Spin-Decoupled Multifunctional Metasurface for Asymmetric Polarization Generation

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S Supporting Information

ABSTRACT: Integrating multiple functionalities into a single device is a striking field in metasurfaces. One promising aspect is polarization-dependent meta-devices enabled by simultaneous phase control for orthogonally polarized waves. Among these, Pancharatnam-Berry (PB) metasurfaces have drawn enormous interest owing to their natural and robust phase control ability over different circularly polarized waves. However, the phase responses are locked to be opposite with each other, resulting in interrelated functionalities under the circularly polarized incidence. Here, a generic designing method based on transmission-type dielectric metasurfaces is proposed in the terahertz regime, which breaks this relation by further incorporating dynamic phase with geometric phase, namely, spin-decoupled phase control method. We demonstrate this method by designing and characterizing an efficient multifunctional meta-grating, which splits different circularly polarized waves to asymmetric angles under normal incidences. More importantly, we promote this method by designing several multiplexed meta-gratings for applications of asymmetric polarization generation, which can convert arbitrary linearly polarized wave to two different linearly polarized waves with nearly equal strength and split them to asymmetric angles with a polarization-insensitive efficiency. The designing strategy proposed here shows an impressive robustness and a great flexibility for designing multifunctional metasurface-based devices and opens new avenues toward modulation of polarization states and the application of metasurfaces in beam steering and polarization multiplexing systems.

KEYWORDS: dielectric metasurfaces, multifunction, spin-decoupled phase control, asymmetric polarization generation, terahertz

Recently, multifunctional metasurfaces with polarization's degree of freedom have drawn enormous attentions owing to their potential in achieving polarization-dependent wavefront control.^{1–5} To realize this effect, it is crucial to introduce anisotropy into the structural design. Such metasurfaces are working with orthogonally polarized incidences, where independent phase control method is necessary. For linear-polarization-dependent metasurfaces, one can separately engineer the corresponding dynamic phase responses by designing a series of birefringent structures,^{6–8} or by multiplexing two kinds of structures with orthogonal-polarization-selective features.^{1,9} For circular-polarization-dependent (spin-dependent) metasurfaces, the design becomes easier by using the Pancharatnam-Berry (PB)

metasurfaces, which relies on a geometric phase acquired from spin flips to control the wavefronts.^{10–15} This method does not require multiple structures to control the phases, as they can be tuned by simply rotating an element. The absolute values of the phase shifts will be exactly the same, but the signs are opposite for the two different circularly polarized incidences. Therefore, the output wavefronts are naturally different with each other, but having fixed relations. For instance, anomalous deflections with symmetric angles,^{11,16–18} focusing and diverging lens with same absolute focus length,^{14,19,20} vortex beams with opposite topological

Received: July 18, 2019

Published: October 28, 2019

60 charges,^{16,21,22} and holographic images with flipped
61 shapes,^{15,23,24} and so on. One route to break such relations
62 is introducing iterative algorithms, however, it increases the
63 designing complexity.²⁵ Another route is applying multiplexed
64 metasurfaces composed of absorptive or reflective chiral
65 structures, however, half of the incident power is wasted.^{26–28}

66 Beside wavefront control, multifunctional metasurfaces with
67 polarization's degree of freedom are also very promising in
68 polarization control, which currently receives much less
69 attention. For example, they could generate arbitrary polar-
70 ization states and control its wavefront at the same time. To
71 realize such effect, it is required to introduce superposition of
72 two orthogonal polarizations, such as circular polarizations.
73 Multiplexed metasurfaces provide an effective way to
74 accomplish the task.^{1,4} More importantly, by deflecting the
75 polarized waves away from the zero-order output, background-
76 free polarization generation can be achieved. However,
77 previously reported polarization generation using multiplexed
78 metasurfaces based on circular polarization commonly have a
79 symmetric polarization response for the two deflected beams
80 due to a sole geometric phase.⁴ Namely, the polarization states
81 of the two deflected beams are identical. Additional freedom is
82 required to break such a polarization response, that is,
83 asymmetric polarization generation, which can be very useful
84 in realizing novel polarization devices with complex function-
85 alities.

86 In order to simultaneously solve the above two problems, it
87 is necessary to realize spin-decoupled phase control. One way
88 is to combine the detour phase and geometric phase by
89 compounding two meta-atoms into one unit cell, which allows
90 spin-decoupled wavefront generation at the first diffraction
91 order through engineering the positions and orientation angles
92 of the two meta-atoms.^{29,30} Another way is to combine the
93 dynamic phase and geometric phase of one single meta-atom,
94 which not only provides the freedom to decouple the phase
95 responses of the two circularly polarized waves, but also can
96 even be engineered to realize independent phase control of
97 two arbitrarily orthogonal elliptically polarized waves.^{7,31} Very
98 recently, it has even been demonstrated that this method is
99 promising in achieving more complex and exotic function-
100 alities, such as an achromatic lens by further engineering the
101 phase dispersion,^{32,33} vectorial holograms, and arbitrary orbital
102 angular momentum generation by fully taking advantage of the
103 adjustable phase freedoms.^{34,35} However, asymmetric polar-
104 ization generation based on this method thus far is seldom
105 reported. Moreover, related studies are mainly focused on the
106 optical and microwave ranges, but rarely in the terahertz
107 regime. Actually, seeking new ways to control the terahertz
108 polarization states is very critical to many applications in
109 various fields, ranging from polarizing beam generating,
110 imaging, communication to signal processing.^{2,3,36–46}

111 In this Article, we propose a straightforward method for
112 spin-decoupled terahertz phase control using dielectric
113 metasurfaces by taking advantages of their high efficiency
114 and large phase tuning range. A multifunctional meta-grating
115 that deflects different circularly polarized waves toward
116 asymmetric angles is designed and experimentally character-
117 ized to demonstrate the effectiveness of the proposed method.
118 Here, we denote it as an asymmetric spin-decoupled meta-
119 grating (ASM). Next, we apply this method in asymmetric
120 polarization generation using multiplexed technique. A group
121 of multiplexed ASMs (MASMs) are designed. Each one is
122 composed of two ASMs with interchanged phase gradients and

different output phases. Under the linearly polarized incidence, 123
the metasurfaces could convert it into two linearly polarized 124
waves with nearly equal strength, but different orientation 125
angles, and then, deflect them toward different angles. To 126
prove this strategy, one representative MASM is chosen and 127
experimentally demonstrated. The proposed meta-gratings 128
broaden and deepen the applications of metasurfaces and 129
may be applied in specific polarization-related systems. 130

131 RESULTS

Spin-Decoupled Phase Control. Figure 1a schematically 132
illustrates a basic unit cell of the dielectric metasurfaces, which 133

Figure 1. Schematic of the structure design and the ASM. (a) Schematic of a basic unit cell, which is a rectangular silicon pillar patterned on a silicon substrate. (b) Schematic of the rotation of the unit cell. (c) Schematic of a conventional meta-grating based on the sole geometric phase, which can only deflect the LCP and RCP output components toward symmetric angles of θ and $-\theta$ under normal incidence. (d) Schematic of an ASM based on both dynamic and geometric phases, which can deflect the LCP and RCP output components toward different angles of θ_1 and θ_2 under normal incidence.

is a rectangular-shaped silicon pillar patterned on a silicon 134
substrate. The pillar can be regarded as a truncated waveguide, 135
which confines the field inside or around it. Thus, we can 136
approximately analyze and utilize its electromagnetic response 137
locally. Figure 1b illustrates a schematic of the relation of the 138
local fs coordinate system of the unit cell and the global xy 139
coordinate system, which has a relative rotation angle α . Here, 140
 f and s axes are the two symmetric directions of the pillar, 141
respectively. The transmission matrix of the pillar in the fs 142
coordinate T^{fs} can be expressed as 143

$$T^{fs} = \begin{bmatrix} A_f e^{i\varphi_f} & 0 \\ 0 & A_s e^{i\varphi_s} \end{bmatrix} \quad (1) \quad 144$$

where A_i and φ_i represent the eigen transmission amplitude 145
and phase shift when the incidence polarization is along the $i \in$ 146
 $\{f, s\}$ axis, respectively. The amplitude is determined by the 147
effective impedance of the waveguide. The phase shift is 148
determined by the effective refractive index and height of the 149
waveguide, which can be denoted as the dynamic phase. Both 150
the amplitude and phase shift are controlled by the length and 151

width of the pillar. The difference either in the amplitudes or the phase shifts along the f and s directions will make the pillar anisotropic. When arranging the pillars into the metasurfaces, it is more convenient to study the transmission matrix of the pillar in the xy coordinate system, which can be expressed as

$$T^{xy} = M(-\alpha)T^f M(\alpha) \quad (2)$$

with $M(\alpha) = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix}$ being the rotation matrix between the two coordinate systems. When the eigen transmission response is anisotropic, the cross-polarized output will be generated under the x -/ y -polarized incidence as long as $\alpha \neq n\pi/2$, with n being an integer. To study the corresponding transmission response, we can further transform the T^{xy} into that in the circular polarization basis as

$$T^{lr} = C^\dagger T^{xy} C = \begin{bmatrix} t_{ll} & t_{lr} \\ t_{rl} & t_{rr} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} A_f e^{i\varphi_f} + A_s e^{i\varphi_s} & (A_f e^{i\varphi_f} - A_s e^{i\varphi_s}) e^{-i2\alpha} \\ (A_f e^{i\varphi_f} - A_s e^{i\varphi_s}) e^{i2\alpha} & A_f e^{i\varphi_f} + A_s e^{i\varphi_s} \end{bmatrix} \quad (3)$$

where $C = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix}$ represents the transformation matrix from the circular-polarization basis to the xy basis while $C^\dagger$ represents the back transformation matrix; the subscripts l and r represent the left-handed circularly polarized (LCP) component and right-handed circularly polarized (RCP) component, with the latter and former subscripts being the incident and output polarization states, respectively. It can be seen that the cross-circularly polarized output components (t_{rl} and t_{lr}) will be generated as long as the unit cell is anisotropic. The $+2\alpha$ and -2α in the phase terms of t_{rl} and t_{lr} are the well-known geometric phases that are determined by the spin state of the circularly polarized incident wave and the rotation angle of the unit cell. Though different, the geometric phases are locked with each other. Besides, the phase shifts of t_{rl} and t_{lr} are also determined by the difference between the eigen transmission responses, which provide an additional freedom to decouple the phase shifts of t_{rl} and t_{lr} . If the sole geometric phase is applied in a metasurface, such as a meta-grating composed of same structures with different rotation angles, the cross-circularly polarized components will be deflected to symmetric anomalous angles due to reversed phase gradient, as illustrated in Figure 1c. However, if the meta-grating is designed by further incorporating the dynamic phase contribution from the eigen transmission responses of each unit cell, it is possible to independently control the anomalous angles of the cross-circularly polarized components, namely, an ASM, as illustrated in Figure 1d.

Considering a special case of $A_f = A_s = A$ and $\varphi_s - \varphi_f = \pi$, which represents that the unit cell is functioning as a half waveplate. Equation 3 can be simplified as

$$T^{lr} = \begin{bmatrix} 0 & A e^{i(\varphi_f - 2\alpha)} \\ A e^{i(\varphi_f + 2\alpha)} & 0 \end{bmatrix} \quad (4)$$

The outputs in this case only contain cross-circularly polarized components, indicating a perfect polarization conversion. The corresponding efficiencies are determined by A , while the phase shifts are determined by both geometric phase and dynamic phase. To achieve fully spin-decoupled phase control, it is required that the contributions from both dynamic (including both linear polarizations along the two axis

of the structure) and geometric phases cover at least the whole 2π range individually and independently.

Design and characterization of the ASM. For the geometric phases, they are quite easy to cover the 2π range by simply rotating the structure. For the dynamic phases, they require a group of unit cells with different geometric parameters to cover the 2π range. Here, we directly adopt the structure database developed in our previous study, which fulfill this requirements and allows high-efficiency independent wavefront control for two orthogonally linearly polarized waves.³ These rectangular silicon pillars have a period of $P = 150 \mu\text{m}$ and a height of $h = 200 \mu\text{m}$. Their length and width D_f and D_s vary from 30 to $140 \mu\text{m}$. They are designed to work at 1.0 THz. Suppose that the desired phase distributions to generate independent cross-polarized wavefronts under the LCP and the RCP incidences are $P_{rl}(x, y)$ and $P_{lr}(x, y)$, respectively. According to eq 4, the relations of $P_{rl}(x, y)$ and $P_{lr}(x, y)$ to the corresponding dynamic phase distribution $\Phi_f(x, y)$ and rotation angle distribution $\Omega(x, y)$ can be expressed as

$$\Phi_f(x, y) + 2\Omega(x, y) = P_{rl}(x, y) \quad (5)$$

$$\Phi_f(x, y) - 2\Omega(x, y) = P_{lr}(x, y) \quad (6)$$

It is seen that, different from the rotation angle, which contributes opposite values to the phases of the two cross-circularly polarized output components, the dynamic phase contributes equally to them. Meanwhile, there is no crosstalk between these two types of phases, which allows independent manipulations on them. By solving the above equations, we can get

$$\Phi_f(x, y) = \frac{P_{rl}(x, y) + P_{lr}(x, y)}{2} \quad (7)$$

$$\Omega(x, y) = \frac{P_{rl}(x, y) - P_{lr}(x, y)}{4} \quad (8)$$

As for the other dynamic phase distribution Φ_s , it can be calculated by using the half-waveplate feature of the structures

$$\Phi_s(x, y) = \Phi_f(x, y) + \pi \quad (9)$$

Equations 7–9 mean that we can transfer the direct requirements on the phase distributions $P_{lr}(x, y)$ and $P_{rl}(x, y)$ to the indirect requirements on the dynamic phase distributions $\Phi_f(x, y)$ and $\Phi_s(x, y)$, as well as the rotation angle distribution $\Omega(x, y)$. Whereas the dynamic phase distributions can be directly and also more easily used to select the geometric distributions of the pillars, that is, the lengths and widths, since the dynamic phases are more compatible to the current simulation and characterization methods.

To find the optimal geometric distributions, one can extract them one by one through selecting pillar that provides minimum of $[\phi_f - \Phi_f(x_0, y_0)]^2 + [\phi_s - \Phi_s(x_0, y_0)]^2$ from the structure database,³ where (x_0, y_0) is an arbitrary position among the designed ranges of x and y . If there are more than one pillar that satisfy the above condition, then pick the pillar that provides maximum of $t_f^2 + t_s^2$. After that, one can rotate the selected pillars one by one according to the calculated rotation angle distribution $\Omega(x, y)$. In this manner, metasurfaces with spin-decoupled wavefront control ability can be realized. To demonstrate this method, a simple ASM is designed to deflect different circularly polarized incidences

Figure 2. Simulation results of the designed ASM. (a) Theoretical (solid and dash lines) and simulated (hollow triangles) phase profiles, as well as the corresponding simulated (hollow squares and circles) amplitude profiles of the ASM for deflecting the RCP and LCP outputs toward different angles under the LCP and RCP incidences at 1.0 THz. The amplitudes are amplitudes of the transmission of the sole structured surface, same hereinafter. (b, c) Simulated output RCP and LCP field distributions of the ASM under the LCP and RCP normal incidences, respectively, at 1.0 THz. The top-shaded regions represent the structure areas. The white dotted lines illustrate the corresponding directions of the output wave vectors. (d, e) Simulated angle-resolved RCP and LCP transmittance profiles of the sole structured surface of the ASM under the LCP and RCP normal incidences, respectively, at 1.0 THz.

toward asymmetric angles. The corresponding phase profiles under the LCP and the RCP incidences are designed by $P_{rl} = 2\pi x/n_l P + \varphi_0$ and $P_{lr} = -2\pi x/n_r P + \varphi_0$, with $n_l = 6$, $n_r = 8$, and φ_0 being a constant phase value, respectively, as indicated by the blue lines in Figure 2a. Such phase gradients will result in a larger overall period that contains 24 unit cells along the x -direction, corresponding to a length of 3.6 mm. The hollow blue triangles in Figure 2a represent the simulated phase profiles of the picked structures using the above method at 1.0 THz, which agree well with the requirements. The hollow red squares and circles in Figure 2(a) represent the corresponding simulated transmission amplitude profiles, showing very good uniformities and high efficiencies. According to the generalized Snell's law,⁴⁷ the anomalous deflection angles for the RCP and the LCP outputs under the LCP and the RCP normal incidences are $\theta_l = \arcsin\left(\frac{dP_{rl}}{kdx}\right) = \arcsin\left(\frac{\lambda}{n_l P}\right) = 19.47^\circ$ and $\theta_r = \arcsin\left(\frac{dP_{lr}}{kdx}\right) = \arcsin\left(-\frac{\lambda}{n_r P}\right) = -14.48^\circ$, respectively,

corresponding to a relative asymmetric deflection angle of $\Delta = |\theta_l + \theta_r|/2 = 2.33^\circ$, where $k = 2\pi/\lambda$ is the wave vector, with $\lambda = 300 \mu\text{m}$. Figure 2b,c illustrates the simulated output RCP and LCP field distributions under the LCP and RCP normal incidences at 1.0 THz, respectively, where asymmetric deflection angles are clearly seen by the tilted wavefront. Further evidence can be found in Figure 2d,e, where the corresponding calculated angle-resolved transmittance profiles of the sole structured surface are illustrated. The extracted deflection angles of the peaks are 19.84° and -14.03° , which agree well with the theoretical values. The corresponding efficiencies are illustrated by the peak values, which are 60.97% and 61.02%, respectively.

Next, we fabricate the designed ASM using conventional lithography together with deep reactive ion etching on a high-resistivity silicon wafer. Figure 3a illustrates the microscope image of part of the fabricated ASM. Microscope images that include all the 24 unit cells in one overall period can be seen in

Figure 3. Experimental characterization of the designed ASM. (a) Microscope image of part of the fabricated ASM. (b) Schematic of the experimental setup. (c–f) Measured broadband angle-resolved transmittances T_{ll} , T_{lr} , T_{rl} , and T_{rr} of the sole structured surface of the ASM under normal incidences. The white dashed lines in (d) and (e) are the theoretical dependences between frequency and deflection angle calculated by the generalized Snell's law.

the Supporting Information. A broadband, fiber-based, angle-resolved terahertz time-domain spectroscopy (THz-TDS) system is used to experimentally characterize the performance of the ASM. Figure 3b illustrates the schematic of the experimental setup (see Methods). To obtain the broadband angle-resolved transmission of the output components under

Figure 4. Schematic of the MASM design for asymmetric polarization generations and the corresponding simulation results. (a) Schematic of the designing strategy of the MASM, which is composed of two sets of ASMs (ASM-A and ASM-B). (b–e) Theoretical (solid and dash lines) and simulated (hollow triangles) phase profiles, as well as the corresponding simulated (hollow squares and circles) amplitude profiles of the ASM-Bs for deflecting the RCP and LCP outputs toward different angles under the LCP and RCP incidences at 1.0 THz with $\Delta\phi_1 = 0, \pi/2, \pi$, and $3\pi/2$, respectively. The corresponding phase and amplitude profiles of the ASM-As in the four cases are all identical to those in Figure 2a. The deflection angles of the ASM-A and ASM-B in each MASM are just flipped with each other to allow polarization superposition. (f–i) Corresponding simulated angle-resolved x - and y -polarized transmittance profiles of the sole structured surface of the above four MASMs under the x -polarized normal incidences at 1.0 THz. The top insets are the corresponding extracted polarization states of the deflected waves at θ_1 and θ_2 , respectively.

the circularly polarized incidences, we first measure the corresponding results under the linearly polarized incidences, namely, t_{xx} , t_{yy} , t_{xy} , and t_{yx} . Then, we transform them into the circular polarization basis to t_{ll} , t_{rr} , t_{lr} , and t_{rl} using the same way as eq 3. Figure 3c–f illustrates the angle-resolved transmittances of T_{ll} , T_{rr} , T_{lr} , and T_{rl} , respectively. Here, $T_{jk} = |t_{jk}|^2$, with $j, k \in \{l, r\}$. Broadband asymmetric anomalous deflections are observed for T_{rl} and T_{lr} from 0.6 to 1.4 THz. The deflection angles agree well with the theoretical predications, as indicated by the white dash lines. It is seen that there are almost no outputs at the zero-order transmittances of the copolarized components t_{ll} and t_{rr} at the designed frequency 1.0 THz. Nearly all the transmitted waves are converted to cross-polarized components and deflected. The measured deflection efficiencies of the sole structured surface are around 30%. At other frequencies, the corresponding efficiencies become weaker, which can be attributed to the eigen transmission responses that gradually deviate from the conditions of $A_f = A_s = A$ and $\varphi_s - \varphi_f = \pi$. For example, the dynamic phases φ_f and φ_s can be calculated as $kn_{\text{eff}}^f h$ and $kn_{\text{eff}}^s h$, with n_{eff}^f and n_{eff}^s representing the effective indexes of the f - and s -polarized waves, respectively. If the condition $\varphi_s - \varphi_f = \pi$ is satisfied at 1.0 THz, it is no longer satisfied at other frequencies, resulting in reduced polarization conversions and, thus, decreased deflection efficiencies. Besides the proposed ASM, other ASMs with different asymmetric deflection angles for the LCP and RCP incidences can also be realized, such as deflecting only one circularly polarized incidence and deflecting the two circularly polarized incidences

toward the same side of the normal line, see the Supporting Information. Such a feature validates the proposed method in realizing a spin-decoupled wavefront control very well. Meanwhile, it also allows to tune the relative asymmetric deflection angle. According to the generalized Snell's law $\theta = \arcsin\left(\pm \frac{\lambda}{nP}\right)$, where n is the number of the pillars in one overall period, the minimum n here is 3 at 1.0 THz under the condition of $nP > \lambda$, corresponding to a maximum deflection angle of $\theta_{1\text{max}} = \theta_{2\text{max}} = 41.81^\circ$. Therefore, the maximum relative asymmetric deflection angle we can achieve here is $\Delta = 41.81^\circ$.

Design of the MASMs for Asymmetric Polarization Generations.

Based on the above designing principles, we propose a strategy to achieve controllable asymmetric polarization generations with linearly polarized incidence using a multiplexed technique. Figure 4a illustrates the schematic of the design. The MASM contains two sets of ASMs interleaved along the y -direction: ASM-A and ASM-B. The ASM-A is exactly the same with the above designed ASM. The ASM-B is designed in an inverse way to ASM-A, with similar efficiencies. The corresponding phase profiles under the LCP and the RCP incidences are designed by $P_{rlB} = P_{rlA} - \Delta\phi_2 = P_{lr} - \Delta\phi_2$ and $P_{lrB} = P_{rlA} + \Delta\phi_1 = P_{rl} + \Delta\phi_1$, respectively. In this case, the ASM-B will deflect the RCP and LCP outputs under the LCP and the RCP normal incidences toward θ_2 and θ_1 , respectively, at 1.0 THz, indicating that the deflection angles are just flipped compared to those of ASM-A. Here, $\Delta\phi_{1(2)} \in [0, 2\pi]$ represents the structure induced phase

Figure 5. Experimental characterization of the designed MASM with $\Delta\varphi_1 = \pi$. (a) Microscope image of part of the fabricated MASM. (b–e) Measured broadband angle-resolved copolarized transmittances T_{xx} , T_{yy} , T_{+45+45} , and T_{-45-45} of the sole structured surface of the MASM under the x -, y -, $+45^\circ$, and -45° -polarized normal incidences, respectively. (f–i) Corresponding measured broadband angle-resolved cross-polarized transmittances T_{yx} , T_{xy} , T_{-45+45} , and T_{+45-45} . The white dashed lines are the theoretical dependences between frequency and deflection angle calculated by the generalized Snell's law. (j–m) Extracted angle-resolved x -, y -, $+45^\circ$, and -45° -polarized transmittance profiles around θ_1 and θ_2 from (b) to (i) at 1.0 THz, respectively.

difference between the output LCP components deflected by ASM-B (ASM-A) and the output RCP components deflected by ASM-A (ASM-B) at angle $\theta_1(\theta_2)$. By multiplexing ASM-A and ASM-B, the MASM will deflect the LCP and the RCP output components toward both θ_1 and θ_2 at the same time, if the incident wave contains both the LCP and RCP components. Thus, the polarization states of the output waves at θ_1 and θ_2 are the superposition of the corresponding LCP and RCP components, which can be different when $\Delta\varphi_1 \neq \Delta\varphi_2$.

In particular, under the linearly polarized incidences, the strength of the output LCP and RCP components at both angles are equal, since any linearly polarized wave can be decomposed to the LCP and RCP waves with equal strength and initial phase difference of $\Delta\varphi_0 = \varphi_{l0} - \varphi_{r0} = -2\gamma$, where $\gamma \in [-\pi/2, \pi/2]$ is the orientation angle of the incident linear polarization, φ_{l0} and φ_{r0} are the initial phases of the LCP and RCP components of the incident linearly polarized wave. Therefore, the output polarization states are also linearly

polarized, which can be freely controlled by designing $\Delta\varphi_1$ and $\Delta\varphi_2$, as described by the Jones matrixes

$$\text{Pol}_{\theta_1} = \frac{\sqrt{2}}{2} \text{C} \begin{bmatrix} e^{i(-\Delta\varphi_0 + \Delta\varphi_1)} \\ 1 \end{bmatrix} \propto \begin{bmatrix} \cos\left(-\frac{\Delta\varphi_1}{2} - \gamma\right) \\ \sin\left(-\frac{\Delta\varphi_1}{2} - \gamma\right) \end{bmatrix} \quad (10)$$

and

$$\text{Pol}_{\theta_2} = \frac{\sqrt{2}}{2} \text{C} \begin{bmatrix} e^{i(-\Delta\varphi_0 + \Delta\varphi_2)} \\ 1 \end{bmatrix} \propto \begin{bmatrix} \cos\left(-\frac{\Delta\varphi_2}{2} - \gamma\right) \\ \sin\left(-\frac{\Delta\varphi_2}{2} - \gamma\right) \end{bmatrix} \quad (11)$$

for the output waves at θ_1 and θ_2 , respectively. The corresponding polarization orientation angles become $(-\Delta\varphi_1/2 - \gamma) + n\pi$ and $(-\Delta\varphi_2/2 - \gamma) + n\pi$, where n is an

integer that is used to correct the polarization orientation angle in the defined range of $[-\pi/2, \pi/2]$. The “−” sign before $\Delta\varphi_0$ in the above two equations is induced by the flip of the input and output helicities. Therefore, arbitrary polarization orientation angles of the two output split linearly polarized waves can be realized by designing $\Delta\varphi_1$ and $\Delta\varphi_2$. It can be deduced that, under elliptically polarized incidence, the MASMs will generate two elliptically polarized waves with the same ellipticity at θ_1 and θ_2 . The corresponding polarization orientation angles can also be described by eqs 10 and 11. However, the helicities of both the generated elliptically polarized waves will be opposite to that of the incidence. Here, to demonstrate the above strategy of controllable polarization generation, we set $\Delta\varphi_2 = 0$ for simplicity.

We first carried out numerical simulations to characterize the output polarization states under the x -polarized incidence ($\gamma = 0$), in which we set $\Delta\varphi_1 = 0, \pi/2, \pi$, and $3\pi/2$, respectively. The corresponding phase profiles of the ASM-B under the LCP and the RCP incidences are illustrated in Figure 4b–e, respectively. The hollow blue triangles show that the picked structures are well consistent with the requirements. The hollow red squares and circles represent the corresponding simulated transmission amplitude profiles, showing very good uniformities and high efficiencies. Figure 4f–i illustrates the simulated angle-resolved transmittance profiles of the output x - and y -polarized components at 1.0 THz under the x -polarized incidences, respectively. It is seen that the transmittances at θ_1 and θ_2 greatly suppress those at the other angles, indicating a good deflection effect. The top insets are the extracted polarization states of the deflected waves at θ_1 and θ_2 . Obviously, the polarization states are all well linearly polarized. The polarization state of the output waves at θ_2 in the four cases are all nearly x -polarized owing to $\Delta\varphi_2 = 0$, while the polarization orientation angles of the output waves at θ_1 vary with $\Delta\varphi_1$. The corresponding extracted polarization orientation angles of the transmitted waves are $0^\circ, -50.92^\circ, 88.53^\circ$, and 51.27° at θ_1 , while $0^\circ, 1.58^\circ, -1.50^\circ$, and 2.04° at θ_2 , respectively. All of these values agree well with eqs 10 and 11, showing a good performance of controllable asymmetric polarization generation. The slight deviations from the theoretical values and the slight different efficiencies between the generated linearly polarized waves at θ_1 and θ_2 can be attributed to the weak couplings among adjacent structures, since not all of the selected pillars can confine the field well inside them, and the environments of these pillars change when the two ASMs are interleaved together. Further simulations show that, if the incidence linear polarization is rotated by γ , the output linear polarizations at both θ_1 and θ_2 will be rotated by $-\gamma$. Notice that the multiplexed method will make the overall period along the y -direction enlarged. If this period is larger than the working wavelength, undesired high diffraction orders will gradually occur in the y -direction according to the diffraction theory, which would bring down the efficiencies of the deflections toward θ_1 and θ_2 along the x -direction.

To experimentally demonstrate the asymmetric polarization generation behavior, we fabricated one MASM with $\Delta\varphi_1 = \pi$. This MASM generates two orthogonal linearly polarized waves under arbitrary linearly polarized incidence, which can be useful in novel polarizing beam splitting applications. Figure 5a illustrates a microscope image of part of the fabricated MASM. Microscope images that include all the unit cells in one overall

period can be seen in the Supporting Information. Figure 5b–e illustrates the measured angle-resolved copolarized transmittances of the sole structured surface under linearly polarized incidences with the orientation angles $\gamma = 0^\circ$ (x), 90° (y), $+45^\circ$, and -45° , respectively, while Figure 5f–i illustrates the corresponding measured cross-polarized transmittances. It is seen that the deflection angles agree well with the theoretical predictions, as indicated by the dash lines. According to the above analysis, the $[(-90^\circ - \gamma) + n\pi]$ -polarized and $-\gamma$ -polarized components should be deflected to θ_1 and θ_2 , respectively. Such features are clearly indicated by the corresponding measured angle-resolved transmittance profiles in Figure 5j–m, respectively, at 1.0 THz, where the corresponding polarization contrasts at θ_1 and θ_2 between the two orthogonally polarized components are quite obvious, agreeing well with the theoretical design and simulation. The measured efficiencies $T_{xx}, T_{yy}, T_{xy}, T_{yx}, T_{+45+45}, T_{-45+45}, T_{+45-45}$, and T_{-45-45} are 7.69%, 9.06%, 10.52%, 14.46%, 11.36%, 11.03%, 12.74%, and 7.14%, respectively, showing a polarization-insensitive feature. Such a feature greatly differs from the polarization beam splitters, which could only deflect certain orthogonal polarization components of the incident waves toward different direction, resulting in strongly polarization-dependent efficiencies. The strong copolarized output at the zero-order transmittances and the smaller efficiencies here can be attributed to the deviations between the geometric parameters of the designed and fabricated structures.

CONCLUSION

We propose a spin-decoupled phase control method by combining the dynamic phase and the geometric phases using all-silicon dielectric metasurfaces in the terahertz regime. More importantly, we further apply a multiplexed method for asymmetric polarization generation, which could generate arbitrarily different linear polarizations at different deflection angles under linearly polarized incidence. The proposed method based on a dielectric metasurface platform breaks the limitation of previous multiplexed meta-gratings for polarization generations with sole geometric phase and opens new potential avenues to modulate the wavefronts and polarizations, thus, offering potential applications in various fields, including meta-holography, polarizing beam splitters, and polarization multiplexing systems. Though it is demonstrated in the terahertz regime, it could be well extended to other frequency ranges of the electromagnetic spectrum.

METHODS

Experimental Characterization. The experiments were carried out using broadband angle-resolved terahertz time-domain spectroscopy, as illustrated in Figure 3b. First, the terahertz waves generated by a transmitter were collimated by a lens, which then illuminated and propagated through the sample. Next, the transmitted terahertz waves scattered toward different angles from $+40^\circ$ to -40° were collected by another lens to a receiver in a step of 1° , both of which were placed on a rail fixed on a rotator, whose central axis overlapped with that of the sample. Here, both the transmitter and receiver were made from photoconductive antennas, which were pumped by a 1560 nm fiber femtosecond laser. To allow the polarization-resolved measurements of the transmitted waves, six metallic-grid-based broadband terahertz linear polarizers P1–P6 were applied. Three were placed before the sample and the other

three were after the sample. P1 and P6 were placed to allow only x -polarized transmission for all the measurements. To measure T_{xx} , T_{yy} , T_{xy} , and T_{yx} , P2 and P5 were placed to allow 45° -polarized transmission, while P3 and P4 were placed to allow either x - or y -polarized transmission. To measure T_{+45+45} , T_{-45+45} , T_{+45-45} , and T_{-45-45} , P2 and P5 were placed to allow x -polarized transmission, while P3 and P4 were placed to allow either $+45^\circ$ - or -45° -polarized transmission.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsphotonics.9b01047.

Controllable asymmetric deflection of the ASM and microscope images of the fabricated ASM and MASM (PDF)

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Notes

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ACKNOWLEDGMENTS

National Natural Science Foundation of China (Grant Nos. 61605143, 61735012, 61705167, 61875150, and 61420106006); Tianjin Municipal Fund for Distinguished Young Scholars (Grant No. 18JCJC45600); Scientific Research Project of Tianjin Education Commission (Grant No. JWK1608); Start-up project of scientific research of Tianjin University of Technology and Education (Grant No. KYQD1718); Guangxi Key Laboratory of Automatic Detecting Technology and Instruments (YQ17203, YQ18205); King Abdullah University of Science and Technology, Office of Sponsored Research (Grand Nos. URF-2950-CRG5, CRF-2016-2950-RG5, and CRF-2017-3427-CRG6).

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