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2019

Li, M., Jing, L., Lin, X., Xu, S., Shen, L., Zheng, B., ... Chen, H. (2019). Angular-adaptive spin-locked retroreflector based on reconfigurable magnetic metagrating. *Advanced Optical Materials*, 7(13), 1900151-. doi:10.1002/adom.201900151

<https://hdl.handle.net/10356/143470>

<https://doi.org/10.1002/adom.201900151>

This is the accepted version of the following article: Li, M., Jing, L., Lin, X., Xu, S., Shen, L., Zheng, B., ... Chen, H. (2019). Angular-adaptive spin-locked retroreflector based on reconfigurable magnetic metagrating. *Advanced Optical Materials*, 7(13), 1900151-. doi:10.1002/adom.201900151, which has been published in final form at <https://doi.org/10.1002/adom.201900151>. This article may be used for non-commercial purposes in accordance with the Wiley Self-Archiving Policy [<https://authorservices.wiley.com/authorresources/Journal-Authors/licensing/self-archiving.html>].

DOI: 10.1002/ ((please add manuscript number))

Article type: Full Paper

Title: Angular-adaptive Spin-locked Retroreflector Based on Reconfigurable Magnetic Metagrating

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Keywords: spin-locked, retroreflector, angular-adaptive, metagrating, reconfigurable

Abstract

Retroreflectors made of gradient metasurfaces have recently attracted intense interests due to their ability in reflecting incident light back to its source. So far, the current retroreflectors can only flip the transverse momenta of incident photons in specific incidence angles and thus have limitations in wide-angle applications. Here, we propose a switchable metagrating based retroreflector for high-efficient spin-locked retroreflection and suppression of undesired diffractions. Upon reflection, the handedness of the waves is kept the same as the incidence. Furthermore, by mechanically altering the folding state of the reconfigurable retroreflector, adaptive tangential momenta could be imparted to the incidence photons, providing a high-

performance retroreflection over a continuous range of incidence angles from 27.3° to 52.5° . As a proof of concept, a magnetic metagrating based retroreflector has been fabricated at microwave frequencies and experimental measurements show consistent behaviors at various incidence angles. The proposed retroreflector is compact (overall thickness of 0.204 of the wavelength) and inherently insensitive to the illumination angle. As the design concept introduced in our paper could be extended to terahertz and optical frequencies, our design may serve as a promising platform towards reconfigurable spin-based retroreflection devices for not only interface electromagnetics but also ultra-flat photonics.

1.Introduction

For a long time, the ability to manipulate the flow of electromagnetic wave (EM wave) at will has fascinated scientists and engineers. The emerging metasurfaces which are ultrathin two-dimensional(2D) arrangements composed of carefully designed subwavelength resonators, have been widely explored to direct electromagnetic waves in the desired manner, such as anomalous reflection or negative refraction^[1-11], beam splitting^[12-15], polarization control^[16-19] and cloaking^[20-23]. Specifically, a phase gradient metasurface has been widely used as a ubiquitous tool to control the reflection and transmission of a known incidence wave^[19, 24-28]. The majority of these metasurfaces have been based on the generalized laws of reflection and refraction^[27] which provide the gradient surface impedance so that the impinging wave acquires the tangential momentum necessary to be locally rerouted towards the desired direction.

One fascinating wavefront control for EM wave is retroreflection that is defined as the

reflection of the EM wave propagating back along its incident direction. It is very important for compact optical path setup to achieve ultra-flat retroreflector in laser fabrication. Heretofore, a conventional cat's-eye retroreflector is composed of a focusing lens and a concave mirror, which behaves like a cat's-eye device in optics^[29, 30]. **Figure 1(a)** shows this conventional conceptual design schematics for achieving retroreflection. This volumetric retroreflector is bulky and not planar, thus not natively compatible for integration and miniaturization. Shortly afterwards, utilizing phase gradient metasurface, low-weight planar ultrathin retroreflector can be implemented. However, as illuminated in Figure 1(b), the tangential momenta added by the gradient metasurface have negligible dependence on the incident angle^[11]. As a consequence, the gradient metasurface reflects photons back at a particular incident angle, but reflects other incident photons into different directions. An adaptive phase gradient metasurface using subwavelength-thick reconfigurable C-shaped resonators has been designed for tunable periodicity and multi-angle performance^[31]. However, it is impossible for such metasurface to realize retroreflection under a continuous range of incidence angles, because the period of the metasurface can only be tuned to some discrete values rather than continuous ones thus limiting its practical application. In addition to the strict restriction on incidence angle for retroreflection, some recent works^[4, 25, 28] have pointed out such phase gradient metasurfaces suffer from the inherent limitation in conversion efficiency, especially when extreme wave manipulation is considered. Extreme wave manipulation refers to large-angle beam deflection for wave front control. The efficiency of conventional phase-gradient metasurface reduces dramatically as the

steering angle increases ^[28]. The underlying reason is that this method does not take into account the impedance mismatch between impinging and desired wave fronts, leading to significant parasitic reflections in undesired directions or energy absorption in the reflector ^[28, 32]. Furthermore, it has been demonstrated that in all known structures based on generalized laws of reflection and refraction, the power efficiency is lower than the numerical prediction due to imperfections in fabrication and discretization problems ^[25]. These inherent limitations on efficiency of these gradient metasurfaces can be overcome by introducing the active or strongly nonlocal metasurfaces ^[25] which is capable of transforming an incidence wave towards the desired direction with near-unity efficiency. However, such metasurfaces are still subject to implementation difficulties due to the requirements of high-resolution discretization on gradient surface impedance profiles.

Recently, the concept of the metagrating ^[33] has been proposed for arbitrary wavefront transformation with near-unity efficiency without deeply subwavelength elements compared to the phase gradient metasurface. It provides an alternative route and turns away from the discretization of a continuous phase or impedance profile. Metagrating is composed of a single or several metamaterial subwavelength scatterers that can be carefully designed to enrich the wavefront control. Therefore, this concept is fundamentally different from the one of conventional grating, whose building blocks scatter energy into all diffraction orders including the undesired ones thus reducing the efficiency of the devices. However, previous structures or methods utilizing metagrating ^[33-35] for wavefront control suffers from a notorious dependence on

polarization state of the incidence plane wave. This is because only specified polarized incidence wave is capable of inducing the essential magnetic or electric surface currents from the dipoles placed above the ground plane. As a consequence, this polarization dependence makes the metagrating impossible to handle spin-polarized waves. The spin of light refers to the right and left-handed circular polarization (RCP and LCP) of a light beam, whereby the handedness is dependent on the direction of propagation. Spin-based metasurface^[36-39] has drawn considerable attention due to the cutting-edge research field of spin optics^[40, 41].

Here, to realize retroreflection for spin photons over a continuous range of incidence angles, we generalize the previously proposed concepts and propose a spin-locked metagrating which can suppress undesired diffraction orders totally and reroute spin-polarized incidence waves (Figure 1(c)). Upon reflection, the handedness of the waves can be kept the same as the incidence. Furthermore, inspired by Origami and Kirigami-based reconfigurable metamaterials presented in our previous works^[42, 43], arrays of horizontally oriented C-shaped resonators offering a magnetic response have been printed on ultrathin dielectric substrate. Such configuration has the flexibility to continuously alter its folding state so that adaptive tangential momenta could be imparted to the incoming photons and high-performance retroreflection over a continuous range of incidence angles can be realized. The overall thickness of the designed spin-locked metagrating based retroreflector is only 0.204λ , where λ is the working wavelength. Compared with previous methods mentioned above, our proposed angular-adaptive spin-locked retroreflector has a great potential to serve as a candidate

platform towards reconfigurable spin-based retroreflection devices.

Results and Discussion

We start with the underlying physics of the spin-locked metagrating that is composed of a periodic arrays of subwavelength scatters located over the ground plane. With appropriate dimensions, the metagrating can reroute an obliquely incidence wave towards the desired direction with a near-unity efficiency. Based on the retroreflection theory of metagrating^[33], we set the periodicity to align the direction of the specific propagating Floquet mode with flipped transverse momenta of photons. Meanwhile, other high-order diffractions are designed to be suppressed upon reflection. Here, the (-1)0 Floquet mode is selected as the desired reflection direction, the first and second indices are the Floquet orders with respect to the x and y axes, respectively. The periodicity of the metagrating p can be written in terms of the wavelength λ , the angle of the (-1)0 Floquet mode $\theta_{(-1)0}$ and the angle of incidence θ_{in} as :

$$p = \frac{\lambda}{\sin \theta_{in} - \sin \theta_{(-1)0}} \quad (1)$$

Diffraction angles are defined in the clockwise direction with respect to the z-axis (see **Figure 2(a)**). Notably, in order to make the cancellation of the undesirable Floquet modes less challenging, the number of the propagating Floquet modes should be as less as possible. Therefore, we choose 00 and (-1)0 modes to be the propagating Floquet modes. To achieve this, we need to make sure that all higher-order modes other than (-1)0 do not carry power away from the metasurface. For instance, the closest higher-order modes [i.e.,(1)0 and (-2)0] could be evanescent. Such required conditions to suppress higher-order modes are given by^[33].

$$\begin{aligned}
\theta_{(-1)0} < \arcsin(2 \sin \theta_{\text{in}} - 1), 0 < \theta_{\text{in}} < \arcsin\left(\frac{1}{3}\right) \\
\theta_{(-1)0} < \arcsin\left(\frac{1}{2} \sin \theta_{\text{in}} - \frac{1}{2}\right), \arcsin\left(\frac{1}{3}\right) < \theta_{\text{in}} < \frac{\pi}{2}
\end{aligned} \tag{2}$$

In previous works ^[33-35], the incidence wave and the reflection wave are co-polarized and the whole grating system can not produce the cross-polarized Floquet modes, such neglect of cross-polarization contributes to efficient suppress of unwanted orders. However, in order to handle the spin-polarized incidence wave and further keep the spin state of the reflection identical to the incidence wave, the polarization of each Floquet mode must be considered. Figure 2(a) shows the schematic of the general spin-locked metagrating with two open Floquet channels (four Floquet modes) for transverse magnetic (TM) polarization. The metagrating is designed to fully transmit the TM-polarized incidence wave to a direction different from the specular one with polarization conversion, namely TM-polarized incidence wave has to be totally transferred into $\text{TE}_{(-1)0}$ Floquet mode. Likewise, the desired Floquet mode would be $\text{TM}_{(-1)0}$ when the structure is illuminated with TE-polarized incidence wave. Therefore, the metagrating could redirect the incidence wave towards an anomalous direction and simultaneously convert the incident polarization state. To clarify its spin-locked property for the circular polarized EM wave, here we assume φ_1 and φ_2 are the introduced phase by the metagrating to the cross-polarized reflection for the incidence of TE and TM-polarized, respectively; A_1 and A_2 are the corresponding amplitude modulation. To achieve spin-locked retroreflection, the cross-polarized amplitude and phase modulation must be identical for both TE and TM modes ^[31], i.e. $A_1 = A_2$, $\varphi_1 = \varphi_2$. Here, taking the TM-polarized incidence as an example, the building block scatterer is designed so that

radiation of the TM_{00} Floquet mode is canceled by the destructive interference with the specular reflected field from TM incidence plane wave. Additionally, the scatterer needs to be designed so that its radiation field of the $TM_{(-1)0}$ and TE_{00} Floquet modes could be canceled through the near-field interaction between the induced electric dipoles or magnetic dipoles.

The designed structure of the metagrating is demonstrated in Figure 2(b). An array of horizontally oriented magnetically polarizable particles are located at a distance from a ground plane. Excited with an oblique incident plane wave, the metasurface sustains the induced magnetic surface currents on each magnetic dipole. By using the Floquet modal analysis^[44], the radiated fields for $n0$ Floquet mode (in our cases, $n = -1, 0$) can then be written as the superposition of TM and TE-polarized plane wave, the scattered electric field in terms of TM plane wave can be expressed as (see Supporting Information)

$$\mathbf{E}_{n0}^{TM} = (-\mathbf{x} \frac{k_{zn0}}{k_0} + \mathbf{z} \frac{k_{xn0}}{k_0}) \Phi_{n0}^{TM} \exp(ik_{xn0}x + ik_{zn0}z) \quad (3)$$

where $\Phi_{n0}^{TM} = \frac{1}{ab} \cdot \frac{1}{1 - i \tan(k_{zn0}h)} \cdot \frac{k_0}{k_{zn0}} \left[I_{m2}^y + I_{m4}^y \exp(-ik_{xn0}d) \right]$. The scattered electric

field in terms of TE plane wave can be expressed as

$$\mathbf{E}_{n0}^{TE} = -\mathbf{y} \Phi_{n0}^{TE} \exp(ik_{xn0}x + ik_{zn0}z) \quad (4)$$

with $\Phi_{n0}^{TE} = \frac{1}{ab} \cdot \frac{1}{1 - i \tan(k_{zn0}h)} \cdot \left[I_{m1}^x + I_{m3}^x \exp(-ik_{xn0}d) \right]$. Here, a and b are the periodicities in the y and x -directions, respectively. $I_{m1,3}^x$ and $I_{m2,4}^y$ are the x and y -components of the induced magnetic currents on the first and second dipole respectively as illustrated in Figure 2(b), d is the distance between two dipoles in a unit cell, and h

is the distance of the particles from the ground plane, θ_{n0} is the reflection angle for $n0$ Floquet mode. For $n0$ Floquet mode, $k_{xn0} = k_{x0} + \frac{2n\pi}{b} = k_0 \sin \theta_{n0}$ is the wave number in the x-direction, $k_{zn0} = \sqrt{k_0^2 - k_{xn0}^2} = k_0 \cos \theta_{n0}$ is the wave number in the z-direction. In order to fully transmit the TM plane wave towards the Floquet mode $TE_{(-1)0}$ and suppress the undesired Floquet modes totally as illuminated in Figure 2(a), the induced magnetic surface currents must meet the following requirements (see Supporting Information)

$$\begin{aligned}
I_{m2}^y + I_{m4}^y \exp(-ik_{x(-1)0}d) &= 0 \\
I_{m1}^x + I_{m3}^x \exp(-ik_{x00}d) &= 0 \\
\frac{1}{ab} \cdot \frac{I_{m2}^y + I_{m4}^y \exp(-ik_{x00}d)}{1 - i \tan(k_{z00}h)} \cdot \frac{k_0}{k_{z00}} - E_0 &= 0
\end{aligned} \tag{5}$$

In the Supporting Information, we demonstrate that an electric planar metagrating based on induced tangential electric surface currents satisfying a similar requirement can also suppress the undesired orders totally and redirect the incidence wave to an anomalous direction with polarization conversion. Notably, standing shapes are easier to stretch horizontally and hence results in continuously change of the period. Such continuous deformation is crucial to realize an ideal retroreflector with ultrawide dynamical tuning range. Therefore, in the following, we choose the retroreflector based on surface magnetic currents.

To realize such configuration mentioned above, arrays of carefully tailored copper split-ring resonators (thickness 0.035 mm) are periodically printed on a Halogenfree frame-resistant type polyimide film (thickness 0.1 mm) with a permittivity of 3, located on top of a perfect electric conductor as shown in top panel of Figure 2(c). The schematic

of the C-shape resonators and one unit of the metagrating are shown in the middle and bottom panel respectively. The structure is symmetrical with respect to the zy plane. Attributing to such standing configuration of resonators, the period of the metagrating can be flexibly tuned by mechanical stretching, with a relationship with the folding angle:

$$b = 2n \cos \alpha \quad (6)$$

Here, the folding angle α is a parameter determining the folding state of the metagrating. In order to guarantee no radiation in the zy plane, the period along the y direction has been set to a constant value of 10 mm. To realize retroreflection, such adaptive metagrating is thus designed to meet the condition

$$-\theta_r = \theta_i = \arcsin\left(\frac{\lambda}{2b}\right) = \arcsin\left(\frac{\lambda}{4n \cos \alpha}\right) \quad (7)$$

Where θ_r is the angle of retroreflection whose absolute value equals to incidence angle θ_i , λ is the wavelength of EM wave. It is clear that retroreflection over a continuous range of incidence angles can be achieved via tuning the folding angle α continuously.

Figure 3(a) and (b) shows the reflected power towards the four Floquet modes as a function of frequency under TE and TM-polarized incidence with the folding angle tuned to 45° , showing a moderately broad response in terms of frequency. At the design frequency 9 GHz, the oblique incident power has been redirected into the desired Floquet mode as expected, namely $TM_{(-1)0}$ for TE-polarized incidence and $TE_{(-1)0}$ for TM-polarized incidence, with an identical efficiency reaching almost 97%. The total power into all the other undesired Floquet modes is largely suppressed to near zero. The phase of $TM_{(-1)0}$ and $TE_{(-1)0}$ under TE and TM-polarized incidence is identical as shown

in Figure 3(c). These verify the proposed retroreflector can realize spin-locked retroreflection with near-unity efficiency under illumination angle $\theta_{in} = 34^\circ$. Figure 3(d) further reveal the underlying principle of the spin-locked retroreflection where we treat the spin-polarized wave as a superposition of TE and TM-polarized wave. Figure 3(e) and (f) shows the scattered electric field distribution in the zx plane for TE and TM-polarized incidence with incidence angle θ_{in} at 34° , respectively. The three panels in figure 3(e) and (f) represent the components of the scattered electric field along three directions. Upon reflection, the TE-polarized waves (E_y) are retroreflected and converted to the TM waves (E_x, E_z) and vice versa.

Spin-locked retroreflection with various angles can be achieved by tuning the folding state of the designed reconfigurable metagrating mechanically. The performance of angular-adaptive retroreflection is illustrated in **Figure 4**. At 9 GHz ($\lambda = 33.3$ mm), by tuning the folding angle from 30° to 60° , spin-locked retroreflection over a continuous range of incidence angles from 27.3° to 52.5° are achievable. The corresponding period along x -direction of the metagrating varies from 36.4 mm to 21.1 mm. Figure 4(a) shows the simulated cross-polarized retroreflection amplitude and phase shift as a function of the folding angle under TE and TM-polarized incidence waves. Both the cross-polarized retroreflection amplitude and phase shift for TE and TM-polarized incidence wave are approximately identical. This property verifies that, over the whole range of incident angles from 27.3° to 52.5° , the retroreflector has the ability to handle the circular polarized EM waves for retroreflection and further keep the spin state of the EM waves perfectly. It is worth noting that reflection amplitude reaches the

maximum value 98.3% for TE-polarized incidence and 98.5% for TM-polarized incidence when the folding angle α is 45° .

In Figure 4(b), the blue solid line represents the maximum value of $\theta_{(-1)0}$ obtained from the required conditions expressed in Equation (2), which will guarantee only $(-1)0$ and 00 are the propagating Floquet modes. The brown solid line represents the calculated retroreflection angle versus folding angle, while the symbols of red circles and blue stars represent the simulated retroreflection for TE and TM-polarized incidence respectively. When the reconfigurable metagrating is properly folded, retroreflection at the same angle is realized for both TE and TM-polarized incidence. Figure 4(c)-(h) shows the retroreflection behaviors for TE and TM modes at the incidence angles of 31° , 38° and 44° , with the corresponding folding angles of 40° , 50° and 55° , respectively.

Figure 5(a) shows the simulated results of far-field scattered intensity distribution for retroreflection at various incidence angles under TE and TM-polarized incidence. The scattered intensity is normalized to the intensity of specular reflection at the corresponding incidence angle for a perfect electric conductor with the same size. The maximum efficiency of retroreflection appears at the folding angle of 45° and the incidence angle of 34° , where the scattered intensity for the specular direction has been suppressed to near zero. All of the incident power is thus transferred to the desired direction of retroreflection under a plane wave illumination. At other folding states, some of the incident power can be reflected to the specular direction due to the slight impedance mismatching of the retroreflector. To clarify this behavior more clearly,

Figure 5(b) shows the reflected power into specular direction versus folding angle. As expected, the incidence power scattered into the specular direction increases when the folding angle deviates more and more from the optimized 45° .

The spin-locked retroreflection has been experimentally verified in an anechoic chamber with a setup of two wideband double-ridged horn antennas connected with a vector network analyzer. The spin-locked retroreflector composing of 12×13 unit cells has been fabricated and put at the center of an arc track with radius of 1.2 m. The two horn antennas have been mounted on the arc track. One of the horn antennas serves as the source to illuminate oblique incidence plane wave to the reconfigurable retroreflector. TE and TM-polarized waves can be generated by rotating the antenna. Another horn antenna works as the receiver moving along the arc track to measure the co and cross-polarized scattered fields at various angles.

Figure 6(a) and 6(b) show the fabricated metagrating based retroreflector and the experimental apparatus. Figure 6(c)~(f) show the experimental results of the cross-polarized reflection intensity for different retroreflection angles (31° , 34° , 38° and 44°). The reflection spectra represent the cross-polarized reflection coefficients in different directions, thus precisely describing the efficiency of the retroreflector. The peak of the cross-polarized reflected field intensity is normalized to the specular co-polarized intensity, which is obtained by measuring the specular reflection intensity from an ordinary metallic plate at the same incidence angle. The black line in each figure shows the retroreflection angle where the incident waves are reflected back exactly to the same directions. In all cases, experimental results are in well agreement with the full-wave

simulations.

Moreover, due to the scaling properties of Maxwell's equations, the proposed strategy for spin-locked retroreflection can be extended to other frequencies, from millimeter-scale architectures in microwave regimes to micro-/nanofabrication in terahertz regimes. The major challenge would be the micro-/nanofabrication techniques for standing resonant structures. Fortunately, persistent efforts are being devoted to address the problem and up to now, some methods have been developed for the fabrication of vertical SRRs in micro- or nanoscale^[45-48]. Additionally, large dissipative loss of metal will be another issue in optical frequency range, but this might be solved by utilizing low loss materials and dielectric meta-atoms. Here, based on the focused ion beam folding technologies^[48], a magnetic metagrating retroreflector operating in terahertz regimes is designed and verified by the full-wave simulations in CST MICROWAVE STUDIO (More details can be found in the Supporting Information). With the ongoing development of micromanufacturing techniques, we expect our work could be realized at higher frequencies in the future.

Conclusion

In conclusion, we have demonstrated theoretically and experimentally a spin-locked retroreflector with subwavelength thickness based on magnetic metagrating working at 9 GHz. By mechanically tuning the folding state of the reconfigurable retroreflector continuously, spin-locked retroreflection for circularly polarized waves at a continuous range of incidence angles can be realized. Compared to conventional retroreflector based on gradient metasurfaces, the proposed reconfigurable retroreflector possesses

low structural complexity, high efficiency and large dynamical range. The design methodology is general and can be flexibly extended to other frequencies, especially in terahertz regime with Micro-Electro-Mechanical Systems (MEMS) techniques. We expect our work can open alternative research avenues in the context of highly efficient spin-polarized wave manipulation.

Supporting Information

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

Acknowledgement

The work at Zhejiang University was sponsored by the National Natural Science Foundation of China under Grants Nos. 61625502, 61574127, 61601408 and 61801426, the Top-Notch Young Talents Program of China, the Fundamental Research Funds for the Central Universities, and the Innovation Joint Research Center for Cyber-Physical-Society System. The work at Shandong University was sponsored by the National Natural Science Foundation of China under Grants No. 61801268, the Natural Science Foundation of Shandong Province under Grant No. ZR2018QF001.

References

- [1] A. M. H. Wong, G. V. Eleftheriades, *Phys. Rev. X* **2018**, 8, 11036.
- [2] R. A. Shelby, D. R. Smith, S. Schultz, *Science* **2001**, 292, 77.
- [3] C. Pfeiffer, A. Grbic, *Phys. Rev. Lett* **2013**, 110, 197401.
- [4] S. Sun, K. Yang, C. Wang, T. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W. Kung, G. Guo, L. Zhou, D. P. Tsai, *Nano Lett* **2012**, 12, 6223.
- [5] A. Arbabi, E. Arbabi, Y. Horie, S. M. Kamali, A. Faraon, *Nat. Photonics* **2017**, 11, 415.
- [6] G. V. Eleftheriades, A. K. Iyer, P. C. Kremer, *IEEE Trans. Microwave Theory Tech.* **2002**, 50, 2702.
- [7] N. Fang, H. Lee, C. Sun, X. Zhang, *Science* **2005**, 308, 534.
- [8] J. B. Pendry, *Phys. Rev. Lett* **2000**, 85, 3966.
- [9] F. Monticone, N. M. Estakhri, A. Al U, *Phys. Rev. Lett* **2013**, 110, 203903.
- [10] L. Zhou, J. M. Kahn, K. S. J. Pister, *J. Microelectromech. Syst.* **2003**, 12, 233.
- [11] S. M. Kamali, A. Arbabi, E. Arbabi, Y. Horie, A. Faraon, *Nat. Commun.* **2016**, 7, 11618.
- [12] F. Ding, A. Pors, Y. Chen, V. A. Zenin, S. I. Bozhevolnyi, *ACS PHOTONICS* **2017**, 4, 943.
- [13] M. Farmahini-Farahani, H. Mosallaei, *Opt. Lett.* **2013**, 38, 462.
- [14] Z. Guo, L. Zhu, F. Shen, H. Zhou, R. Gao, *RSC Adv.* **2017**, 7, 9872.
- [15] Y. Ran, J. Liang, T. Cai, W. Ji, G. Wang, *AIP Adv.* **2018**, 8, 95201.

- [16] G. V. Eleftheriades, A. K. Iyer, P. C. Kremer, *IEEE Trans. Microwave Theory Tech.* **2002**, 50, 2702.
- [17] T. Niemi, A. O. Karilainen, S. A. Tretyakov, *IEEE Trans. Antennas Propag.* **2013**, 61, 3102.
- [18] S. Tripathi, H. Li, T. L. Poulos, *Science* **2013**, 340, 1227.
- [19] L. Jing, Z. Wang, R. Maturi, B. Zheng, H. Wang, Y. Yang, L. Shen, R. Hao, W. Yin, E. Li, H. Chen, *Laser Photonics Rev.* **2017**, 11, 1700115.
- [20] M. Gharghi, C. Gladden, T. Zentgraf, Y. Liu, X. Yin, J. Valentine, X. Zhang, *Nano Lett* **2011**, 11, 2825.
- [21] X. Ni, Z. J. Wong, M. Mrejen, Y. Wang, X. Zhang, *Publ. Am. Assoc. Adv. Sci.* **2015**, 349, 1310.
- [22] B. Zheng, R. Zhu, L. Jing, Y. Yang, L. Shen, H. Wang, Z. Wang, X. Zhang, X. Liu, E. Li, H. Chen, *Adv. Sci.* **2018**, 5, 1800056.
- [23] Y. Yang, L. Jing, B. Zheng, R. Hao, W. Yin, E. Li, C. M. Soukoulis, H. Chen, *Adv. Mater.* **2016**, 28, 6866.
- [24] D. Lin, P. Fan, E. Hasman, M. L. Brongersma, *Science* **2014**, 345, 298.
- [25] A. Diaz-Rubio, V. S. Asadchy, A. Elsakka, S. A. Tretyakov, *Sic. Adv.* **2017**, 3, e1602714.
- [26] S. Sun, Q. He, S. Xiao, Q. Xu, X. Li, L. Zhou, *Nat. Mater.* **2012**, 11, 426.
- [27] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J. Tetienne, F. Capasso, Z. Gaburro, *Science* **2011**, 334, 333.
- [28] N. Mohammadi Estakhri, A. Alù, *Phys. Rev. X* **2016**, 6, 41008.
- [29] S. Nemoto, J. Kida, *Appl. Opt.* **1991**, 30, 815.
- [30] J. J. Snyder, *Appl. Opt.* **1975**, 14, 1825.
- [31] L. Yan, W. Zhu, M. F. Karim, H. Cai, A. Y. Gu, Z. Shen, P. H. J. Chong, D. Kwong, C. Qiu, A. Q. Liu, *Aav. Mater.* **2018**, 1802721.
- [32] V. S. Asadchy, M. Albooyeh, S. N. Tcvetkova, A. D I Az-Rubio, Y. Ra'Di, S. A. Tretyakov, *Phys. Rev. B* **2016**, 94, 75142.
- [33] Y. Ra'Di, D. L. Sounas, A. Alù, *Phys. Rev. Lett* **2017**, 119, 67404.
- [34] Y. Ra Di, A. Alù, *ACS PHOTONICS* **2018**, 5, 1779.
- [35] H. Chalabi, Y. Ra'Di, D. L. Sounas, A. Alù, *Phys. Rev. B* **2017**, 96, 75432.
- [36] N. Shitrit, I. Yulevich, E. Maguid, D. Ozeri, D. Veksler, V. Kleiner, E. Hasman, *Science* **2013**, 340, 724.
- [37] G. Li, M. Kang, S. Chen, S. Zhang, E. Y. Pun, K. W. Cheah, J. Li, *Nano Lett* **2013**, 13, 4148.
- [38] A. Shaltout, J. Liu, A. Kildishev, V. Shalaev, *Optica* **2015**, 2, 860.
- [39] X. Yin, Z. Ye, J. Rho, Y. Wang, X. Zhang, *Science* **2013**, 339, 1405.
- [40] N. M. Litchinitser, *Science* **2012**, 337, 1054.
- [41] A. Niv, V. Kleiner, E. Hasman, Y. Gorodetski, *Phys. Rev. Lett* **2008**, 101, 43903.
- [42] Z. Wang, L. Jing, K. Yao, Y. Yang, B. Zheng, C. M. Soukoulis, H. Chen, Y. Liu, *Aav. Mater.* **2017**, 29, 1700412.
- [43] L. Jing, Z. Wang, B. Zheng, H. Wang, Y. Yang, L. Shen, W. Yin, E. Li, H. Chen, *NPG Asia Mater.* **2018**, 10, 888.
- [44] A. K. Bhattacharyya, *Phased Array Antennas: Floquet Analysis, Synthesis, BFNs*

and Active Array Systems, Wiley, Hoboken, NJ USA 2006.

[45] W. T. Chen, C. J. Chen, P. C. Wu, S. Sun, L. Zhou, G.-Y. Guo, C. T. Hsiao, K.-Y. Yang, N. I. Zheludev, D. P. Tsai, *Opt. Express* **2011**, 19, 12837.

[46] K. Fan, A. C. Strikwerda, H. Tao, X. Zhang, R. D. Averitt, *Opt. Express* **2011**, 19, 12619.

[47] a) X. Xiong, S.-C. Jiang, Y.-H. Hu, R.-W. Peng, M. Wang, *Adv. Mater.* **2013**, 25, 3994; b) X. Xiong, Z.-H. Xue, C. Meng, S.-C. Jiang, Y.-H. Hu, R.-W. Peng, M. Wang, *Phys. Rev. B* **2013**, 88, 115105.

[48] Z. Liu, S. Du, A. Cui, Z. Li, Y. Fan, S. Chen, W. Li, J. Li, C. Gu, *Adv. Mater.* **2017**, 29, 1606298.

(a.u in all figures have been deleted)

(a) Cat's-eye retroreflector

(b) Gradient metasurface based retroreflector

(c) Reconfigurable metagrating based retroreflector

Figure 1. Schematic representation of: a) cat'-eye retroreflector, b) gradient metasurface based retroreflector, c) reconfigurable metagrating and retroreflection can be realized in a continuous range of incidence angles via mechanically tuning the folding state of the metagrating continuously.

Figure 2. a) Schematic representation of the general spin-locked metagrating with four Floquet modes under TM-polarized incidence. b) An array of horizontal magnetically polarizable particles located over a ground plane. c) Schematic of the designed reconfigurable metagrating. Copper C-shaped resonators stand on a long belt of ultrathin dielectric substrate with permittivity $\epsilon = 3$ and thickness $d = 0.1\text{mm}$. Top panel shows overview of practical configuration. Middle panel shows the details of the building block. Parameters m , n , r_1 , r_2 , g , h are fixed as 6.8mm , 21mm , 1.3mm , 2.8mm , 0.44mm and 3mm . The bottom is the top view of the unit cell. The period along the y axis has been set to 10mm while the period along the x axis is determined by the folding angle α and can be altered mechanically.

Figure 3. Reflected power into different Floquet modes versus frequency under a) TE and b) TM-polarized incidence. c) The phase of $TM_{(-1)0}$ and $TE_{(-1)0}$ under TE and TM-polarized incidence respectively. d) Schematic of spin-locked retroreflection. Spin-polarized EM wave can be decomposed into TE and TM-polarized wave. Corresponding scattered electric field distribution across zx plane under illumination angle $\theta_{in} = 34^\circ$ for e) TE and f) TM-polarized incidence when the folding angle α of the retroreflector is tuned to be 45° .

Figure 4. Spin-locked retroreflection under a continuous range of incidence angles. a) Simulated results of cross-polarized retroreflection amplitude and phase shift as a function of the folding angle under TE and TM-polarized incidence wave. b) Reflection angle versus folding angle under TE and TM-polarized incidence. Simulated electric field distribution of spin-locked retroreflection at 31° for : c) TE and f) TM-polarized modes with the folding angle tuned to 40° . Simulated electric field distributions of spin-locked retroreflection at 38° for : d) TE and g) TM-polarized modes with the folding angle tuned to 50° . Simulated electric field distributions of spin-locked retroreflection at 44° for : e) TE and h) TM-polarized modes with the folding angle tuned to 55° .

Figure 5. a) The scattered intensity versus the reflection angle under TE and TM-polarized incidence with various incidence angles at 27° , 29° , 31° , 34° , 38° , 44° and 53° . b) The reflected power into the specular direction as a function of folding angle α for TE and TM-polarized incidence. The specular reflection has been totally suppressed with folding angle at 45° .

Figure 6. Experimental demonstration. a) A photo of the experimental apparatus, showing the transmit and receive antennas and the test surface platform. b) A close-up of the fabricated retroreflector. Experimental results of the cross-polarized scattered intensity distribution for retroreflection at various incidence angles of: c) 31° , d) 34° , e) 38° and f) 44° under TE and TM-polarized incidence.

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Supporting Information

Title: Angular-adaptive Spin-locked Retroreflector Based on Reconfigurable Magnetic Metagrating

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1. Necessary requirements for induced surface electric and magnetic current to realize spin-locked retroreflection

We assume that the structure is illuminated with the TM plane wave $\mathbf{E}_{\text{in}} = E_0(\mathbf{x}\cos\theta_{\text{in}} + \mathbf{z}\sin\theta_{\text{in}})\exp(ik_0\sin\theta_{\text{in}}x - ik_0\cos\theta_{\text{in}}z)$ where E_0 is its amplitude, k_0 is the wave number in free space and θ_{in} is the incidence angle defined in the counterclockwise direction with respect to the z axis. The magnetic field can be solved by applying Maxwell equation. Due to this excitation, surface currents will be induced on the array located above the ground plane.

Figure S1. Array of horizontal electrically or magnetically polarizable particles located over the ground plane. Red arrow represents induced surface current oriented along: a) x and b) y axis.

As illuminated in **Figure S1(a)**, the induced electric surface current is oriented along the x axis, which can be express as

$$\mathbf{I} = \mathbf{x} I_e^x \sum_m \sum_n \delta(x - mb) \delta(y - na) \exp(ik_{x0}mb) \quad S(1)$$

where $k_{x0} = k_0 \sin \theta_{in}$, $\delta(x)$ is the Dirac's delta function, I_e^x is the electric current on each dipole, and a, b are the periodicities in the y and x directions, respectively.

Depending on the period of the structure, the array can possibly re-radiate the received power through different Floquet modes. For the sake of simplicity, here we limit the problem to the case where no higher order modes can propagate due to the periodicity in y direction. The periodicity of x direction ensures only $(-1)^0$ and 0^0 are the propagating Floquet modes. Using Floquet modal analysis^[1], the radiated fields for n^0 Floquet mode can then be written as

$$\mathbf{E}_{n^0} = \left(-\mathbf{x} \frac{k_{zn^0}}{k_0} + \mathbf{z} \frac{k_{xn^0}}{k_0} \right) \Phi_{n^0} \exp(ik_{xn^0}x + ik_{zn^0}z) \quad S(2)$$

Where $\Phi_{n0} = \frac{\eta}{ab} \cdot \frac{I_e^x}{1 + i \cot(k_{zn0}h)}$. Here, $k_{xn0} = k_{x0} + \frac{2n\pi}{a} = k_0 \sin \theta_{n0}$ is the wave number in x direction, $k_{zn0} = \sqrt{k_0^2 - k_{xn0}^2} = k_0 \cos \theta_{n0}$ is the wave number in z direction, η is the impedance in free space, h is the distance between the dipole and ground plane. Like wisely, if the induced electric surface current is oriented along the y axis, the radiated fields for n0 Floquet mode can be written as

$$\mathbf{E}_{n0} = \mathbf{y} \Phi_{n0} \exp(ik_{xn0}x + ik_{zn0}z) \quad S(3)$$

Where $\Phi_{n0} = \frac{\omega\mu}{k_{zn0}} \cdot \frac{1}{ab} \cdot \frac{I_e^y}{1 + i \cot(k_{zn0}h)}$, ω is the working angular frequency, all the other parameters are the same as mentioned above. From equation S(2) and (3), it is obvious that the radiated fields for electric surface current along x and y-direction is TM and TE mode respectively.

In order to fully transfer the TM incidence wave towards the desired Floquet mode $TE_{(-1)0}$, the specular reflection of the TM incidence wave could be canceled by the radiated TM_{00} mode, and the radiated $TM_{(-1)0}$ and TE_{00} mode may be canceled through near field interaction between the induced electric surface current. However, from the expression of the radiated electric fields for x and y-oriented surface electric current, such two surface currents fail to cancel the radiated $TM_{(-1)0}$ and TE_{00} mode. Therefore, we introduce another pairs of surface current which have a carefully tailored distance between the former.

Figure S2. Practical realization of surface electric current for spin-locked retroreflection. a) Schematics of the designed electric spin-locked metagrating. The building block consists of two crossing-located identical metallic strips and a metal plate separated by a dielectric spacer ($\epsilon = 3$). Parameters L_x , L_y , w , d , L , h are fixed as 30 mm, 10 mm, 1.55 mm, 7.61 mm, 8 mm, and 1.91379 mm, respectively. Reflected power into different Floquet modes versus frequency under b) TE and c) TM-polarized incidence. d) Phase modulation versus frequency under TE and TM-polarized incidence. Scattered electric field distribution across z - x plane under illumination angle $\theta_{in} = 30^\circ$ for e) TE and f) TM-polarized incidence.

As illuminated in **Figure 2(b)** in the main text, two pairs of surface current per unit cell with suitably tailored distance d were induced by the incoming incidence wave.

Following the same procedure, the radiated electric field can be obtained. The radiated

TM₀₀ mode can be canceled by the specular reflection of the incidence TM wave, this can be achieved if

$$\frac{\eta}{ab} \cdot \frac{I_{e1}^x + I_{e3}^x \exp(-ik_{x00}d)}{1 + i \cot(k_{z00}h)} - E_0 = 0 \quad S(4)$$

Here, I_{e1}^x and I_{e3}^x are the x-components of the induced electric currents on the first and second dipole respectively as illustrated in Figure 2(b).

The radiated TM₍₋₁₎₀ mode can be canceled through near-field interaction between I_{e1}^x and I_{e3}^x , which has to meet the requirement

$$I_{e1}^x + I_{e3}^x \exp(-ik_{x(-1)0}d) = 0 \quad S(5)$$

A similar near-field interaction between I_{e2}^y and I_{e4}^y cancel the radiated TE₀₀ mode, which satisfies

$$I_{e2}^y + I_{e4}^y \exp(-ik_{x00}d) = 0 \quad S(6)$$

I_{e2}^y and I_{e4}^y are the y-components of the induced electric currents on the first and second dipole respectively.

Therefore, the requirements expressed in equation S(4)-(6) is the necessary conditions for the incoming TM plane wave been totally transferred towards the desired TE₍₋₁₎₀ Floquet mode.

In order to realize spin-locked retroreflection based on induced surface electric current, a practical structure was proposed as shown in **Figure S2(a)**. To clarify its optical property for spin-locked retroreflection, numerical simulations have been performed using the the microwave studio module of Computer Simulation Technology (CST) software and the design frequency for the sample presented here is 9.954 GHz.

Figure S2(b) and (c) shows the simulated reflected power towards the four Floquet

modes as a function of frequency under TE and TM-polarized incidence wave, showing a moderately broad response in terms of frequency. At the design frequency, the oblique incident power has been redirected into the desired Floquet mode as expected, namely $TM_{(-1)0}$ for TE-polarized incidence and $TE_{(-1)0}$ for TM-polarized incidence, with an identical efficiency reaching almost 98.3%. The total power into all the other undesired Floquet modes is largely suppressed to near zero. The phase modulation for both TE and TM modes is shown in Figure S2(d). At the design frequency, the cross-polarized amplitude and phase modulation are identical for both TE and TM modes which guarantee the realization of spin-locked retroreflection. Figure S3(e) and (f) plot the E-field of spin-locked retroreflection cross the z-x plane for TE and TM-polarized incidence with incidence angle at 30 °, respectively.

Following the similar procedure, if the incoming TM-polarized incidence excites two pairs of surface magnetic current, to transfer the incoming TM plane wave towards the desired $TE_{(-1)0}$ Floquet mode, the necessary requirements can be expressed as

$$\begin{aligned}
I_{m2}^y + I_{m4}^y \exp(-ik_{x(-1)0}d) &= 0 \\
I_{m1}^x + I_{m3}^x \exp(-ik_{x00}d) &= 0 \\
\frac{1}{ab} \cdot \frac{I_{m2}^y + I_{m4}^y \exp(-ik_{x00}d)}{1 - i \tan(k_{z00}h)} \cdot \frac{k_0}{k_{z00}} - E_0 &= 0
\end{aligned} \tag{S(7)}$$

2. Spin-locked retroreflector with nanosized dimensions

To demonstrate the potential of our proposed metagrating based retroreflector into micro or nano scales for high frequencies, motivated by the micro-/nanofabrication techniques presented in ^[2], we investigate a magnetic metagrating based retroreflector operating in terahertz regimes. **Figure S3(a)** shows the fabrication process of the

proposed retroreflector. Periodical arrays of Au SRRs are patterned on the dielectric film after electron beam lithography and metal deposition (left panel in Figure S3(a)). Focused ion beam can be used to cut the dielectric film into rectangular flakes and fold the flakes into designated orientations (right panel in Figure S3(a)). The permittivity of gold in the simulation is described by Drude model and the permittivity of the dielectric film is 4. The structure is illuminated by plane waves propagating in zx plane at an oblique incident angle of 38.5° . To ensure sure $(-1)0$ and 00 modes are reflected, the periodicities along x and y direction are $12\ \mu\text{m}$ and $3\ \mu\text{m}$ respectively. Figure S3(b)-(c) shows the simulated reflected power towards different propagating Floquet modes as a function of frequency under TE and TM-polarized incidence waves. At the design frequency of 20.1 THz, the oblique incident power has been redirected into the desired Floquet mode as expected, namely $\text{TM}_{(-1)0}$ for TE-polarized incidence and $\text{TE}_{(-1)0}$ for TM-polarized incidence, with an identical efficiency reaching 81.4%. All the other undesired Floquet modes is largely suppressed. The reflected power towards the desired mode is lower than the efficiency in microwave region, which can be attributed to the larger dissipative losses at high frequencies. The phase modulation for both TE and TM modes is shown in Figure S3(d). At the operating frequency, the cross-polarized amplitude and phase modulation are identical for both TE and TM modes, guaranteeing the spin-locked retroreflection at 38.5° . These results show that our approach is still applicable in the nanometer scale.

Figure S3. (a) Schematics of the fabrication process of the nanoscale retroreflector. Au SRRs are patterned on a dielectric film, and with the focused ion beam, rectangular flakes can be folded into designed orientations. The parameters of the copper SRR are the same notations introduced in main text, but the values are set to be: $r_2 = 1.2 \mu\text{m}$, $r_1 = 650 \text{ nm}$, $g = 550 \text{ nm}$ and the thickness is 80 nm . The transverse and vertical side length of the dielectric flakes is $2.88 \mu\text{m}$ and $3.3 \mu\text{m}$, and the thickness is 100 nm . Reflected power into different propagating Floquet modes under 38.5° oblique incidence for (b) TE incidence and (c) TM incidence. (d) Phase modulation versus frequency under TE and TM incidence. Spin-locked retroreflection is realized with incident angle at 38.5° .

References:

- [1] A. K. Bhattacharyya, *Phased Array Antennas: Floquet Analysis, Synthesis, BFNs and Active Array Systems*, Wiley, Hoboken, NJ, USA **2006**.
- [2] Z. Liu, S. Du, A. Cui, Z. Li, Y. Fan, S. Chen, W. Li, J. Li, C. Gu, *Adv. Mater.* **2017**, 29, 1606298.