decoding.

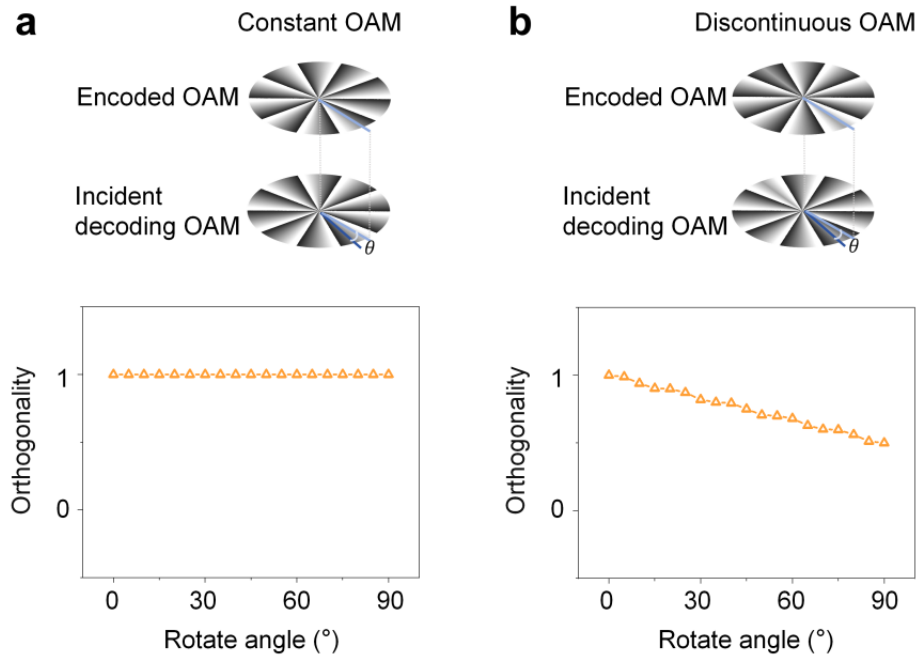


Fig. S4. The inner product between the incident decoding beam and encoded beam. (a) Traditional constant OAM. (b) Discontinuous OAM.

Supplementary Note 5: The flowchart of the modified weighted Gerchberg-Saxton (WGS) algorithm for each holographic channel.

The algorithm flowchart is shown in the Fig. S5. In order to maintain the OAM characteristics in each pixel of the reconstructed holographic image, it is necessary to spatially sample the holographic image using a two-dimensional (2D) Dirac comb function that depends on OAM to avoid spatial overlap of the spiral wavefront kernel. The sampled image and random phase are used as the complex amplitude of WGS for iteration².

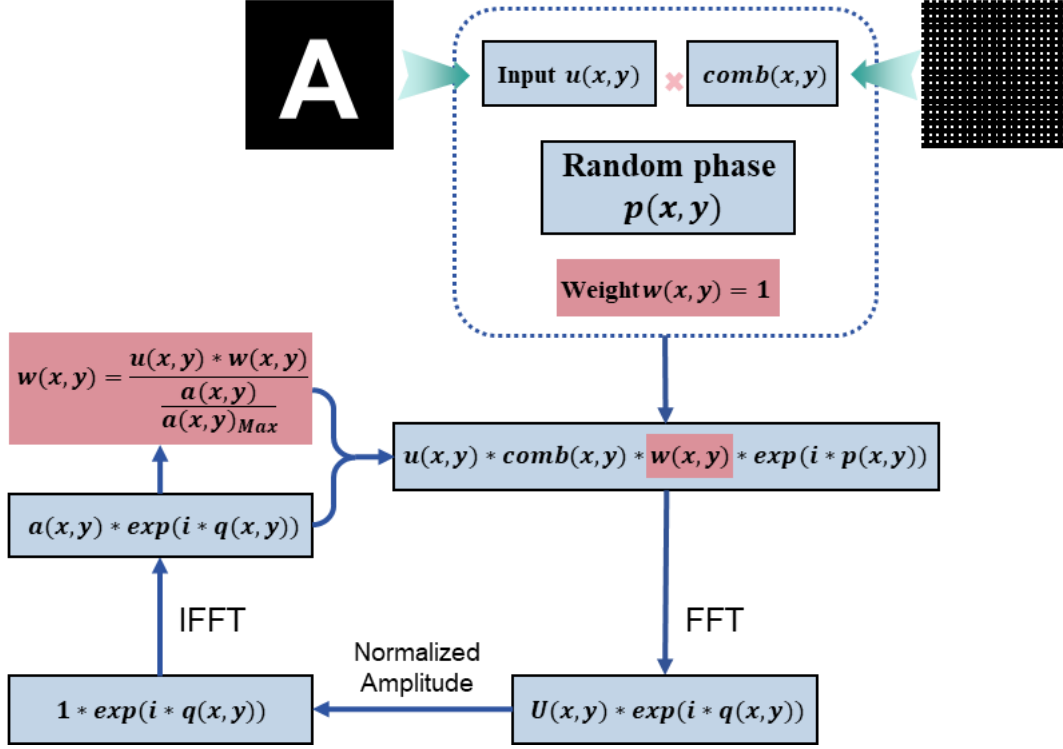


Fig. S5. The flowchart of modified WGS algorithm for each holographic channel.

Here, (x,y) represent the coordinates, $w(x,y)$ represents the weight factor, $u(x,y)$ represent the amplitude of the input image, $p(x,y)$ represents the phase on the image plane, $a(x,y)$ and $q(x,y)$ represent the amplitude and phase in the metasurface plane, $\frac{a(x,y)}{a(x,y)_{Max}}$ indicates the normalized amplitude, $comb(x,y)$ denotes the sampling function to conserve the OAM selectivity, FFT represents the Fast Fourier Transform, IFFT is the inverse Fast Fourier Transform. Through sufficient iterations, the amplitude $a(x,y)$ in the metasurface plane converges to near-unity. Therefore, a pure holographic phase information $q(x,y)$ for each holographic channel can be obtained.

Supplementary Note 6: Design of the geometry-phase metasurface.

The transmission efficiency and phase retardation of light scattered from TiO₂ nanopillars were numerically characterized using the commercial software COMSOL as shown in Fig. S6. Numerical characterization of cross-polarization amplitude transmission and phase after transmission through nanopillars of different widths and lengths. Selected nanopillar is marked with asterisks in the Fig. S6a and Fig. S6b. δ represents the rotation angle of the nanopillar. When the incident light is left-handed circularly polarization (LCP), the nanopillar will convert it into right-handed circularly polarization (RCP) and impose a geometry phase of 2δ as shown in Fig. S6c. The circular polarization (CP) conversion efficiency of the nanopillar is shown in the red line, showing high CP conversion efficiency across all rotation angles. The rotation angle of the nanopillars can be determined using the following formula:

$$\delta = \frac{\varphi - \sigma}{2} \quad (\text{S16})$$

where φ represents the holography phase, σ represents the propagation phase of the nanopillar. Since all the nanopillars have the same length and width, the propagation phase is constant and can be ignored. Therefore, a pure geometry-phase is used in our design. The blue dots represent the simulated geometry-phase at different rotation angles, with the theoretical values presented by the blue line. The nanopillars exhibit high conversion efficiency across the wavelength of 450 nm - 700 nm in Fig. S6d, enabling broadband modulation capabilities. In the experiment, the discontinuous OAM multiplexed meta-hologram with a footprint of 280 μm by 280 μm and a lattice constant of 350 nm by 350 nm is fabricated.

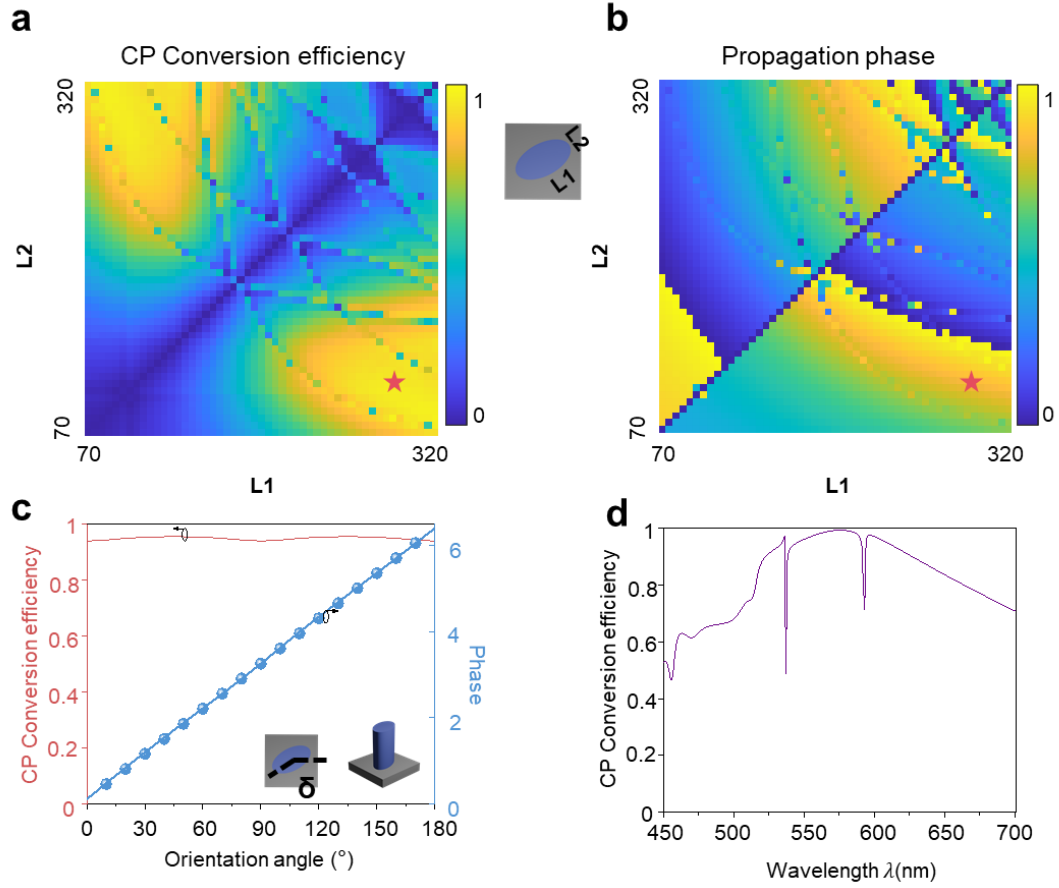


Fig. S6. The simulation results of CP conversion efficiency, propagation phase and geometry phase of the nanopillars. (a) Calculated CP conversion efficiency of the nanopillars at the wavelength of 532 nm. (b) Calculated propagation phase of the nanopillars at the wavelength of 532 nm. L_1 and L_2 are the length and width of the nanopillars. The chosen nanopillars is marked by a red star. (c) The CP conversion efficiency and geometry phase of the nanopillars as a function of the rotation angle δ . (d) The spectrum of the CP conversion efficiency of the chosen nanopillars at the wavelength range of 450 nm - 700 nm.

Supplementary Note 7: Numerical characterization of the impact of angular and lateral misalignment in discontinuous OAM holography.

Our investigation into the effects of angular and lateral misalignment in discontinuous OAM holography reveals important operational characteristics of this technique. Using a four-channel discontinuous OAM hologram as an example, we find that this holographic approach demonstrates practical tolerance to angular misalignment, maintaining a clear reconstruction of image “A” with near-perfect Gaussian spots within a $\pm 4^\circ$ rotation range as shown in Fig. S7a. This indicates the inherent robustness of the technique in image decoding. However, at a rotation angle of $\pm 5^\circ$, the Gaussian spots in the reconstructed image begin to deteriorate. Fig. S7b shows that as the angular deviation increases significantly, the reconstructed image completely shifts to the output pattern of a different channel.

Regarding positional deviations, Fig. S8 shows that lateral misalignment up to 2% ($\sim 6 \mu m$) preserves the near-perfect Gaussian spot characteristics of image “A”, while at 3% ($\sim 9 \mu m$) deviation, the Gaussian profile deteriorates. This tolerance also extends to combined x - y plane misalignments, where the holographic reconstruction successfully decodes image “A” with recognizable Gaussian spots at 1-2% composite deviation.

These findings demonstrate that discontinuous OAM holography maintains functionality under practical alignment variations while providing enhanced security through its angular dependence and misalignment tolerance characteristics.

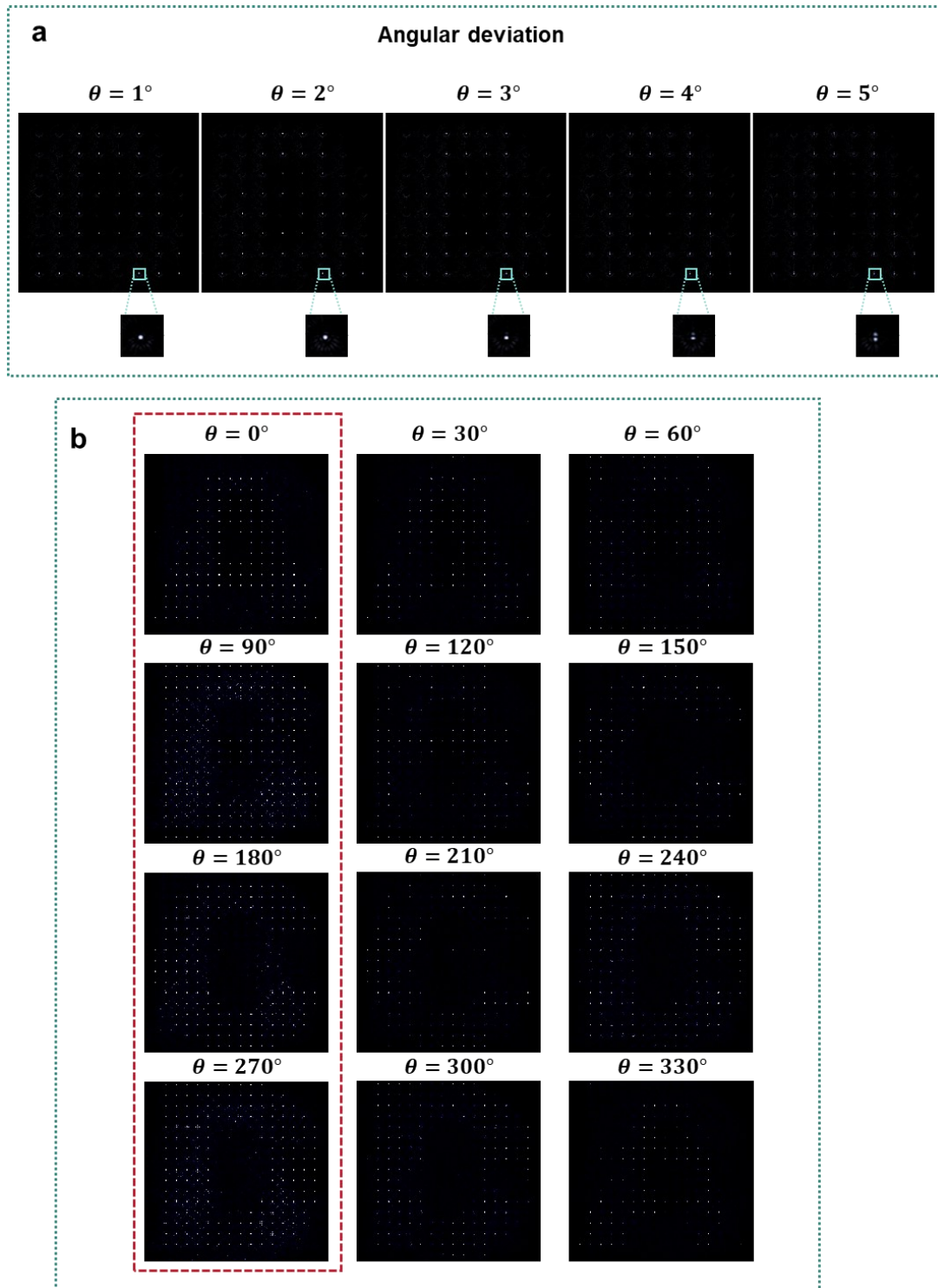


Fig. S7. Numerical results demonstrating the impact of angular misalignment in discontinuous OAM holography. (a) Holographic reconstruction based on a discontinuous OAM meta-hologram with slight angular deviation. (b) Holographic reconstruction based on a discontinuous OAM meta-hologram with large angular deviation. When the incident angle is rotated at different angles, the decoded holography appears clear “A”, “B”, “C” and “D” patterns at the rotation angle of 0° , 90° , 180° , and 270° , respectively. However, for other rotation angles, significant crosstalk is observed.

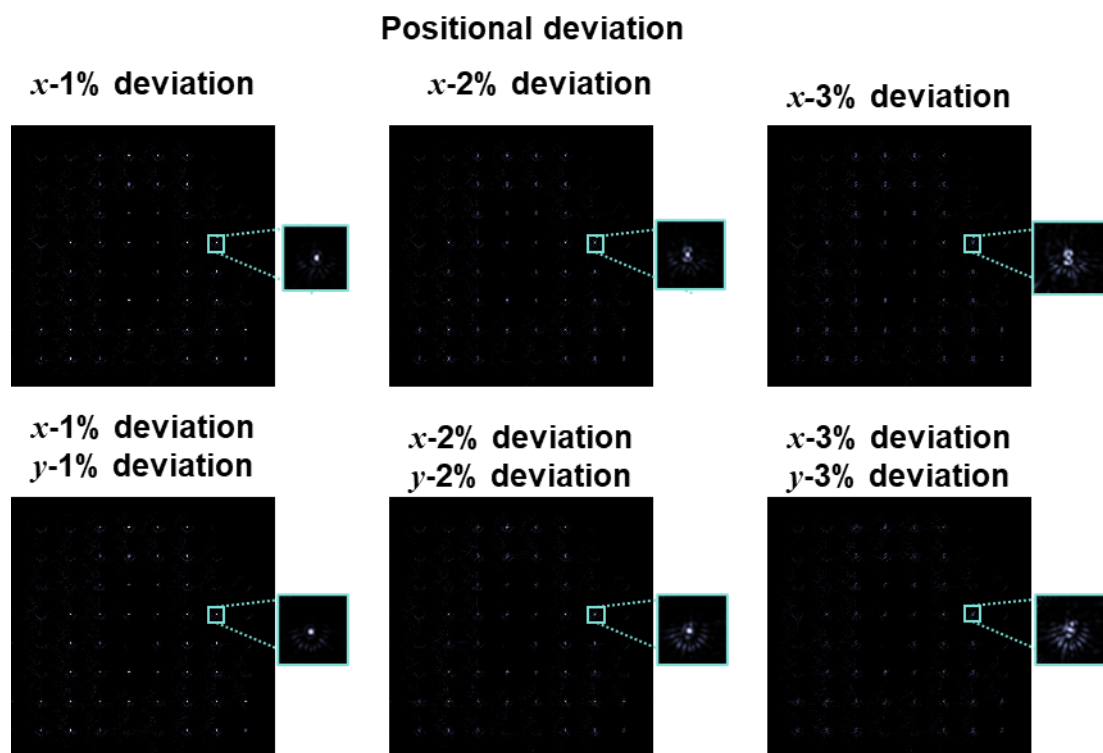


Fig. S8. Numerical results of the reconstructed images demonstrating the impact of lateral misalignment in discontinuous OAM holography.

Supplementary Note 8: Image quality analysis between conventional OAM holography and discontinuous OAM holography based on a phase-only metasurface

Both discontinuous OAM holography and conventional OAM holography can reconstruct high-quality images featuring Gaussian-like spot distributions when fully decoded as shown in Fig. S9. We employ the SNR as the quantitative metric for image quality assessment, calculated as:

$$SNR = 10 \lg \frac{P_s}{P_n} \quad (S17)$$

P_s represents the signal power of the image, and here we use the intensity of the encoded image instead, while P_n denotes the noise power. When the SNR is 1 (i.e., 0 dB), it indicates that the average power of the signal is equal to the average power of the noise. To quantitatively compare cross-talk levels between the two methods, we selected decoded single-channel image “A” within a four-channel holography system for quality analysis. This approach enables direct comparison of cross-talk magnitudes generated by both methods as shown in Fig. S10. As shown by the blue curve, SNR remains essentially constant as the incident light rotates, maintaining relatively good image quality and low cross-talk. In discontinuous OAM holography, high-quality decoding of image “A” occurs around 0° rotation angle, while reconstruction fails at other angles. However, under full decoding conditions, both methods exhibit comparable cross-talk levels.

Consequently, our proposed discontinuous OAM holography methodology achieves multi-channel switching under single-incident-beam illumination without increasing cross-talk.

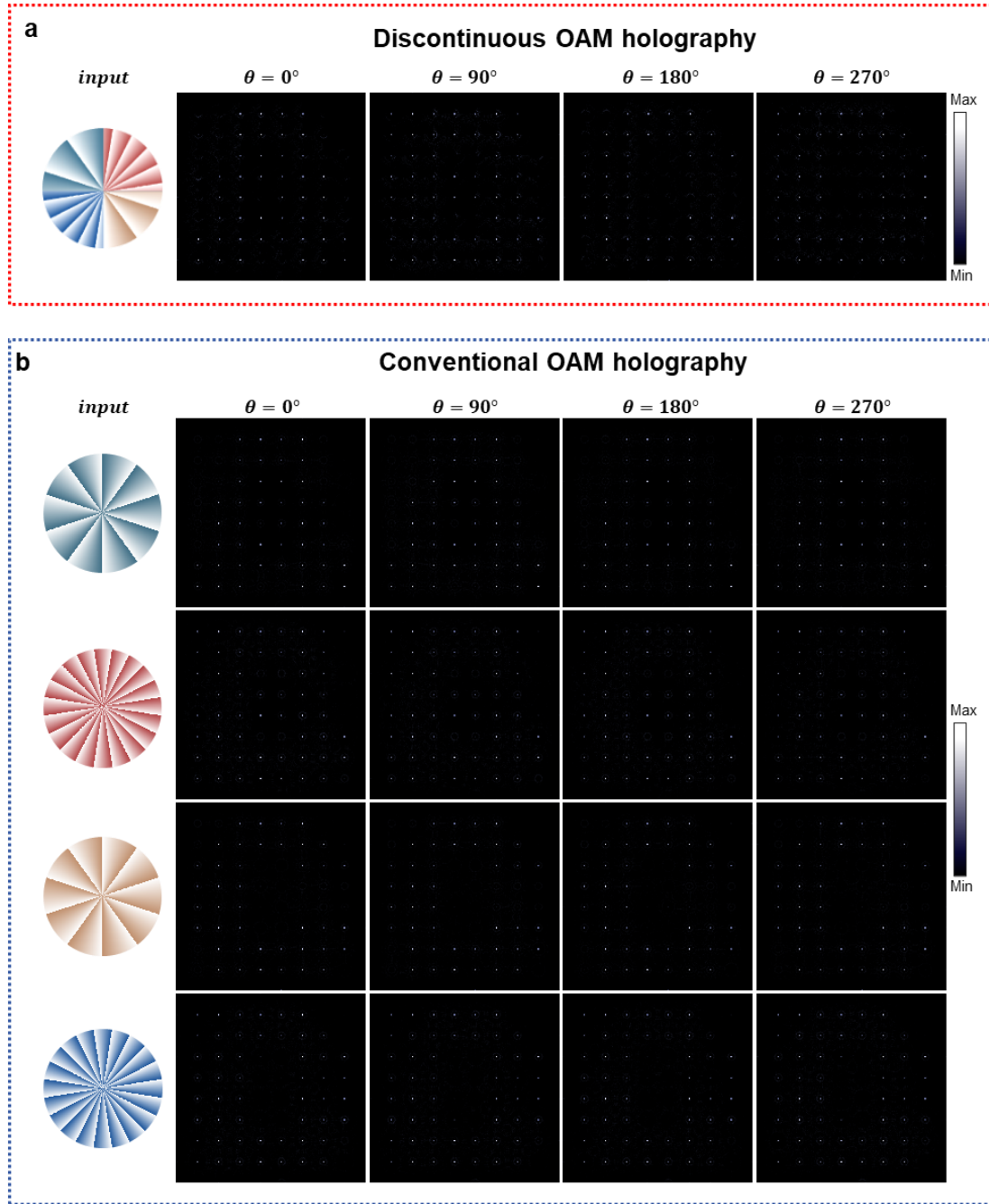


Fig. S9. The decoded holographic images of discontinuous OAM holography and conventional OAM holography with a phase-only metasurface. (a) Simulation results of discontinuous OAM holography. (b) Simulation results of conventional holography.

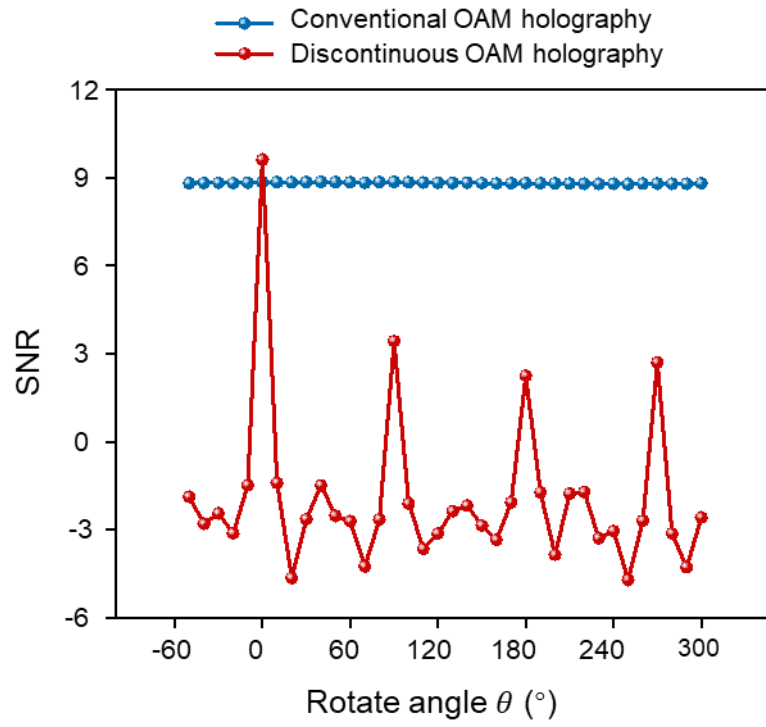


Fig. S10. Relationship between SNR and incident light rotation angle for conventional OAM holography and discontinuous OAM holography.

Supplementary Note 9: Discontinuous OAM holography with same-sign TCs

To expand the application scope of discontinuous OAM holography, we computationally and experimentally demonstrated that discontinuous OAM holography can be achieved using same-sign TCs. Specifically, we encoded two-channel discontinuous OAM holography with two all-positive TCs $l = 1/l = 11$. The phase distributions, simulated and experimental results of the two-channel discontinuous OAM modes are shown in Fig. S11. The results demonstrate that discontinuous OAM holography encoded with all-positive TCs can also achieve multi-channel multiplexing.

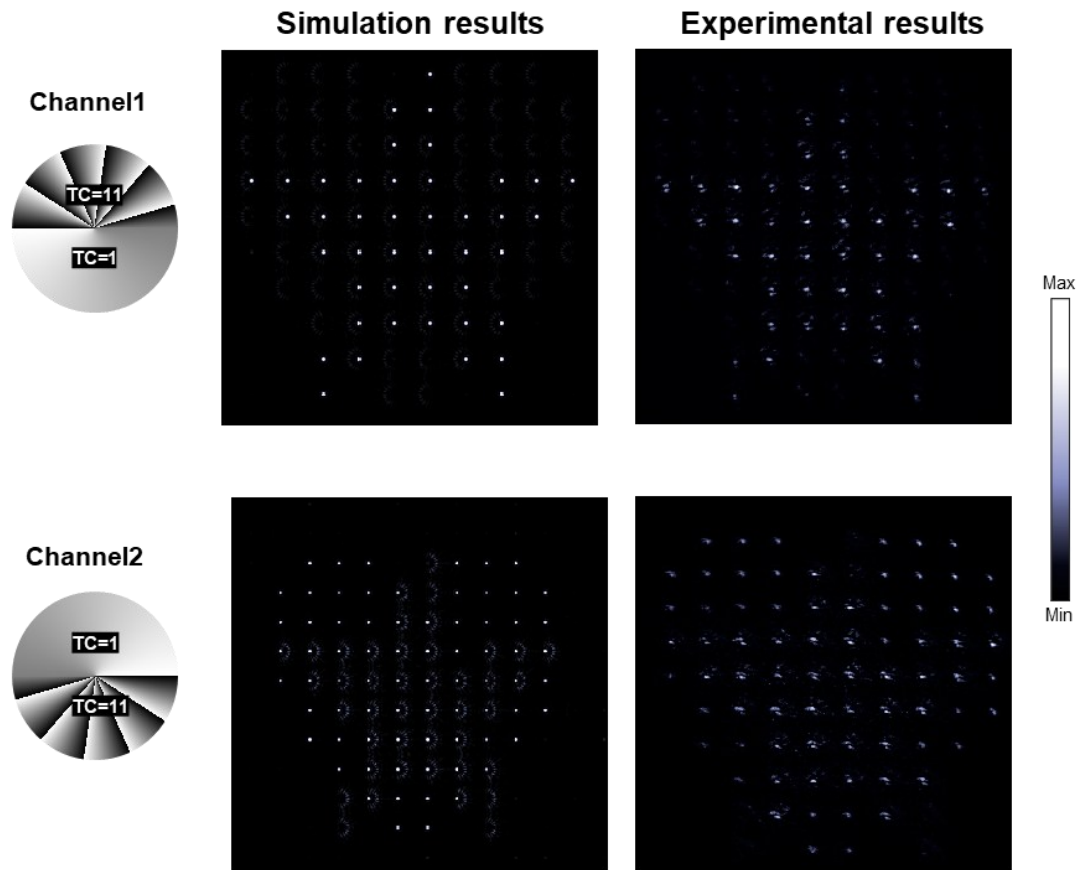


Fig. S11. Simulated and experimental results of two-channel discontinuous OAM holography with same-sign topological charges.

Supplementary Note 10: The design of multiple-discontinuous-OAM multiplexing holography.

To further expand multiplexing dimensions and enhance channel capacity, we incorporated multiple pairs of discontinuous OAMs as an additional degree of freedom. Specifically, we designed a six-channel multiplexed metasurface holography by integrating three pairs of discontinuous OAM. The design workflow of the holographic phase information is detailed in Fig. S12. In each channel, the input image is multiplied by a 2D Dirac comb function spatially positioned at distinct locations across the optical field. Following a modified WGS algorithm for phase extraction, the acquired phase is encoded by three orthogonal discontinuous OAM modes: $l = 10/l = -10, l = 15/l = -15, l = 20/l = -20$. The superposition of all channels enables the realization of multiple-discontinuous-OAM multiplexing holography. The discontinuous OAM azimuthal distributions of these modes are shown in the left panel of Fig. S13a. This spectral complexity inherently enhances security by preventing unauthorized access through brute-force OAM mode matching. Experimental results in Fig. S13b demonstrate the successful decoding of all six channels at different locations, with the reconstructed images exhibiting near-perfect Gaussian spot profiles.

It should be noted that the numerals and letters in the holographic images across different channels are designed to occupy the same spatial position in all figures of the main text and Supplementary materials, except for Figs. S13, S14, S16 and S19, where they are intentionally placed at different positions to demonstrate the versatility of our approach for improving the channel numbers.

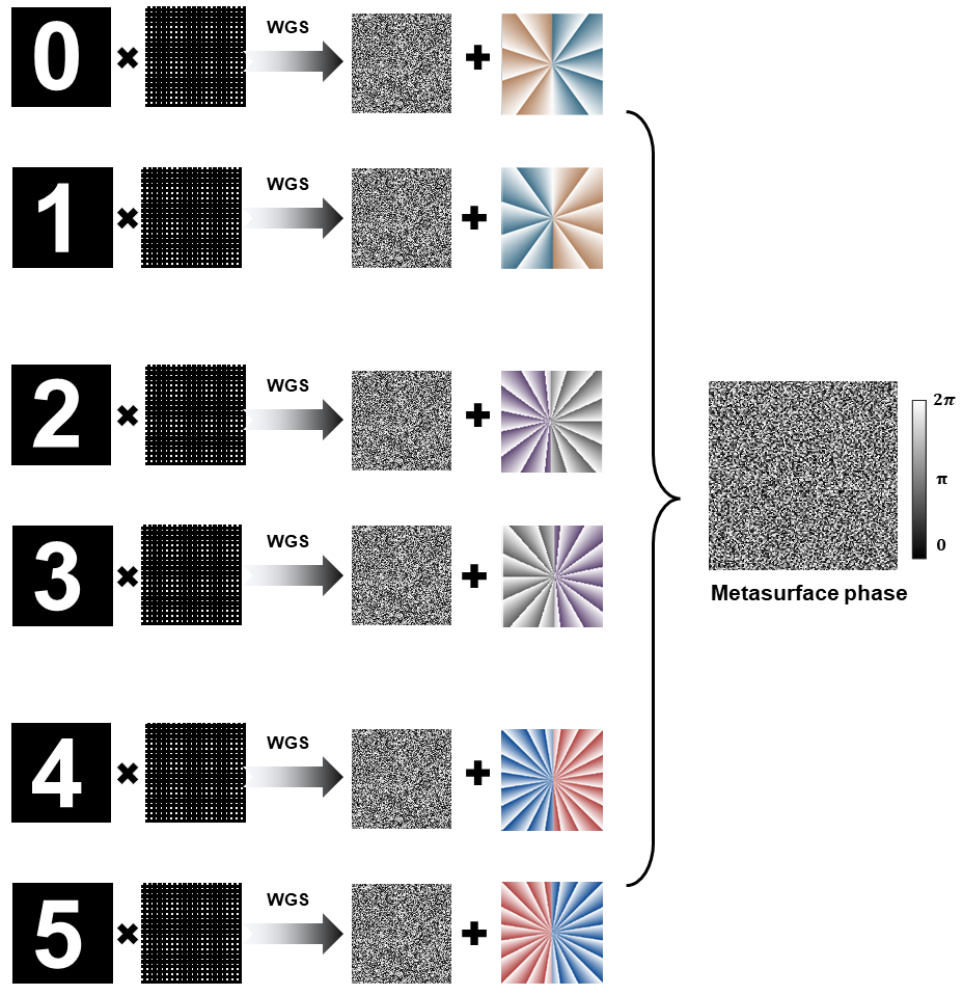


Fig. S12. The algorithm flowchart of multiple-discontinuous-OAM multiplexing holography.

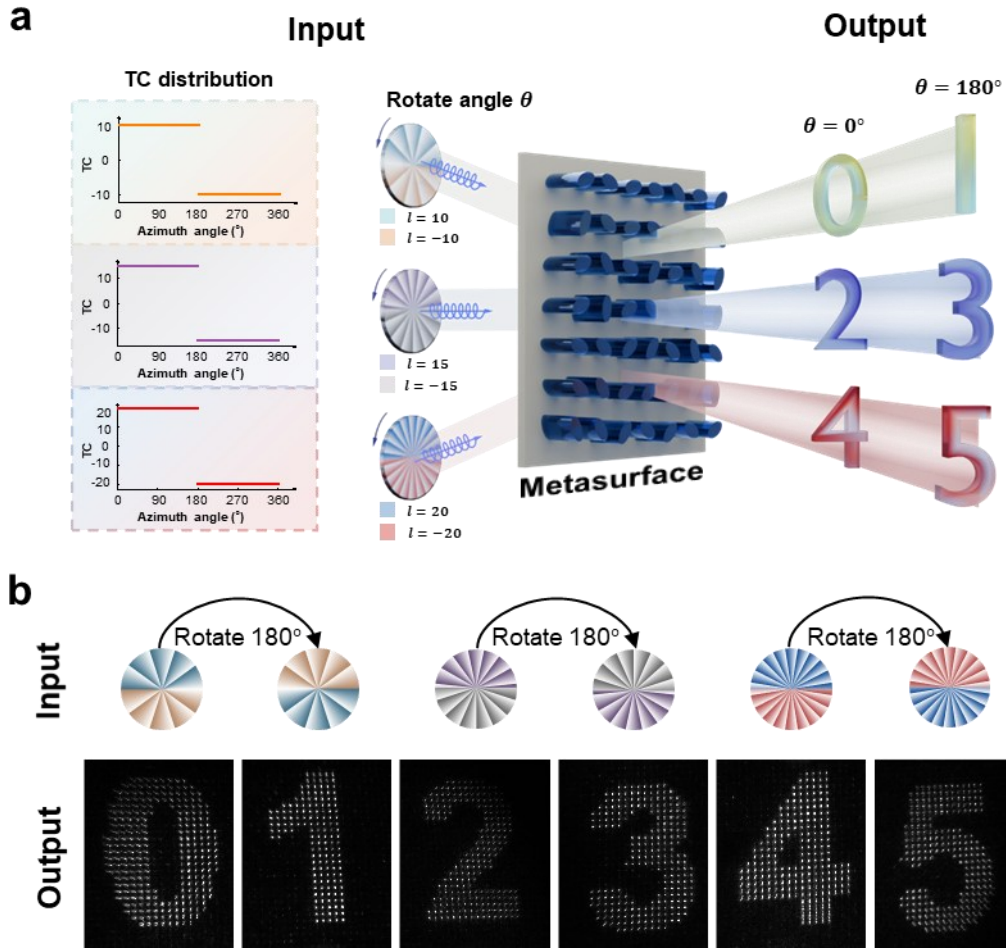


Fig. S13. Multiplexing OAM holography by integrating various pairs of discontinuous OAM modes. (a) Schematic diagram. When the incident discontinuous OAM mode is $l = 10/l = -10$, the output images are “0” and “1”; when the incident discontinuous OAM mode is $l = 15/l = -15$, the output images are “2” and “3”; when the incident discontinuous OAM mode is $l = 20/l = -20$, the output images are “4” and “5”. The TC distributions of these three modes are shown in the left panel. (b) Experiment results of the six channels under proper illumination of TC distribution and rotation angle of incident beam.

The experimental results of multiple-discontinuous-OAM multiplexing holography are shown in Fig. S14. To better visualize the spatial intensity profiles of non-decoded channels under discontinuous OAM illumination, we strategically positioned six channels at distinct areas. This design enables clear differentiation: only the fully decoded image exhibits a Gaussian spot (indicating perfect orthogonality), while non-decoded channels display semi-annular or hybrid intensity patterns, resulting from partial overlap between incident discontinuous OAM and encoded phase profiles.

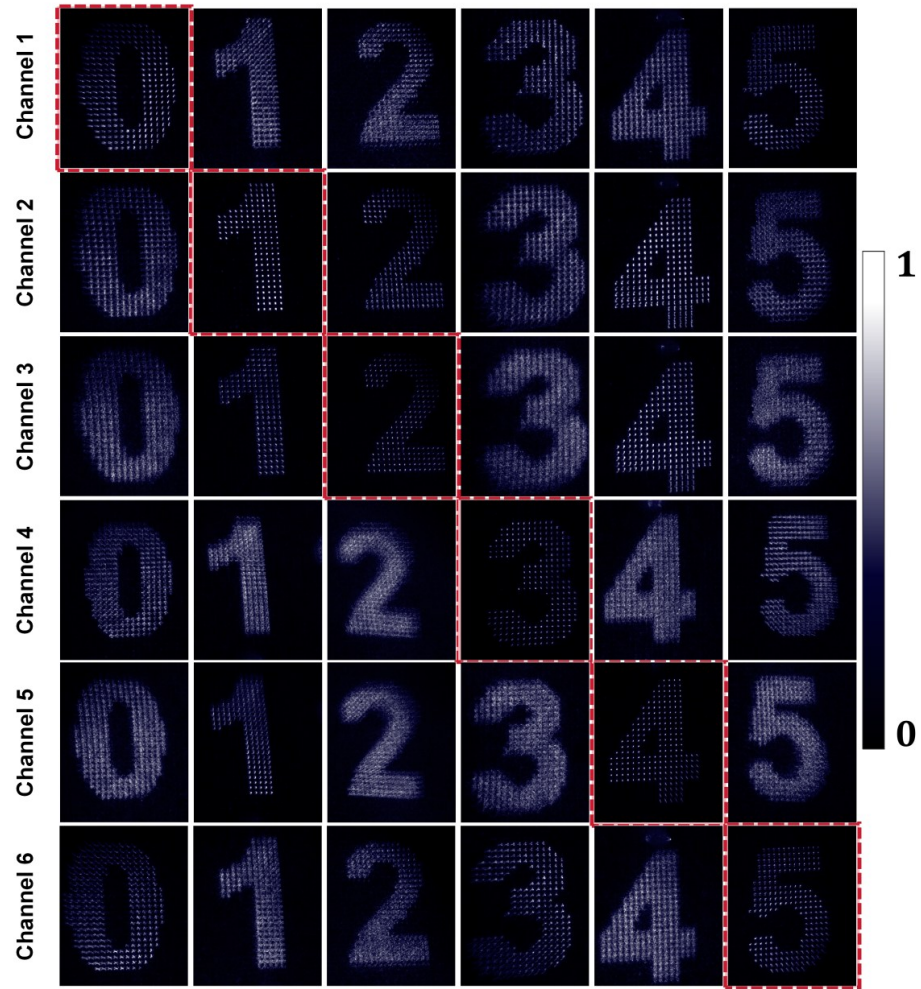


Fig. S14. Experimental results of multiple-discontinuous-OAM holography. The red boxes indicate the fully decoded images under proper discontinuous OAM illumination.

Supplementary Note 11: Alignment of metasurface with the discontinuous OAM during experiments.

In discontinuous OAM holography, precise alignment between the discontinuous OAM beam and the metasurface center is critical for successful decoding. For the decoding process, the angle of the rotating incident light can be controlled by either rotating the SLM or the metasurface. In our experiment, we fix the SLM and rotate the metasurface. Specifically, the metasurface is mounted on a manual rotation platform (model: CMRM1 from LBTEK) with a minimum scale of 2° , which fully meets the precision requirements of this study. To ensure that the center of the sample coincides with the rotation axis of the rotating platform, an XY translator (model: TXY1SQ from LBTEK) is added, as shown in Fig. S15c. The fully assembled unit, including the rotation platform and XY translator, is placed on a translation stage (model: LSS40-13C3 from LBTEK) to align the metasurface with the discontinuous OAM.

The alignment process consists of two stages: coarse adjustment and fine adjustment.

1. Coarse adjustment

To facilitate coarse alignment of the metasurface and incident OAM beam, we constructed a direct imaging path with two-lens relay to magnify both the metasurface and the incident OAM beam. This configuration allows for clear visualization on the CMOS, as illustrated Fig. S15a. The original holograph optical setup is shown in Fig. S15b, where an additional lens is inserted in front of the CMOS to perform a Fourier transform, thereby enabling the acquisition of holographic images.

The coarse adjustment results are as shown in Fig. S15d. The first row displays the magnified metasurface and incident beam captured by the CMOS. The red dashed circle marks the incident discontinuous OAM beam, while the blue dashed circle outlines the metasurface. The second row shows the corresponding holographic images. When the incident OAM beam and metasurface show no overlap, the beam remains unmodulated by the metasurface, resulting in no holographic output. Partial overlap between the beam and metasurface generates a superposition of image “0” and “1” in the imaging plane. Only when the incident beam fully overlaps with the metasurface does a relatively clear reconstructed image emerge.

2. Fine adjustment

Once coarse alignment is achieved, fine alignment is then performed by precisely adjusting the translation stage, ensuring that the image spot evolves into a well-defined Gaussian profile. After fine adjustment, a clear resolved image “0” with a Gaussian spot is shown in Fig. S15e.

It should be noted that the angle of the rotating incident light is equivalently represented by changing the phase distribution of the SLM, which is the most straightforward and simplest method that can be used in the experiment.

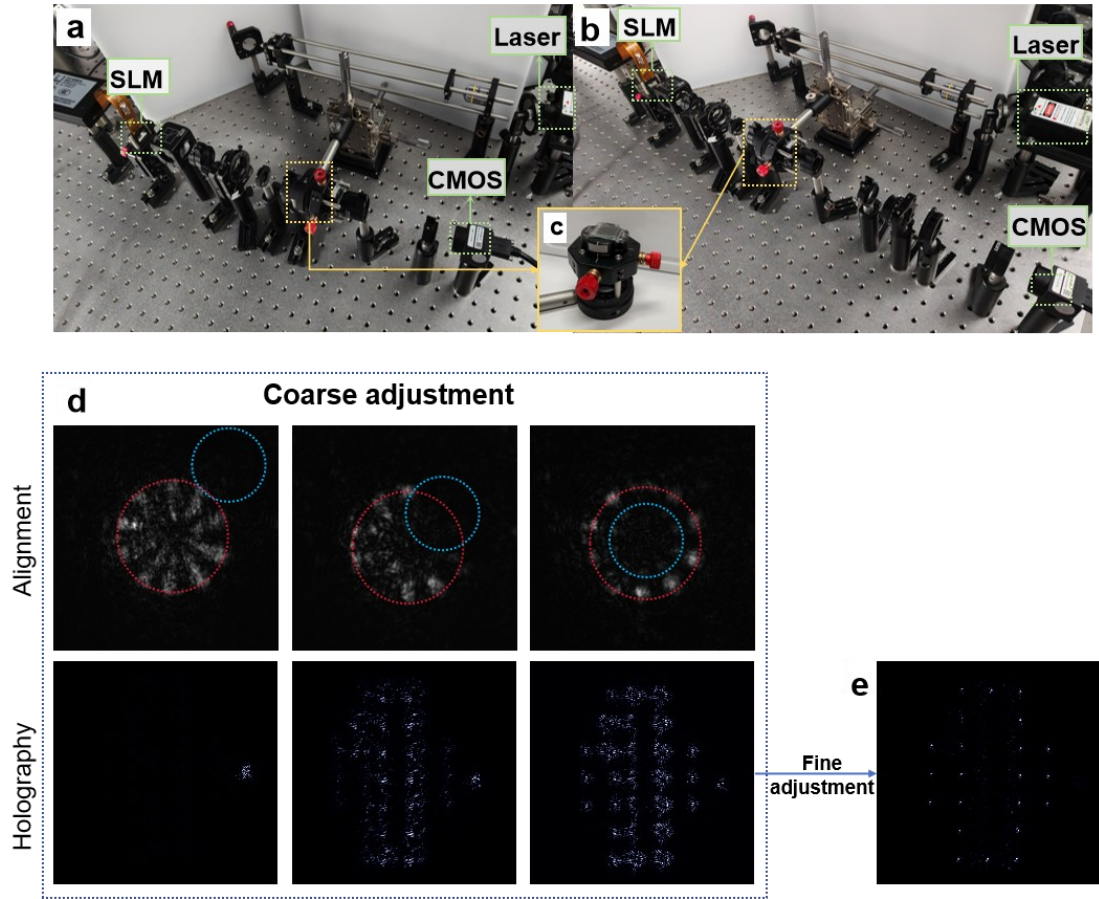


Fig. S15. Optical setup of discontinuous OAM holography. (a) Optical setup for coarse adjustment. (b) Optical setup of discontinuous OAM holography. (c) The manual rotation platform added with an XY translator. (d) First row: the alignment of incident discontinuous OAM and metasurface. Second row: the corresponding holographic images. The red dashed circle marks the incident discontinuous OAM beam, while the blue dashed circle outlines the metasurface. (e) Holographic image after fine adjustment.

Supplementary Note 12: The capacity limit of discontinuous OAM holography.

Theoretically, the number of channels in discontinuous OAM holography is unlimited because the 2π azimuthal angle can be infinitely divided. However, the crosstalk between different channels will increase. As shown in Fig. S16, we calculated the SNR of discontinuous OAM holography with different numbers of channels. As the number of channels grows, the SNR of the decoded image gradually increases, while the crosstalk also intensifies. When the number of channels in discontinuous OAM holography increases to 42, the SNR of all holographic channels drops to the range of 0-2 which indicates that the signal and noise have become inseparable. This indicates that the noise (i.e., crosstalk) becomes nearly equivalent to the signal (the decoded hologram), demonstrating that the quality of the decoded holographic signal is severely degraded and multi-channel encryption can no longer be effectively achieved.

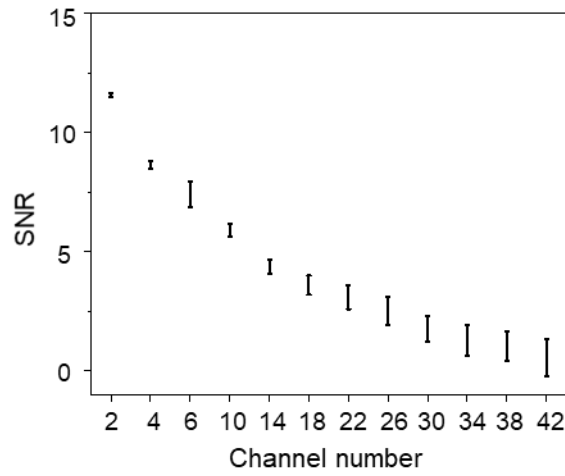


Fig. S16. The SNR of discontinuous OAM holography with different numbers of channels. The error bars represent the range between the maximum and minimum SNR values across all channels in the multi-channel discontinuous OAM holography.

Supplementary Note 13: Discontinuous fractional and perfect OAM holography.

The concept of discontinuous OAM holography can be extended to other types of beams. This method is universal—it is applicable not only to conventional OAM beams, but also to fractional vortex beams^[3] and perfect vortex beams^[4]. The only requirement is that the OAM modes encoded at different angular positions must be mutually orthogonal. Here, we demonstrate the implementation of two-channel discontinuous OAM holography using fractional vortex beams and perfect vortex beams as an example.

The discontinuous OAM is encoded with fractional TC of +10.5 in the upper half and −10.5 in the lower half, as shown in Fig. S17a. These two regions correspond to two independent holographic channels. The decoded reconstructed results are shown in Fig. S17b. When illuminated by the discontinuous fractional OAM beams with this specific configuration, the image “0” is successfully decoded, after rotating the beam by 180 degrees, the decoded image switches from image “0” to image “1”. Also, the discontinuous OAM encoded with perfect vortex beams is shown in Fig. S17c. The decoded reconstruction results are shown in Fig. S17d. Both channels of discontinuous fractional OAM holography and discontinuous perfect OAM holography demonstrate excellent performance.

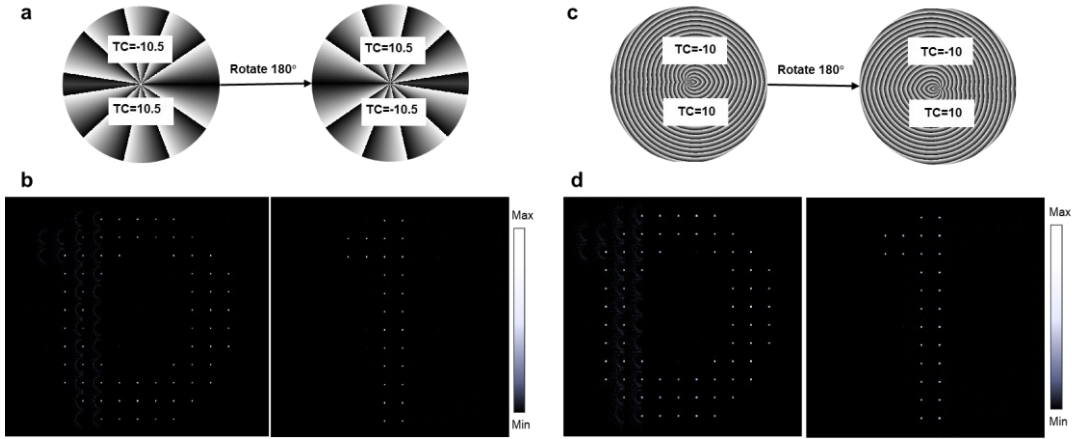


Fig. S17. Discontinuous OAM holography using fractional vortex beams and perfect vortex beams. (a) Phase distribution of discontinuous fractional vortex beams. **(b)** Experimental results of two-channel discontinuous fractional OAM holography. **(c)** Phase distribution of discontinuous perfect vortex beams. **(d)** Experimental results of two-channel discontinuous perfect OAM holography.

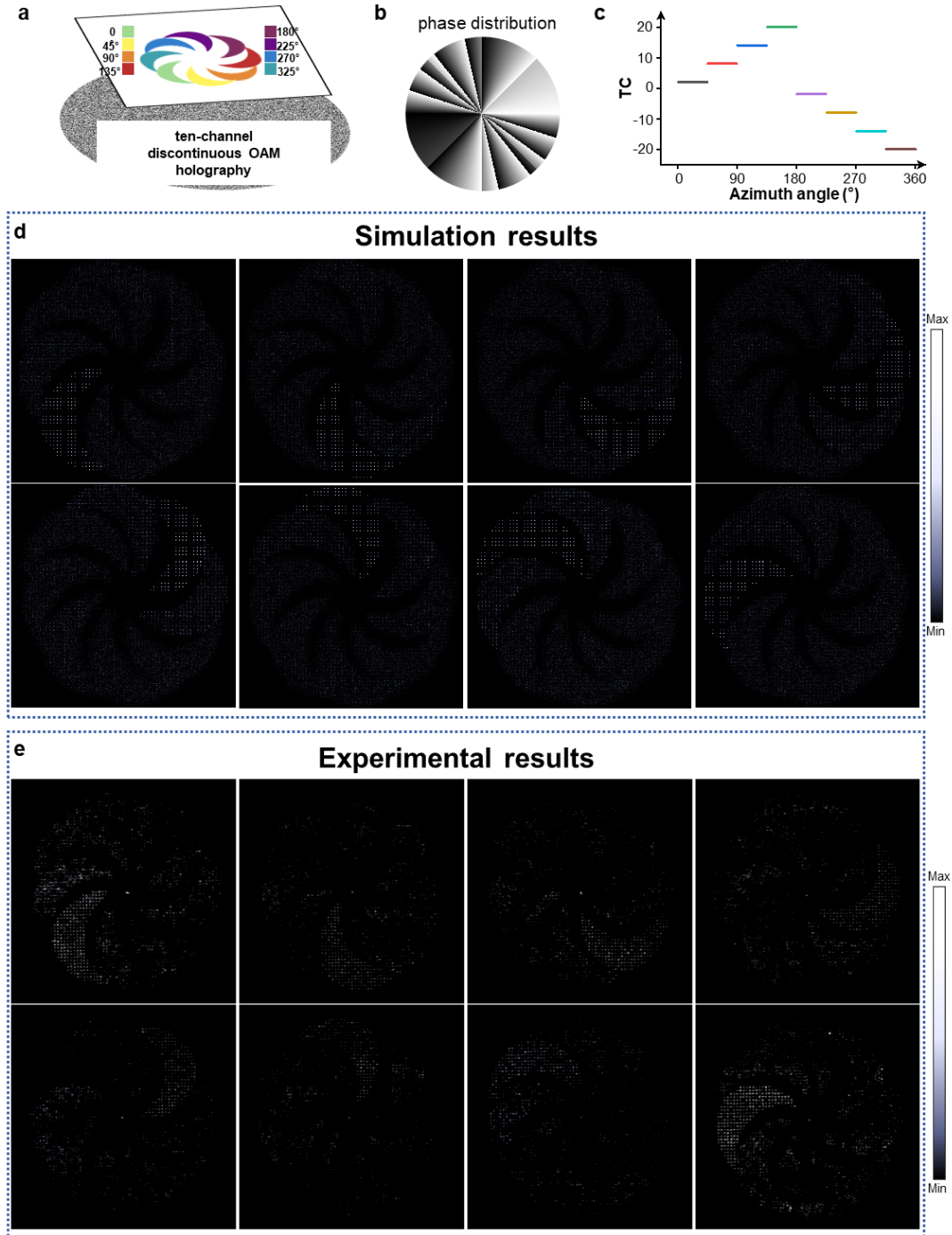


Fig. S18. Eight-channel discontinuous OAM holography. (a) Schematic of an discontinuous OAM-coded image target and its resulting multiplexing meta-hologram. Pseudo colors are used to visualize rotation angle of discontinuous OAM modes. (b) The phase distribution of ten-channel discontinuous OAM holography. (c) The distribution of TC across azimuth angle. (d) Simulation holographic images reconstructed from eight-channel discontinuous OAM meta-hologram. (e) Experimental holographic images reconstructed from eight-channel discontinuous OAM meta-hologram.

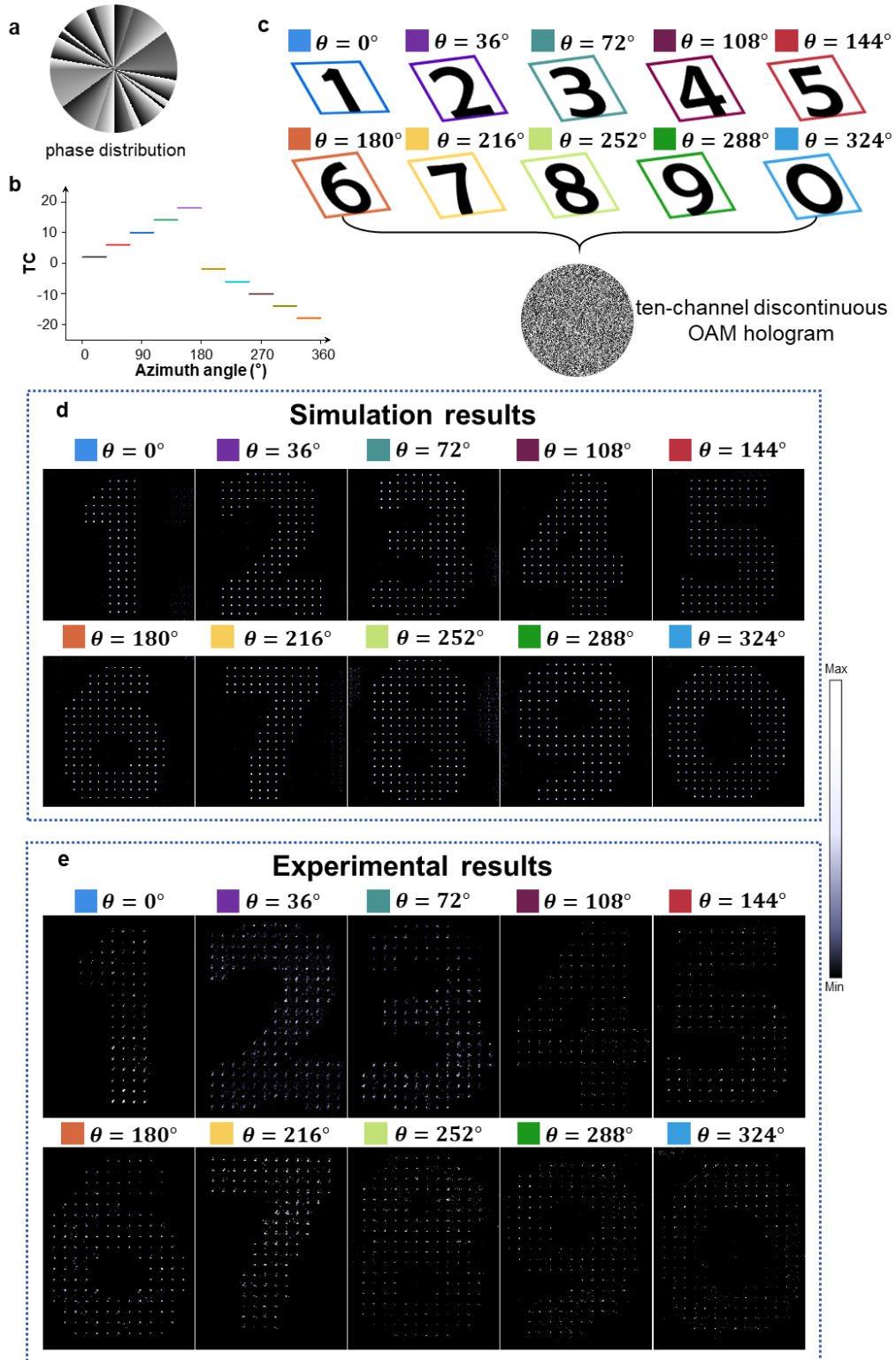


Fig. S19. Ten-channel discontinuous OAM holography. (a) The phase distribution of ten-channel discontinuous OAM holography. (b) The distribution of TC across azimuth angle. (c) OAM-encoded image multiplexing based on one discontinuous OAM states with ten rotate angles. These holographic images appear in the same location. (d) Simulated holographic images reconstructed from ten-channel discontinuous OAM meta-hologram. (e) Experimental holographic images reconstructed from ten-channel discontinuous OAM meta-hologram.

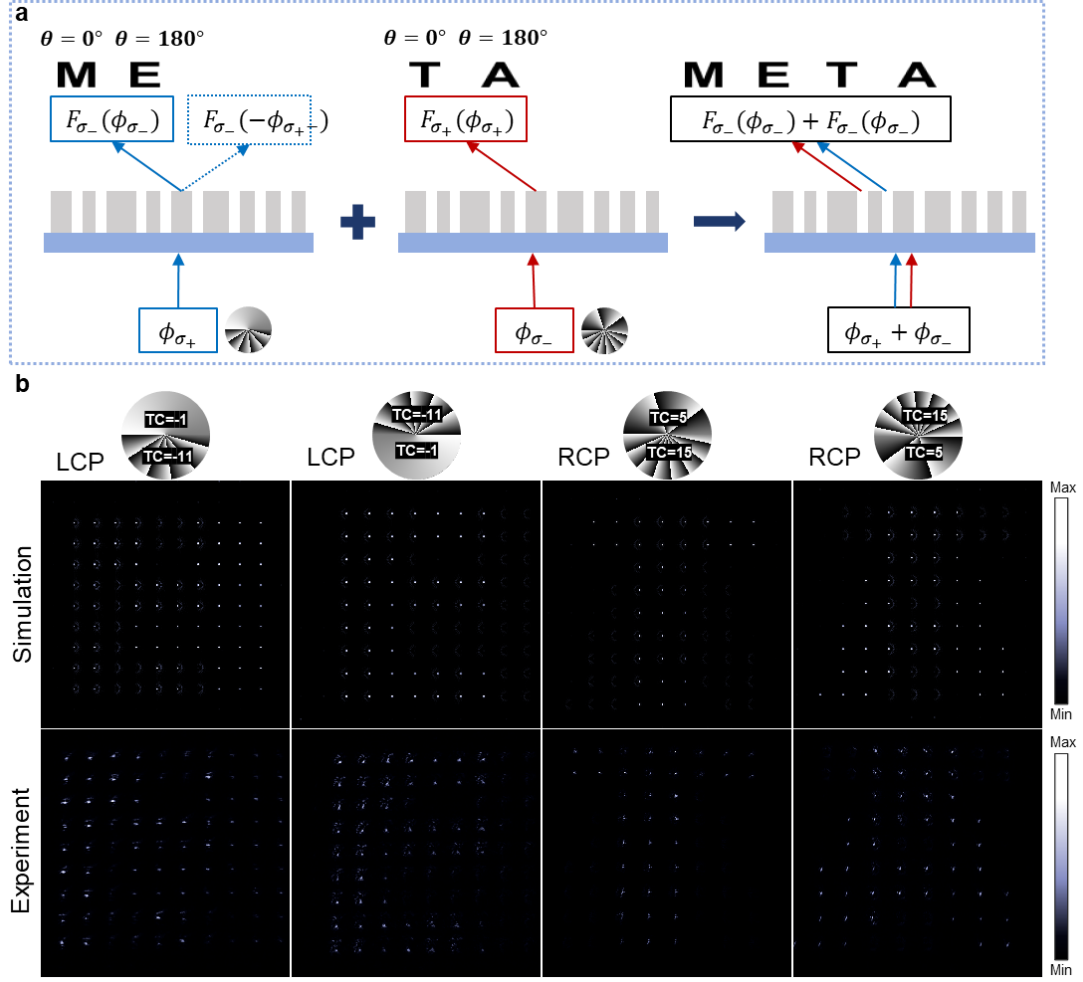


Fig. S20. Polarization-discontinuous OAM encoding holography. (a) The demonstration of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a non-interleaved method in each channel. F represents the Fourier transform. (b) Phase distribution of the incident discontinuous OAM beam and corresponding simulation results of reconstructed images.

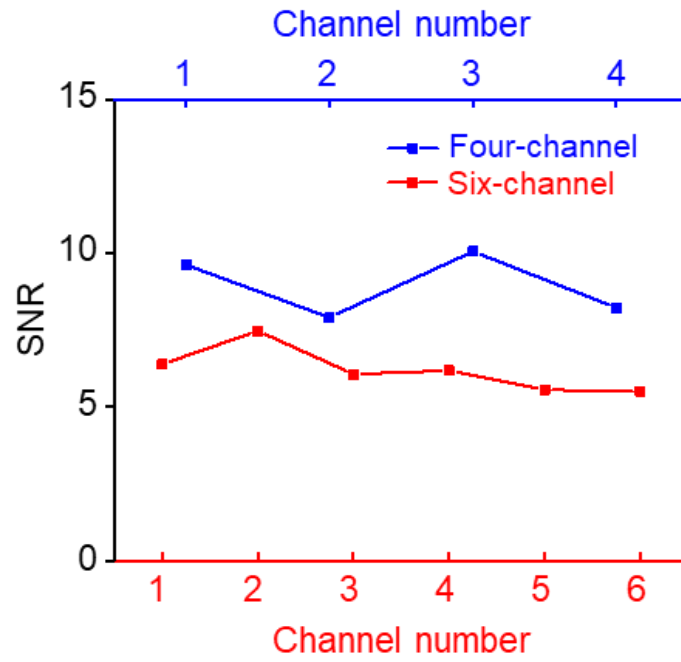


Fig. S21. SNR Comparison between four-channel and six-channel discontinuous OAM Holography. The blue dots represent the SNR of each channel image in the four-channel discontinuous OAM holography. The red dots represent the SNR of each channel image in the six-channel discontinuous OAM holography.

propagation characteristics

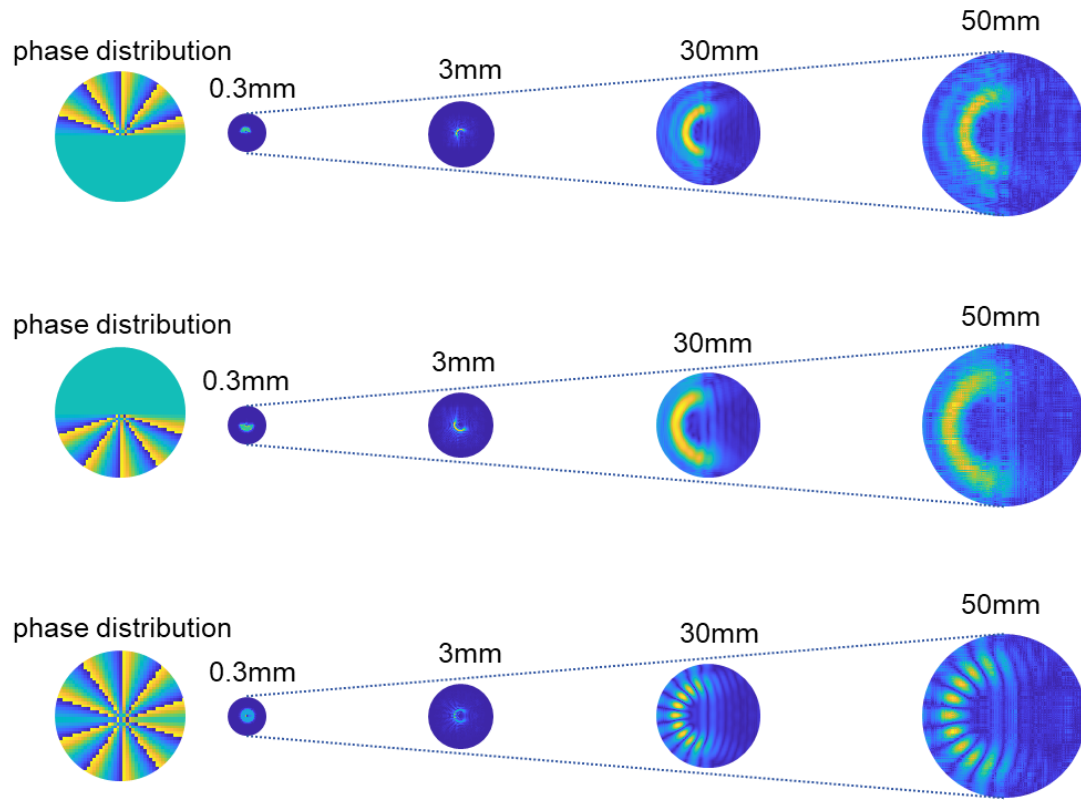


Fig. S22. The simulated propagation characteristics of the discontinuous OAM beam in free space. After the Fresnel diffraction regime, i.e., in the far field, the discontinuous OAM beam propagates stable in free space.

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