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• **Supplementary File** •

Diverse terahertz wavefront manipulations empowered by the spatially interleaved metasurfaces

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Appendix A The characterization method

The characterization system is shown as Figure A1. A femtosecond laser outputs a 50 fs duration pulse with 800 nm central wavelength, and it through the beam splitter L1 is separated into a probe beam and a pump beam. The slender pump beam reflected by the mirror L2 is firstly expanded via a concave lens L3 to cover enough the surface (1 cm × 1 cm) of < 110 > ZnTe crystal, and then induces optical rectification effects to radiate the linear polarization THz wave. Using a metallic parabolic mirror L4 collimate the THz beam before sample being irradiated by THz wave. THz wave through sample is received by a ZnTe detection crystal. At the same time, the slender probe beam is also expanded by a beam expanding system consisting of a series of lenses, and then adjust probe polarization through a half wave plate (HWP) and a polarizer. The probe beam will be reflected onto the detection crystal by the beam splitter L5. Subsequently, the received THz field excites Pockels effect in ZnTe detection crystal to modulate the polarization of probe beam. Then, the probe beam with polarization modulation through L5 is acquired by CCD camera to form eventually a THz image based on a balanced electro-optics detection technique. This detection process is essentially the electro-optical sampling, and this system includes two convex lenses L6 and L7, a quarter wave plate (QWP) and a Wollaston prism (PBS). Besides, it is required to synchronously control the mechanical chopper and CCD camera for using a dynamics subtraction method to eliminate the background intensity of the probe beam.

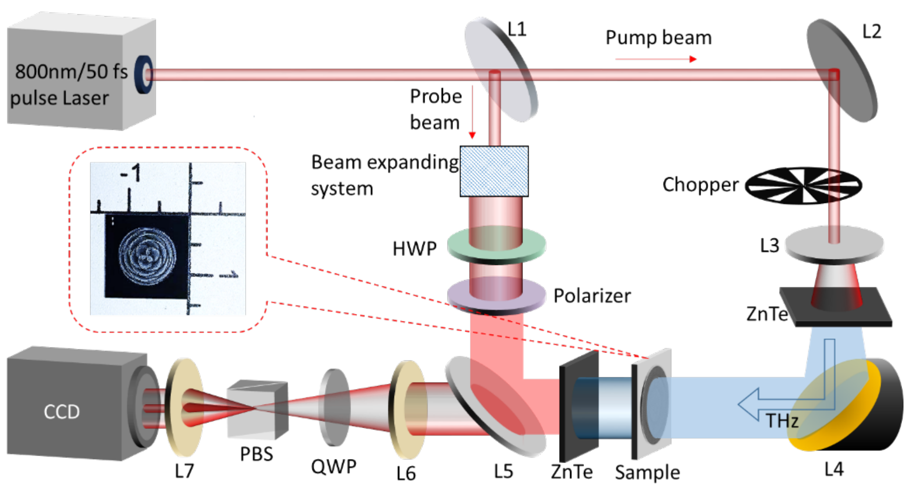

Figure A1 The schematic characterization system for THz field test [1].

Appendix B Metasurface construction using a series of unit cells with discrete phases

The phase profile determined by Eq. 1 in main text changes continuously with the coordinate change. Here, we take the simple focusing phase profile (m=0) as an example to introduce the common method for phase discretization. Considering a complete phase period ($0 \to 2\pi$), the ideal phase profile is shown in Figure B1(a). This ideal situation is impossible to achieve by metasurfaces, and in practice the phase profiles on which metasurfaces depend are discrete [2, 3], as shown in Figure B1(b). The technique of phase discretization can be briefly described as follows. According to Figure 2(i-j) in main text, the metasurface has six basic units

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assigned to six relative phase: 0, $\pi/3$, $2\pi/3$, π, $4\pi/3$ and $5\pi/3$, respectively, expressed as $P_i(i = 1, 2, 3, 4, 5, 6)$. They are generally arithmetic sequence with a common difference of $\pi/3$. Hence, the continuous phase will also be divided into six equal parts to adapt to the actual situation. In detail, make the continuous phases in the range of $(P_i - \pi/6) \leqslant P_i < (P_i + \pi/6)$ equal to P_i, that is [Figure B1(b)], the continuous $0 \to \pi/6$ is regarded as 0, $\pi/6 \to 3\pi/6$ is regarded as $\pi/3$, $3\pi/6 \to 5\pi/6$ is regarded as $2\pi/3$, $5\pi/6 \to 7\pi/6$ is regarded as π, $7\pi/6 \to 9\pi/6$ is regarded as $4\pi/3$, $9\pi/6 \to 11\pi/6$ is regarded as $5\pi/3$, and the continuous phase over $11\pi/6$ is regarded as 2π (return to 0).

Meanwhile, three phenomena must be mentioned. 1) In order to facilitate the interleaving of unit cells, the equivalent structure of Figure 2(c) in main text is used instead of the original structure shown in Figure 2(a). As a result, the irregular shape may be constructed at the phase profile transition, due to the inconsistent shape of two adjacent unit cells, as shown in Figure B1(c) . 2) To successfully realize the interleaving of two metasurfaces, the structural axis directions for all the units of a metasurface must be consistent (all x or all y directions), and those for all the units of the other metasurface are perpendicular to the former. For example, as shown in Figure B1(d), the structural axis directions for all the units of metasurface 1 are y, then those for all the units of metasurface 2 must be x. 3) The unit cell of the interleaved metasurface is often composed of two unit cells with different sizes, unless the phase profiles of the two metasurfaces are exactly the same, as shown in Figure B1(e).

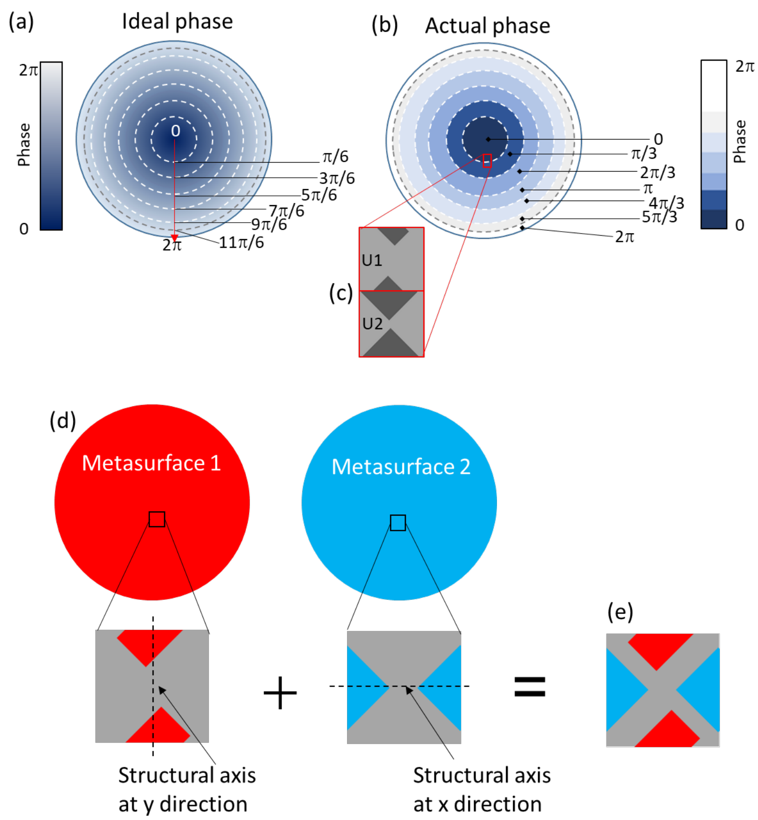

Figure B1 (a, b) The comparison between ideal and actual phase profiles. (c) The schematic two adjacent unit cells at phase profile transition. (d) Two metasurfaces use the unit cells that structural axis directions are perpendicular to each other. (e) Generally, the unit cell of the interleaved metasurface is composed of two unit cells with different sizes, unless the phase profiles of the two metasurfaces are exactly the same.

Appendix C Investigation on interaction between units after incorporation

As the absence of any structural overlap and unit space sharing, which is an ideal situation, the interaction between the two units can be simply described as the sum of Jones matrices, namely $0.5 \times (J_1 + J_2)$, where coefficient of 0.5 is considered for energy normalization. Thus, the ideal transmitted electric field is the superposition of the independent complex amplitudes of the two units without crosstalk, expressed as $0.5 \times [E_1 \exp(i\varphi_1) + E_2 \exp(i\varphi_2)]$. Nevertheless, it should be noted that in this work, although the incorporation of the two units has no overlap of Si pillars, there is still a sharing of unit space, which will generate complex crosstalk between units, making the overall transmitted electric field no longer an idealsuperposition of the complex amplitudes of two units.

We show the transmission spectra of two independent unit cells with different sizes operating at 0.8 THz, and compare the magnitude and phase of their transmission spectra for self-interleaving and hybrid-interleaving situations. The self-interleaved unit cell is interleaved from two equivalent unit cells with the same size, and the hybrid-interleaved unit cells is interleaved from two unit cells with different sizes [see insets in Figure C1(c, e)]. Two independent unit cells are 1st and 2nd structures selected from Figure 2(i) in main text, and the size parameters shown in Table 1 in main text. Note that two units we selected have been able to illustrate the consideration on crosstalk, no more units are required. As shown in Figure C1(a-b) , at 0.8 THz, the transmission amplitudes for two independent unit cells are the same, and the phase difference is about $\pi/3$, which is previously reported in Figure 2(i) in main text. It can be seen from Figure C1(c-f) that whether self-interleaving or hybrid-interleaving, at 0.8 THz, the

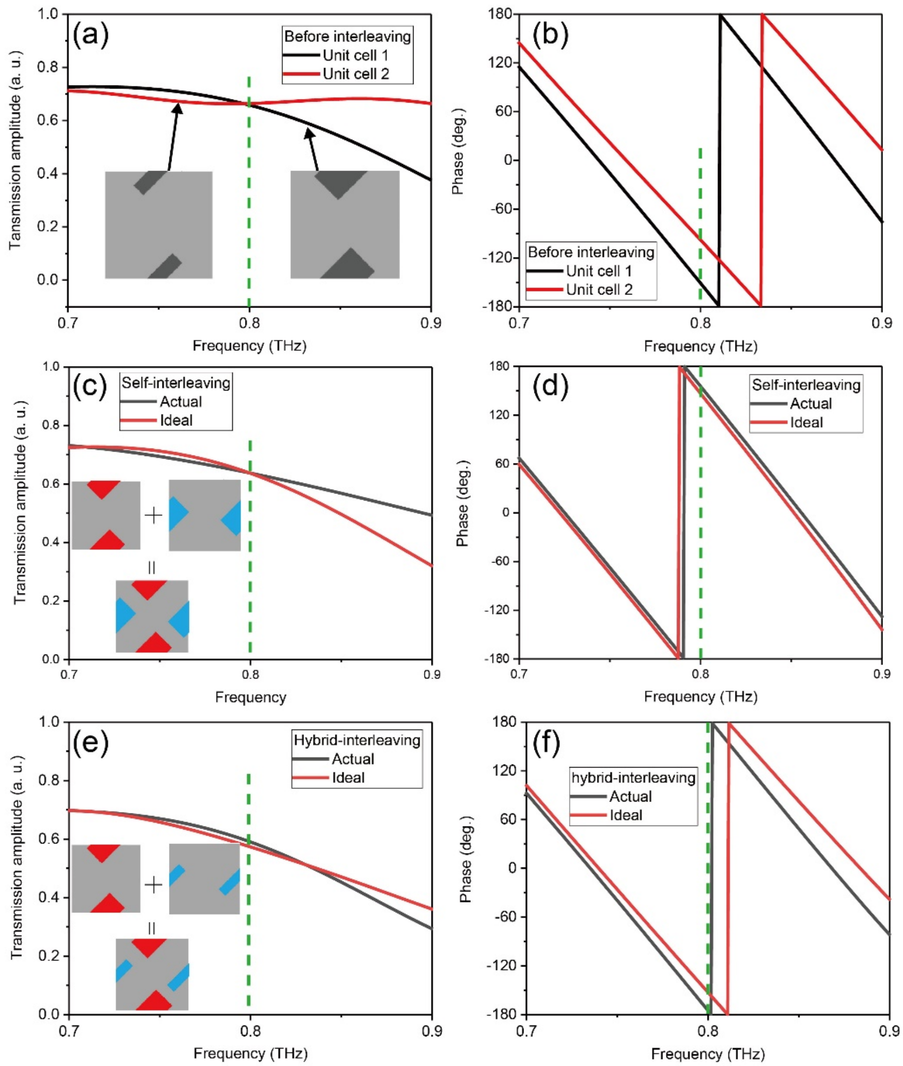

Figure C1 (a, b) The transmission amplitude and phase of two independent unit cells with different sizes operating at 0.8 THz. Two independent unit cells are 1st and 2nd structures in Figure 2(i) in main text, and the size parameters shown in Table 1 in main text. (c, d) The transmission amplitude and phase of the self-interleaved unit cell, and (e, f) those of the hybrid-interleaved unit cell, in which the actual values arise from the direct simulation on an interleaved unit cell, and the ideal values arise from the complex amplitude superposition of the two independent units, namely $0.5 \times [E_1 \exp(i\varphi_1) + E_2 \exp(i\varphi_2)]$.

transmission field of the interleaved unit is not exactly equal to the superposition of the complex amplitudes of the two independent units, which proves that the undesired crosstalk between units exists indeed. However, such crosstalk is not serious, as shown in Figure C1(c-d), the actual amplitude and phase of the self-interleaved unit at 0.8 THz are comparable to the ideal amplitude and phase obtained by the complex amplitude superposition of two independent units. As shown in Figure C1(e-f), the amplitude of the hybrid-interleaved unit at 0.8 THz is also generally equal to the ideal amplitude, correspondingly, the difference between the actual phase and the ideal phase is small, not exceeding 30^o.

Moreover, the interleaved unit may mask the independent properties of two units, but this does not mean that the spatially interleaved metasurface will also mask the respective properties of the two original metasurfaces. This is because the performance of the interleaved metasurface is affected not only by the interaction between units, but also by the overall phase profile of the original metasurface. Metasurfaces assembled from specific phase profiles have unique beam propagation characteristics in spatial domain, and the final functions of the interleaved metasurface is related to the pre-designed beam paths of the two metasurfaces (their beams are either spatially overlapping or spatially separated, which results in different functions of the interleaved metasurface). Our experimental and simulative results have demonstrated that the two metasurfaces after interleaving can still maintain their respective pre-designed beam propagation paths to some extent, and the crosstalk between units only attenuates these performances.

References

1 Li JT, Wang GC, Yue Z, et al. Dynamic phase assembled terahertz metalens for reversible conversion between linear polarization and arbitrary circular polarization. Opto-Electronic Advances, 2022, 5: 210062

2 Yu N, Genevet P, Kats M, et al. Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction. Science, 2011, 334: 333-337

3 Wang Q, Zhang X, Xu Y, et al. A Broadband Metasurface-Based Terahertz Flat-Lens Array. Advanced Optical Materials, 2015, 3: 779-785