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Optically transparent and flexible assembled metasurface rasorber for infrared-microwave camouflage based on hybrid anapole state

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Supplementary information

1: FDTD simulation

The simulations were carried out by using commercial finite-difference time-domain (FDTD) software (Ansys Lumerical). Periodical boundary conditions are adopted in the x and y directions, and perfectly matching layers (PML) are employed in the z direction. y-polarized plane waves are normally incident on the metasurface along the negative z-axis.

2: Fabrication of samples

At first, ITO films with different thicknesses were deposited on PET substrates by magnetron sputtering to obtain the desired sheet resistances of 5 Ω/sq and 40 Ω/sq, respectively. Then the designed ITO patterns were obtained through micro-precision etching by using femtosecond laser beams. The fabricated samples were cut to have an area of 200 mm ×250 mm, and the number of unit cells in the IR shielding layer is 26×33, whereas that in the frequency selective transmission layer is 26×66. Both layers were attached to PDMS substrates with different thicknesses. Finally, the two layers were assembled together with an optically clear adhesive, forming the metasurface rasorber.

3: Measurement method

The visible transmittance spectrum of the metasurface rasorber was measured by an ultraviolet-visible spectrophotometer and the measured optical spectral range covered 300 nm-1000 nm.

A Fourier transform IR spectroscopy (Nicolet iS 50R) was utilized to measure the specular reflectance and transmittance of the fabricated samples.

The measurement in microwave band was carried out by using a vector network analyzer (Agilent e8363b) and two broadband horn antennas, which emits and receives microwaves, respectively.

4: Multipole decomposition

For a metasurface with electromagnetic multipole responses, the total scattering field can be decomposed into the scattering fields of electric, magnetic, and toroidal modes with different orders. Here we only consider the multipole contributions of electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ), magnetic quadrupole (MQ), electric toroidal dipole (ETD), magnetic toroidal dipole (MTD), electric toroidal quadrupole (ETQ), and magnetic toroidal quadrupole (MTQ) moments. In a Cartesian coordinate system, the multipole decomposition of ED, MD, EQ, MQ, ETD, MTD, ETQ, MTQ can be expressed as:

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$$\text{Electric dipole (ED): } \boldsymbol{P}_{\alpha} = \frac{1}{i\omega}\int \boldsymbol{j}_{\alpha} d^3\boldsymbol{r} . \quad \text{(S1)}$$

$$\text{Magnetic dipole (MD): } \boldsymbol{m}_{\alpha} = \frac{1}{2}\int (\boldsymbol{r}\times\boldsymbol{j})_{\alpha} d^3\boldsymbol{r} . \quad \text{(S2)}$$

$$\text{Electric quadrupole (EQ): } \boldsymbol{Q}_{\mathbf{e}\_\alpha,\beta} = \frac{1}{i\omega}\int \left[r_{\alpha} j_{\beta} + r_{\beta} j_{\alpha} - \frac{2}{3}(\boldsymbol{r}\cdot\boldsymbol{j})\delta_{\alpha,\beta} \right] d^3 r . \quad \text{(S3)}$$

$$\text{Magnetic quadrupole (MQ): } \boldsymbol{Q}_{\mathbf{m}\_\alpha,\beta} = \frac{1}{3}\int \left[(\boldsymbol{r}\times\boldsymbol{j})_{\beta} r_{\alpha} + (\boldsymbol{r}\times\boldsymbol{j})_{\alpha} r_{\beta} \right] d^3 r. \quad \text{(S4)}$$

$$\text{Electric toroidal dipole (ETD): } \boldsymbol{t}_{\mathbf{e}\_\alpha} = \frac{1}{10}\int \left[(\boldsymbol{r}\cdot\boldsymbol{j})\boldsymbol{r}_{\alpha} - 2\boldsymbol{r}^2 \boldsymbol{j}_{\alpha} \right] d^3 r . \quad \text{(S5)}$$

$$\text{Magnetic toroidal dipole (MTD): } \boldsymbol{t}_{\mathbf{m}\_\alpha} = \frac{i\omega}{20}\int \left[r^2 (\boldsymbol{r}\times\boldsymbol{j})_{\alpha} \right] d^3 r . \quad \text{(S6)}$$

$$\text{Electric toroidal quadrupole (ETQ): } \boldsymbol{t}_{\mathbf{Qe}\_\alpha,\beta} = \frac{1}{42}\int \left[4(\boldsymbol{r}\cdot\boldsymbol{j}) r_{\alpha} r_{\beta} + 2(\boldsymbol{j}\cdot\boldsymbol{r}) r^2 - 5r^2 \left(r_{\beta} j_{\alpha} + r_{\beta} j_{\alpha} \right) \right] d^3 r . \quad \text{(S7)}$$

$$\text{Magnetic toroidal quadrupole (MTQ): } \boldsymbol{t}_{\mathbf{Qm}\_\alpha,\beta} = \frac{i\omega}{42}\int r^2 \left[r_{\alpha} (\boldsymbol{r}\times\boldsymbol{J})_{\beta} + (\boldsymbol{r}\times\boldsymbol{J})_{\alpha} r_{\beta} \right] d^3 r . \quad \text{(S8)}$$

where $\boldsymbol{P}$, $\boldsymbol{m}$, $\boldsymbol{Q}_e$, $\boldsymbol{Q}_m$, $\boldsymbol{t}_e$, $\boldsymbol{t}_m$, $\boldsymbol{t}_{Qe}$, and $\boldsymbol{t}_{Qm}$ represent the complex ED, MD, EQ, MQ, ETD, MTD, ETQ, and MTQ moments, respectively; α, β = x, y, z; ω is the angular frequency of the electromagnetic wave, i is imaginary number (i^2 =-1), $\boldsymbol{j}$ is displacement current density vector, $\boldsymbol{r}$ represents position vector.

The corresponding radiating intensities are[2,10,34,35]:

$$\text{Electric dipole (ED): } \boldsymbol{I}_{\mathbf{P}} = \frac{2\omega^4}{3c^3}|\boldsymbol{P}|^2 . \quad \text{(S9)}$$

$$\text{Magnetic dipole (MD): } \boldsymbol{I}_{\mathbf{m}} = \frac{2\omega^4}{3c^3}|\boldsymbol{m}|^2 . \quad \text{(S10)}$$

$$\text{Electric quadrupole (EQ): } \boldsymbol{I}_{\mathbf{Qe}} = \frac{\omega^6}{5c^3}\sum \left|\boldsymbol{Q}_{\mathbf{e}\_\alpha,\beta}\right|^2 . \quad \text{(S11)}$$

$$\text{Magnetic quadrupole (MQ): } \boldsymbol{I}_{\mathbf{Q}\mathrm{m}} = \frac{\omega^6}{40c^5}\sum \left|\boldsymbol{Q}_{\mathbf{m}\_\alpha,\beta}\right|^2 . \quad \text{(S12)}$$

$$\text{Electric toroidal dipole (ETD): } \boldsymbol{I}_{\mathbf{t}_e} = \frac{2\omega^4}{3c^3}\left|\frac{ik\varepsilon_d}{c}\boldsymbol{t}_e\right|^2 . \quad \text{(S13)}$$

$$\text{Magnetic toroidal dipole (MTD): } \boldsymbol{I}_{\mathbf{t}_m} = \frac{2\omega^4}{3c^3}\left|\frac{ik\varepsilon_d}{c}\boldsymbol{t}_m\right|^2 . \quad \text{(S14)}$$

$$\text{Electric toroidal quadrupole (ETQ): } \boldsymbol{I}_{\mathbf{t}_{Qe}} = \frac{\omega^6}{5c^3}\sum\left|\frac{ik\varepsilon_d}{c}\boldsymbol{Q}_{\mathbf{t}_{Qe\_\alpha,\beta}}\right|^2 . \quad \text{(S15)}$$

$$\text{Magnetic toroidal quadrupole (MTQ): } \boldsymbol{I}_{\mathbf{t}_{Qm}} = \frac{\omega^6}{40c^5}\sum\left|\frac{ik\varepsilon_d}{c}\boldsymbol{Q}_{\mathbf{t}_{Qm\_\alpha,\beta}}\right|^2 . \quad \text{(S16)}$$

where ε_d is the permittivity of the surrounding medium, k is the free-space wave number, and c is light velocity in vacuum.