Article type: Full Paper

Stereo Metasurfaces for Efficient and Broadband Terahertz Polarization Conversion

Yuehong Xu, Quan Xu, Xueqian Zhang*, Xi Feng, Yongchang Lu, Xixiang Zhang, Ming Kang, Jiaguang Han* and Weili Zhang*

Y. Xu, Q. Xu, X. Zhang, X. Feng, Y. Lu, Prof. J. Han
Center for Terahertz Waves and College of Precision Instrument and Optoelectronics Engineering, Key Laboratory of Optoelectronic Information Technology (Ministry of Education of China), Tianjin University, Tianjin 300072, China
E-mail: alearn1988@tju.edu.cn; jiaghan@tju.edu.cn

X. Zhang
Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia.

M. Kang
College of Physics and Materials Science, Tianjin Normal University, Tianjin 300387, China.

Prof. J. Han
Guangxi Key Laboratory of Optoelectron Information Processing, School of Optoelectronic Engineering, Guilin University of Electronic Technology, Guilin 541004, China.

Prof. W. Zhang
School of Electrical and Computer Engineering, Oklahoma State University, Stillwater, Oklahoma 74078, USA
E-mail: weili.zhang@okstate.edu

Keywords: terahertz, polarization conversion, all-metal stereo metasurfaces, coupled-mode theory, Pancharatnam-Berry phase
Abstract

Efficient and flexible manipulation of terahertz (THz) polarization in a broadband manner using metasurfaces has attracted continuous attention in recent years. Previous studies commonly apply multilayer metallic resonators or bonded dielectric structures as the basic units, which are affected by the spacer loss or bonding difficulty and stability. Here, we propose a new design scheme based on all-metal stereo U-shaped meta-atom working in a reflection configuration. The stereo metasurface functions as an efficient and broadband THz waveplate with tailorable birefringence simply controlled by the sunken depth. Such an intriguing property is experimentally verified by a reflection-type THz half-waveplate. The polarization conversion ratio is higher than 90% with 69% relative bandwidth and over 85° angle tolerance for incidence. Furthermore, an efficient and broadband meta-grating based on Pancharatnam-Berry phase method is also experimentally demonstrated. The proposed strategy enriches the design degrees of freedom of polarization-related metasurfaces and may find broad applications in realizing various functional devices.
1. Introduction

Terahertz (THz) technologies hold essential promises in many cutting-edge fields ranging from nondestructive evaluation,[1,2] biochemical sensing,[3,4] to homeland security,[5,6] and high-speed communication.[7] In order to support the ever-increasing demand of both research and applications of THz technology, devices of various functionalities are highly desired, among which the ones that can flexibly and efficiently manipulate the polarization states of THz waves in a broadband manner are of significant importance. However, conventional devices based on birefringent materials with specific thickness are intrinsically limited by their bulky sizes and narrow working bandwidths.

In the last two decades, metasurfaces have emerged as a robust approach to achieve flat and miniaturized photonics devices with unprecedented capabilities.[8–11] By carefully introducing anisotropy into the meta-atom design, various polarization devices have been actualized,[12–15] including linear-to-circular/circular-to-linear polarization converters,[16–21] and orthogonal polarization converters.[20–24] In particular, the orthogonal polarization converters can endow local circularly polarized (CP) outputs with dispersion-less Pancharatnam-Berry (PB) phases determined by the meta-atom orientation.[25–27] Such a method allows the integration of both polarization conversion and wavefront control functionalities within single planar devices, and has elicited great research enthusiasm in developing compact THz devices, such as meta-gratings,[28–30] metalenses,[31,32] special beam generators,[28,33] meta-holograms,[34,35] and surface plasma launchers.[36] Among these demonstrations, pursuing high-efficiency and broadband performances becomes a research frontier. Such designs include transmission-type multilayer plasmonic metasurfaces,[18,21,22,24,37] reflection-type metal-
insulator-metal metasurfaces,\textsuperscript{[16,30,38-40]} and all-dielectric metasurfaces,\textsuperscript{[17,23,41-44]} The former two designs require thin-film fabrications whose efficiencies are directly affected by the thin-film quality (thickness, uniformity, and absorption). The latter design requires bonding process, which results in reduced physical stability. Further development of this field entails not only continuous endeavors to optimize the performance using existing methods, but also efforts to seek new paradigms of enhanced design flexibility and application adaptability.

In this article, we propose a robust and flexible design scheme of reflection-type THz polarization converter based on all-metal metasurfaces,\textsuperscript{[45-47]} which are composed by gold stereo U-shaped meta-atoms (U-pillars). The reflected phase difference between the two orthogonal linearly polarized (LP) components can be flexibly tailored by controlling the sunken depth of the U-pillar. The underlying mechanism can be well explained by coupled-mode theory (CMT). This strategy can be applied to design versatile polarization converters. As a proof-of-concept demonstration, we design a high-performance orthogonal polarization convertor, which is of not only broadband, high efficiency and high tolerance for incident angle, but also of a high subwavelength depth ratio and multiband working feature. Furthermore, an efficient THz meta-grating is also demonstrated based on the same unit cell through incorporating PB phase method. The proposed strategy provides new opportunities for efficiently designing various broadband polarization-related THz functional devices. Besides, it can also be widened to other electromagnetic ranges by simply scaling the dimensions.

2. Results

2.1 Structure design and reflection properties

The proposed gold stereo U-pillar is schematically illustrated in Figure 1(a). It has a period of
Figure 1. Schematic of the stereo U-pillar and the corresponding simulated results. (a) Schematic of the proposed all-gold U-pillar. (b),(c) Simulated amplitude reflection spectra $|r_{xx}|$ and $|r_{yy}|$ under x-LP and y-LP normal incidences. (d) Simulated phase difference $\Delta \varphi = \varphi_{yy} - \varphi_{xx}$. (e),(f) Simulated phase shift spectra $\varphi_{xx}$ and $\varphi_{yy}$ under x-LP and y-LP normal incidences. The former and latter subscripts represent the detected and incident polarizations. The same hereinafter.

$P = 75 \text{ } \mu\text{m}$, an overall length, width and height of $a = 62 \text{ } \mu\text{m}$, $b = 25 \text{ } \mu\text{m}$, and $h = 150 \text{ } \mu\text{m}$, a groove sink width of $w = 42 \text{ } \mu\text{m}$, and a sunken depth of $d$, respectively. Figure 1(b),(c) and 1(e),(f) illustrate the simulated amplitude reflection ($|r_{xx}|$ and $|r_{yy}|$) and phase shift ($\varphi_{xx}$ and $\varphi_{yy}$) spectra at different $d$ under the x-LP and y-LP normal incidences, respectively. The reference reflection plane is selected at the top surface of the U-pillar. Under the x-LP incidences, two resonances around 0.53 THz and 1.37 THz are observed nearly for all cases, as illustrated in Figure 1(b) and 1(e). Among resonance ranges, both $|r_{xx}|$ and $\varphi_{xx}$ change dramatically with $d$. Whereas between the two resonances, $|r_{xx}|$ is close to unity and $\varphi_{xx}$ changes smoothly. Under the y-LP incidences, the U-pillars almost perform the same property as a perfect metal mirror,
as indicated by the overlapped results in Figure 1(c) and 1(f), where $|r_{yy}|$ is uniformly unity. In an overall view, the design presents a broad frequency range between the two resonances with nearly perfect amplitude reflections and adjustable phase difference along $x$ and $y$ directions. Figure 1(d) illustrates the corresponding phase difference spectra of $\Delta \varphi = \varphi_{yy} - \varphi_{xx}$. Relatively flat features are observed throughout the mentioned frequency range, especially when $d$ changes from 60 $\mu$m to 140 $\mu$m, the variation of $\Delta \varphi$ is larger than $\pi/2$ containing the case of $\Delta \varphi = \pi$. These properties indicate that our design can serve as efficient and broadband waveplates for achieving various polarization conversions by simply adjusting a single parameter $d$.

![Figure 2. Simulated electric field distributions and CMT fitting parameters.](image)

Before checking the polarization conversion ability, the resonance feature of the U-pillar is first examined. **Figure 2(a)** and **2(b)** map the simulated electric field of an exemplary U-pillar with $d = 70 \mu$m at the two resonances of 0.53 THz and 1.37 THz under $x$-LP incidence. It is seen that the resonances are constructed in the gap between adjacent U-pillars along the $x$
direction. This can be understood as that the adjacent arms of the U-pillars form an effective parallel-plate waveguide for the $x$-LP field, which can simply penetrate it and excite the resonances. The lower resonance has a single field maximum, while the higher resonance has two. They can be respectively referred to standing magnetic dipolar resonance and quadrupolar resonance, as indicated by the corresponding surface current distributions. No obvious resonance features exist under the $y$-LP incidence, and the corresponding simulated electric field distributions are illustrated in Supplementary Figure S1. The same results can also be found at the other frequencies, since the corresponding parallel-plate waveguide is not uniform and the field leakage is too large to support localized resonances.

To understand the influence of $d$ to the reflection under the $x$-LP incidence, a temporal CMT is employed to analyze its underlying mechanism.\textsuperscript{[48,49]} The complex reflection coefficient $r_{xx}$ can be derived as:

$$r_{xx} = -1 + \frac{-4\gamma_1\gamma_2 + 2\gamma_1\Gamma_2 + 2\gamma_2\Gamma_1}{\Gamma_1\Gamma_2 - \gamma_1\gamma_2},$$

(1)

where $\Gamma_m = i(f - f_m) + \alpha_m + \gamma_m$ with $m = 1, 2$ denoting the lower and higher resonance mode, $f$ denoting the frequency, $f_m$, $\alpha_m$ and $\gamma_m$ separately denoting the resonance frequency, absorption loss rate and scattering loss rate. Based on it, the simulated reflection spectra are fitted with $|r_{xx}| = \text{abs}(r_{xx})$ and $\varphi_{xx} = \text{angle}(r_{xx}) - 2\pi gf/c + \varphi_0$. Here, $g$ is an additional fitting distance introduced by $d$, $c$ is the speed of light in vacuum, and $\varphi_0$ is an initial phase. Several exemplary fitting spectra are shown in Supplementary Figure S2. In the fittings, the resonance frequencies $f_1$ and $f_2$ are directly extracted from simulations, $\alpha_1$ and $\alpha_2$ are set as 0.042 THz and 0.024 THz, and $\varphi_0$ is set as around 2.77 rad. Figure 2(c) illustrates the fitted $\gamma_1$, $\gamma_2$ and $g$ as a function of $d$. It is seen that $g$ increases linearly with a slope of $\sim$2 which indicates a direct change of the
reflection plane at the sunken bottom position, while \( \gamma_1 \) decreases monotonically and \( \gamma_2 \) floats up and down. The different responses of \( \gamma_1 \) and \( \gamma_2 \) can be attributed to the perturbations of the sunken to the two resonances. When the sunken approaches the resonance field antinode, it brings additional radiation channel and thus results in a larger scattering loss rate, as indicated by the nearly overlapped positions of \( d \) in the antinodes of the resonance fields and the corresponding scattering rates. This can also explain the variation of \( g \) with respect to \( d \), where the resonance radiations are just leaked from the sunken bottom owing to its perturbations, while the direct reflection is also from the sunken bottom since the \( x \)-LP field can only penetrate into the structure though the parallel-plate waveguide part. Such a unique adjusting freedom together with careful design of the other parameters contributes the presented efficient and broadband phase control ability between the two resonances.

2.2 Efficient and broadband polarization conversion

To demonstrate the above design approach in achieving polarization conversion, two exemplary U-pillars with \( d = 68 \, \mu m \) and \( d = 94 \, \mu m \) are investigated. At \( d = 68 \, \mu m \), the corresponding simulated amplitude reflection and phase (including phase shift and phase difference) spectra under the \( x \)-LP and \( y \)-LP normal incidences are illustrated in Figure 3(a) and 3(b). Owing to the structure symmetry, there is no cross-polarized reflection. The resonance features of the co-polarized reflections are the same to those in Figure 1. Between the two resonance frequencies of 0.52 and 1.37 THz, \( |r_{xx}| \) and \( |r_{yy}| \) are both nearly equal to 1.0 whereas \( \Delta \phi \) is close to a constant \( \pi \). This indicates that this U-pillar design can function as an efficient and broadband half-wave plate in that range. At \( d = 94 \, \mu m \), the corresponding simulated results
are shown in Supplementary Figure S3. In this case, $\Delta \phi$ is close to a constant $3\pi/2$ between the two resonance frequencies, and the U-pillar acts as an efficient and broadband quarter-wave plate.

![Figure 3. Simulated and measured results of the U-pillar metasurface with half-wave plate feature.](image)

(a),(b) Simulated reflection amplitude and phase spectra of the U-pillar metasurface with half-wave plate feature under x-LP and y-LP normal incidences. (c),(d) Simulated reflectance and PCR spectra under CP normal incidences. (e)-(h) Corresponding measured results with respect to (a)-(d). The inset in (e) shows the partial SEM image of the fabricated metasurface.

For experimental verification, we choose and fabricate the U-pillar metasurface with $d = 68 \ \mu m$ (see Experimental Section and Supplementary Figure S4). The corresponding partial scanning electron microscope (SEM) image is illustrated in the inset of Figure 3(e). A broadband all-fiber terahertz time-domain spectroscopy (THz-TDS) is applied to measure its polarization response (see Experimental Section and Supplementary Figure S5). Figure 3(e) and 3(f) respectively illustrate the measured amplitude reflection and phase spectra, which are consistent well with the simulation. The slight resonance shifts and enlarged $\Delta \phi$ are caused by the deviation in the structure geometry of the fabricated sample (see Supplementary Figure S6),
whereas the larger resonance bandwidths can be attributed to the larger intrinsic loss of the real gold. The measured half-wave plate range is between 0.71 THz and 1.34 THz, where $|r_{xx}|, |r_{yy}| > 0.9$ and $\Delta \phi$ is close to $\pi$.

Next, the polarization conversion properties of the above half-wave plate design are characterized by checking its reflection responses under the CP normal incidences, including reflectance $|r|^2$ that determines the absolute polarization conversion efficiency, polarization conversion ratio (PCR) that determines the purity of the desired polarization component in the final output, and relative bandwidth (RBW) that determines the operating bandwidth nature.

They can be respectively expressed as:[35]

$$
\begin{bmatrix}
  r_{++} & r_{+-} \\
  r_{-+} & r_{--}
\end{bmatrix} = \frac{1}{2}\begin{bmatrix}
  r_{xx} - r_{xy} + i(r_{xy} + r_{yx}) & r_{xx} + r_{yy} - i(r_{xy} - r_{yx}) \\
  r_{xx} + r_{yy} + i(r_{xy} - r_{yx}) & r_{xx} - r_{yy} - i(r_{xy} + r_{yx})
\end{bmatrix},
$$

(2)

$$
\text{PCR} = \frac{|r_{\text{converted}}|^2}{|r_{\text{converted}}|^2 + |r_{\text{un-converted}}|^2},
$$

(3)

$$
\text{RBW} = \frac{\Delta f}{f_c},
$$

(4)

where the subscript symbols $+$ and $-$ represent left-handed and right-handed CP (LCP and RCP) state, $|r_{\text{converted}}|$ and $|r_{\text{un-converted}}|$ represent the amplitudes of polarization-converted ($r_{++}, r_{--}$) and polarization-unconverted ($|r_{-+}|, |r_{+-}|$) reflections, $\Delta f$ represents the operating bandwidth, and $f_c$ represents the center frequency, respectively. Figure 3(c) and 3(d) illustrate the simulated CP reflectance and PCR spectra, whereas Figure 3(g) and 3(h) illustrate the corresponding measured results. Efficient and broadband helicity-maintained reflection spectra are observed with negligible helicity-converted reflection, which is a clear feature of a reflection-type half-wave plate. With PCR $> 90\%$ defined as the threshold, the simulated operating bandwidth achieves 0.7 THz between 0.58 THz and 1.28 THz (see the shaded regions), corresponding to
a RBW of 75%, and the average polarization conversion efficiency $|r_{++}|^2 = |r_{--}|^2$ achieves $\sim97\%$.

Whereas the measured results show an operating bandwidth of 0.67 THz between 0.64 THz and 1.31 THz, a RBW of 69% and an average polarization conversion efficiency of $\sim89\%$, which are all in very good consistence with the design.

Figure 4. Performance of the U-pillar half-wave plate metasurface under oblique incidences. (a) Schematic of the oblique incidence of the U-pillar half-wave plate metasurface. (b)-(e) Simulated reflection amplitude spectra $|r_{++}|$, $|r_{--}|$, $|r_{+-}|$ and $|r_{-+}|$ as the incident angle $\beta$ varies from $0^\circ$ to $85^\circ$ in the $\phi = 45^\circ$ plane, respectively. (f)-(i) Corresponding measured results as the incident angle $\beta$ varies from $15^\circ$ to $85^\circ$.

For reflection-type half-wave plate, one superior advantage in real applications is the ability of simultaneously working as a reflection mirror. Thus, the operating angular bandwidth
becomes an important parameter. To explore it, CP reflection responses under oblique incidences are also characterized. As illustrated in Figure 4(a), the incident plane is selected as $\phi = 45^\circ$, where $\phi$ is defined as the angle between the incident plane and the structural basic plane along the base direction of the U-pillars (orange). Figure 4(b)-(e) illustrate the simulated results of the CP amplitude reflection spectra as the incident angle $\beta$ sweeps from 0° to 85° at a step of 5°. It can be seen that the efficient and broadband polarization-converted reflection feature nearly remains over the operating bandwidth throughout the whole incident angle range. The average polarization conversion efficiency approaches 95%. Figure 4(f)-(i) illustrate the corresponding measured results [see Experimental Section and Supplementary Figure S7(a)]. The blank results from 0° to 15° are due to the experimental limitation of our setup by the size of the THz transmitter and receiver. The experimental results also show a broad operating angular bandwidth from 15° to 85°. The average polarization conversion efficiency is around 80%, exhibiting a robust tolerance of our device to the incident angle. Such a phenomenon can be related to the smaller feature size of the gap (~0.08$\lambda_c$ with $\lambda_c$ being the wavelength of $f_c = 0.93$ THz) which would not bring two much phase difference between adjacent edges under oblique incidence,$^{[24]}$ and the strong localization behavior of the resonances inside the gap which results in negligible coupling between adjacent U-pillars and thus reduces the spatial dispersion. We also investigate the performances within the incident planes of $\phi = 0^\circ$ and $\phi = 90^\circ$, which also show good operating angular bandwidth of around 40°, see Supplementary Figure S8 and S9. This smaller angular bandwidth can be attributed to the structural anisotropy, where the planes of $\phi = 0^\circ$ and $\phi = 90^\circ$ are just the symmetric planes of the U-pillar and the intrinsic resonances in them are more sensitive to the incident angle.
2.3 PB phase meta-grating for spin decomposition

An efficient unit half-wave plate can be applied as a PB phase element, which can be used to control the propagation of CP light by controlling the orientation distributions of the elements.

To demonstrate the ability of our design in this aspect, the PB phase control behavior of the above U-pillar is firstly characterized, where \( r_{++} \) and \( r_{--} \) will theoretically acquire PB phases of \(+2\theta\) and \(-2\theta\) with \( \theta \) representing the orientation angle, see Figure 5(a). Figure 5(b) and 5(c) illustrate the simulated amplitude and phase shift spectra of \( r_{++} \) as a function of \( \theta \) from 0 to \( 7\pi/8 \) with a step of \( \pi/8 \) under normal incidence. The amplitudes are all greater than 0.9 in the

Figure 5. PB phase control and meta-grating. (a) Schematic of the rotating U-pillar. (b),(c) Simulated amplitude reflection \( |r_{++}| \) and phase shift \( \phi_{++} \) spectra under normal incidences at different \( \theta \). (d) Partial SEM image of the designed meta-grating for spin decomposition. (e),(f) Measured \( |r_{++}| \) and \( |r_{--}| \) as a function of deflection angle \( \eta \) from \(-80^\circ\) to \(-20^\circ\) and \(20^\circ\) to \(80^\circ\), respectively. The inset dashed lines are calculated results based on the generalized Snell’s law.
presented frequency range of 0.6 THz to 1.3 THz, whereas the corresponding phase shifts linearly change with $+2\theta$ as expected. The same results can also be found for the case of $r-$ whose phase shifts linearly changes with $-2\theta$.

Then, a meta-grating is designed by rotating the U-pillars to form reversed linear phase gradients for the LCP and RCP incidences. Thus, the LCP and RCP reflections will be deflected towards angles of opposite sign, corresponding to a spin decomposer. The meta-grating contains eight U-pillars in one supercell with a $\pi/8$ interval of the adjacent orientation angles, which forms an absolute phase gradient of $2\pi/8P$. Figure 5(d) illustrates the partial SEM image of the fabricated meta-grating. The performance of the device is experimentally characterized under the CP normal incidences [see Experimental Section and Supplementary Figure S7(b)].

The measured $|r_{++}|$ and $|r_{--}|$ spectra at different deflection angles $\eta$ in the ranges of $-80^\circ$ to $-20^\circ$ and $20^\circ$ to $80^\circ$ are shown in Figure 5(e) and (f), respectively. The other results are illustrated in Supplementary Figure S10. Efficient and broadband anomalous reflections for spin decomposition are observed clearly in both cases as expected, where the deflection angles of the peak THz amplitudes agree well with the generalized Snell’s law $\eta = \sin^{-1}[c/(f \times 8P)]$, as indicated by the inset dashed lines. In a broadband range from 0.67 THz to 1.14 THz, the measured $|r_{++}|$ is higher than 0.74 with the maximum approaching 0.82 at 0.85 THz. Whereas the measured frequency range of $|r_{--}| > 0.74$ is from 0.65 THz to 1.33 THz with the maximum approaching 0.94 at 1.07 THz. This discrepancy between different CP incidences can be attributed to the fabrication which slightly breaks the mirror symmetry of the U-pillars.
3. Conclusion

An efficient and broadband polarization converter design based on reflection-type all-metal stereo U-pillar structure is proposed and experimentally demonstrated, which allows flat and adjustable phase differences between two featured resonances and also has high PCR, RBW and incident angle tolerance, as experimentally verified by a metasurface design with half-wave plate feature. As a comparison, the performances of the fabricated half-wave plate and those reported ones are summarized in Table 1, where the proposed design can exhibit superior overall responses, especially for the angle tolerance. Furthermore, the design can also function as a good PB phase element for controlling CP THz propagation and is verified using a meta-grating. Our design can find broad applications requiring robust polarization and propagation control. Though the design is studied in the terahertz regime, it could be well extended to the other frequency ranges.

Table 1. Performance comparison of terahertz metasurface half-wave plates among reported works and this work. ER: extinction ratio, defined as $10\log_{10}(|r_{\text{converted}}|^2/|r_{\text{un-converted}}|^2)$.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Definition of bandwidth</th>
<th>Operating range</th>
<th>RBW</th>
<th>Max. incident angle</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013[22]</td>
<td>$</td>
<td>r_{\text{converted}}</td>
<td>^2 &gt; 80%$</td>
<td>0.73 – 1.8 THz</td>
<td>85%</td>
</tr>
<tr>
<td>2014[36]</td>
<td>PCR &gt; 50%</td>
<td>0.53 – 1.36 THz</td>
<td>88%</td>
<td>45°</td>
<td>Reflection</td>
</tr>
<tr>
<td>2017[40]</td>
<td>PCR &gt; 80%</td>
<td>0.37 – 1.05 THz</td>
<td>96%</td>
<td>55°</td>
<td>Reflection</td>
</tr>
<tr>
<td>2018[23]</td>
<td>PCR &gt; 80%</td>
<td>0.92 – 1.06 THz</td>
<td>14%</td>
<td>–</td>
<td>Transmission</td>
</tr>
<tr>
<td>2018[21]</td>
<td>PCR &gt; 90%</td>
<td>0.79 – 1.58 THz</td>
<td>66%</td>
<td>45°</td>
<td>Reflection</td>
</tr>
<tr>
<td>2021[24]</td>
<td>ER &gt; 15 dB</td>
<td>0.22 – 0.3 THz</td>
<td>32%</td>
<td>45°</td>
<td>Transmission</td>
</tr>
<tr>
<td>This work</td>
<td>$</td>
<td>r_{\text{converted}}</td>
<td>^2 &gt; 80%$</td>
<td>0.67 – 1.32 THz</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>PCR &gt; 90%</td>
<td>0.64 – 1.31 THz</td>
<td>69%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCR &gt; 80%</td>
<td>0.62 – 1.42 THz</td>
<td>78%</td>
<td>85°</td>
<td>Reflection</td>
</tr>
<tr>
<td></td>
<td>PCR &gt; 50%</td>
<td>0.6 – 1.52 THz</td>
<td>87%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ER &gt; 10 dB</td>
<td>0.64 – 1.24 THz</td>
<td>64%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Experimental Section

Sample Fabrication: All samples are fabricated on a high-resistivity silicon wafer using conventional lithography, deep reactive ion etching and magnetron sputtering. After two times of conventional lithography together with deep reactive ion etching, the stereo U-pillars made of silicon are obtained. Subsequently, the whole silicon surfaces are coated with a 200 nm-thickness gold film using magnetron sputtering method (see Supplementary Figure S4 for details). Such gold-coated silicon pillars could be equivalently treated as pure gold pillars since the gold thickness is larger than the THz penetration depth.

Experimental Measurement: A broadband all-fiber THz-TDS system is used for measuring the responses of the fabricated samples. The THz transmitter and receiver are all based on photoconductive antennas with integrated fibers. Each of them is configured with a lens to constitute a 4f optical system. For measuring the normal reflection from the U-pillar metasurface with half-wave plate feature, a 2 mm-thickness high-resistance silicon wafer is inserted to transmit incident terahertz beam while reflect reflected terahertz beam from the metasurface, see Supplementary Figure S5. For measuring the reflection from the U-pillar metasurface with half-wave plate feature under oblique incidences, the transmitter and receivers are mounted on two rails that can concentrically rotate with a rotation state, the angle-resolved reflections are thus measured by symmetrically rotating the two rails from 15° to 85° in a step of 5° simultaneously, see Supplementary Figure S7(a). For measuring the spin decomposition response of the PB phase meta-grating, the angle of the transmitter rail is fixed.
at 0°, while the angle of the receiver rail is rotated from −80° to −20° and 20° to 80° in a step of 5°, see Supplementary Figure S7(b). In all measurements, there are two polarizers respectively placed in the incident and reflected terahertz paths to initialize and extract the polarizations to be either $x$ or $y$ polarized.

**Supporting Information**
Summary Information is available from the Wiley Online Library or from the author.

**Acknowledgements**
Y. X and Q. X contributed equally to this work. This work is supported by the National Natural Science Foundation of China (Grant Nos. 62075158, 62005193, 62025504, 61735012, 11974259, 61875150, 61935015); Tianjin Municipal Fund for Distinguished Young Scholars (grant No. 18JCJQJC45600).

Received:  
Revised:  
Published online:

**Conflict of Interest**
The authors declare no conflict of interest.

**Data Availability Statement**
The data that support the findings of this study are available from the corresponding author upon reasonable request.

**References**


[45] Y. Liang, H. Lin, S. Lin, J. Wu, W. Li, F. Meng, Y. Yang, X. Huang, B. Jia, Y. Kivshar,

