

Discontinuous Orbital Angular Momentum Metasurface Holography

Corresponding Author: Professor Qinghua Song

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors of manuscript NCOMMS-25-25303 proposed and demonstrated a novel kind of metasurface holography based on discontinuous orbital angular momentum (OAM). This discontinuous OAM has a spatially varying TC across the azimuthal angle, and thus breaks the rotational symmetry of the beam for information retrieval. Generally, this study differentiates itself from traditional OAM-based holographic approaches through the employment of discontinuous OAM modes. However, after careful evaluation, I am currently hesitant to recommend this study, based on the following reasons.

1. Their proposal provides significance such as using a single beam in information retrieval. However, this method may also bring along limitations, such as extra complexities in precisely controlling the rotation angle and spatial position of the input beam in retrieving the information.
2. The conventional OAM holography has significant merit of information encryption. I'm doubt of the scenarios with necessity to further enhance the security of the information, especially at the cost of adding extra complexity in information retrieval, because the authors said 'any deviation in the rotation angle, or illumination with conventional constant OAM, will trigger severe inter-channel crosstalk.'
3. In the text, the authors mentioned that 'We prove that by strategically arranging the azimuthally distributed TCs, the discontinuous OAM exhibits self-orthogonality at different rotation angles, ensuring minimal cross-talk between channels.' The comparison of cross-talk with the conventional metasurface holography and state-of-the-art holography techniques with small cross-talk has not been fully discussed.
4. The authors mentioned that 'This enables multiple holographic images to be encoded at different rotation angles of the incident OAM mode, significantly enhancing the multiplexing channel numbers under single beam illumination.' However, in the experiment, the detail of how to precisely control the rotation angle in coding and decoding has not been fully discussed.
5. Does the phase distribution necessarily require topological charges with opposite signs, or could the same functionality be achieved using same-sign charges with discontinuous phase profiles (such as $TC=1, 2, 3, 4$)?
6. Are the light spots at the letter edges in the experimental optical field of Figure 4d manually traced? If so, this image processing procedure should be explicitly declared in the main text.

Reviewer #2

(Remarks to the Author)

This manuscript proposes a new paradigm of metasurface holography based on discontinuous orbital angular momentum (OAM), which enables multi-channel holographic encoding under a single incident beam by breaking the rotational symmetry of conventional OAM modes. The work demonstrates certain innovation in enhancing optical information security and capacity, particularly in the design and application of spatially varying topological charge (TC) distributions. However, considering the high academic standards and scientific rigor expected by Nature Communications, the current manuscript still exhibits certain shortcomings in theoretical depth, experimental validation, and practical feasibility, falling short of the publication threshold. To improve the overall quality of the manuscript, the authors are advised to systematically address the following key issues.

First, traditional OAM multiplexing holography has shown great potential in high-capacity communication due to its propagation-invariant and stable characteristics. However, the proposed discontinuous OAM mode, while breaking the central symmetry, may adversely affect the beam's transmission properties. For example, it remains insufficiently verified

whether the structural integrity of the beam can be preserved after transmission through optical fibers (such as few-mode or ring-core fibers) or through free space. Therefore, the application prospects emphasized in the manuscript require further substantiation, and it is recommended that the authors supplement the manuscript with relevant experimental or simulation-based analyses of transmission performance.

Second, although the authors claim that the method effectively enhances the capacity of encryption channels, the experimental results presented in the manuscript demonstrate only a limited number of multiplexed channels—just a few in total. In contrast, traditional OAM holography has already achieved tens or even hundreds of multiplexed channels, with some metasurface-based schemes reaching over ten channels. As such, the advantage of the current approach in terms of capacity enhancement is not yet clearly demonstrated. The authors are encouraged to more explicitly clarify the core competitiveness of their method compared to traditional techniques and to further validate its potential by expanding the number of channels or integrating additional degrees of freedom.

Third, although conventional centrally symmetric OAM multiplexing holography imposes certain alignment requirements on the devices, its inherent symmetry to some extent reduces the difficulty of alignment. After breaking this symmetry, however, the precision required for alignment may significantly increase, especially when rotational operations are introduced, where accurate centering becomes critical to decoding performance. The manuscript should therefore include a discussion on alignment error tolerance and assess its impact on overall system performance.

Fourth, while the manuscript emphasizes the advantage of discontinuous OAM in resisting spiral spectrum analysis, it lacks thorough security analysis under more complex attack scenarios, such as phase reconstruction based on machine learning or partial information leakage. It is recommended that the authors supplement the manuscript with corresponding experimental or simulation data to verify the system's robustness under different attack models and explore potential mechanisms for enhancing security.

Finally, the manuscript mentions the possibility of further expanding channel capacity by integrating other degrees of freedom, such as polarization and wavelength. However, specific technical pathways and challenges have not been adequately addressed, especially regarding possible crosstalk between different degrees of freedom. It is suggested that the authors include preliminary experimental or simulation results on multi-degree-of-freedom multiplexing—for instance, validating the feasibility of combined polarization-OAM encoding—and analyze the coupling mechanisms between different degrees of freedom (e.g., polarization-dependent phase modulation), proposing effective decoupling strategies to demonstrate the future potential of this technology in high-dimensional multiplexing.

In summary, this manuscript presents a forward-looking technical concept, but there remains significant room for improvement in terms of theoretical completeness, depth of experimental validation, and practical feasibility. If the authors can systematically revise and enhance the manuscript in response to the above-mentioned concerns, the scientific value and engineering relevance of the work could be substantially strengthened, making it a stronger candidate for reconsideration for publication.

Reviewer #3

(Remarks to the Author)

This manuscript presents a novel approach for multi-channel holographic imaging by encoding multiple holographic images into a single metasurface and decoding them using structured light generated by a spatial light modulator (SLM). Compared to conventional methods—where a single orbital angular momentum (OAM) pattern generated by the SLM typically decodes only one hologram—this work utilizes discontinuous OAM beams with spatially separated topological charges. This design allows different holographic images to be selectively decoded by rotating the input beam, thereby enabling dynamic and secure multiplexing. Overall, this work demonstrates an innovative and technically sound advancement in the areas of OAM optics, holography, cryptographic imaging, and multifunctional metasurface design. Considering the following technical issues, I believe the manuscript is suitable for publication in Nature Communications after minor revision.

1. In the manuscript, does Equation (2) specifically refer to the angular range $[\pi/2, 3\pi/2]$? If so, would it be more appropriate to explicitly label this range near the equation for clarity? Additionally, I reviewed Supporting Information Equation (6), but I couldn't clearly see how this expression explains why the electric field is nearly zero in the angular range $[-\pi/2, \pi/2]$. Why the "petal-like" intensity pattern only appears on the left side? Could the authors clarify how this behavior is captured by Eq. (6), or whether any assumptions or approximations are involved?

2. In Figures 1(c) and 1(d), the bottom panels are labeled as "electric field distributions." However, based on the visual patterns, they appear to represent intensity profiles rather than complex field amplitudes. Should these be labeled as "intensity" instead of "electric field" for accuracy and clarity?

3. I recommend that the authors consider adding a colorbar next to the phase distributions in Figure 1 of the main text for clarity. Additionally, I noticed a potential inconsistency in the phase color mapping. In Figure 1c, the brown-colored phase progresses from dark brown to white as the azimuthal angle increases, which corresponds to a positive topological charge ($\ell=+10$). However, in the brown segment of Figure 2a, the same color progression—from dark brown to white with increasing azimuth—appears to represent a negative topological charge ($\ell=-10$). For clarity and consistency, I suggest the authors ensure that the color mapping of phase is consistently represented throughout the figures, especially for readers interpreting the sign of the OAM from the color gradient.

4. While Supplementary Note 3 provides insight into the orthogonality behavior via inner product analysis, it would be helpful if the authors could clarify the specific method used to compute the SNR values shown in Figures 3c and 3d—such as how the signal and noise regions are defined, and whether any averaging or normalization is applied. In particular, the near-perfect Gaussian spot distribution appears only when angular orthogonality is achieved. However, even in the absence of orthogonality, there is still observable power forming a petal-like intensity pattern. This raises the question of how exactly the SNR and orthogonality are defined and processed in the data analysis.

5. In Figure 2a, I noticed that the phase distributions corresponding to images B and C appear highly similar. Since the authors mention that the meta-atoms are based on geometric phase, and the Methods section only specifies LCP illumination, the polarization state of the incident light is not fully described throughout the manuscript. Could the authors clarify whether different circular polarizations (e.g., LCP vs. RCP) were used to access additional holographic channels? If so, it would be helpful to elaborate on the polarization dependence and specify which channels were designed for which incident polarization state.

6. In Figure 5b, the experimental holographic images for the six-channel configuration appear noticeably clearer than those in the four-channel case shown in Figure 4d. Interestingly, in the six-channel experiment, each decoded holographic image is encoded using two OAM values (i.e., a pair of $\pm\ell$). Does this suggest that encoding each holographic image with a pair of OAM values inherently leads to better reconstruction quality? It would also be helpful if the authors could provide quantitative metrics (e.g., SNR) for the six-channel case to facilitate a direct comparison with the four-channel results.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Thanks to authors for their effort with improved revised manuscript. The authors have addressed most of questions raised in previous round reviewing. Therefore, I recommend considering potential publication of this study after addressing two remaining questions still unclear.

1. The discontinuous OAM modes are used as a new dimension to enhance the capacity of holographic multiplexing. However, the capacity limit of the proposed method remains unclear, when the inter-channel crosstalk and deviations are small and acceptable. Please provide discussions and quantitatively estimate this limit.
2. The vortex beam with discontinuous OAM in this study is normal, which means that the beams with varied TCs also have different beam profile, such as beam size and central area with null field. Is the proposed method still effective in case of fractional vortex beams and perfect vortex beams such as (Yao, J. et al. A spatial-frequency patching metasurface enabling super-capacity perfect vector vortex beams. *eLight* 4, 21 (2024))?

Reviewer #2

(Remarks to the Author)

The revised manuscript demonstrates the authors' considerable efforts in addressing the questions and concerns raised by myself and the other reviewers. Overall, the manuscript has been significantly improved. Nevertheless, one critical issue remains that precludes me from recommending acceptance: the quality and signal-to-noise ratio of the experimental results are substantially inadequate. Without the reference dashed boxes, it would be difficult to identify which letter the decrypted experimental image represents. The specific concerns are outlined below:

1. In Figure 5, stray speckles are still present in non-letter regions. What criteria were used to distinguish these artifacts from actual characters, and how were they excluded? Explicit justification should be provided. Moreover, certain areas within the letter and number regions suffer from severely diminished brightness or a complete lack of signal. What may have caused these irregularities?
2. The problems in Figure S18 are more pronounced. Some numerals exhibit extensive missing data points, and the font style in the experimental results diverge noticeably from that in the simulations. Additionally, the experimental images display inconsistent rotational misalignment across different numerals. What is the origin of these rotational errors, and how were the angles determined during the experiments?

Reviewer #3

(Remarks to the Author)

After a thorough review of the revised manuscript and supporting materials, I confirm that the authors have satisfactorily addressed the technical issues raised by Reviewers 1, 2, and myself (Reviewer 3). The relevant technical clarifications are appropriately documented in the Supplementary Information. This work demonstrates an innovative and technically sound advancement in OAM optics, holography, cryptographic imaging, and multifunctional metasurface design. I believe the manuscript is suitable for publication in *Nature Communications*.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have almost addressed all of my concerns. There is only one point that is unclear. In the reply, the authors said the SNR approaches zero when the topological charge reaches 40. However, in the Supplementary notes 12, the limit of TC is given as 42. Moreover, the authors should also include some discussions on the acceptable level of SNR so that the authors can get a clear concept of this limit. Finally, some classic references would be necessary to help the audience understand PVB and FVB mentioned in the Supplementary Notes. After fully addressing these minor issues, I would be delighted to recommend this article for publication in Nature Communications.

Reviewer #2

(Remarks to the Author)

Based on the revised manuscript, the author has addressed the relevant questions and concerns I raised, and it can now be recommended for publication.

Reviewer #3

(Remarks to the Author)

In this revision, the authors have carefully addressed the reviewers' comments. For example, the SNR analysis for non-integer OAM requested by Reviewer 1, and the improved measurement methodology raised by Reviewer 2, have both been clearly incorporated. These updates allow the experimental data to better reflect the target designs, with or without reference dashed boxes. In my opinion, the manuscript could be accepted after addressing a few minor points:

1. In Response 1.1 and Supplementary Note 12, the statement "SNR drops to approximately 0" seems unusual. Typically, when SNR approaches 1, the signal becomes indistinguishable from noise, which should already indicate the capacity limit. The choice of "SNR ~ 0 " as the threshold feels inconsistent and should be clarified.

2. In the revised experimental holograms of Figure 5b and 5c, the target designs are not as visually clear as in Figure S19 if the dashed boxes are removed. I assume this is because Figure 5 involves multiple polarization channels and fewer sampling points per channel, while Figure S19 provides denser sampling for each holographic image. Overall, this does not undermine the authors' contribution to the field but could be clarified in the discussion.

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Reply report to reviewer #1

Comment: *The authors of manuscript NCOMMS-25-25303 proposed and demonstrated a novel kind of metasurface holography based on discontinuous orbital angular momentum (OAM). This discontinuous OAM has a spatially varying TC across the azimuthal angle, and thus breaks the rotational symmetry of the beam for information retrieval. Generally, this study differentiates itself from traditional OAM-based holographic approaches through the employment of discontinuous OAM modes. However, after careful evaluation, I am currently hesitant to recommend this study, based on the following reasons.*

Response: We would like to thank the reviewer for the affirmation of the novelty of our work. We are happy to address all the concerns raised by the reviewer.

Comment 1.1: *Their proposal provides significance such as using a single beam in information retrieval. However, this method may also bring along limitations, such as extra complexities in precisely controlling the rotation angle and spatial position of the input beam in retrieving the information.*

Response 1.1: As pointed out by the reviewer, compared to traditional OAM holography, controlling the rotation angle and spatial position of the input beam is necessary in our discontinuous OAM holography. However, slight deviations within a certain range of angles and positions are acceptable in practical implementation, as explained now in **Supplementary Note 7**.

“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% ($\sim 6 \mu\text{m}$) preserves the near-perfect Gaussian spot characteristics of image “A”, while at 3% ($\sim 9 \mu\text{m}$) 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.

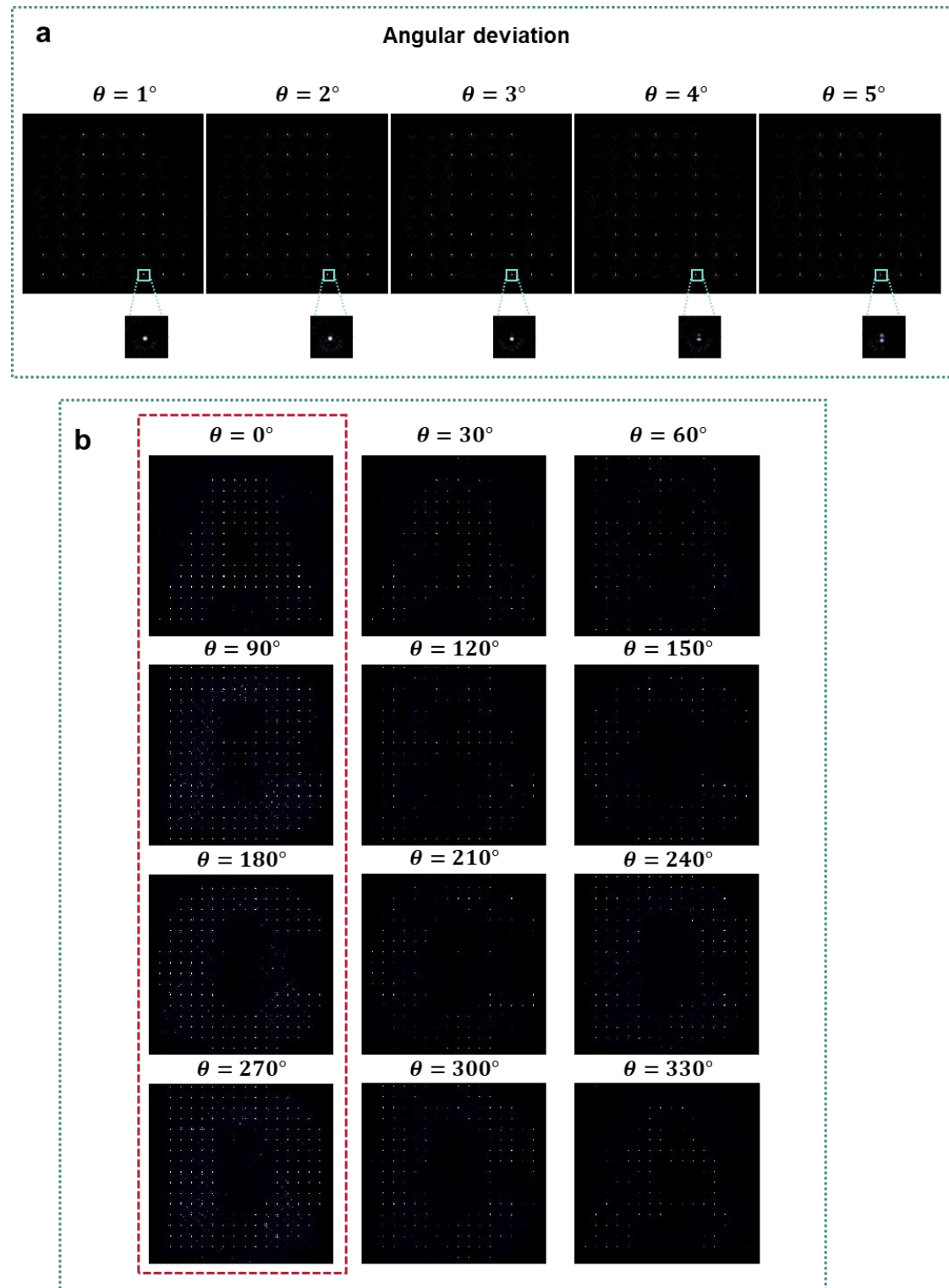


Fig. S7. Numerical results demonstrating the impact of angular misalignment in discontinuous OAM holography. (a) Holographic reconstruction based on a discontinuous OAM meta-hologram with slight angular deviation. (b) Holographic reconstruction based on a discontinuous OAM meta-hologram with large angular

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.

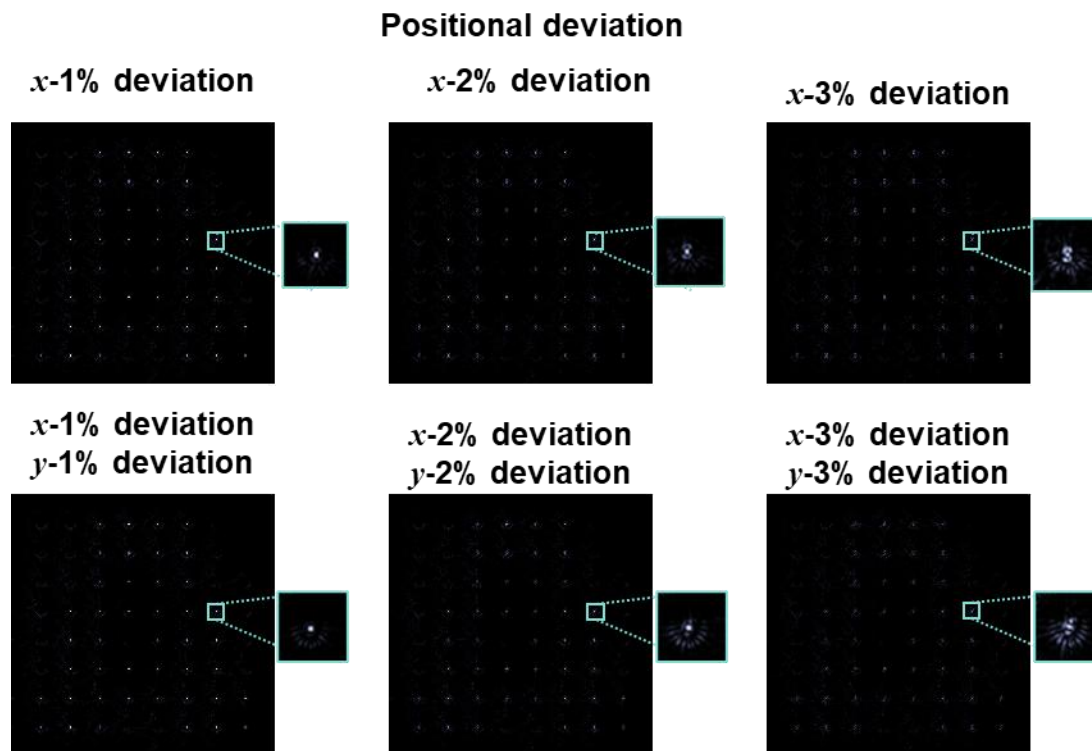


Fig. S8. Numerical results of the reconstructed images demonstrating the impact of lateral misalignment in discontinuous OAM holography.”

Comment 1.2: *The conventional OAM holography has significant merit of information encryption. I’m doubt of the scenarios with necessity to further enhance the security of the information, especially at the cost of adding extra complexity in information retrieval, because the authors said ‘any deviation in the rotation angle, or illumination with conventional constant OAM, will trigger severe inter-channel crosstalk.’*

Response 1.2: The authors thank the reviewer for this point. 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.

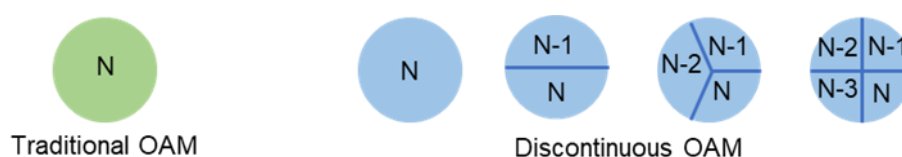


Fig. R1-1 The possibility of conventional OAM and discontinuous OAM modes formed by N topological charges.

As a proof of concept, to quantitatively analyze the information security of these two techniques, we use $N = 200$ (with topological charge ranging from -100 to 100) 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 200 distinct OAM modes, which takes only **14 seconds** in total. However, for discontinuous OAM holography, the azimuthal partitioning is uncertain. Assuming only four possibilities of equal partitions (1/2/3/4), the total number of possible combinations is calculated as:

$$N + N * (N - 1) + N * (N - 1) * (N - 2) + N * (N - 1) * (N - 2) * (N - 3) \quad (R1)$$

With 200 TCs, this results in 1560359200 possible configurations, requiring 1264 days—or approximately **3.5 years**—to decode by using a commercialized SLM with the same refresh rate of 70 ms. This doesn't even account for the effects of topological charge mismatches during rotation. Therefore, our discontinuous OAM holography offers a security enhancement of at least 7 orders of magnitude over traditional OAM holographic encryption.

This discussion has been added in Supplementary Note 1 as:

“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 combination and azimuthal phase distribution for successful image reconstruction.

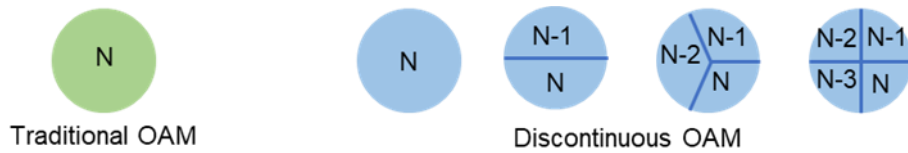


Fig. S1. The number of multiplexing possibilities of conventional OAM and discontinuous OAM modes formed by N topological charges.

As a proof of concept, to quantitatively compare the information security of conventional and discontinuous OAM holography, we use $N = 200$ (with topological charge ranging from -100 to 100) 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 200 distinct OAM modes, which takes only 14 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 200 TCs, this results in 1560359200 possible configurations, requiring 1264 days—or approximately 3.5 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 topological charge 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.”

Comment 1.3: *In the text, the authors mentioned that ‘We prove that by strategically arranging the azimuthally distributed TCs, the discontinuous OAM exhibits self-orthogonality at different rotation angles, ensuring minimal cross-talk between channels.’ The comparison of cross-talk with the conventional metasurface holography and state-of-the-art holography techniques with small cross-talk has not been fully discussed.*

Response 1.3: The authors thank the reviewer for this point. The current state-of-the-art for minimizing crosstalk in conventional OAM holography is the complex-amplitude OAM holography developed by Ren Haoran et al. (Nat. Nanotechnol.15, 948–955, 2020). This method achieves optimal crosstalk suppression through precise modulation of metasurface amplitude and phase profiles. However, due to fabrication constraints that prevent reliable amplitude control in our laboratory, we adopted a phase-only metasurface design for discontinuous OAM holography. We systematically compared the decoded image quality between our phase-only discontinuous OAM holography and conventional phase-only OAM holography, which is discussed in **Supplementary Note 8** as:

“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 signal-to-noise ratio (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. 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.

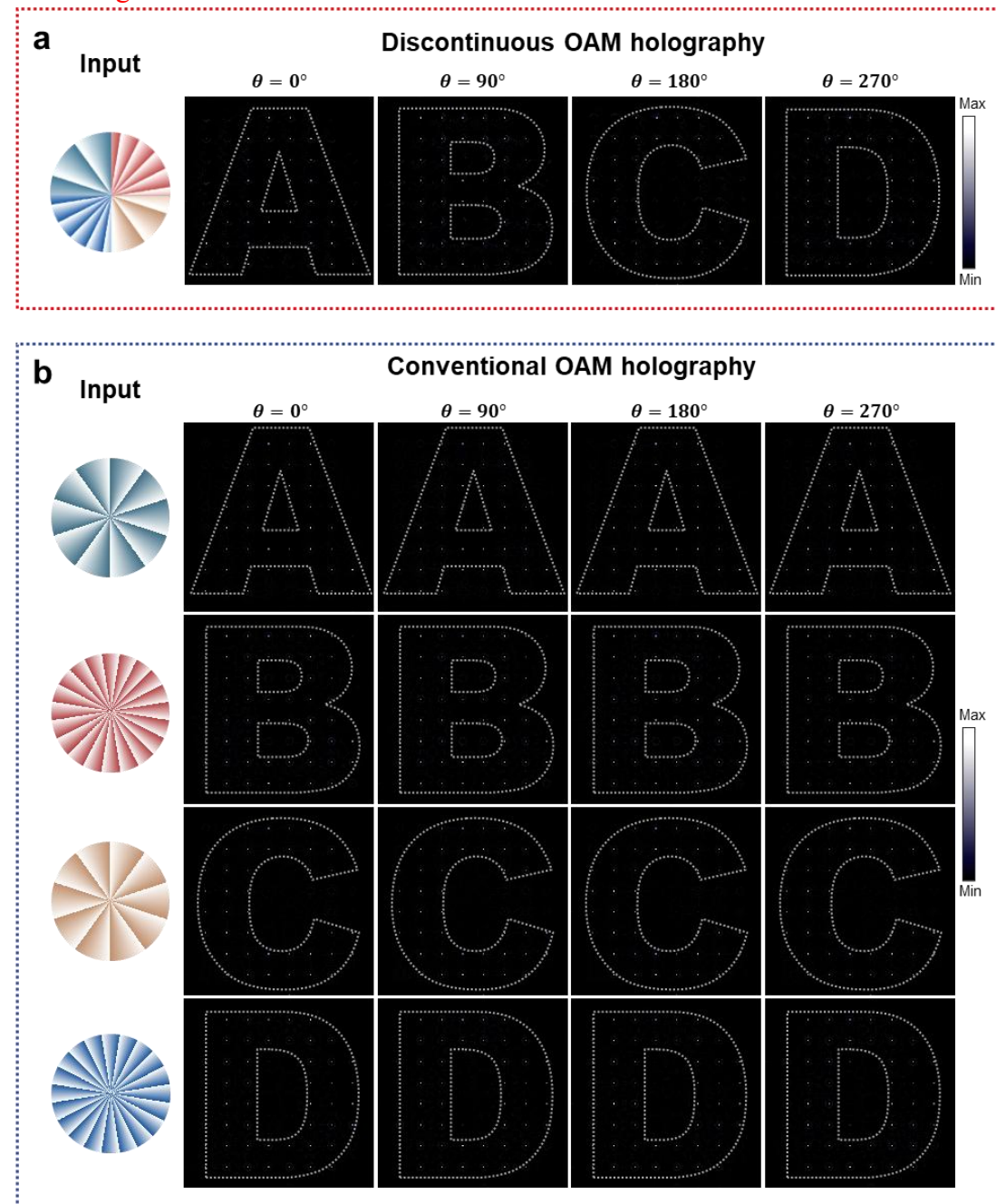


Fig. S9. The decoded holographic images of discontinuous OAM holography and conventional OAM holography with a phase-only metasurface. (a) Simulation results of discontinuous OAM holography. (b) Simulation results of conventional holography.

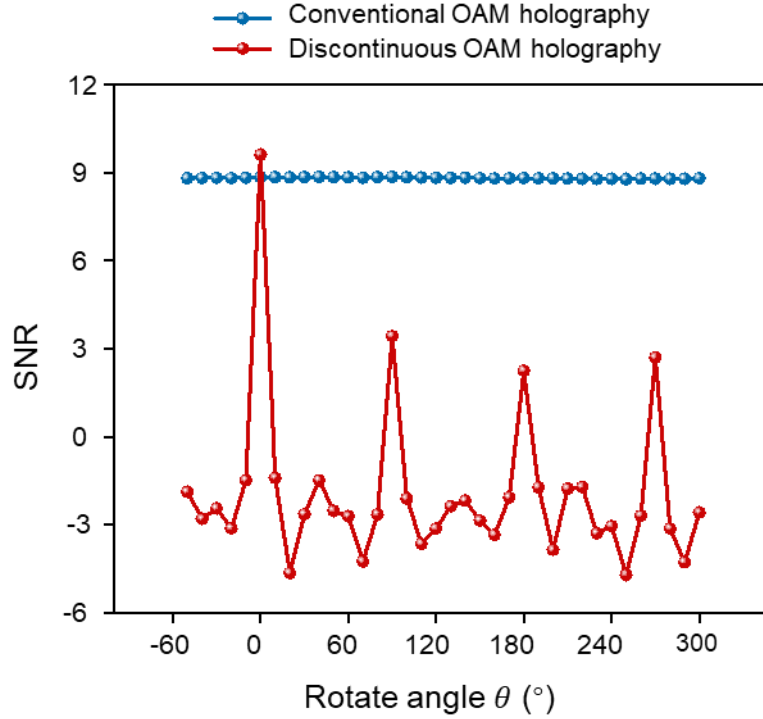


Fig. S10. Relationship between SNR and incident light rotation angle for conventional OAM holography and discontinuous OAM holography.”

Comment 1.4: *The authors mentioned that ‘This enables multiple holographic images to be encoded at different rotation angles of the incident OAM mode, significantly enhancing the multiplexing channel numbers under single beam illumination.’ However, in the experiment, the detail of how to precisely control the rotation angle in coding and decoding has not been fully discussed.*

Response 1.4: The authors thank the reviewer for this point. We would like to answer from the following two aspects regarding encoding and decoding processes.

1. During the encoding process, we achieve precise control over the angular partitioning of the encoded phase. Taking the four-channel discontinuous OAM holography proposed in this manuscript as an example, defining azimuthal sectors where discontinuous OAM phases carry specific TC. We equally divide the 2π azimuthal range into four sectors, encoding TC of 10, 20, -10, and -20 respectively. The phases for the remaining three channels are generated by rotating the obtained discontinuous OAM by 90° , 180° , and 270° as shown in **Fig. R1-2**. The TC and its corresponding azimuthal region in discontinuous OAM can be arbitrarily designed.

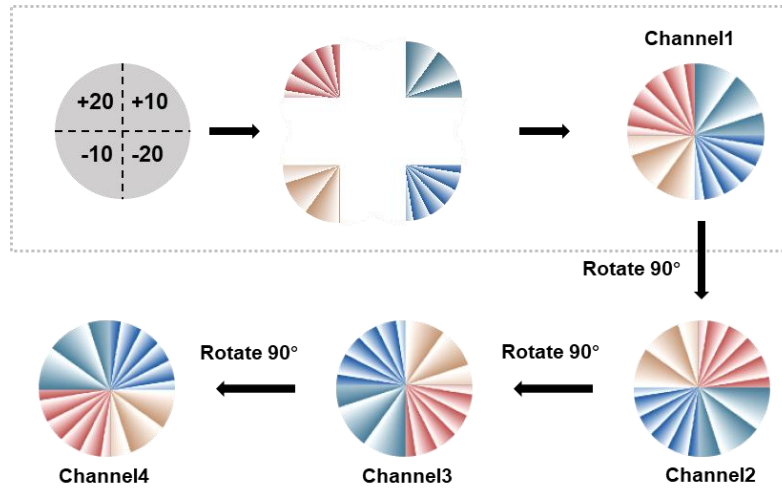


Fig. R1-2 Four-channel discontinuous OAM phase design method.

2. 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. R1-3c**. 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.

(i). Coarse adjustment

To facilitate coarse alignment of 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. R1-3a**. The original holographic optical setup is shown in **Fig. R1-3b**, 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 shown in **Fig. R1-3d**. The first row displays the magnified metasurface and incident OAM 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 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 of “0” emerge.

(ii). 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. R1-3e.

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.

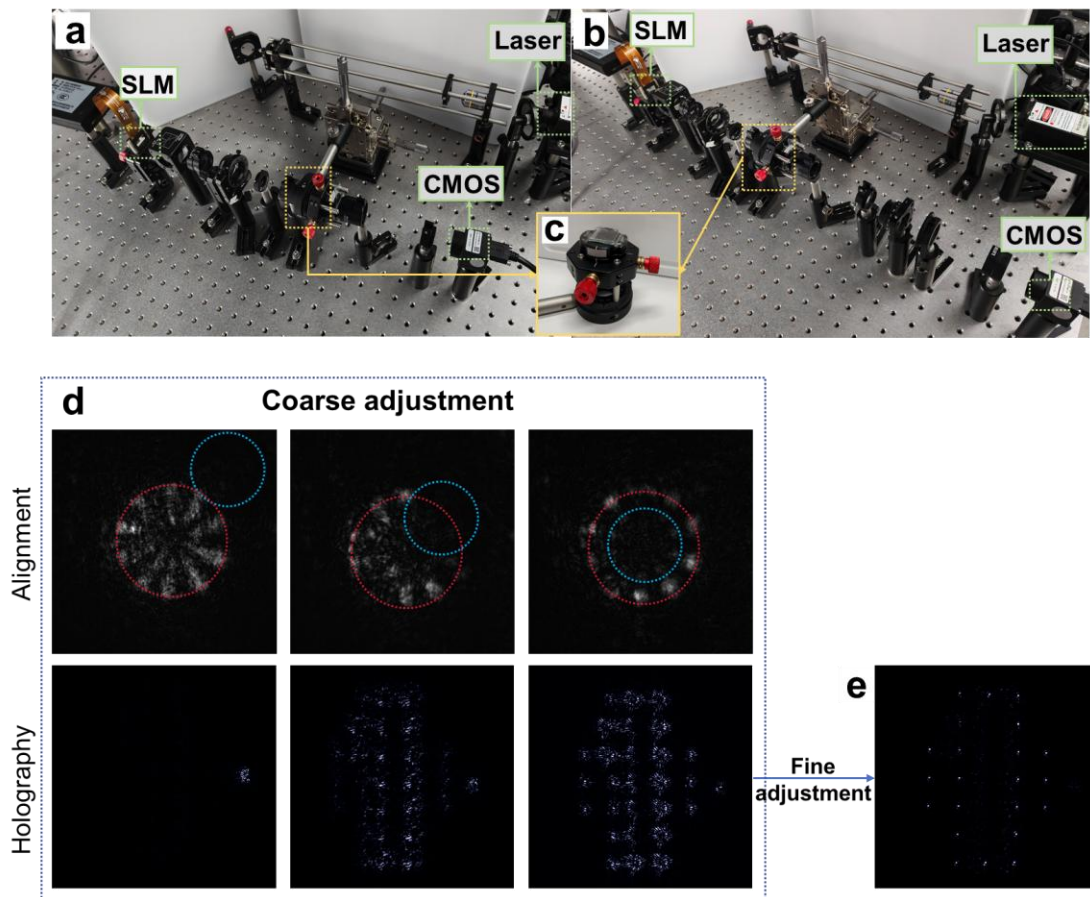


Fig. R1-3. Optical setup of discontinuous OAM holography. (a) Optical setup for coarse adjustment. (b) Optical setup of discontinuous OAM holography. (c) The manual rotation platform added with an XY translator. (d) First row: the alignment of incident discontinuous OAM and metasurface. Second row: the 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.

This discussion has been added in Supplementary Note 11 as:

“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. S16c**. 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. S16a**. The original holograph optical setup is shown in **Fig. S16b**, 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. S16d**. 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. S16e**.

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.

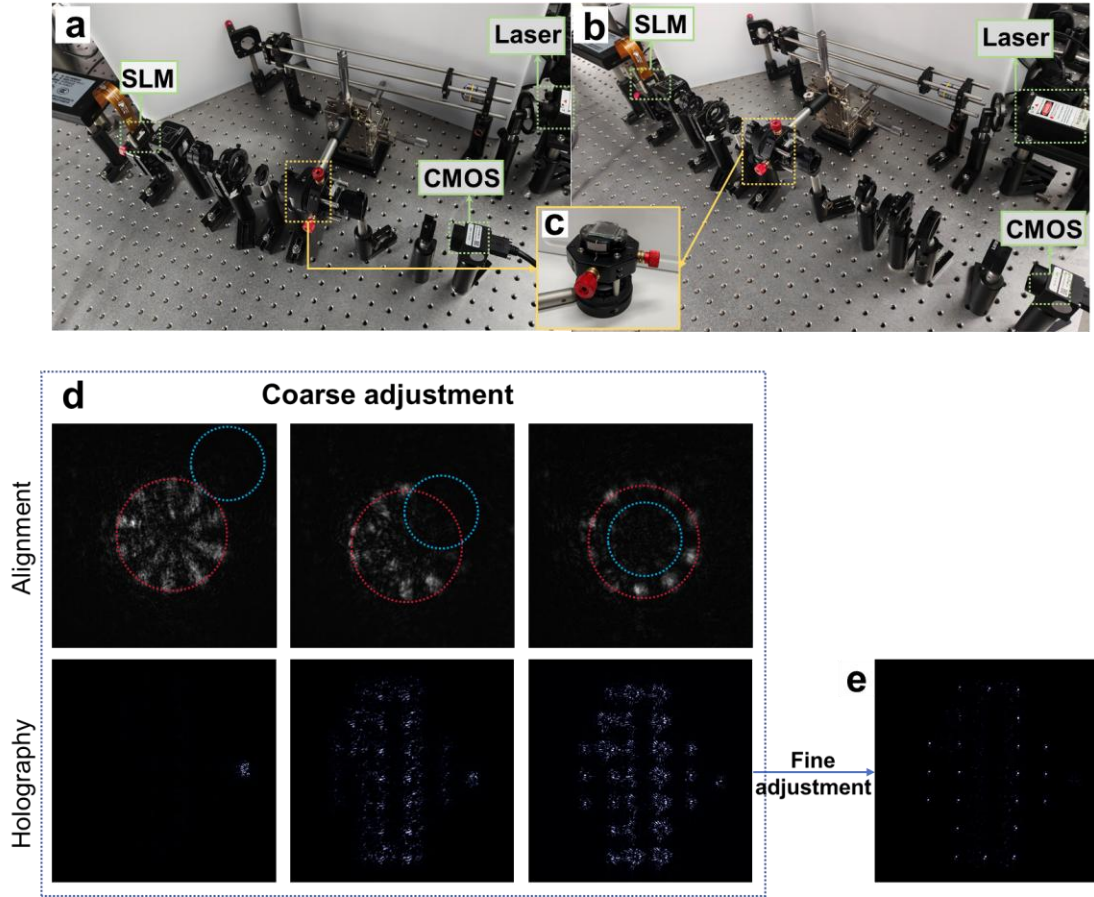


Fig. S16. Optical setup of discontinuous OAM holography. (a) Optical setup for coarse adjustment. (b) Optical setup of discontinuous OAM holography. (c) The manual rotation platform added with an XY translator. (d) First row: the alignment of incident discontinuous OAM and metasurface. Second row: the 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.”

Comment 1.5: *Does the phase distribution necessarily require topological charges with opposite signs, or could the same functionality be achieved using same-sign charges with discontinuous phase profiles (such as $TC=1, 2, 3, 4$)?*

Response 1.5: As pointed out by the reviewer, the same functionality can be achieved using same-sign charges with discontinuous phase profiles. Specifically, when different sectors carry distinct TCs – whether all positive, all negative, or mixed – the system inherently achieves orthogonality, enabling robust channel isolation, as experimentally validated in **Supplementary Note 9**. To reduce crosstalk, we employed OAM modes with larger TC intervals for encoding the same-sign charges 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 $l = 1/l = 11$ and four azimuthal regions with four all-positive TCs $l = 1/l = 8/l = 15/l = 22$. The phase distributions, simulated and experimental results of the two-channel discontinuous OAM modes are shown in **Fig. S11**. In addition, the discontinuous OAM modes with four-channel holography are shown in **Fig. S12a**, with the corresponding simulation and experimental results presented in **Figs. S12b** and **Fig. S12c**, respectively. The results demonstrate that discontinuous OAM holography encoded with all-positive TCs can also achieve multi-channel multiplexing.

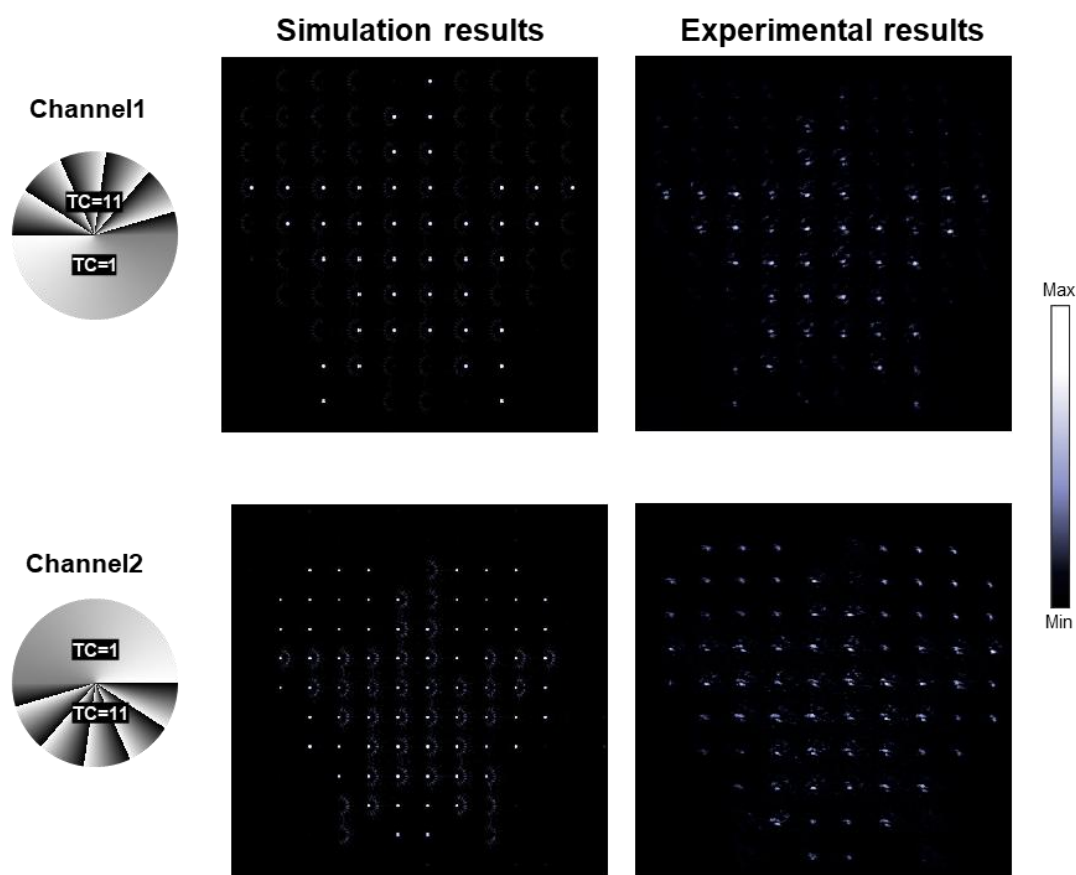


Fig. S11. Simulated and experimental results of two-channel discontinuous OAM holography with same-sign topological charges.

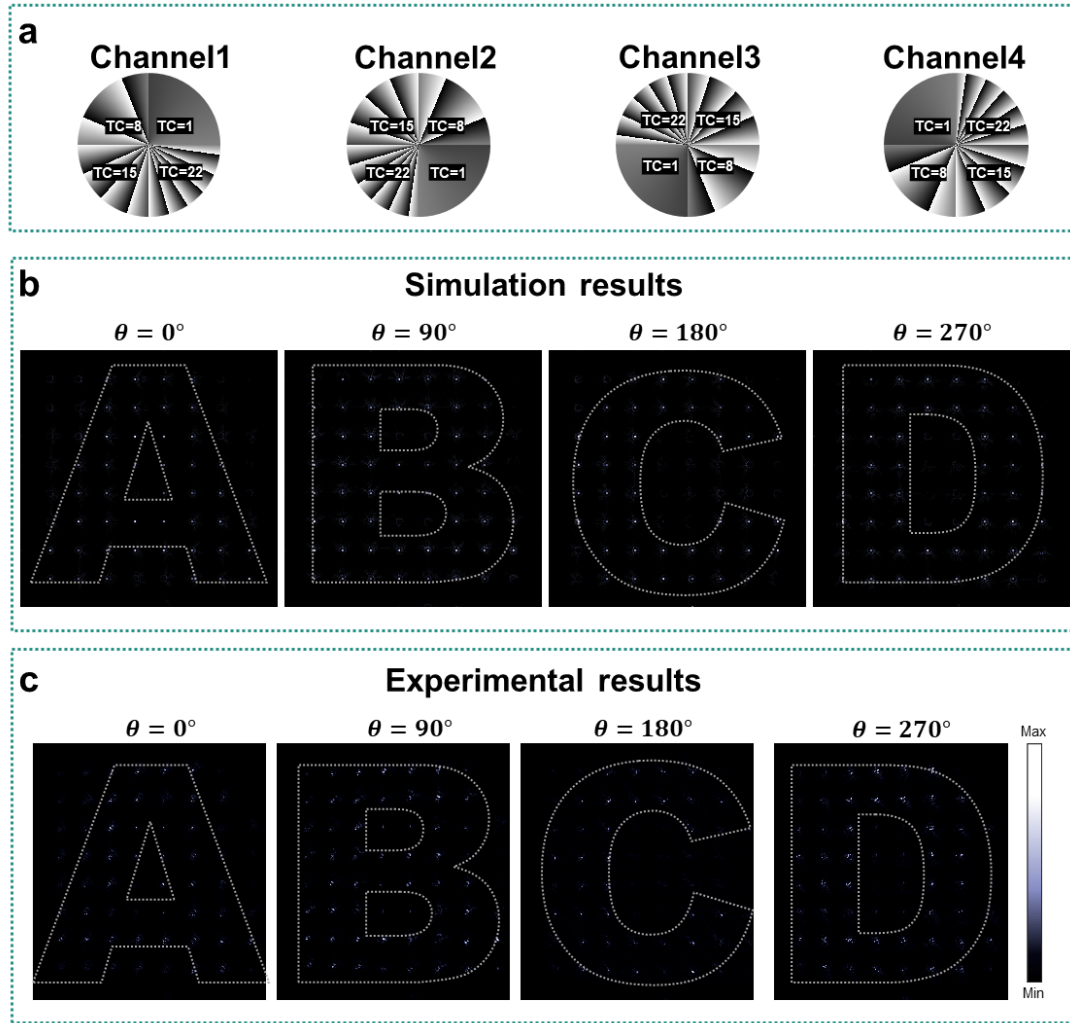


Fig. S12. Simulated and experimental results of four-channel discontinuous OAM holography with same-sign topological charges. (a) The phase distributions of the four discontinuous OAM modes. (b) The simulation and (c) experimental results of four-channel discontinuous OAM holography use same-sign charges.”

Comment 1.6: *Are the light spots at the letter edges in the experimental optical field of Figure 4d manually traced? If so, this image processing procedure should be explicitly declared in the main text.*

Response 1.6: The authors thank the reviewer for this point. Since OAM holography requires sampling the original image, the experimentally obtained pictures are all composed of Gaussian dots. To facilitate visibility, we have added frame dash lines around the edge of the letters to make the display clearer. This clarification has been added in the revised manuscript as “To facilitate visibility, we have added frame dash lines around the edge of the letters to make the display clearer” in Line 201-202 Page 8.

In summary, we have addressed all the comments of reviewer #1.

Reply report to reviewer #2

Comment 2: *This manuscript proposes a new paradigm of metasurface holography based on discontinuous orbital angular momentum (OAM), which enables multi-channel holographic encoding under a single incident beam by breaking the rotational symmetry of conventional OAM modes. The work demonstrates certain innovation in enhancing optical information security and capacity, particularly in the design and application of spatially varying topological charge (TC) distributions. However, considering the high academic standards and scientific rigor expected by Nature Communications, the current manuscript still exhibits certain shortcomings in theoretical depth, experimental validation, and practical feasibility, falling short of the publication threshold. To improve the overall quality of the manuscript, the authors are advised to systematically address the following key issues.*

Response 2: We would like to thank the reviewer for the affirmation of the novelty of our work. We are happy to address all the concerns raised by the reviewer.

Comment 2.1: *First, traditional OAM multiplexing holography has shown great potential in high-capacity communication due to its propagation-invariant and stable characteristics. However, the proposed discontinuous OAM mode, while breaking the central symmetry, may adversely affect the beam's transmission properties. For example, it remains insufficiently verified whether the structural integrity of the beam can be preserved after transmission through optical fibers (such as few-mode or ring-core fibers) or through free space. Therefore, the application prospects emphasized in the manuscript require further substantiation, and it is recommended that the authors supplement the manuscript with relevant experimental or simulation-based analyses of transmission performance.*

Response 2.1: The authors thank the reviewer for this point. Taking two-channel discontinuous OAM as an example. Within the Fresnel diffraction regime, a vortex beam carrying half-integer OAM exhibits a semi-vortex morphology. The opening direction of this semi-vortex rotates with propagation distance until attaining a 90° phase offset relative to its initial state. The rotation direction is determined by the sign of the TC as explained in **Supplementary Note 2**. The discontinuous OAM proposed in this manuscript arises from the superposition of two such semi-vortices, which generate a petal-like beam profile. After the Fresnel diffraction regime, i.e., in the far field, the discontinuous OAM beam propagates stable in free space as shown in **Fig. S21**.

Propagation characteristics

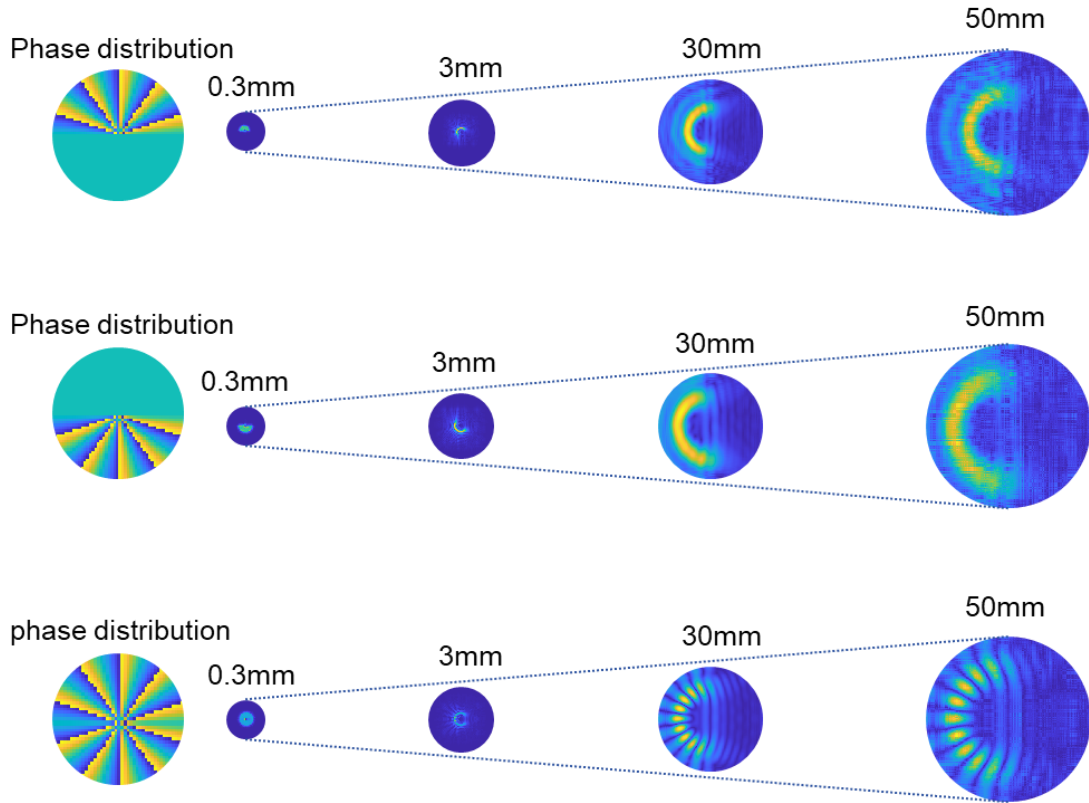


Fig. S21. The simulated propagation characteristics of the discontinuous OAM beam in free space. After the Fresnel diffraction regime, i.e., in the far field, the discontinuous OAM beam propagates stable in free space.

Comment 2.2: *Second, although the authors claim that the method effectively enhances the capacity of encryption channels, the experimental results presented in the manuscript demonstrate only a limited number of multiplexed channels—just a few in total. In contrast, traditional OAM holography has already achieved tens or even hundreds of multiplexed channels, with some metasurface-based schemes reaching over ten channels. As such, the advantage of the current approach in terms of capacity enhancement is not yet clearly demonstrated. The authors are encouraged to more explicitly clarify the core competitiveness of their method compared to traditional techniques and to further validate its potential by expanding the number of channels or integrating additional degrees of freedom.*

Response 2.2: The authors thank the reviewer for this valuable point. Conventional OAM metasurface holography achieving tens or hundreds of multiplexed channels relies on complex-amplitude metasurfaces. Compared to phase-only metasurfaces, complex-amplitude designs exhibit lower crosstalk and higher image fidelity. However, due to fabrication constraints in realizing complex-amplitude structures in our laboratory, we adopted a phase-only metasurface approach utilizing Pancharatnam-Berry (PB) phase for multi-channel multiplexing. In the previous paper presented by

Ren Haoran et al. (Nat. Commun., 10, 2986, 2019), they demonstrated ten-channel phase-only OAM holography in simulations. For comparison, we present both simulation and experimental results for ten-channel discontinuous OAM holography. In Fig. S17 and Fig. S18, we show that both eight-channel and ten-channel discontinuous OAM holography can be successfully achieved.

The key advantage over discontinuous OAM holography lies in enabling channel switching through metasurface rotation under single-beam illumination, which is an unattainable feature in traditional systems. Moreover, it offers enhanced security as decoding requires precise knowledge of both the encoded azimuthal sectors and their corresponding TC.

This discussion has been added in Figs. S17 & S18 as,
“

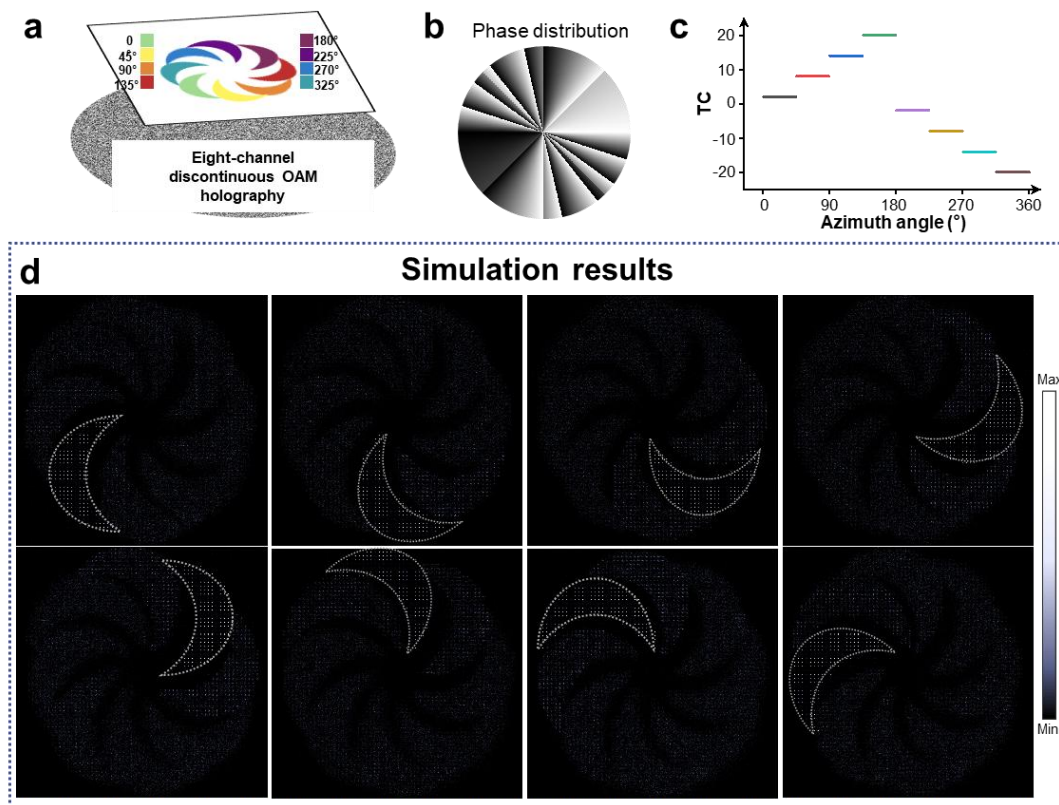


Fig. S17. Eight-channel discontinuous OAM holography. (a) Schematic of a discontinuous OAM-coded image target and its resulting multiplexing meta-hologram. Pseudo colors are used to visualize rotation angle of discontinuous OAM modes. (b) The phase distribution of ten-channel discontinuous OAM holography. (c) The distribution of TC across azimuth angle. (d) Simulation holographic images reconstructed from eight-channel discontinuous OAM meta-hologram.

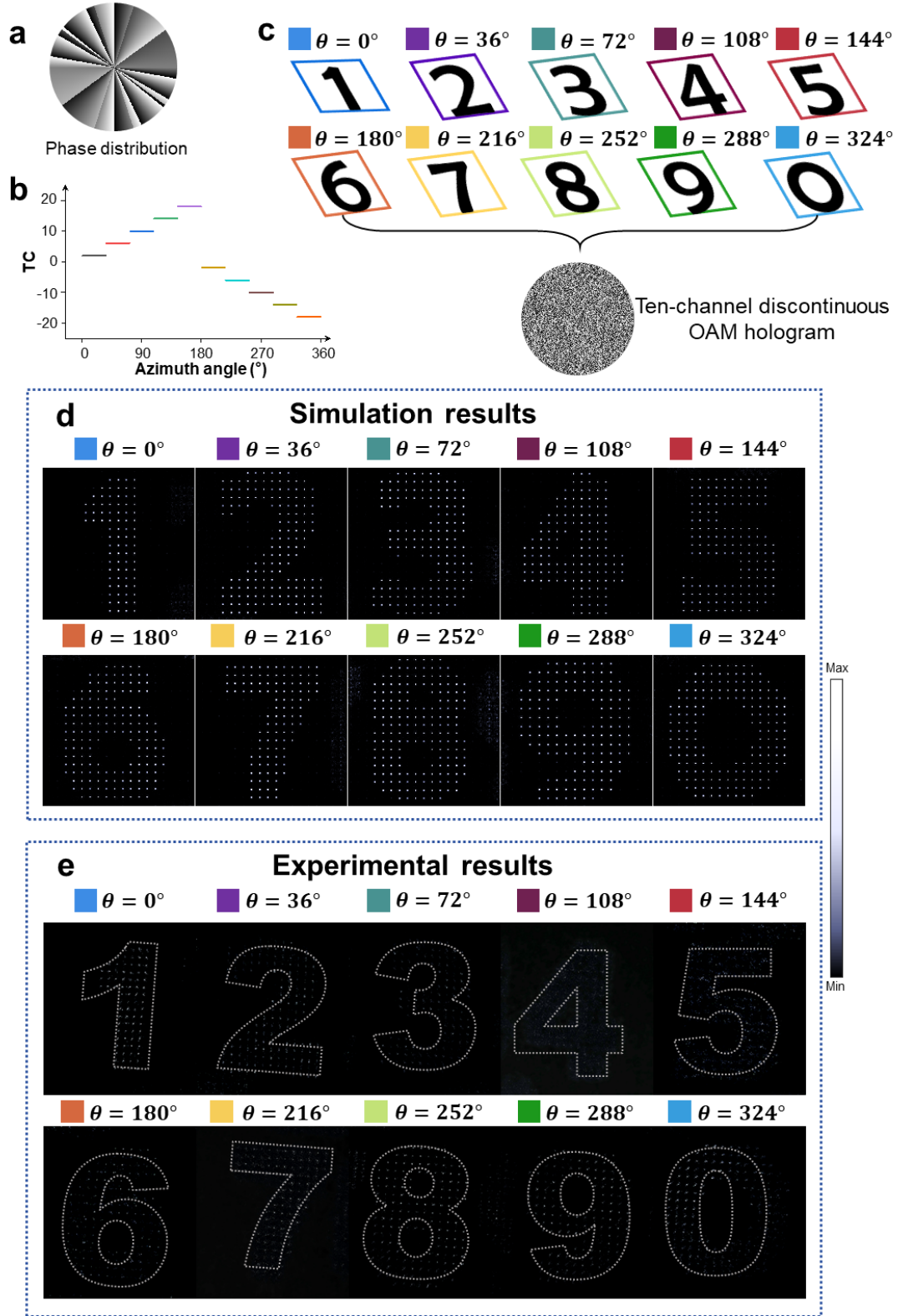


Fig. S18. Ten-channel discontinuous OAM holography. (a) The phase distribution of ten-channel discontinuous OAM holography. (b) The distribution of TC across azimuth angle. (c) OAM-encoded image multiplexing based on one discontinuous OAM states with ten rotation angles. (d) Simulated and (e) experimental results of holographic images reconstructed from ten-channel discontinuous OAM meta-

hologram.”

Comment 2.3: *Third, although conventional centrally symmetric OAM multiplexing holography imposes certain alignment requirements on the devices, its inherent symmetry to some extent reduces the difficulty of alignment. After breaking this symmetry, however, the precision required for alignment may significantly increase, especially when rotational operations are introduced, where accurate centering becomes critical to decoding performance. The manuscript should therefore include a discussion on alignment error tolerance and assess its impact on overall system performance.*

Response 2.3: The authors thank the reviewer for this point. In contrast to conventional OAM holography, our proposed discontinuous OAM holography requires angular alignment—a deliberate design feature that enhances information security. Random illumination with integer-OAM modes cannot decode the information, while the system maintains robust tolerance to both angular misalignment and center-position offsets. The discussion has been added in **Supplementary Note 7**.

“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% ($\sim 6 \mu\text{m}$) preserves the near-perfect Gaussian spot characteristics of image “A”, while at 3% ($\sim 9 \mu\text{m}$) 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.

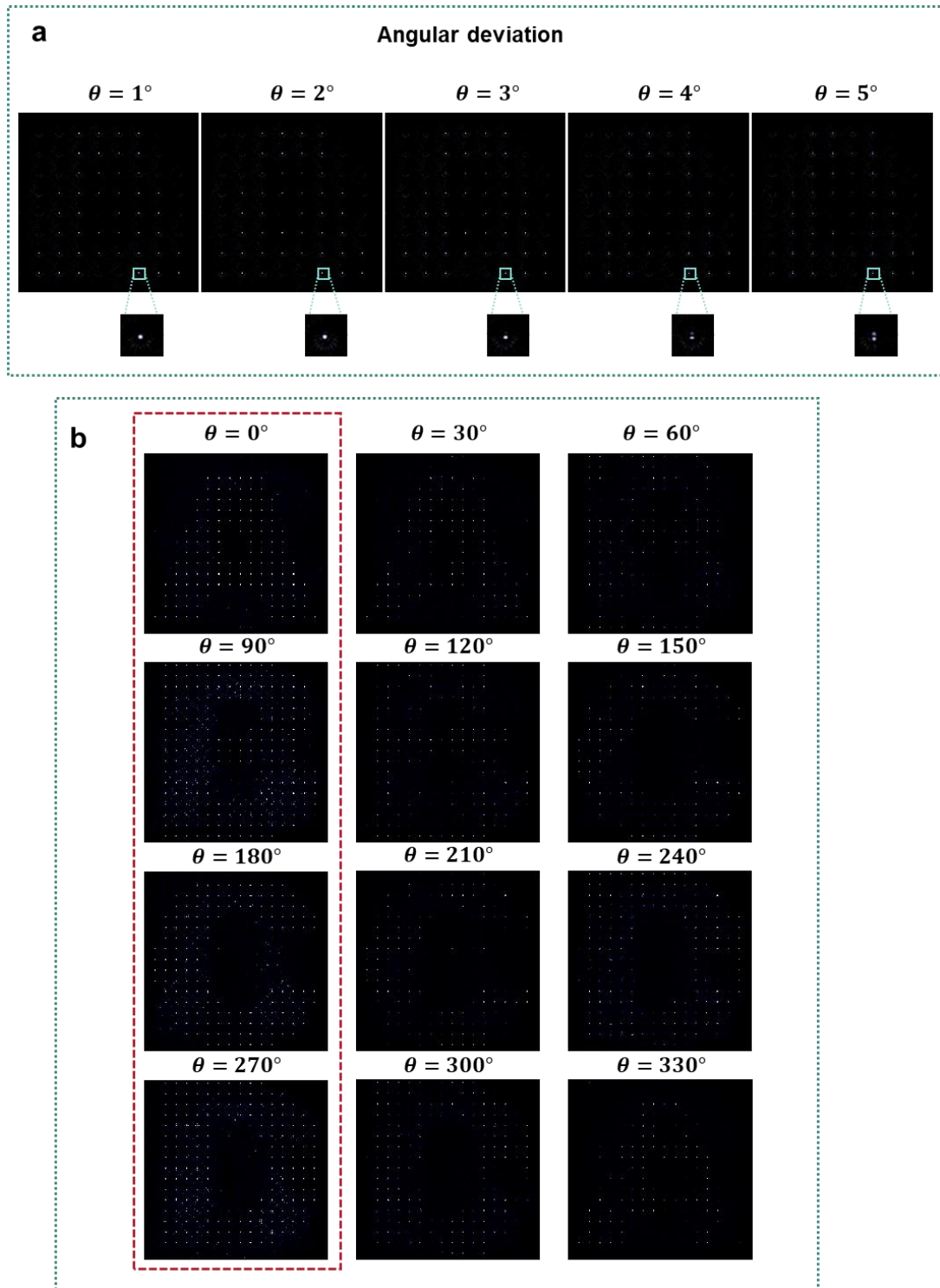


Fig. S7. Numerical results demonstrating the impact of angular misalignment in discontinuous OAM holography. (a) Holographic reconstruction based on a discontinuous OAM meta-hologram with slight angular deviation. (b) Holographic reconstruction based on a discontinuous OAM meta-hologram with large angular 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.

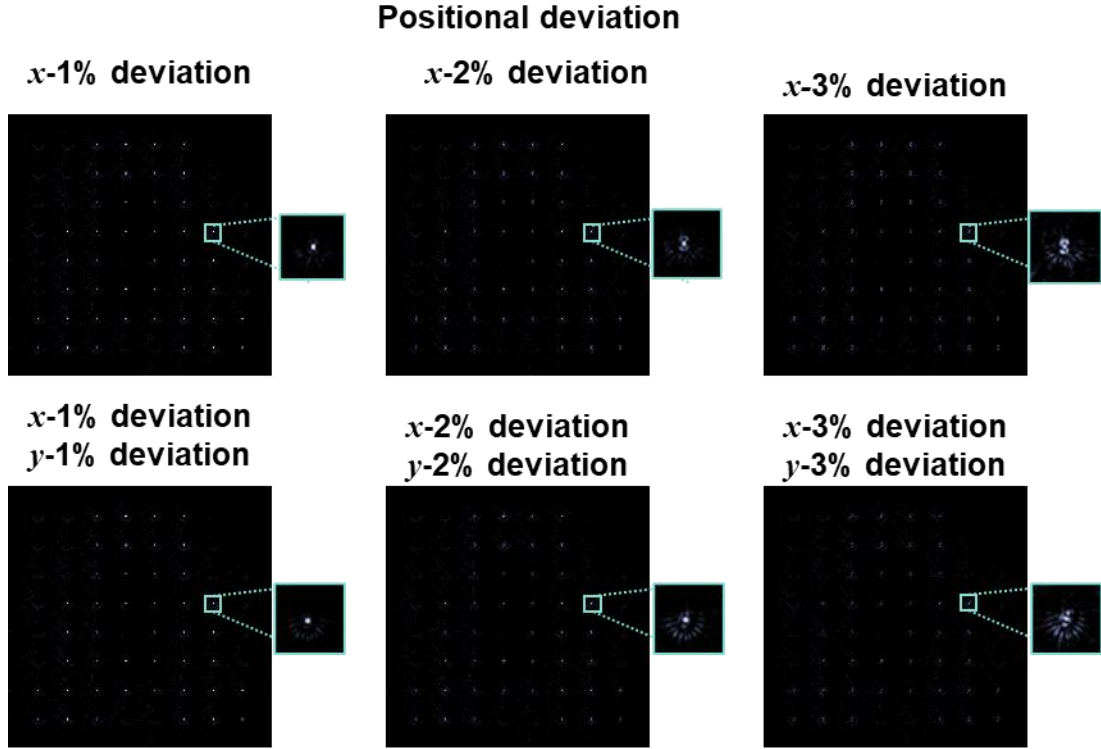


Fig.S8. Numerical results of the reconstructed images demonstrating the impact of lateral misalignment in discontinuous OAM holography.

Comment 2.4: *Fourth, while the manuscript emphasizes the advantage of discontinuous OAM in resisting spiral spectrum analysis, it lacks thorough security analysis under more complex attack scenarios, such as phase reconstruction based on machine learning or partial information leakage. It is recommended that the authors supplement the manuscript with corresponding experimental or simulation data to verify the system's robustness under different attack models and explore potential mechanisms for enhancing security.*

Response 2.4: We sincerely appreciate the reviewer's suggestions, which have provided valuable insights for our research. Indeed, there are some related researches using deep learning to recover the conventional holography (such as Opt. Commun., 529(15), 129100, 2023). We will further investigate the potential vulnerabilities of both conventional and discontinuous OAM holography using machine learning techniques in our future work.

At this stage, however, we can demonstrate that the proposed discontinuous OAM offers superior anti-attack capability compared to conventional OAM under simple attack scenarios. For example, conventional OAM holography 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 TC combination and azimuthal phase distribution for successful image reconstruction.

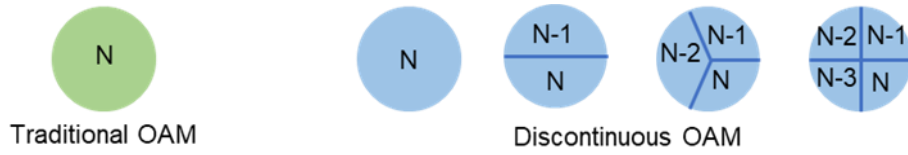


Fig. R2-1 The number of conventional OAM and discontinuous OAM modes formed by N topological charges.

As a proof of concept, to quantitatively compare the information security of conventional and discontinuous OAM holography, we use $N = 200$ (with topological charge ranging from -100 to 100) as an example. The commercialized SLM (model: HOLOEYE PLUTO-2.1-NIR-135) typically generates vortex beams with a refresh rate of 70 ms. For conventional OAM holography, decoding the information requires inputting 200 distinct OAM modes, which takes only **14 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:

$$N + N * (N - 1) + N * (N - 1) * (N - 2) + N * (N - 1) * (N - 2) * (N - 3) \quad (R1)$$

With 200 TCs, this results in 1560359200 possible configurations, requiring 1264 days—or approximately **3.5 years**—to decode. Therefore, our discontinuous OAM holography offers a security enhancement of nearly 7 orders of magnitude over traditional OAM holographic encryption.

This discussion has been added in Supplementary Note 1 as:

“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 combination and azimuthal phase distribution for successful image reconstruction.

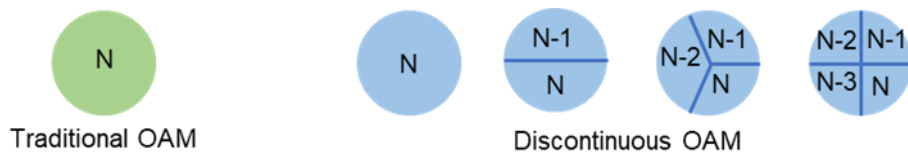


Fig. S1. The number of multiplexing possibilities of conventional OAM and discontinuous OAM modes formed by N topological charges.

As a proof of concept, to quantitatively compare the information security of conventional and discontinuous OAM holography, we use $N = 200$ (with topological charge ranging from -100 to 100) 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 200 distinct OAM modes, which takes only 14 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 200 TCs, this results in 1560359200 possible configurations, requiring 1264 days—or approximately 3.5 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 topological charge 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.”

Comment 2.5: *Finally, the manuscript mentions the possibility of further expanding channel capacity by integrating other degrees of freedom, such as polarization and wavelength. However, specific technical pathways and challenges have not been adequately addressed, especially regarding possible crosstalk between different degrees of freedom. It is suggested that the authors include preliminary experimental or simulation results on multi-degree-of-freedom multiplexing—for instance, validating the feasibility of combined polarization-OAM encoding—and analyze the coupling mechanisms between different degrees of freedom (e.g., polarization-dependent phase modulation), proposing effective decoupling strategies to demonstrate the future potential of this technology in high-dimensional multiplexing.*

Response 2.5: The authors thank the reviewer for this point. In the revised manuscript, we have incorporated the combination of polarization with discontinuous OAM as an additional degree of freedom. As a proof of concept, we designed a two-channel discontinuous OAM holography integrated with polarization multiplexing (LCP and RCP) as shown in **Fig. S19**. **Fig. S19a** demonstrates the design principle of using a pure PB phase metasurface for the decoupling of LCP and RCP (see detailed design principle in Ref. *Adv. Mater.* 37, 2415142, 2025). The simulated and experimental results of the reconstructed images are shown in **Fig. S19b**, which clearly show the images for the corresponding channels.

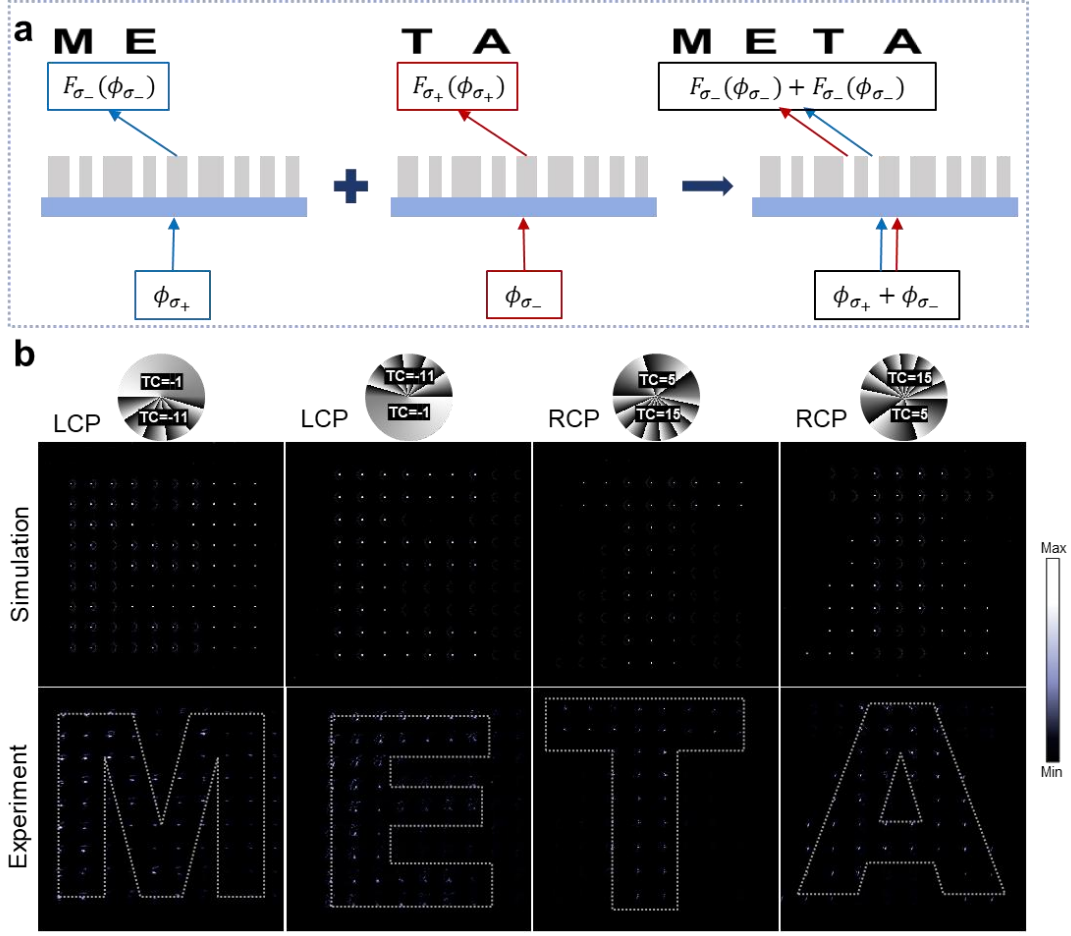


Fig. S19. Polarization-OAM multiplexing holography. (a) The design principle of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a non-interleaved method in each channel. F represents the Fourier transform. (b) Phase distribution of the incident discontinuous OAM beam and corresponding simulation results of reconstructed images.”

To further expand the multiplexing dimension and increase the number of multiplexed channels, we introduced the OAM dimension into polarization-discontinuous OAM multiplexing. For each polarization state, two sets of two-channel holograms were encoded, achieving a total of eight channels. Both simulation and experimental results validate the feasibility of this polarization-OAM hybrid encoding scheme, which are shown in the main text Fig. 5 as,

“Experiments of multiple polarization and discontinuous-OAM hybrid multiplexing holography

To further expand multiplexing dimensions and enhance channel capacity, we incorporated polarization and multiple pairs of discontinuous OAMs as an additional degree of freedom. Specifically, by integrating two pairs of discontinuous OAM modes with two orthogonal polarization states, we have designed an eight-channel metasurface multiplexed holography in Fig. 5. For left-circularly polarized (LCP) light, two pairs of

orthogonal discontinuous OAM modes $l = -1/l = -15, l = -8/l = -22$ are employed to encode four distinct images. Similarly, for right-circularly polarized (RCP) light, the set of OAM modes $l = -7/l = -15, l = -10/l = 10$ encodes another four independent images. The superimposed phase of LCP light denoted by σ_+ is inverted due to the opposite phase response between RCP and LCP, as shown in **Fig. 5a**. Consequently, the phase profile can be expressed as,

$$\varphi = \arg[\sum_{n=1}^N e^{j(\varphi_{\sigma_-}^n + \phi_{r1}^n)} + \sum_{m=1}^M e^{j(-\varphi_{\sigma_+}^m - \phi_{r2}^m)}] \quad (3)$$

where channel $n = 1, 2, \dots, N$, with N being the channel number of discontinuous OAM holography for RCP, $m = 1, 2, \dots, M$, with M being the channel number of discontinuous OAM holography for LCP, σ_- and σ_+ denote RCP and LCP, respectively, $\varphi_{\sigma_-}^n$ and $\varphi_{\sigma_+}^m$ is the calculated phase by WGS algorithm. The phase of discontinuous OAM ϕ_{r1}^n and ϕ_{r2}^m is then added to the holographic phase.

The demonstration of a geometry-phase metasurface supporting the polarization-discontinuous OAM hybrid encoding is based on a non-interleaved method^[36]. We integrated two-channel discontinuous OAM encoding with polarization multiplexing. When illuminated with an LCP beam carrying TC of $l = 1/l = 15$, the letter “M” is successfully decoded. When the metasurface is rotated by 90° , the decoded image switches from letter “M” to letter “E”, demonstrating dynamic channel switching through angular control as shown in **Fig. 5b**. Similarly, when illuminated with LCP beam carrying $l = 8/l = 22$, the letter “T” is decoded, and a 90° rotation of the metasurface enables switching from “T” to “A”. For RCP beam illumination, four distinct images “1”, “2”, “3”, and “4” can likewise be decoded as shown in **Fig. 5c**, demonstrating polarization multiplexing capability.

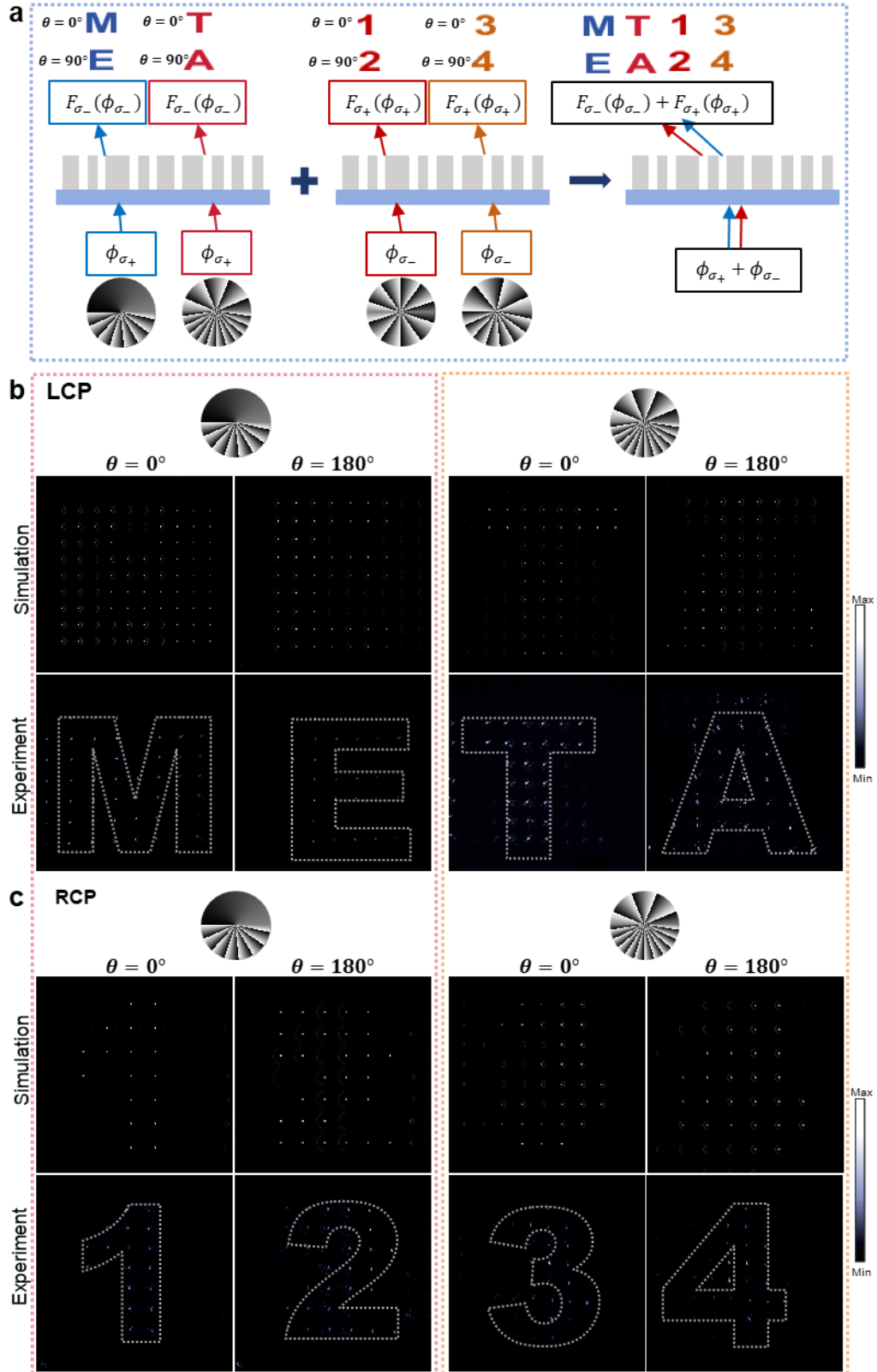


Fig. 5. Polarization-OAM multiplexing holography. (a) The design principle of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a non-interleaved method for each channel. F represents the Fourier transform. Simulated and experimental results of reconstructed images when (b) LCP and (c) RCP light

carried discontinuous OAM is incident to the metasurface.”

In summary, we have addressed all the comments of reviewer #2.

Reply report to reviewer #3

Comment 3: *This manuscript presents a novel approach for multi-channel holographic imaging by encoding multiple holographic images into a single metasurface and decoding them using structured light generated by a spatial light modulator (SLM). Compared to conventional methods—where a single orbital angular momentum (OAM) pattern generated by the SLM typically decodes only one hologram—this work utilizes discontinuous OAM beams with spatially separated topological charges. This design allows different holographic images to be selectively decoded by rotating the input beam, thereby enabling dynamic and secure multiplexing. Overall, this work demonstrates an innovative and technically sound advancement in the areas of OAM optics, holography, cryptographic imaging, and multifunctional metasurface design. Considering the following technical issues, I believe the manuscript is suitable for publication in Nature Communications after minor revision.*

Response 3: We are grateful to the reviewer's positive feedback and recommendation to publish in Nature Communications. We are happy to address all the concerns raised by the reviewer.

Comment 3.1: *In the manuscript, does Equation (2) specifically refer to the angular range $[\pi/2, 3\pi/2]$? If so, would it be more appropriate to explicitly label this range near the equation for clarity? Additionally, I reviewed Supporting Information Equation (6), but I couldn't clearly see how this expression explains why the electric field is nearly zero in the angular range $[-\pi/2, \pi/2]$. Why the “petal-like” intensity pattern only appears on the left side? Could the authors clarify how this behavior is captured by Eq. (6), or whether any assumptions or approximations are involved?*

Response 3.1: Thank you very much for your valuable comment. Following your suggestions, we have implemented the corresponding modifications in the manuscript, labeling the range near the equation.

The corresponding changes were made in the main text as follows:

“The spatial electric field distributions of the two partitioned regions overlap coherently in free space as shown in the bottom-left panel of Fig. 1c, which can be described as,

$$E \propto \cos(10\phi), \quad \phi \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right] \quad (2)$$

” in Line 119, Page 5.

Through more detailed calculations, we have demonstrated that the “petal-like” pattern only appears on the left side in **Supplementary Note 2** as:

“For discontinuous OAM, each partition can be considered as a partially blocked spiral phase plate. The phase of one partition is written as,

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

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,

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

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

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,

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

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

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:

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

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,

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

The electric field distribution is given by:

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

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:

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

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

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

It can be seen that the electric field distribution of the dual-partition discontinuous OAM is proportional to $\cos(l\phi)$. By plotting $\cos(l\phi)$ as shown in **Fig. S3**, we can observe ten zeros in the range of $\phi = [\frac{\pi}{2}, \frac{3\pi}{2}]$, 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**. ”

In **Fig. S21**, we demonstrate the propagation characteristics of the discontinuous OAM beam in free space. Numerical simulations demonstrate the evolution of intensity distributions for both half-OAM and discontinuous OAM beams, which exhibit stable patterns during propagation.

Propagation characteristics

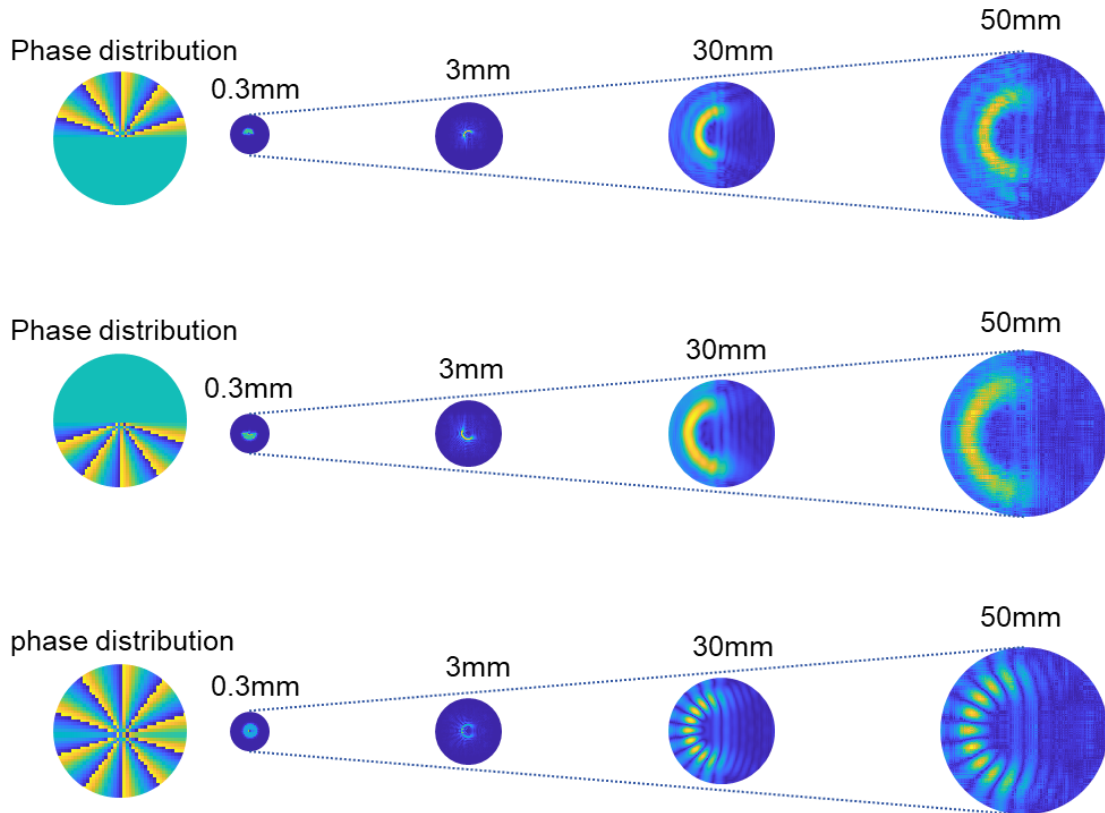


Fig. S21. The simulated propagation characteristics of the discontinuous OAM beam in free space. After the Fresnel diffraction regime, i.e., in the far field, the discontinuous OAM beam propagates stable in free space.

Comment 3.2: In Figures 1(c) and 1(d), the bottom panels are labeled as "electric field distributions." However, based on the visual patterns, they appear to represent intensity profiles rather than complex field amplitudes. Should these be labeled as "intensity" instead of "electric field" for accuracy and clarity?

Response 3.2: Thank you very much for your significant comment. We've modified the label of Figs. 1c and 1d accordingly.

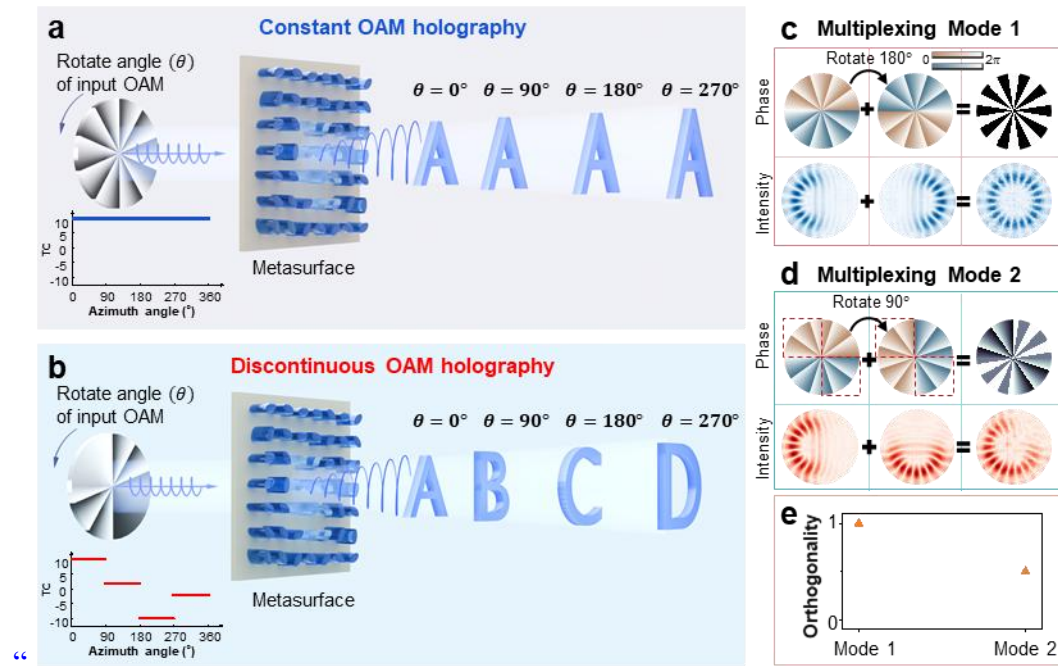


Fig. 1. Schematic illustration of the discontinuous OAM metasurface holography.”

Comment 3.3: *I recommend that the authors consider adding a colorbar next to the phase distributions in Figure 1 of the main text for clarity. Additionally, I noticed a potential inconsistency in the phase color mapping. In Figure 1c, the brown-colored phase progresses from dark brown to white as the azimuthal angle increases, which corresponds to a positive topological charge ($\ell=+10$). However, in the brown segment of Figure 2a, the same color progression—from dark brown to white with increasing azimuth—appears to represent a negative topological charge ($\ell=-10$). For clarity and consistency, I suggest the authors ensure that the color mapping of phase is consistently represented throughout the figures, especially for readers interpreting the sign of the OAM from the color gradient.*

Response 3.3: Thank you very much for your significant comment. The sign definition for TC is shown as follows: a positive TC corresponds to phase increasing in the clockwise direction, while a negative TC indicates phase increasing counterclockwise, as illustrated in **Fig. R3-1**.

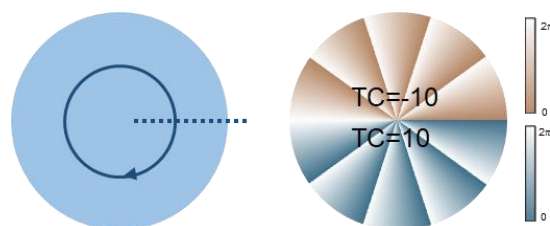


Fig. R3-1. The sign definition for TC.

In Fig. 1c, the brown-colored phase denoted negative topological charge ($l = -10$).

Following the reviewers' suggestions, we have added a colorbar next to the phase distributions in Fig. 1c and Fig. 2a.

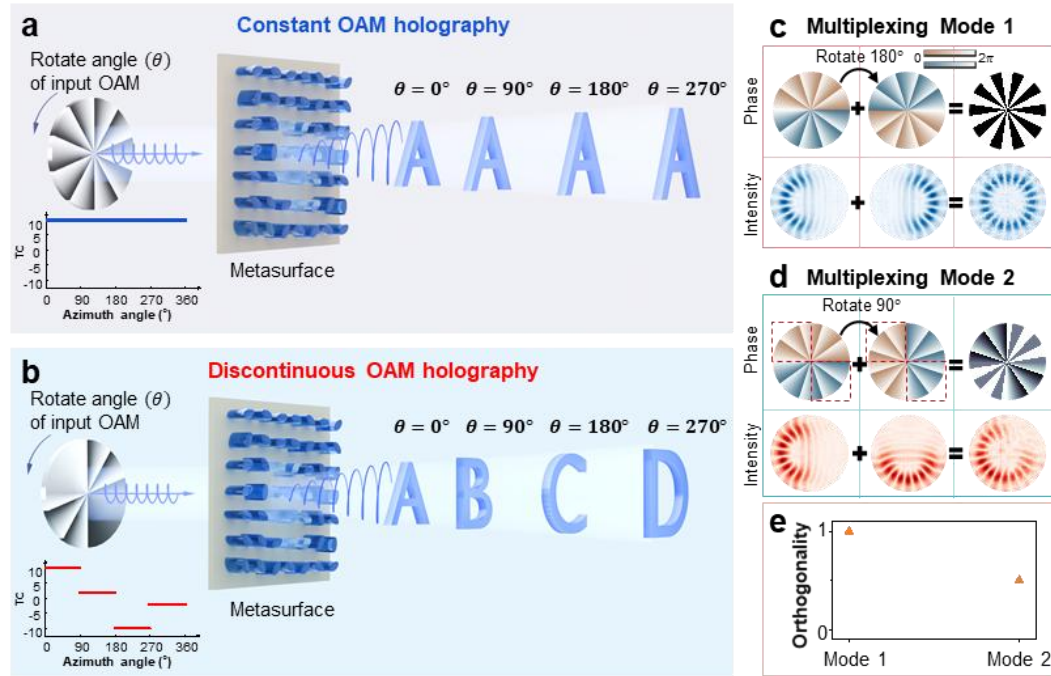


Fig. 1. Schematic illustration of the discontinuous OAM metasurface holography.

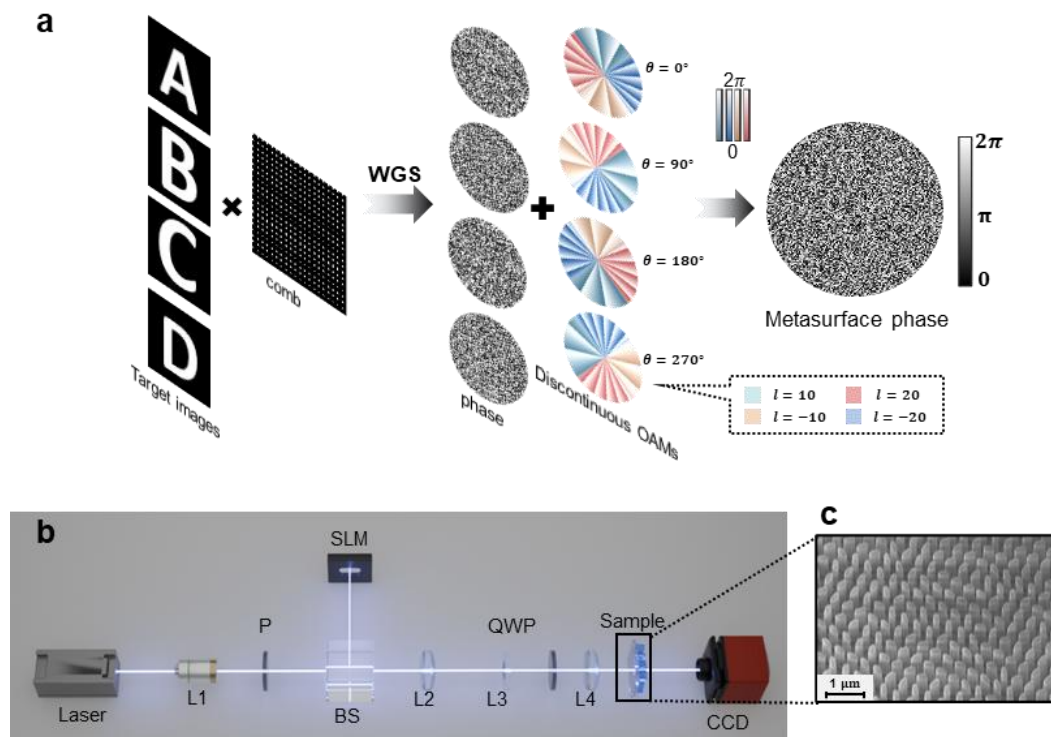


Fig 2. Algorithm flowchart and setup of the discontinuous OAM metasurface holography.

Comment 3.4: *While Supplementary Note 3 provides insight into the orthogonality behavior via inner product analysis, it would be helpful if the authors could clarify the specific method used to compute the SNR values shown in Figures 3c and 3d—such as how the signal and noise regions are defined, and whether any averaging or normalization is applied. In particular, the near-perfect Gaussian spot distribution appears only when angular orthogonality is achieved. However, even in the absence of orthogonality, there is still observable power forming a petal-like intensity pattern. This raises the question of how exactly the SNR and orthogonality are defined and processed in the data analysis.*

Response 3.4: Thank you very much for your significant comment. In **Supplementary Note 8**, we provide a detailed explanation of the SNR calculation methodology, where the noise is obtained by subtracting the reconstructed image from the sampled original image. Since the original image has a binary distribution, we normalized the reconstructed image to quantify crosstalk. Although decoding remains possible even with non-Gaussian spot formation when the encoded and decoded discontinuous OAM modes are misaligned, the SNR under such conditions is significantly low. Maximum SNR is achieved only when perfect mode matching occurs during decoding.

“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 signal-to-noise ratio (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. 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.

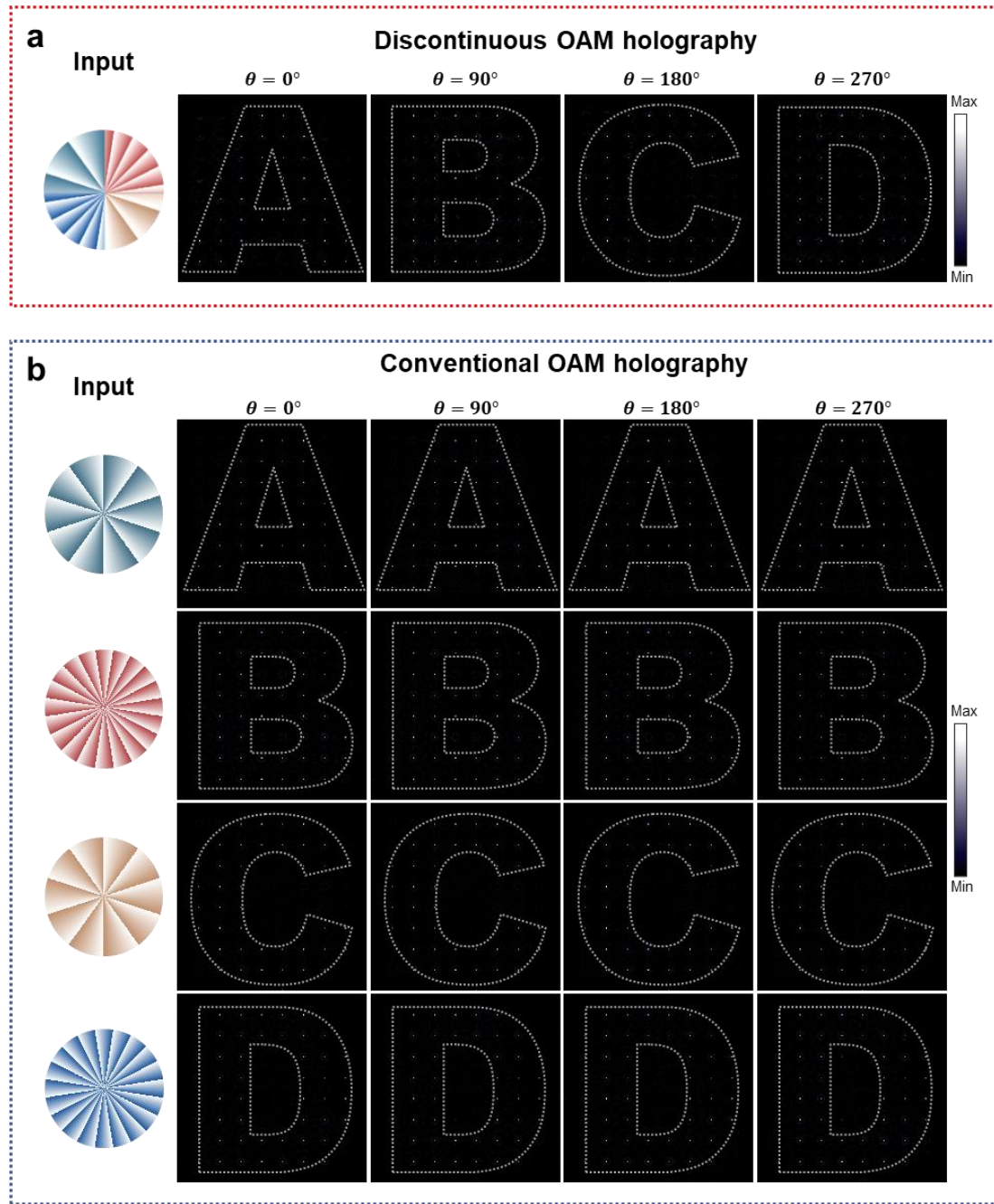


Fig. S9. The decoded holographic images of discontinuous OAM holography and conventional OAM holography with a phase-only metasurface. (a) Simulation results of discontinuous OAM holography. (b) Simulation results of conventional holography.

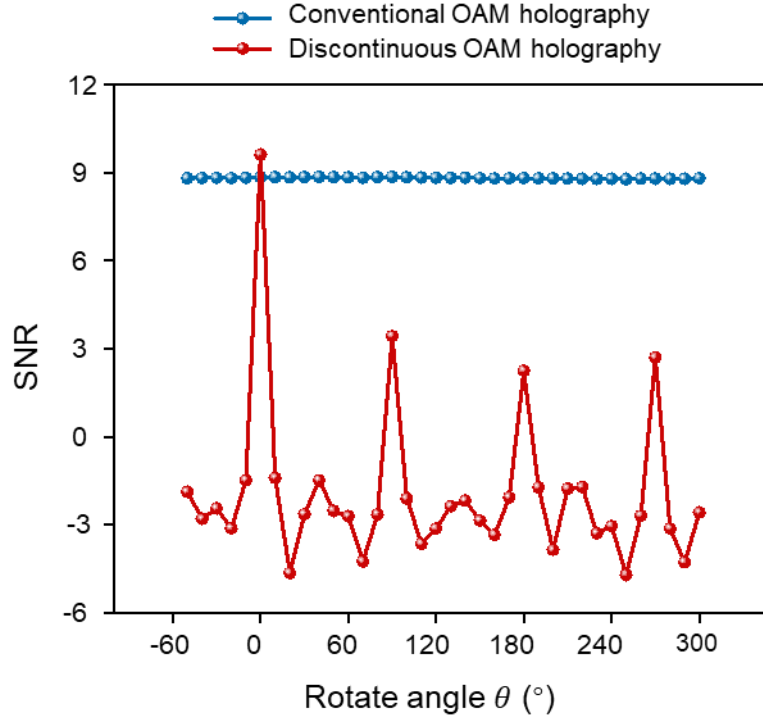


Fig. S10. Relationship between SNR and incident light rotation angle for conventional OAM holography and discontinuous OAM holography.”

Comment 3.5: *In Figure 2a, I noticed that the phase distributions corresponding to images B and C appear highly similar. Since the authors mention that the meta-atoms are based on geometric phase, and the Methods section only specifies LCP illumination, the polarization state of the incident light is not fully described throughout the manuscript. Could the authors clarify whether different circular polarizations (e.g., LCP vs. RCP) were used to access additional holographic channels? If so, it would be helpful to elaborate on the polarization dependence and specify which channels were designed for which incident polarization state.*

Response 3.5: Thank you very much for your significant comment. The four-channel discontinuous OAM patterns shown in **Fig. 2a** originate from the same vortex beam but with different rotation angles. This fundamental characteristic enables holographic channel switching through metasurface rotation.

In our original manuscript, we solely utilized the PB phase to control LCP beam, resulting in a single polarization channel where all incident beams were LCP carrying discontinuous OAM. Inspired by the reviewers’ insightful comments, to enhance the capacity and expand multiplexing dimensions, we have now implemented PB phase control for both LCP and RCP beams, achieving polarization-OAM hybrid encoding. For PB metasurface, the phase modulation exhibits opposite responses for LCP and RCP. When encoding LCP light, the outgoing RCP beam is deflected to the left side. For RCP beam encoding, the total phase must be inverted (multiplied by -1). This ensures that both polarization channels (LCP and RCP) are steered to the same spatial position under linear polarization incidence. Therefore, it is able to use pure PB phase

to decouple LCP and RCP. As a proof of concept, we designed a two-channel discontinuous OAM holography integrated with polarization multiplexing (see more detailed design principle in Ref. *Adv. Mater.* 37, 2415142, 2025). In **Fig. S17**, we demonstrated a two-channel discontinuous OAM holography combined with polarization multiplexing.

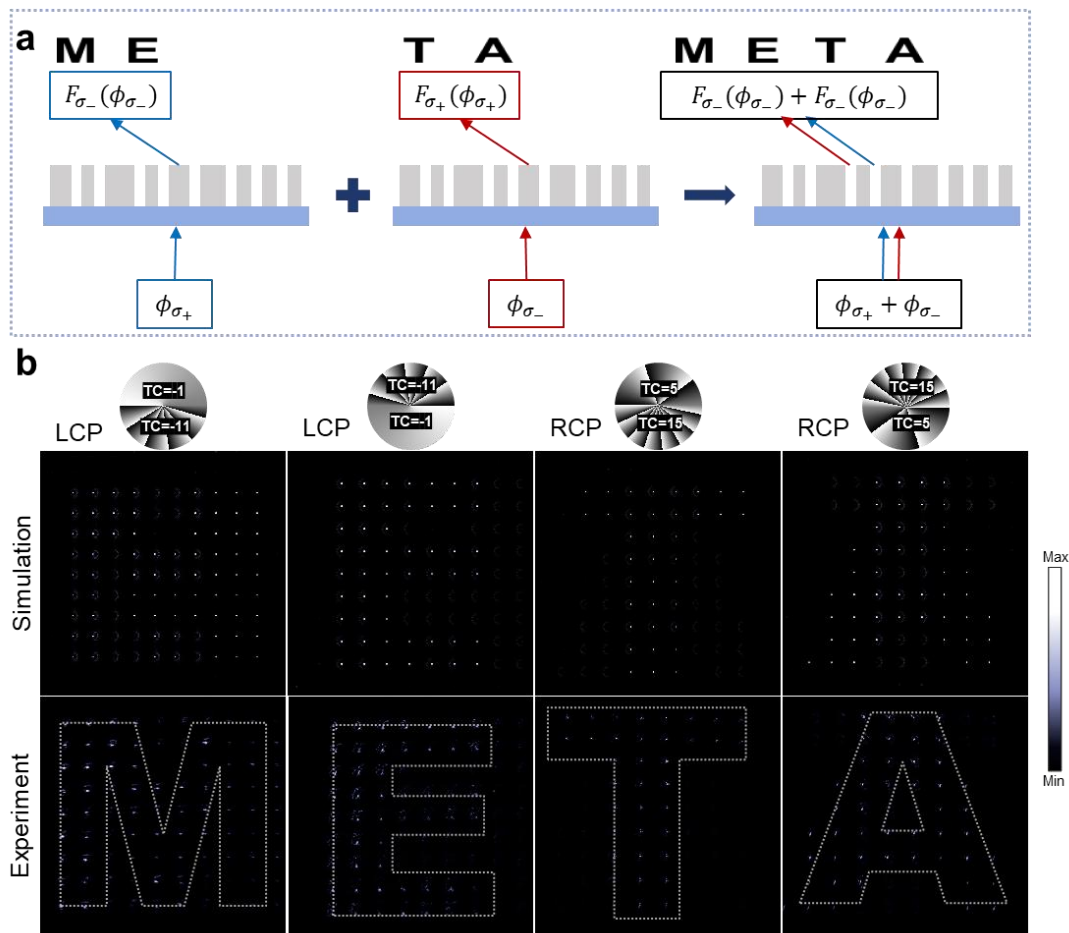


Fig. S19. Polarization-discontinuous OAM encoding holography. (a) The demonstration of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a non-interleaved method in each channel. F represents the Fourier transform. (b) Phase distribution of the incident discontinuous OAM beam and corresponding simulation results of reconstructed images.”

To further expand the multiplexing dimension and increase the number of multiplexed channels, we introduced the OAM dimension into polarization-discontinuous OAM multiplexing. For each polarization state, two sets of two-channel holograms were encoded, achieving a total of eight channels. Both simulation and experimental results validate the feasibility of this polarization-OAM hybrid encoding scheme, which are shown in the main text Fig. 5 as:

“Experiments of multiple polarization and discontinuous-OAM hybrid multiplexing holography

To further expand multiplexing dimensions and enhance channel capacity, we incorporated polarization and multiple pairs of discontinuous OAMs as an additional degree of freedom. Specifically, by integrating two pairs of discontinuous OAM modes with two orthogonal polarization states, we have designed an eight-channel metasurface multiplexed holography in **Fig. 5**. For left-circularly polarized (LCP) light, two pairs of orthogonal discontinuous OAM modes $l = -1/l = -15, l = -8/l = -22$ are employed to encode four distinct images. Similarly, for right-circularly polarized (RCP) light, the set of OAM modes $l = -7/l = -15, l = -10/l = 10$ encodes another four independent images. The superimposed phase of LCP polarization denoted by σ_+ is inverted due to the opposite phase response between RCP and LCP, as shown in **Fig. 5a**. Consequently, the phase profile can be expressed as,

$$\varphi = \arg[\sum_{n=1}^N e^{j(\varphi_{\sigma_-}^n + \phi_{r1}^n)} + \sum_{m=1}^M e^{j(-\varphi_{\sigma_+}^m - \phi_{r2}^m)}] \quad (3)$$

where channel $n = 1, 2, \dots, N$, with N being the channel number of discontinuous OAM holography of RCP, $m = 1, 2, \dots, M$, with M being the channel number of discontinuous OAM holography of LCP. σ_- and σ_+ denote RCP and LCP, respectively, $\varphi_{\sigma_-}^n$ and $\varphi_{\sigma_+}^m$ is the calculated phase by WGS algorithm. The phase of discontinuous OAM ϕ_{r1}^n and ϕ_{r2}^m is then added to the holographic phase.

The demonstration of a geometry-phase metasurface supporting the polarization-discontinuous OAM hybrid encoding is based on a non-interleaved method^[36]. We integrated two-channel discontinuous OAM encoding with polarization multiplexing. When illuminated with an LCP beam carrying TC of $l = 1/l = 15$, the letter “M” is successfully decoded. When the metasurface is rotated by 90° , the decoded image switches from letter “M” to letter “E”, demonstrating dynamic channel switching through angular control as shown in **Fig. 5b**. Similarly, when illuminated with LCP beam carrying $l = 8/l = 22$, the letter “T” is decoded, and a 90° rotation of the metasurface enables switching from “T” to “A”. For RCP beam illumination, four distinct images “1”, “2”, “3”, and “4” can likewise be decoded as shown in **Fig. 5c**, demonstrating polarization multiplexing capability.

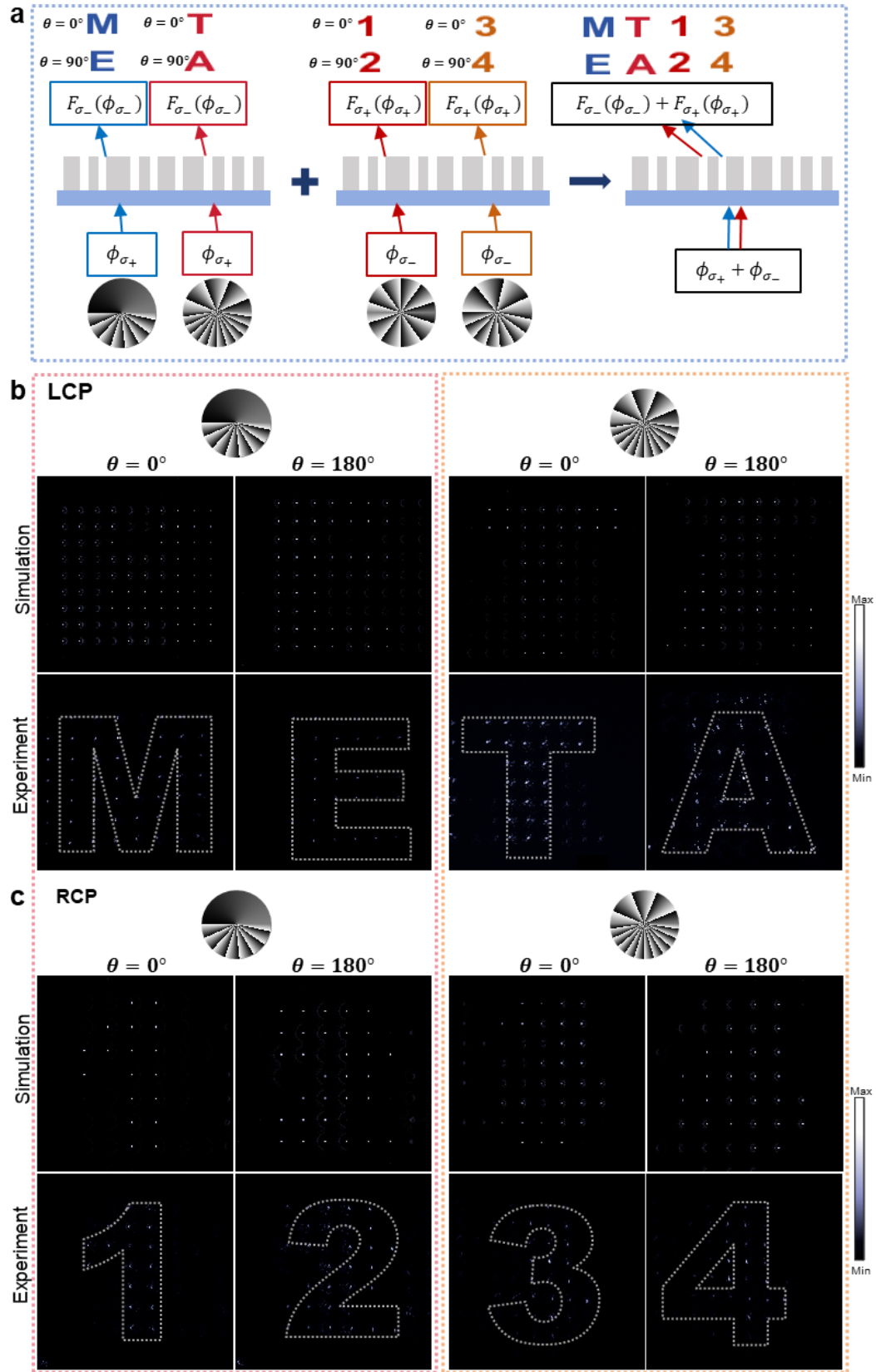


Fig. 5. Polarization-OAM multiplexing holography. (a) The design principle of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a

non-interleaved method for each channel. F represents the Fourier transform. Simulated and experimental results of reconstructed images when (b) LCP and (c) RCP light carried discontinuous OAM is incident to the metasurface.”

Comment 3.6: *In Figure 5b, the experimental holographic images for the six-channel configuration appear noticeably clearer than those in the four-channel case shown in Figure 4d. Interestingly, in the six-channel experiment, each decoded holographic image is encoded using two OAM values (i.e., a pair of $\pm\ell$). Does this suggest that encoding each holographic image with a pair of OAM values inherently leads to better reconstruction quality? It would also be helpful if the authors could provide quantitative metrics (e.g., SNR) for the six-channel case to facilitate a direct comparison with the four-channel results.*

Response 3.6: Thank you very much for your significant comment. In Supplementary Note 9, to enhance image clarity and enable quantitative characterization of inter-channel crosstalk magnitude and intensity, we spatially separated the encoded images of each channel into distinct regions. This deliberate spatial isolation results in significantly improved visual discernibility, with detailed crosstalk patterns for other channels provided in Fig. S14.

As rightly noted by the reviewers, the four-channel OAM holography achieves higher SNR compared to the six-channel configuration. We calculated the SNR for each channel in both four-channel and six-channel discontinuous OAM holography. As shown in Fig. S20, the four-channel system exhibits higher SNR values than the six-channel system, indicating superior image quality in the four-channel configuration. However, the reviewer observed that the experimental results appeared to show better quality in the six-channel system. This apparent contradiction stems from our design methodology, the six channels were spatially distributed across different physical locations, thereby dispersing crosstalk to other spatial regions as shown in Fig. S13. In contrast, the encoded images in two-channel and four-channel discontinuous OAM holography overlap spatially.

“Supplementary Note 11: 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. S13. 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. S14a. This spectral complexity inherently enhances security by preventing

unauthorized access through brute-force OAM mode matching. Experimental results in **Fig. S14b** demonstrate the successful decoding of all six channels at different locations, with the reconstructed images exhibiting near-perfect Gaussian spot profiles.

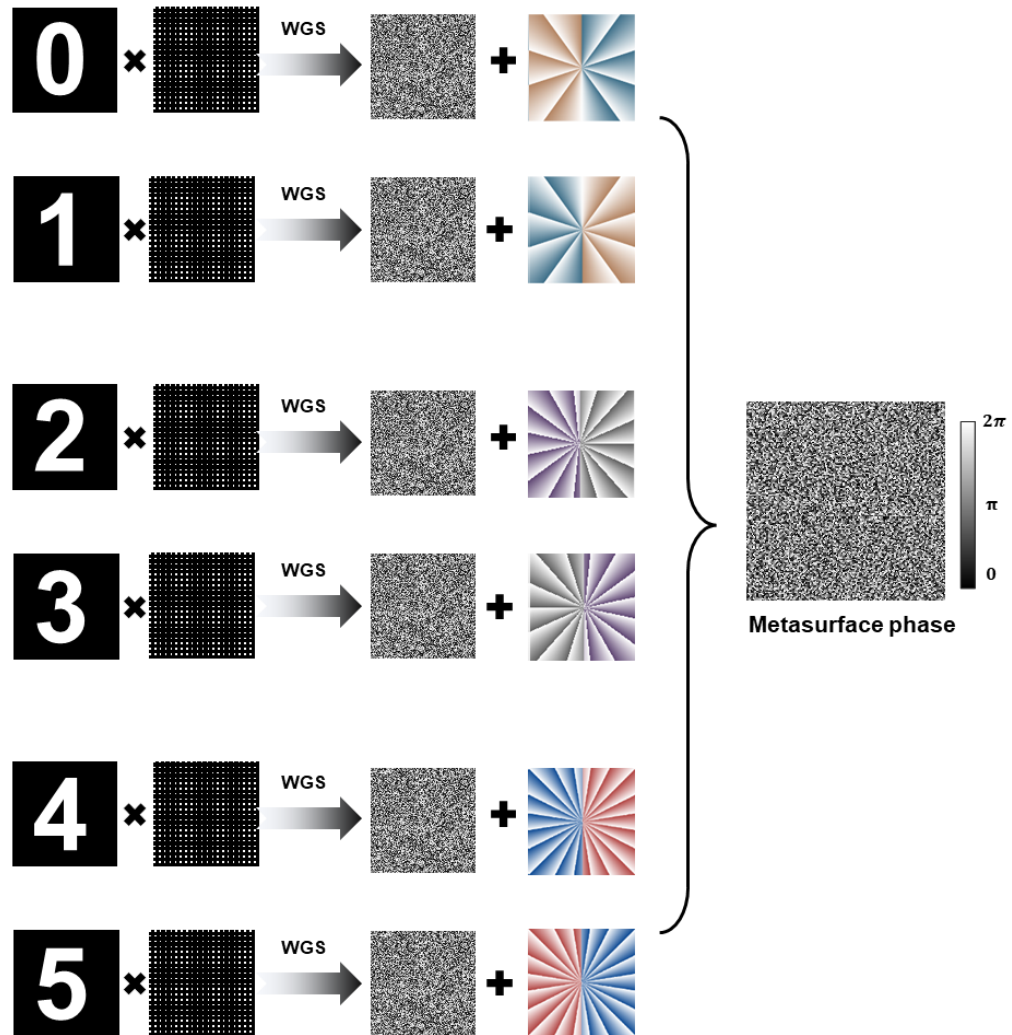


Fig. S13. The algorithm flowchart of multiple-discontinuous-OAM multiplexing holography.

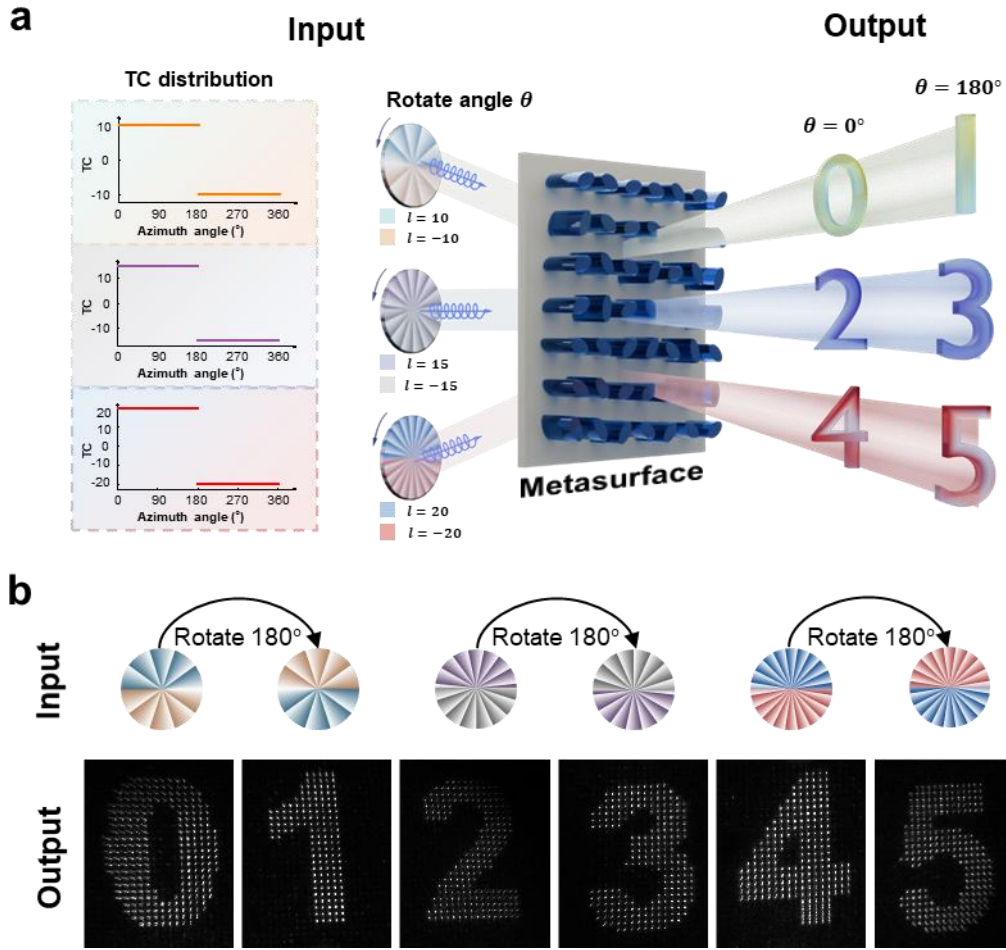


Fig. S14. Multiplexing OAM holography by integrating various pairs of discontinuous OAM modes. (a) Schematic diagram. When the incident discontinuous OAM mode is $l = 10/l = -10$, the output images are “0” and “1”; when the incident discontinuous OAM mode is $l = 15/l = -15$, the output images are “2” 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 comprehensive experimental results of multiple-discontinuous-OAM multiplexing holography are shown in **Fig. S15**. 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.

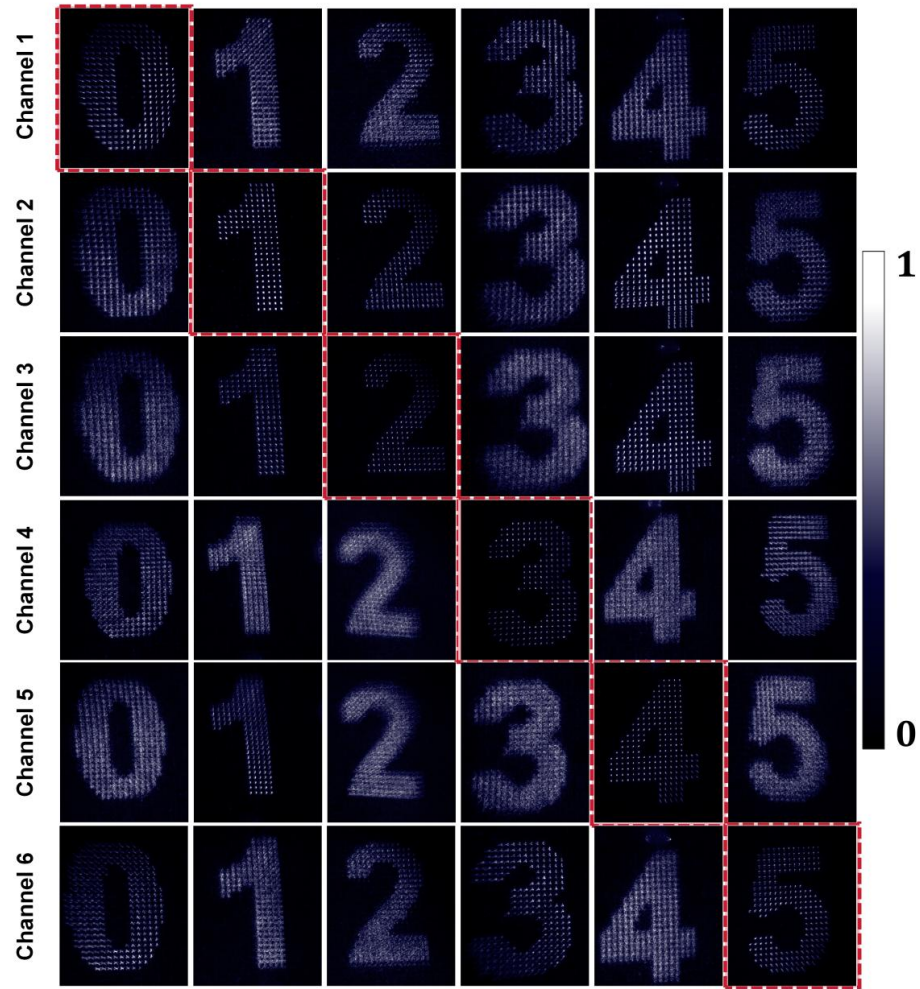


Fig. S15. Experimental results of multiple-discontinuous-OAM holography. The red boxes indicate the fully decoded images under proper discontinuous OAM illumination.”

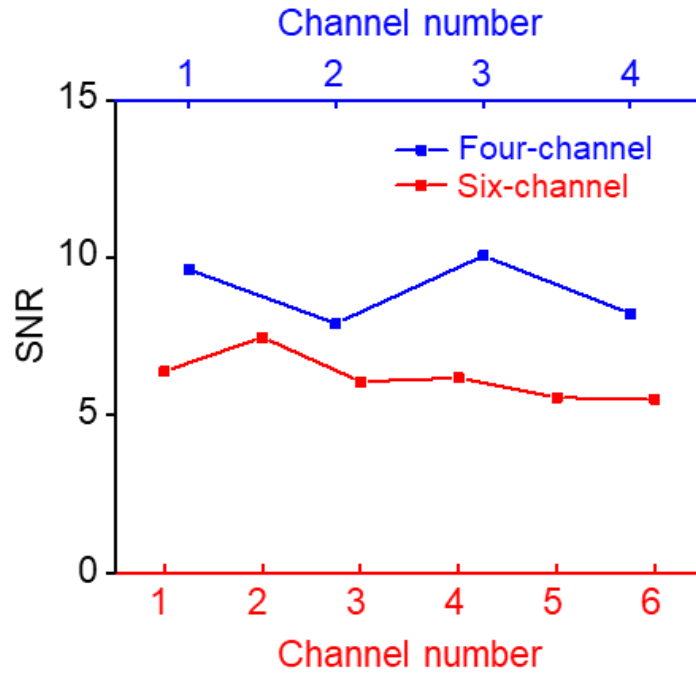


Fig. S20. SNR Comparison between four-channel and six-channel discontinuous OAM Holography. The blue dots represent the SNR of each channel image in the four-channel discontinuous OAM holography. The red dots represent the SNR of each channel image in the six-channel discontinuous OAM holography.

In summary, we have addressed all the comments of reviewer #3.

Reply report to reviewer #1

Comment: *Thanks to authors for their effort with improved revised manuscript. The authors have addressed most of questions raised in previous round reviewing. Therefore, I recommend considering potential publication of this study after addressing two remaining questions still unclear.*

Response: We would like to thank the reviewer for recognizing our effort in improving the manuscript. We are happy to address the remaining concerns raised by the reviewer.

Comment 1.1: *The discontinuous OAM modes are used as a new dimension to enhance the capacity of holographic multiplexing. However, the capacity limit of the proposed method remains unclear, when the inter-channel crosstalk and deviations are small and acceptable. Please provide discussions and quantitatively estimate this limit.*

Response 1.1: The authors thank the reviewer for this point. To present the capacity limit of our proposed method, we have calculated the SNR for different channels. As the number of topological charges encoded by discontinuous OAM increases, the number of azimuthal partitions rises, making the crosstalk more significant. When the number of channels in discontinuous OAM holography reaches forty, the SNR drops to approximately 0. This indicates that the noise (i.e., crosstalk) becomes almost equal 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.

The channel capacity of discontinuous OAM holography is analyzed in **Supplementary Note 12**.

“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. When the number of channels in discontinuous OAM holography increases to forty-two, the SNR drops to approximately 0. 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.

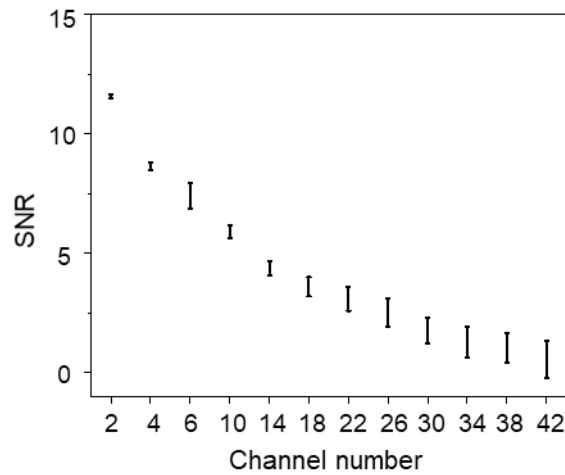


Fig. S16. The SNR of discontinuous OAM holography with different numbers of channels. The error bars represent the range between the maximum and minimum SNR values across all channels in the multi-channel discontinuous OAM holography.”

Comment 1.2: *The vortex beam with discontinuous OAM in this study is normal, which means that the beams with varied TCs also have different beam profile, such as beam size and central area with null field. Is the proposed method still effective in case of fractional vortex beams and perfect vortex beams such as (Yao, J. et al. A spatial-frequency patching metasurface enabling super-capacity perfect vector vortex beams. eLight 4, 21 (2024))?*

Response 1.2: The authors thank the reviewer for this point. Our approach of discontinuous OAM holography is universal—it is applicable not only to conventional OAM beams, but also to fractional vortex beams and perfect vortex beams. The only requirement is that the OAM modes encoded at different angular positions must be mutually orthogonal.

This discussion has been added in **Supplementary Note 13** as:

“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 and perfect vortex beams. 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.

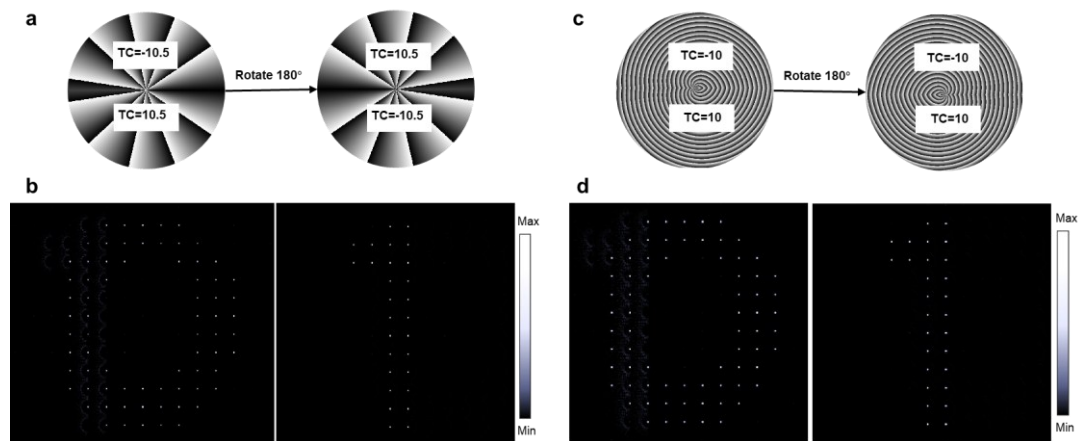


Fig. S17. Discontinuous OAM holography using fractional vortex beams and perfect vortex beams. (a) Phase distribution of discontinuous fractional vortex beams. (b) Experimental results of two-channel discontinuous fractional OAM holography. (c) Phase distribution of discontinuous perfect vortex beams.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

In summary, we have addressed all the comments of reviewer #1.

Reply report to reviewer #2

Comment 2: *The revised manuscript demonstrates the authors' considerable efforts in addressing the questions and concerns raised by myself and the other reviewers. Overall, the manuscript has been significantly improved. Nevertheless, one critical issue remains that precludes me from recommending acceptance: the quality and signal-to-noise ratio of the experimental results are substantially inadequate. Without the reference dashed boxes, it would be difficult to identify which letter the decrypted experimental image represents.*

Response 2: We would like to thank the reviewer for recognizing our effort in improving the manuscript. We are happy to address the concerns raised by the reviewer. In our new results, we have removed all reference dashed boxes for better clarification.

Comment 2.1: *In Figure 5, stray speckles are still present in non-letter regions. What criteria were used to distinguish these artifacts from actual characters, and how were they excluded? Explicit justification should be provided. Moreover, certain areas within the letter and number regions suffer from severely diminished brightness or a complete lack of signal. What may have caused these irregularities?*

Response 2.1: We sincerely appreciate the reviewer's constructive feedback and have conducted a comprehensive analysis of the factors contributing to the suboptimal results in our previous experiment. The stray speckles observed in non-letter regions result from imperfect alignment between the sample and the incident light, as well as spherical aberrations introduced by the previous lens. In addition, certain areas suffer from severely diminished brightness or a complete lack of signal, resulting from multiple holographic channels designed to occupy the same spatial location, causing crosstalk and overlapping decoded images. When the beam is not parallel or properly aligned, the crosstalk at certain points will exhibit intensity comparable to that of the decoded Gaussian spots.

To improve the experimental results, we repeated the experiment by replacing the lens with a high Numerical Aperture (NA) objective (NA=0.6) and adjusted the pitch angle between the lens and the metasurface to achieve precise alignment. The final results demonstrate excellent agreement with simulations, as shown in the updated **Fig. 5** below.

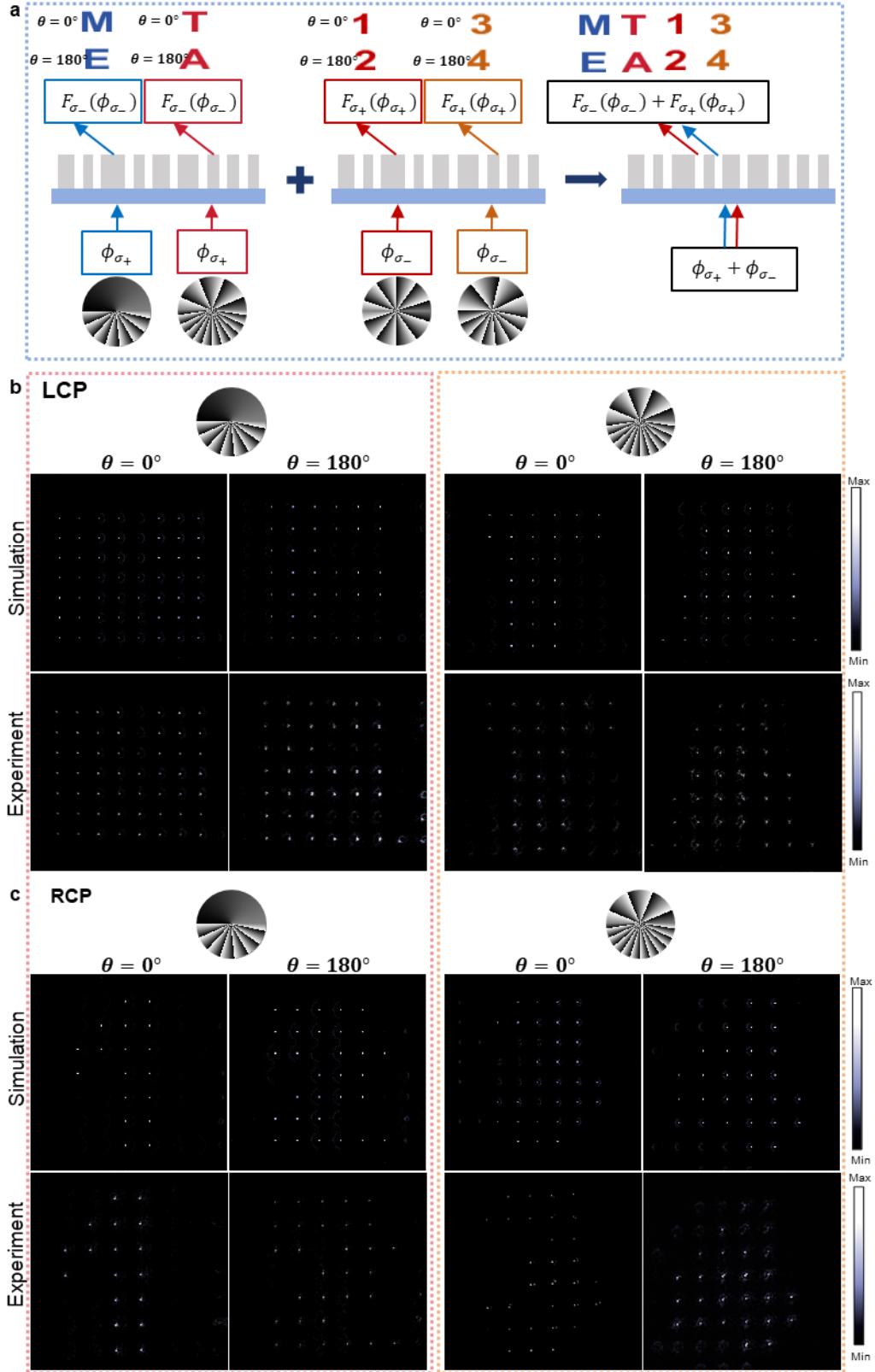


Fig. 5. Polarization-OAM hybrid encoding. (a) The demonstration of a geometry-phase metasurface supporting the polarization-OAM hybrid encoding with a non-interleaved method in each channel. F represents the Fourier transform. Simulated and experimental results of reconstructed images when (b) LCP and (c) RCP light beam carried discontinuous OAM is incident to the metasurface.

Comment 2.2: *The problems in Figure S18 are more pronounced. Some numerals exhibit extensive missing data points, and the font style in the experimental results diverge noticeably from that in the simulations. Additionally, the experimental images display inconsistent rotational misalignment across different numerals. What is the origin of these rotational errors, and how were the angles determined during the experiments?*

Response 2.2: The authors thank the reviewer for this valuable point. Similar to the Response 2.1, the missing data spots in the sample result from imperfect alignment between the sample and the incident light, which induces crosstalk that obscures the Gaussian signal spots. Additionally, the inconsistent rotational misalignment observed across different numerals in the experimental results occurred because, in the previous experiment, the sample was not properly leveled and was tilted at an angle. This caused some angular discrepancies when manually adding the reference dashed boxes, which were not aligned correctly with the original experimental numerals, leading to noticeable variations in angles. We are sorry for this oversight and have now carefully reconduct the experiment. The new experimental results show clear visualization of the outcomes without the need for any postprocessing of the image or adding of reference boxes. The experimental results, shown in the revised **Supplementary Fig. S19** below, are in excellent agreement with the simulated results.

We sincerely appreciate the reviewer's insightful comments, which have allowed us to significantly improve the experimental results and the manuscript.

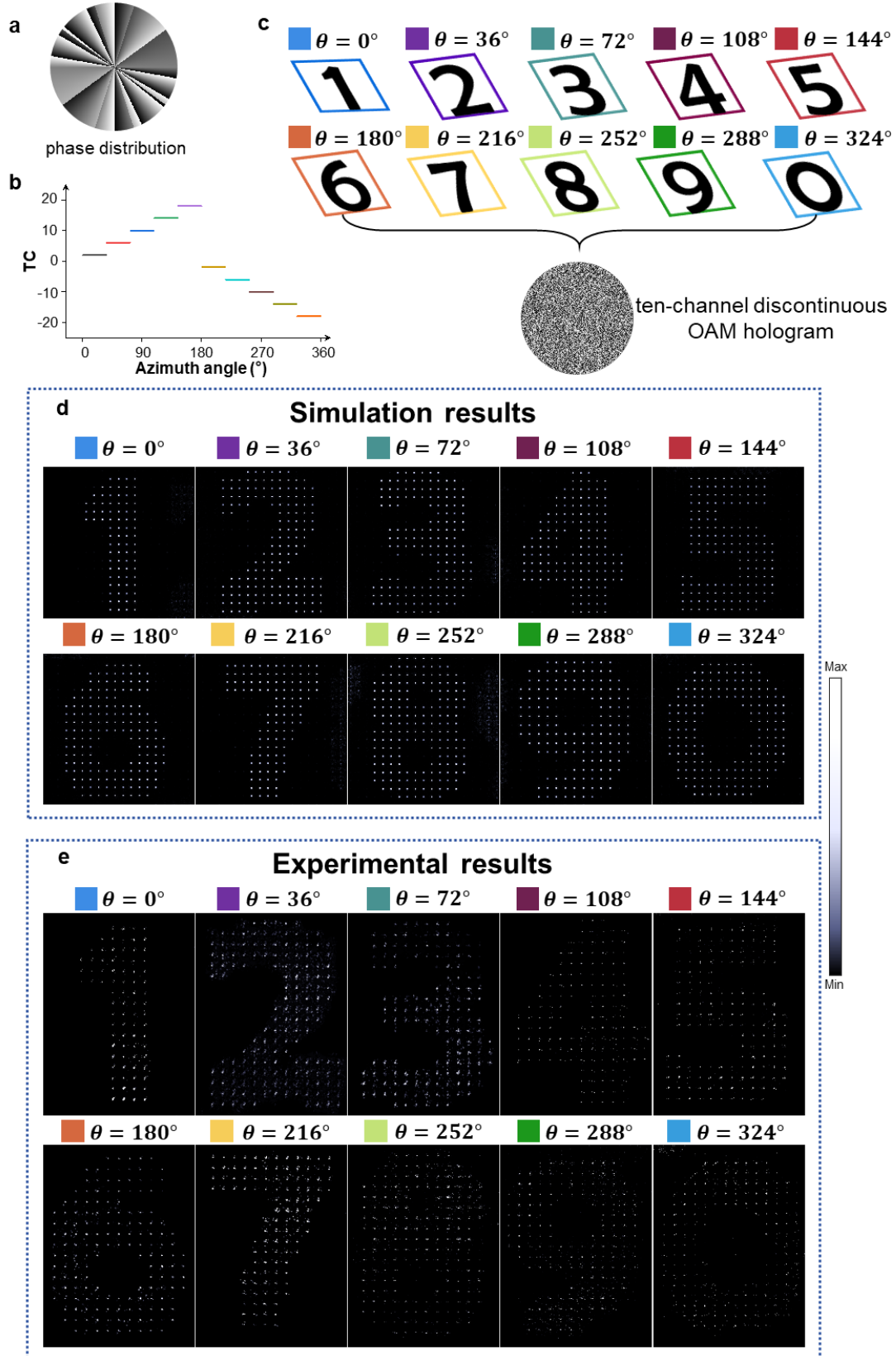


Fig. S19. Ten-channel discontinuous OAM holography. (a) The phase distribution of ten-channel discontinuous OAM holography. (b) The distribution of TC across azimuth angle. (c) OAM-encoded image multiplexing based on one discontinuous OAM states with ten rotate angles. (d) Simulated holographic images reconstructed

from ten-channel discontinuous OAM meta-hologram. (e) Experimental holographic images reconstructed from ten-channel discontinuous OAM meta-hologram.

In summary, we have addressed all the comments of reviewer #2.

Reply report to reviewer #3

Comment 3: *After a thorough review of the revised manuscript and supporting materials, I confirm that the authors have satisfactorily addressed the technical issues raised by Reviewers 1, 2, and myself (Reviewer 3). The relevant technical clarifications are appropriately documented in the Supplementary Information. This work demonstrates an innovative and technically sound advancement in OAM optics, holography, cryptographic imaging, and multifunctional metasurface design. I believe the manuscript is suitable for publication in Nature Communications.*

Response 3: We are grateful to the reviewer's positive feedback and recommendation to publish in Nature Communications.

Reply report to reviewer #1

Comment 1.1: *The authors have almost addressed all of my concerns. There is only one point that is unclear. In the reply, the authors said the SNR approaches zero when the topological charge reaches 40. However, in the Supplementary notes 12, the limit of TC is given as 42.*

Response 1.1: We would like to thank the reviewer for recognizing our effort in improving the manuscript. There is a typo in the original response letter. When the number of channels in discontinuous OAM holography increases to forty-two, the SNR of all holographic channels drops to the range of 0-2 which indicates that the signal and noise have become inseparable.

This modification is detailed in **Supplementary Note 12** as:

“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.

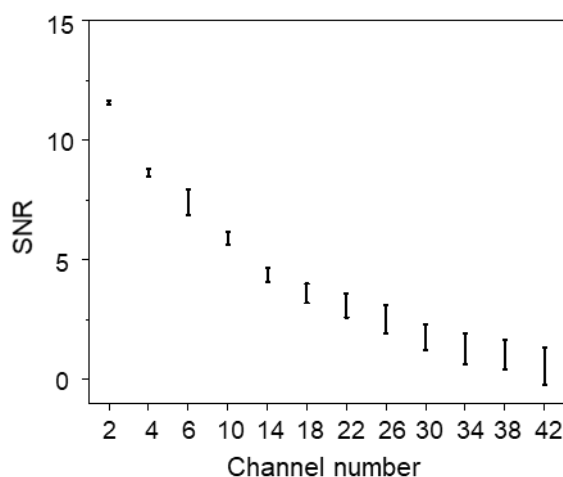


Fig. S16. The SNR of discontinuous OAM holography with different numbers of channels. The error bars represent the range between the maximum and minimum SNR values across all channels in the multi-channel discontinuous OAM holography.”

Comment 1.2: *Moreover, the authors should also include some discussions on the acceptable level of SNR so that the authors can get a clear concept of this limit.*

Response 1.2: The authors thank the reviewer for this point. 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. Therefore, we have modified the threshold for evaluating image quality, determining that when the SNR reaches 1, the signal and noise become inseparable.

This discussion is detailed in **Supplementary Note 8** as:

“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 signal-to-noise ratio (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.”

Comment 1.3: *Finally, some classic references would be necessary to help the audience understand PVB and FVB mentioned in the Supplementary Notes. After fully addressing these minor issues, I would be delighted to recommended this article for publication in Nature Communications.?*

Response 1.3: The authors thank the reviewer for this point. We cited some classic references related to PVB and FVB in the supplementary material.

“3. Zhu J, Wang L, Zhao S. Security-enhanced and high-resolution fractional orbital angular momentum multiplexing holography. *ACS Photonics* **11, 4626-4634 (2024).**

4. Zhu G, Bai Z, Chen J, et al. Ultra-dense perfect optical orbital angular momentum multiplexed holography. *Opt. Express* **29**, 28452-28460 (2021).”

In summary, we have addressed all the comments of reviewer #1.

Reply report to reviewer #2

Comment 2: *Based on the revised manuscript, the author has addressed the relevant questions and concerns I raised, and it can now be recommended for publication.*

Response 2: We are grateful to the reviewer's positive feedback and recommendation to publish in Nature Communications.

In summary, we have addressed all the comments of reviewer #2.

Reply report to reviewer #3

Comment 3: *In this revision, the authors have carefully addressed the reviewers' comments. For example, the SNR analysis for non-integer OAM requested by Reviewer 1, and the improved measurement methodology raised by Reviewer 2, have both been clearly incorporated. These updates allow the experimental data to better reflect the target designs, with or without reference dashed boxes. In my opinion, the manuscript could be accepted after addressing a few minor points:*

Response 3: We are grateful to the reviewer's positive feedback and recommendation to publish in Nature Communications.

Comment 3.1: *In Response 1.1 and Supplementary Note 12, the statement "SNR drops to approximately 0" seems unusual. Typically, when SNR approaches 1, the signal becomes indistinguishable from noise, which should already indicate the capacity limit. The choice of "SNR ~ 0" as the threshold feels inconsistent and should be clarified.*

Response 3.1: The authors thank the reviewer for this point. 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. Therefore, we have modified the threshold for evaluating image quality, determining that when the SNR reaches 1, the signal and noise become inseparable.

This discussion is detailed in **Supplementary Note 8** as:

"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 signal-to-noise ratio (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.”

Comment 3.2: *In the revised experimental holograms of Figure 5b and 5c, the target designs are not as visually clear as in Figure S19 if the dashed boxes are removed. I assume this is because Figure 5 involves multiple polarization channels and fewer sampling points per channel, while Figure S19 provides denser sampling for each holographic image. Overall, this does not undermine the authors' contribution to the field but could be clarified in the discussion.*

Response 3.2: The authors thank the reviewer for this point. In fact, the images of different channels in **Fig. 5** are designed at the same position, whereas in **Fig. S19**, they are placed at distinct positions. Therefore, **Fig. S19** exhibits superior image quality with enhanced clarity compared to **Fig. 5**. A detailed explanation of this aspect is provided in **Supplementary Note 10**. “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.”

In summary, we have addressed all the comments of reviewer #3.