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Supporting Information

All-silicon metasurfaces for polarization multiplexed generation of terahertz photonic orbital angular momentum superposition states

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1. Simulation and experimental methods

Numerical simulations. We simulate the metasurface cells and arrays use commercial software CST MICROWAVE STUDIO (2019, time domain solver). We first calculate the transmission amplitude and phase of the silicon units with different geometric parameters. The x and y directions are both set as periodic boundaries, and the z direction is set as an open boundary. A plane wave is placed under the substrate as the excitation source, and then an electric field probe is used above the cell. After confirming the geometric parameters of each unit, the units are arranged in an array, and the terahertz full-wave transmission intensity and phase distribution of the metasurface under different incident polarizations are calculated. In the simulation, we use MATLAB code to drive the CST MICROWAVE STUDIO to draw the whole structure of the metasurface, and still use the time domain solver for calculation. Then the z, y, and z directions are set as open boundary conditions, and the calculation space in the z direction is larger than the designed focal length. Plane waves with different polarizations are used as the excitation source, and then field monitors are added to observe the electric field components of the x- and y- polarizations. Finally, MATLAB code is used again to process the data when needed.

Sample fabrication. We use ultraviolet lithography and inductively coupled ion etching to process the all-silicon samples. Standard photolithography process is used to form a 6.8 um thick patterned positive photoresist (AZ4620) as a mask on a 500 um thick intrinsic silicon wafer with a diameter of 4 inches. Then we use inductively coupled plasma (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.

Terahertz measurement. We use the two-dimensional electro-optical sampling THz imaging system shown in figure 4(a) to measure the electric field intensity and phase distribution of the terahertz vortex interference beam. The imaging system is mainly composed of a pump module and a probe module, supported by a femtosecond laser amplifier system (pulse width is 50 fs, working wavelength is 800 nm, repetition frequency is 1KHz). Part of the femtosecond laser is irradiated on the electro-optic crystal ZnTe of the pump module to excite terahertz pulses, and the terahertz wave is reflected by an off-axis parabolic mirror and irradiated on the sample. The other part of the laser is incident to another ZnTe crystal as the probe light. The optical imaging module is composed of two lenses, a Wollaston prism (PBS), a quarter-wave plate (QWP), and a CCD camera to image the modulated femtosecond laser. A half-wave plate (HWP) and a polarizer (P) are used to change the polarization of the probe beam, and then detect terahertz waves of different polarizations. In addition, we rotate the sample to equivalently polarization change of the incident terahertz wave.

2. Geometric parameters of the metasurface units.

Table S1. Values of L_y for polarization maintaining units.

φ□(□□□)

φ□(□□□) LY(μm)	**-180**	**-135**	**-90**	**-45**	**0**	**45**	**90**	**135**
-180	115	85	68	61	57	52	47	35
-135	115	85	70	63	58	55	50	40
-90	115	87	71	65	60	56	51	40
-45	120	90	72	65	60	56	52	40
0	120	90	73	66	61	57	53	35
45	110	90	75	65	64	58	52	45
90	120	90	75	67	63	59	54	45
135	120	95	75	70	65	60	55	45

Table S2. Values of L_x for polarization maintaining units.

	φ□(□□□)							
φ□(□□□)	**LX(μm)**	**-180**	**-135**	**-90**	**-45**	**0**	**45**	**90**	**135**
	-180	105	105	110	115	115	115	115	120
	-135	85	85	90	95	95	90	90	90
	-90	70	70	70	70	70	75	75	75
	-45	60	65	65	65	65	65	65	70
	0	55	60	60	60	60	60	60	65
	45	55	55	55	60	60	60	60	60
	90	45	50	50	50	50	50	55	55
	135	35	40	40	35	35	45	45	45

Table S3. Geometric parameters of the polarization-converted units.

Unit	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
DY(μm)	110	83	72	65	110	83	72	65
DX(μm)	54	51	43	32	54	51	43	32
θ(deg)	45	45	45	45	135	135	135	135

According to the calculation results in Figure 2 and Figure 5 in the manuscript, we have listed the selected geometric parameters of the polarization maintaining and polarization converted units. Among them, the minor axis values of all ellipses are 30 μm, and the major axis values are different. The phase shift of the transmitted terahertz for x- and y-polarized components corresponding to the geometric parameters of the polarization maintaining units are shown in Tables S1 and S2. The parameter values and azimuth angles of the polarization converted units are shown in Table S3, where θ is based on the positive direction of y-axis, and a clockwise rotation is regarded as positive value.

3. Theoretical analysis of vortex interference beams.

The complex amplitude expression of the zero-order radial Laguerre-Gaussian beam in cylindrical polar is:

$$\mathrm{LG}_0^l(\mathrm{r},\theta,\mathrm{z})=\left(\frac{2}{\pi|l|!}\right)^{\frac{1}{2}}\cdot\frac{1}{w(\mathrm{z})}\left(\frac{r\sqrt{2}}{w(\mathrm{z})}\right)^{|l|}\exp\left(\frac{-r^2}{w^2(\mathrm{z})}\right)\cdot\exp\left[i\left(kz-\frac{kr^2}{2R}\right)\right] \cdot\exp(-\mathrm{i}\,l\theta)\cdot\exp[\mathrm{i}\,\varphi(\mathrm{z})] \quad (1)$$

where R is the radius of curvature, l is the topological charge, $\mathrm{w(z)} = \mathrm{w}_0 \sqrt{1+(\frac{z}{z_R})^2}$,

$z_R = \frac{\pi w_0^2}{\lambda}$, $\varphi = (l+1)\tan^{-1}(\mathrm{z}/z_R)$ is the Gouy phase, z_R is the Rayleigh range. In the case of a certain value of z (such as z=0), the phase distribution of the beam is mainly determined by the spiral phase factor $\exp(-\mathrm{i}l\theta)$, and the other parts are the amplitude factors. To get a focused vortex beam, we only need to replace the phase $l\theta$ with the phase profile of

$$\varphi = -(\frac{2\pi}{\lambda}\sqrt{r^2+f^2} - f) + l\theta \tag{2}$$

where f is the focal length.

Take the superposition of two vortex beams as an example, suppose the topological charges of the two beams are l_1 and l_2 respectively. Then the complex amplitude of the interference beam should be written as

$$\mathrm{LG}_0^l = \mathrm{LG}_0^{l_1} + \mathrm{LG}_0^{l_2} \tag{3}$$

In order to understand this beam interference more intuitively, we used the commercial software MATLAB to calculate the above equation (Eq. 1), assuming that the the working wavelength is 300 microns, and the topological charges are l_1=1, l_2=-1. The theoretically calculated electric field amplitude and phase are shown in Figure 1. As we all know, the extremely small amplitude of the vortex beam center is caused by the singularity of the spiral phase center. When two vortex beams with different topological charges interfere, new phase singularities or even areas with uncertain phase will appear in the phase distribution. In turn, dark fringes appear in the electric field intensity distribution of the interference beam. For the interference of two zero-order Laguerre-Gaussian beams with opposite topological charges, the number of high intensity regions is equal to $|l_1|+|l_2|$.

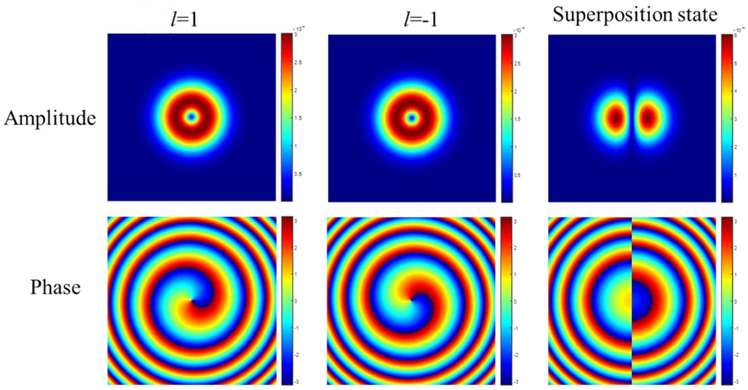

Figure S1. The superposition process of two vortex beams with topological charges of 1 and -1.