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# Miniature tunable Airy beam optical meta-device

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## Section 1: Simulation setup for the nanoantenna design

To conduct simulations for the nanoantenna design, we utilize the COMSOL Multiphysics® commercial simulation software to execute comprehensive analyses. The procedure involves nanopillar structures with varying radii ranging from 50 to 113 nm. The nanoantennas possess a fixed height of 800 nm. The simulation setup includes periodic boundary conditions along the *x*- and *y*-axes, while the *z*-direction incorporates a perfect matching layer (PML) boundary. A uniform mesh with a size of 30 nm is employed in all three directions (*x*, *y*, and *z*) within a single unit cell.

## Section 2: The phase combinations of the two metasurfaces

When light passes through two metasurfaces, it will be tailored by these two metasurfaces. As we rotate the metasurfaces, the direction of the Airy beam's sidelobes shifts due to the rotation of the cubic phase profile. The off-axis Fresnel lens phase profiles on the two metasurfaces combine to generate gradient phases of various directions and magnitudes. This further allows for the manipulation of the transmission trajectory of the Airy beam.

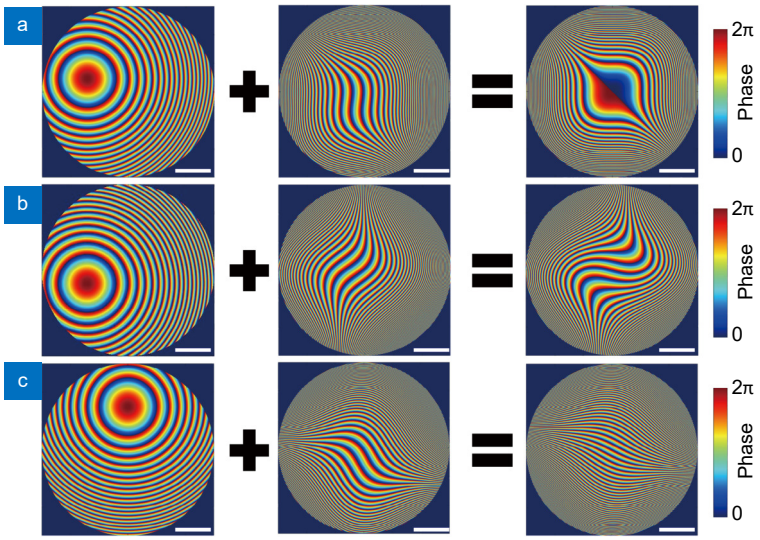


**Fig. S1 | Illustration of how phase profiles merge within a single metasurface for advanced functions.** The phase combinations of the first metasurface (the left column) and the second metasurface (the middle column) determine the phase (the right column) manipulating the incident light.

## Section 3: Nanofabrication processes of metasurfaces

The sample was fabricated on 800 nm thick titanium dioxide ($TiO_2$) film with a quartz substrate. The Zep 520A photoresist layer is a spin coating on $TiO_2$ film. Then, the sample is exposed to electron-beam lithography (EBL, Raith E-line Plus), and the patterns are developed in the developing solution. Next, an electron-gun evaporator (Syskey, 30 kV acceleration voltage) deposits a 23 nm thick Cr layer as a hard mask on the sample. The lift-off process is done in the PG remover solution at 80 °C. Subsequently, the patterns are transferred into $TiO_2$ film by reactive ion etching (RIE, Oxford RIE800 Plus). The final sample is obtained by removing the residual Cr hard mask.

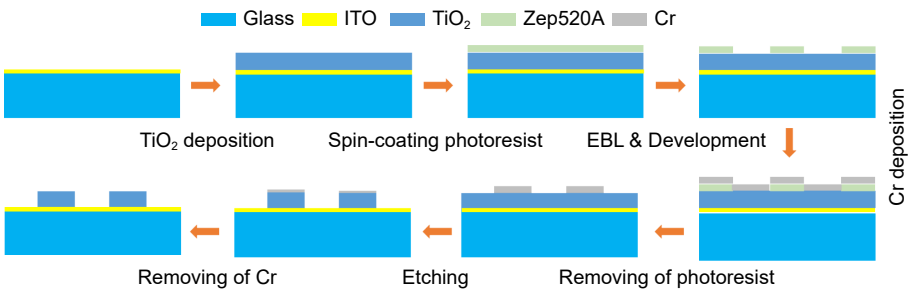


**Fig. S2 | Nanofabrication processes of metasurfaces.**

## Section 4: Experimental setup for characterization of the dynamic Airy beam meta-device

The experimental setup is shown in Fig. S3. The 532 nm light source is generated by MGL-III-532-50mW from Hon Kok Technology Co. The lenses L1 and L2 are used for light expansion. An Objective lens (0.14 NA, 5x) and a camera on the motorized stage are used to capture the Airy beam light field.

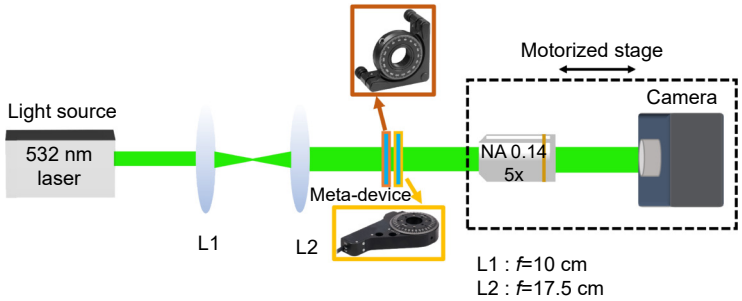


**Fig. S3 | Experimental setup for characterization of the dynamic Airy beam meta-device.** Inserts show the holders of the two metasurfaces to control their rotations. The left is a Kinematic Rotation Mount (KS1RS, Thorlabs Inc.), and the other is a Motorized Precision Rotation Stage (PRM1Z8, Thorlabs Inc.).

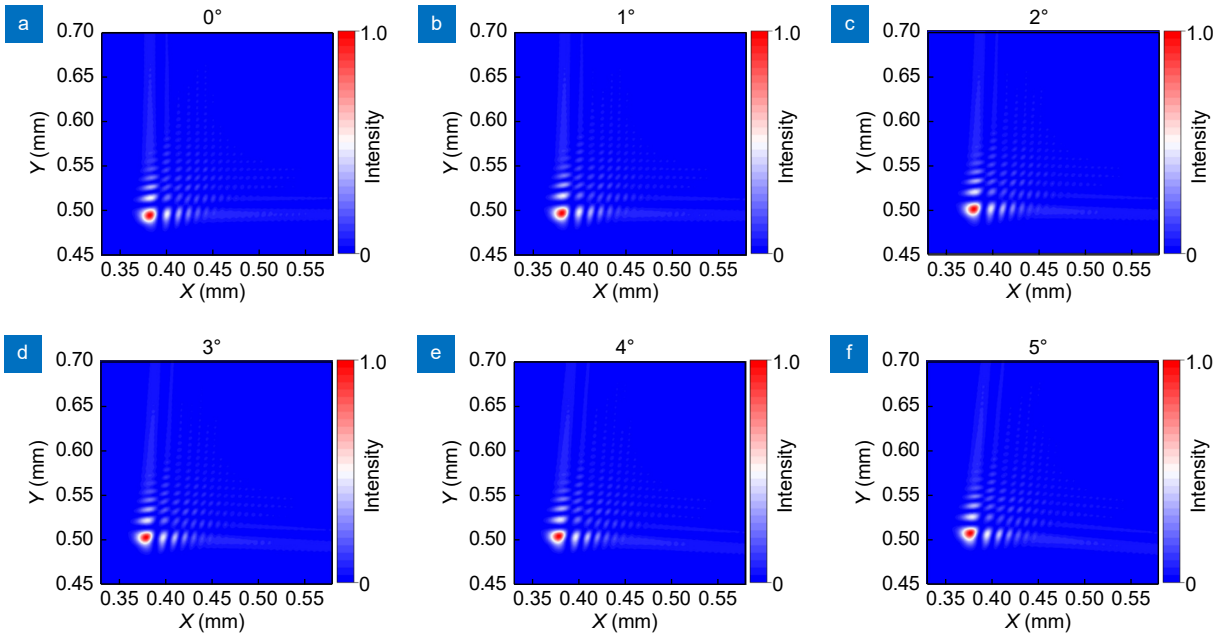


**Fig. S4 | Analysis of the robustness of bilayer metasurface to the rotation angle.** (**a**-**f**) The intensity distribution of the focal plane distributions as the first metasurface rotates more angles ranging from 0 to 5 degrees and other configurations is the same as shown in Fig. 3(a). As the rotation of the first metasurface will influence both the gradient and the cubic phase, thus it is more sensitive to the rotation angle. The results indicate the position of the focal spot with little change under a slight rotation shift.

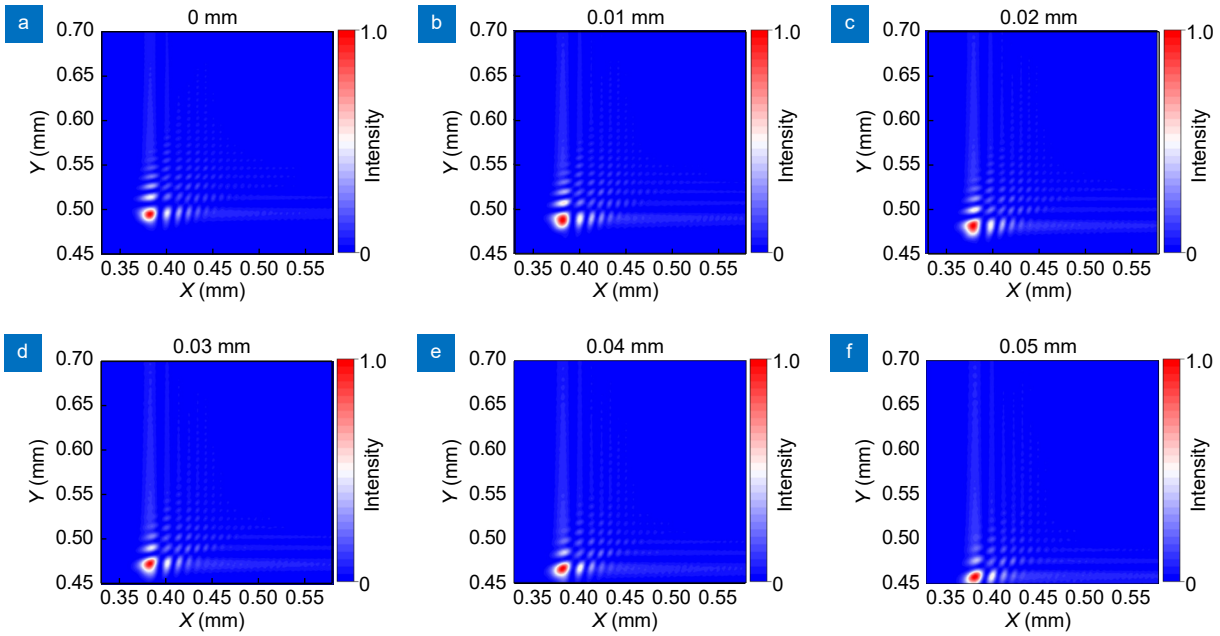


**Fig. S5 | Analysis of the robustness of bilayer metasurface to the transverse shift.** (**a**–**f**) The intensity distribution of the focal plane distributions as the transverse shift of the metasurfaces ranging from 0 to 0.05 mm and other configurations is the same, as shown in Fig. 3(a). The results indicate the position of the focal spot with little change under a slight shift.

## Section 5: Applying the meta-device in practice

To ensure the device's performance stability, we can initially input the measured values of the relationship between the metasurfaces' rotation angles and the positions of the Airy beam's focal spots (Table S1) into the computer. Subsequently, a piezoelectric control apparatus can be employed to manipulate the rotation of the two cascading metasurfaces. This approach enables us to achieve controlled, precise, and real-time dynamic manipulation of the Airy beam.

**Table S1 | Handbook for Airy beam manipulation.**

| $\theta_1$(°) | $\theta_2$(°) | $x$(mm) | $y$(mm) | $\theta_1$ (°) | $\theta_2$(°) | $x$(mm) | $y$(mm) | $\theta_1$(°) | $\theta_2$(°) | $x$(mm) | $y$(mm) | $\theta_1$(°) | $\theta_2$(°) | $x$(mm) | $y$(mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | -0.06 | -0.03 | 0 | 90 | 0.15 | -0.08 | 0 | 180 | 0.18 | 0.08 | 0 | 270 | -0.01 | 0.13 |
| 60 | 0 | -0.08 | -0.08 | 60 | 90 | 0.13 | -0.14 | 60 | 180 | 0.16 | 0.04 | 60 | 270 | -0.03 | 0.08 |
| 120 | 0 | -0.13 | -0.09 | 120 | 90 | 0.08 | -0.13 | 120 | 180 | 0.1 | 0.03 | 120 | 270 | -0.09 | 0.07 |
| 180 | 0 | -0.17 | -0.05 | 180 | 90 | 0.04 | -0.08 | 180 | 180 | 0.07 | 0.07 | 180 | 270 | -0.12 | 0.11 |
| 240 | 0 | -0.15 | 0.03 | 240 | 90 | 0.07 | -0.04 | 240 | 180 | 0.1 | 0.12 | 240 | 270 | -0.1 | 0.17 |
| 300 | 0 | -0.09 | 0.02 | 300 | 90 | 0.12 | -0.06 | 300 | 180 | 0.15 | 0.13 | 300 | 270 | -0.05 | 0.18 |
| 0 | 22.5 | -0.03 | -0.08 | 0 | 112.5 | 0.18 | -0.05 | 0 | 202.5 | 0.14 | 0.13 | 0 | 292.5 | -0.05 | 0.09 |
| 60 | 22.5 | -0.05 | -0.13 | 60 | 112.5 | 0.16 | -0.1 | 60 | 202.5 | 0.12 | 0.08 | 60 | 292.5 | -0.07 | 0.04 |
| 120 | 22.5 | -0.11 | -0.14 | 120 | 112.5 | 0.11 | -0.11 | 120 | 202.5 | 0.06 | 0.07 | 120 | 292.5 | -0.13 | 0.04 |
| 180 | 22.5 | -0.14 | -0.1 | 180 | 112.5 | 0.07 | -0.07 | 180 | 202.5 | 0.03 | 0.11 | 180 | 292.5 | -0.16 | 0.08 |
| 240 | 22.5 | -0.12 | -0.05 | 240 | 112.5 | 0.09 | -0.02 | 240 | 202.5 | 0.05 | 0.16 | 240 | 292.5 | -0.14 | 0.12 |
| 300 | 22.5 | -0.06 | -0.04 | 300 | 112.5 | 0.15 | -0.01 | 300 | 202.5 | 0.11 | 0.17 | 300 | 292.5 | -0.09 | 0.13 |
| 0 | 45 | 0.01 | -0.11 | 0 | 135 | 0.19 | 0 | 0 | 225 | 0.09 | 0.15 | 0 | 315 | -0.06 | 0.05 |
| 60 | 45 | 0 | -0.16 | 60 | 135 | 0.17 | -0.05 | 60 | 225 | 0.06 | 0.1 | 60 | 315 | -0.08 | 0 |
| 120 | 45 | -0.06 | -0.17 | 120 | 135 | 0.12 | -0.06 | 120 | 225 | 0.01 | 0.09 | 120 | 315 | -0.14 | 0 |
| 180 | 45 | -0.1 | -0.12 | 180 | 135 | 0.08 | -0.01 | 180 | 225 | -0.02 | 0.14 | 180 | 315 | -0.17 | 0.04 |
| 240 | 45 | -0.07 | -0.07 | 240 | 135 | 0.1 | 0.03 | 240 | 225 | 0 | 0.19 | 240 | 315 | -0.15 | 0.08 |
| 300 | 45 | -0.02 | -0.06 | 300 | 135 | 0.16 | 0.04 | 300 | 225 | 0.06 | 0.2 | 300 | 315 | -0.1 | 0.09 |
| 0 | 67.5 | 0.08 | -0.11 | 0 | 157.5 | 0.16 | 0.04 | 0 | 247.5 | 0.03 | 0.15 | 0 | 337.5 | -0.07 | 0 |
| 60 | 67.5 | 0.06 | -0.16 | 60 | 157.5 | 0.17 | -0.01 | 60 | 247.5 | 0.01 | 0.1 | 60 | 337.5 | -0.09 | -0.04 |
| 120 | 67.5 | 0.01 | -0.17 | 120 | 157.5 | 0.12 | -0.12 | 120 | 247.5 | -0.04 | 0.09 | 120 | 337.5 | -0.14 | -0.05 |
| 180 | 67.5 | -0.01 | -0.13 | 180 | 157.5 | 0.09 | 0.02 | 180 | 247.5 | -0.07 | 0.14 | 180 | 337.5 | -0.18 | -0.01 |
| 240 | 67.5 | 0 | -0.07 | 240 | 157.5 | 0.1 | 0.07 | 240 | 247.5 | -0.06 | 0.19 | 240 | 337.5 | -0.16 | 0.03 |
| 300 | 67.5 | 0.06 | -0.06 | 300 | 157.5 | 0.16 | 0.08 | 300 | 247.5 | 0 | 0.19 | 300 | 337.5 | -0.1 | 0.05 |