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Supplementary information

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Racemic dielectric metasurfaces for arbitrary terahertz polarization rotation and wavefront manipulation

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Section 1: Sample fabrication

Ultraviolet lithography and inductively coupled plasma (ICP) etching are used to process the samples[S1]. We use standard photolithography to form a 6.8 μm thick patterned positive photoresist (AZ4620) as a mask on a 500 μm thick silicon wafer with a diameter of 4 inch. Then we use ICP etching technology (STS MULTIPLEX ASE-HRM ICP ETCHER, United Kingdom) to etch the sample, and finally the remaining photoresist is washed away to get the final sample. The etching depth is about 200 μm, and the remaining 300 μm thick silicon layer is used as the substrate. The six main steps are shown in Fig. S1.

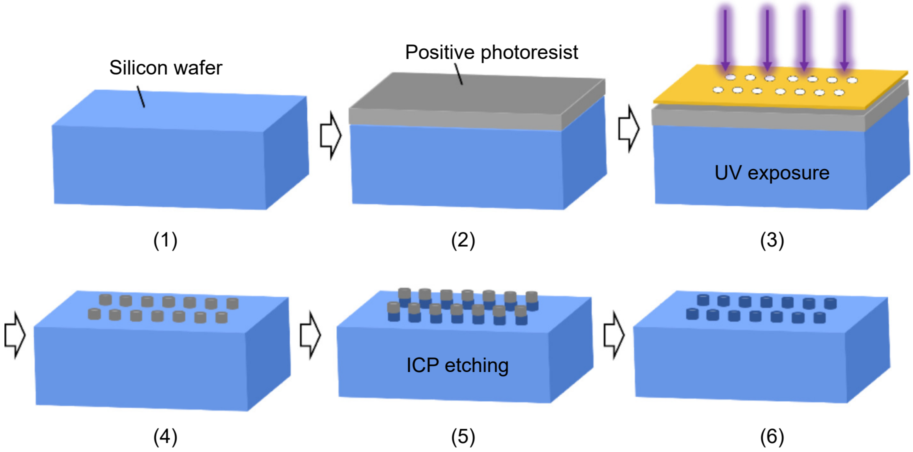

Fig. S1 | Detailed steps for sample preparation.

Section 2: Polarization resolved terahertz time-domain spectroscopy

Since it is difficult to measure two orthogonal polarization components simultaneously using a conventional terahertz time-domain spectroscopy (TDS) system, we need four metal wire grid polarizers to form a polarization resolved terahertz time-domain spectroscopy (PTDS)[S2]. As shown in Fig. 3(b) of the manuscript, during the measurement, the polarization directions of P_1 and P_4 are kept consistent with the polarization of the transmitting and receiving antennas respectively, and then P_2 and P_3 are rotated in turn, while taking the ±45° as the new reference coordinate axes. After the four transmission coefficient components are obtained, the circular polarizations are calculated according to Eq. (2) in the manuscript. The specific theoretical analysis is as follows.

Assuming that the terahertz waves emitted and received by the photoconductive antenna are horizontally polarized, and the x-axis of the initial Cartesian coordinate system is consistent with the polarization direction. The variation of terahertz signal before and after passing through the sample can be described by Jones matrix as:

$$\begin{pmatrix} E_{\mathrm{t}}^{x} \\ E_{\mathrm{t}}^{y} \end{pmatrix} = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix} \begin{pmatrix} E_{i}^{x} \\ E_{i}^{y} \end{pmatrix} = \boldsymbol{T} \begin{pmatrix} E_{\mathrm{i}}^{x} \\ E_{\mathrm{i}}^{y} \end{pmatrix} . \tag{S1}$$

In order to complete polarization resolved terahertz spectral measurements without adjusting the photoconductive antenna, we rotate the coordinate system by 45 degrees clockwise, and the transmission matrix $\boldsymbol{T}$ should be transformed into $\tilde{\boldsymbol{T}}$,

$$\tilde{\boldsymbol{T}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}^{-1} \boldsymbol{T} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} , \tag{S2}$$

where θ=45°. So, in the new coordinate system, the relationship between the incident electric field and the transmitted electric field is

$$\begin{pmatrix} \tilde{E}_{\mathrm{t}}^{x} \\ \tilde{E}_{\mathrm{t}}^{y} \end{pmatrix} = \begin{pmatrix} \tilde{t}_{xx} & \tilde{t}_{xy} \\ \tilde{t}_{yx} & \tilde{t}_{yy} \end{pmatrix} \begin{pmatrix} \tilde{E}_{\mathrm{i}}^{x} \\ \tilde{E}_{\mathrm{i}}^{y} \end{pmatrix} = \tilde{\boldsymbol{T}} \begin{pmatrix} \tilde{E}_{\mathrm{i}}^{x} \\ \tilde{E}_{\mathrm{i}}^{y} \end{pmatrix} . \tag{S3}$$

The transformation of coordinate systems can be achieved in measurement through the operation of rotating polarizers mentioned earlier. It should be noted that after the polarizer is rotated, the detection antenna can still only perceive the vertical electric field component. Therefore, the recorded electric field has the following relationship with the actual electric field (in the new coordinate system):

$$\begin{pmatrix} \tilde{E}_{\mathrm{t}}^{x} \\ \tilde{E}_{\mathrm{t}}^{y} \end{pmatrix} = \sqrt{2} \begin{pmatrix} \tilde{E}_{\mathrm{t}}^{+45°} \\ \tilde{E}_{\mathrm{t}}^{-45°} \end{pmatrix} . \tag{S4}$$

The superscript of the electric field on the right side of the equation indicates that P_2 has been rotated by 45° and −45°, respectively. When P3 is also rotated by 45° and −45° respectively, we can obtain four recording signals,

$$\begin{aligned} \begin{pmatrix} \tilde{E}_{\mathrm{tx}}^{+45°} \\ \tilde{E}_{\mathrm{ty}}^{+45°} \end{pmatrix} &= \begin{pmatrix} \tilde{t}_{xx} & \tilde{t}_{xy} \\ \tilde{t}_{yx} & \tilde{t}_{yy} \end{pmatrix} \begin{pmatrix} \tilde{E}_{\mathrm{i}}^{+45°} \\ 0 \end{pmatrix} \\ \begin{pmatrix} \tilde{E}_{\mathrm{tx}}^{-45°} \\ \tilde{E}_{\mathrm{ty}}^{-45°} \end{pmatrix} &= \begin{pmatrix} \tilde{t}_{xx} & \tilde{t}_{xy} \\ \tilde{t}_{yx} & \tilde{t}_{yy} \end{pmatrix} \begin{pmatrix} 0 \\ \tilde{E}_{\mathrm{i}}^{-45°} \end{pmatrix} \end{aligned} . \tag{S5}$$

So we can derive the calculation formula for the four linearly polarized transmission coefficients in the new coordinate system,

$$\begin{cases} \tilde{t}_{xx} = \tilde{E}_{\mathrm{tx}}^{+45°} / \tilde{E}_{\mathrm{i}}^{+45°} \\ \tilde{t}_{xy} = \tilde{E}_{\mathrm{ty}}^{+45°} / \tilde{E}_{\mathrm{i}}^{+45°} \\ \tilde{t}_{yx} = \tilde{E}_{\mathrm{tx}}^{-45°} / \tilde{E}_{\mathrm{i}}^{-45°} \\ \tilde{t}_{yy} = \tilde{E}_{\mathrm{ty}}^{-45°} / \tilde{E}_{\mathrm{i}}^{-45°} \end{cases} . \tag{S6}$$

Finally, the original transmission matrix can be obtained through the inverse transformation of the coordinate system

$$\boldsymbol{T} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}^{-1} \tilde{\boldsymbol{T}} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} , \tag{S7}$$

where θ=−45°.

Based on the results mentioned above, the transmission matrix of the circular polarization basis and circular dichroism can be calculated.

Section 3: Beam profile measurement of the focused terahertz wave

To measure the electric field amplitude and phase of transmitted terahertz beams, a near-field imaging system (TeraCube Scientific M2) was employed, as shown in Fig. S2. The femtosecond laser source in the system is 780 nm with 100 fs pulse width and 80 MHz repetition rate. In the experiment, a linearly polarized terahertz beam was generated from a photoconductive antenna and collimated by a TPX terahertz lens. The incident terahertz wave was then illuminated vertically from the substrate side of the fabricated all-silicon sample to produce a target spot on a predesigned focal plane. The sample was scanned using a detection module equipped with a microprobe and the electric field distribution on the focal plane was recorded pixel-by-pixel, which was approximately 14 mm away from the sample. Subsequently, the different polarization components were recorded by changing the microprobes. Finally, calculations were performed using standard code to yield the desired electric field distribution.

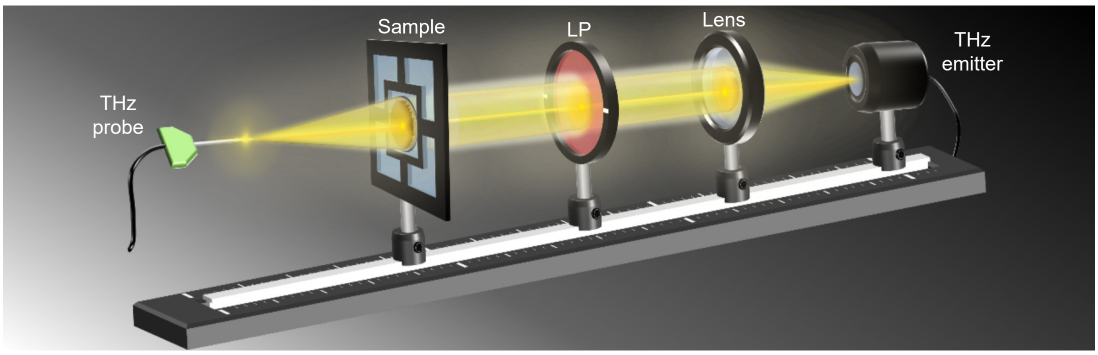

Fig. S2 | Optical path for measuring focused terahertz beam.

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