Research article

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All-dielectric chiral coding metasurface based on spin-decoupling in terahertz band

<https://doi.org/10.1515/nanoph-2020-0622>

Received November 23, 2020; accepted December 28, 2020;
published online January 18, 2021

Abstract: Metamaterials can achieve superior electromagnetic properties over natural materials by adjusting the structure of the meta-atoms. Chiral metamaterials have been widely used in circular dichroism (CD) spectra, polarization imaging, and optical sensing. Here we propose a kind of all-silicon coding metasurfaces to achieve the function similar to chirality by spin decoupling. One of the two circularly polarized (CP) channels is scattered randomly, and the desired function is only designed in the other opposite CP channel. Three kinds of coding metasurfaces are designed to verify the reliability of such approach: one simultaneously possessing dual function of transmitting directly and scattering randomly, one capable of generating the superposition state of vortex beam, and

the other generating the Bessel vortex beam, respectively. And some experimental verifications are carried out. This scheme is simpler and more versatile than previous schemes which require elaborate designed structure of the meta-atoms. Our novel approach provides a new option for implementing tunable chirality.

Keywords: all-dielectric metasurface; circular dichroism; decoupling; terahertz.

1 Introduction

Photons carry spin angular momentum (SAM) [1], which represents the polarization state of light [2]. Chirality is a property of structure that an object cannot coincide with its mirror image by rotation or translation [3]. Chiral materials widely exist in nature, such as amino acids, sugar molecule, and DNA [4]. The two types of CP light have different interactions with chiral materials, showing as chiral optical effects. Optical effects of chirality generally have two characteristics: (1) CD, different transmittances which are caused by the difference of absorption or reflection of left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) light. (2) Optical activity, characterizing the ability of chiral materials to rotate linearly polarized (LP) light, which is caused by the difference in refractive index of chiral materials to LCP and RCP light [5, 6]. Arago discovered that the plane of polarization is rotated when plane polarized light travels through crystals of quartz [7]. Pasteur pointed out that the atomic distribution of optically active materials was asymmetrical, and introduced the concept of chirality [8]. The chirality found in natural materials is weak. Therefore, a large thickness is required to show sufficient chiral strength. This seriously hinders the miniaturization and integration of optical devices.

Due to their potential breakthroughs in optical manipulation, metamaterials have been widely used in many fields, such as lenses [9, 10], holograms [11–14], vortex generators [15–17] and Airy beams generators [18].

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Compared with natural materials with weak chirality, the response strength of chiral metamaterials is improved by orders of magnitude [19]. Pendry introduced chiral structures into metamaterials, which proved theoretically that they could also achieve negative refractive index [20]. Then researchers use the unique electromagnetic properties of chiral metamaterials to study many functional materials, such as gyromagnetic materials, optically active materials and so on. Gansel realized the selective transmission of LCP and RCP light by controlling the rotation direction of the gold helices [21]. Dietrich designed and manufactured three-dimensional (3D) starfish metamaterial with CD in Terahertz (THz) band [22]. In addition, researchers have made many applications using the properties of chiral structures. Yang proposed a method to detect CP light using the sub-wavelength Archimedes spiral structure [23]. Li designed a CP light detector by combining the chiral metal structure with the detector [24]. In fact, CD elements are also widely used in polarization imaging [25], optical sensing [26], CD spectra [27] and other fields. Traditional metamaterials require carefully designed meta-atoms or obliquely incident illumination in order to achieve chirality, which increase the processing difficulty or application limitations.

Recently, the independent controlling of LCP and RCP light has been realized by combining Pancharatnam-Berry (PB) phase and dynamic phase. With the help of such spin-decoupling design, a variety of multifunctional devices have been developed, such as multifunctional vortex generators [28], holograms [29], vector vortex beams generators [30] and so on. In this paper, we use all-silicon coding metasurfaces to achieve the function similar to chirality by spin decoupling. One polarization channel is scattered randomly, and the desired function is only designed in the other channel. We can also exchange polarization channels flexibly to realize the conversion of chiral enantiomers. As a proof of concept, we design three coding metasurfaces: one simultaneously possessing dual function of transmitting directly and scattering randomly, one capable of generating the superposition state of vortex beam, and the other generating the Bessel vortex beam, respectively. And some experimental verifications are carried out. This scheme is simpler and more versatile than previous schemes which require chiral meta-atoms to complete. Our novel approach provides a new option for implementing tunable chirality.

Figure 1a shows the schematic of the proposed coding metasurface for realizing spin-decoupling by combining PB phase and propagation phase, which can modulate the functions of the exit LCP and RCP components, respectively. In other words, with the help of this design,

asymmetric transmission can be realized under the LCP/RCP illumination. For example, under the RCP illumination, the LCP component of the exit wave transmits directly; For the LCP illumination, the RCP component randomly scatters to various directions. With the aid of this design, we can arrange various functions for one of the channels, such as focus, superposition states of vortex, and Bessel beam generator, and the other channel scatters randomly, realizing the function similar to chirality.

2 General scheme for spin decoupling

For realizing the independently controlling dual-helicity channels, arbitrary spin-to-OAM conversion was first proposed in the study by Devlin [25]. Here, we describe the physical mechanism of spin-decoupling starting from CP bases, where the exit fields are related to the input ones through Jones matrix:

$$\mathbf{E}_{\text{circular}} = \mathbf{T} \cdot \begin{pmatrix} E_L^i \\ E_R^i \end{pmatrix} = \begin{pmatrix} T_{LL} & T_{LR} \\ T_{RL} & T_{RR} \end{pmatrix} \cdot \begin{pmatrix} E_L^i \\ E_R^i \end{pmatrix} \quad (1)$$

where $\mathbf{E}_{\text{circular}}$ represents the exit field, $\begin{pmatrix} E_L^i \\ E_R^i \end{pmatrix}$ indicates the incident field. The matrix $\mathbf{T}$ is the Jones matrix. T_{ji} represents the transmission coefficients, where the first subscript 'j' indicates the polarization state of the exit wave and the second 'i' indicates the incident polarization.

Here, we assume the transmission amplitudes of the anisotropic meta-atoms are kept as unity ($T_x = T_y = 1$) for a linearly x- and y-polarized incidences but with a π phase difference ($\varphi_x = \varphi_y + \pi$). On the other hand, based on linear polarization (LP) bases, the Jones matrix of the anisotropic meta-atoms can be described as:

$$\mathbf{J}(\alpha) = \mathbf{M}(\alpha)^T \times \begin{bmatrix} t_x & 0 \\ 0 & t_y \end{bmatrix} \times \mathbf{M}(\alpha) \quad (2)$$

where $\mathbf{M}(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$ is the rotation matrix, α is the rotation angle of the meta-atom, $t_x = T_x e^{i\varphi_x}$, and $t_y = T_y e^{i\varphi_y}$. By combining the Jones matrices in two polarization bases, we can conclude that:

$$\begin{aligned} \mathbf{E}_{\text{circular}} &= \begin{pmatrix} 0 & e^{i(\varphi_x+2\alpha)} \\ e^{i(\varphi_x-2\alpha)} & 0 \end{pmatrix} \cdot \begin{pmatrix} E_L^i \\ E_R^i \end{pmatrix} \\ &= \begin{pmatrix} e^{i(\varphi_x+2\alpha)} \cdot E_R^i \\ e^{i(\varphi_x-2\alpha)} \cdot E_L^i \end{pmatrix} = \begin{pmatrix} e^{i\varphi_R} \cdot E_R^i \\ e^{i\varphi_L} \cdot E_L^i \end{pmatrix} \end{aligned} \quad (3)$$

Figure 1: Characterization of the designed meta-atoms for spin-decoupling.

(a) Schematic of the concept of the function similar to chirality. (b) Schematic of the orthogonal silicon pillars. (c) and (d) Simulated transmission amplitudes and phase shifts along x -axis as a function of the lengths of two pillars L_1 and L_2 under x -polarized illumination at 1.3 THz.

where φ_L and φ_R indicate the additional phase of the exit field. From the Equation (3), the phase shifts and rotation angles that anisotropic meta-atoms need to satisfy in order to achieve spin decoupling can be obtained.

$$\begin{aligned} \alpha &= (\varphi_R - \varphi_L)/4 \\ \varphi_x &= (\varphi_L + \varphi_R)/2 \\ \varphi_y &= (\varphi_L + \varphi_R)/2 - \pi \end{aligned} \quad (4)$$

Equations (3) and (4) establish the relations between the spin decoupling and the structural parameters of anisotropic meta-atoms. For arbitrary phase combinations of φ_L and φ_R , these can be achieved by designing the structure and rotation angle. In other words, arbitrary phase profiles under the LCP and RCP illuminations can come true by combining PB phase and propagation phase.

3 Results and discussion

Figure 1b shows the unit cell for realizing spin-decoupling, which consists of two orthogonal silicon pillars ($\epsilon = 11.9$ and the height of the pillar $h = 150 \mu\text{m}$). The lattice constant is set to $P = 100 \mu\text{m}$. The weights of these two pillars are $w = 30 \mu\text{m}$. Their lengths are L_1 and L_2 , respectively. By gradually varying the lengths of two pillars, the corresponding transmission amplitudes and phase shifts are simulated using CST Microwave Studio. Under the x -polarized illumination, the transmission amplitudes and phase shifts along x -axis of the unit cells are shown in Figure 1c and d. The corresponding transmission amplitudes and phase shifts along y -axis can be trivially derived by transposing Figure 1c and d, respectively. The markers in Figure 1c and d represent the locations of the 15 meta-

atoms we select for achieving the function of spin decoupling. By properly arranging these meta-atoms, we can design two functions under the LCP and RCP incidence, respectively. Based on this, several interesting coding metasurface applications are shown below.

To verify the reliability of this kind of chiral design, the first metasurface is designed and labelled as metasurface-1. In order to achieve the function of direct transmission in the case of RCP incidence, the phase values are all set to zeros. As for LCP incidence, to realize the function of random scattering, its phase is set to random scattering phase between 0 and $-\pi$ (see Figure S1(a)). Figure 2a–d shows the exit amplitudes and phase profiles of the metasurface-1 under the RCP/LCP incidence. From the Figure 2a and b, we can clearly see that the exit LCP E-field transmits directly under the RCP illumination. For the LCP incidence, after the incident field is modulated by the metasurface with a random phase, the phase of the incident field changes randomly and irregularly scatters to different directions. Figure 2e and f shows the simulated three dimensions (3D) far-field scattering patterns under the RCP/LCP incidence, respectively. It is obviously that the scattering power of the scattered beam is 14.5 dB lower

than that of the directly transmitted beam. The intensity of scattering field can be ignored compared with that left of transmission field, which realizes the function similar to chirality.

In order to explain this chiral function more clearly, we fabricate a sample (see Figure 3a) and test its transmission coefficients with terahertz time-domain spectroscopy system (THz TDS). This sample consists of 160×160 meta-atoms, occupying a total size of $16 \times 16 \text{ mm}^2$. The transmitted CD is defined as $\Delta T = T_R - T_L$, where $T_R = T_{RR} + T_{LR}$, $T_L = T_{LL} + T_{RL}$, $T_{RR} = |t_{rr}|^2$, $T_{RL} = |t_{rl}|^2$, $T_{LR} = |t_{lr}|^2$, and $T_{LL} = |t_{ll}|^2$. Here, t_{rr} , t_{rl} , t_{lr} , and t_{ll} represent the transmission coefficients in the CP bases. Figure 3b shows the measured transmission coefficients of the Jones matrix in the LP bases. When converted into the CP bases, the transmission coefficients for CP are related to the LP through:

$$\begin{pmatrix} t_{rr} & t_{rl} \\ t_{lr} & t_{ll} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} t_{xx} + t_{yy} + i(t_{xy} - t_{yx}) & t_{xx} - t_{yy} - i(t_{xy} + t_{yx}) \\ t_{xx} - t_{yy} + i(t_{xy} + t_{yx}) & t_{xx} + t_{yy} - i(t_{xy} - t_{yx}) \end{pmatrix} \quad (5)$$

From the measured transmission coefficients of the LP bases to the CP bases, the transmission coefficients in the CP bases are shown in Figure 3c. Figure 3d shows the

Figure 2: Simulated results of the metasurface-1.

(a) and (b) The exit amplitudes and phase profiles of the metasurface-1 under the RCP incidence. (c) and (d) The corresponding amplitudes and phase profiles under the LCP incidence. (e) and (f) Simulated 3D far-field scattering patterns for the RCP and LCP incidences.

Figure 3: SEM images and experimental results of metasurface-1.

(a) SEM images of part of the fabricated metasurface-1. (b) The measured transmission coefficients of the Jones matrix in the LP bases. (c) The measured transmission coefficients in the CP bases. (d) Transmission circular dichroism of the metasurface-1.

Figure 4: Simulated 3D scattering patterns for the 1-bit coding metasurfaces contain different super unit cells.

(a–c) The scattering phase profiles for the coding metasurfaces contain super unit cells of 1×1 , 2×2 and 4×4 , respectively. (d–f) Simulated 3D far-field scattering patterns for the coding metasurfaces contain super unit cells of 1×1 , 2×2 and 4×4 , respectively.

Figure 5: (a) Schematics of the THz digital holographic imaging system. (Half-wave plate [HWP]; polarizer [P]; quarter-wave plate [QWP], beam splitter [BS]; polarization beam splitter [PBS]; charge coupled device [CCD]). Inset shows the SEM images of the metasurface-5. (b) and (c) The simulated and experimental results of the metasurface-5 under the LCP/RCP illumination, respectively. The red scale bar is 2 mm and the white one is 300 μm.

transmitted CD spectra and the maximum value of CD is equal to 0.35 at 1.4 THz. It can be confirmed that such a design does produce asymmetric transmission under the RCP/LCP incidence, which is realized by randomly scattering one of the two CP channels.

This part the scattering patterns for the 1-bit coding metasurfaces contain super unit cells of different sizes are compared in Figure 4. The total numbers of unit cells for these three metasurfaces are 64×64 . For such 1-bit coding metasurfaces, only two phase values of 0 and $-\pi$ can be taken. Figure 4a–c are scattering phase profiles for the coding metasurfaces contain super unit cells of 1×1 , 2×2 and 4×4 , respectively. The corresponding simulated 3D far-field scattering patterns are shown in Figure 4d–f. It can be seen that the scattering powers of the transmitted fields are almost the same for the coding metasurfaces contain super unit cells of different sizes. The far-field patterns are also calculated and shown in Figure S2. With the increase

of the size of super unit cells, the scattering range and efficiency decrease a little. In other words, the coding metasurface contain super unit cells of 1×1 can get better scattering effect. This also provides a theoretical support for us to design metasurfaces with better scattering effects.

The superposition states of orbital angular momentum (OAM) patterns are important in quantum science [31, 32], metrology [33, 34] and other fields, owing to their OAM characteristics. To generate a superposition state of vortex beam in the transmitted channel, the abrupt phase profile needs to meet:

$$\varphi_{RCP} = \arg \left(\exp \left(i \left(\frac{2\pi}{\lambda} (\sqrt{f^2 + r^2} - f) + \theta \right) \right) + \exp \left(i \left(\frac{2\pi}{\lambda} (\sqrt{f^2 + r^2} - f) - \theta \right) \right) \right) \quad (6)$$

where the focal length is set to $f = 5.8$ mm, (r, θ) is the polar coordinate, λ is the designed wavelength corresponding to

Figure 6: (a) The designed phase profile for generating Bessel vortex beam. (b) The axial intensity profile of the transmitted E-field under the RCP incidence. (c) The simulated intensity profile at $z = 6$ mm. (d) The designed random scattering phase profile for generating scattering beam. (e) The axial intensity profile of the transmitted E-field under the LCP incidence. (f) The simulated intensity profile at $z = 6$ mm.

1.3 THz. For the other scattering channel, its phase is still set to random scattering phase between 0 and $-\pi$ (see Figure S1(c)). Figure 5a shows the THz digital holographic imaging system for characterizing this sample. In the experimental operation, the fabricated sample was placed at a distance of 5.8 mm from the ZnTe crystal. The incident THz wave is y-polarized, and the intensity and phase profiles of the x- and y-polarized transmission fields were measured, marked as xy and yy, respectively. Then the sample was rotated to 90° and repeat the above measurement, marked as xx and yx. After measuring the above four groups of data, convert them into CP bases using Equation (5). The inset in Figure 5a shows the SEM images of the fabricated sample. The specific fabrication process is detailed in the “Sample fabrication” section. Figure 5b₁ shows the axial intensity profile of the transmitted E-field under the LCP incidence. It can be seen that the incident field is randomly scattered in various directions. The simulated intensity and phase profiles at $z = 5.8$ mm are shown in Figure 5b₂ and b₃. The bright spots and messy phases also verify the random scattering of the light field. Figure 5b₄ and b₅ are the corresponding experimental profiles at 1.29 THz. For the RCP illumination, the corresponding axial intensity profile of the transmitted LCP component are shown in Figure 5c₁. Figure 5c₂ and c₃ are

the simulated intensity and phase profiles at the focal plane and they are the superposition state of two vortices with opposite topological charge $((|+1\rangle + |-1\rangle)/\sqrt{2})$. Figure 5c₄ and c₅ show the corresponding experimental profiles at 1.29 THz. It can be seen that the experimental results agree well with the simulation results, except the slight deviation in the measured frequency due to fabricating error.

This part Bessel vortex beam is generated in the transmitted channel, and the other is designed as a scattering channel. To generate m th-order Bessel vortex beam using metasurface, the abrupt phase profile can be described as $m\theta + k_r r$, where θ and r represent the azimuthal angle and the radius in the polar coordinate, and $k_r = 2\pi/(8P)$ is the lattice vector, which is related to the radial phase gradient. Figure 6a shows the designed phase profile for generating first-order Bessel vortex beam with $m = 1$. The proposed metasurface consists of 60×60 unit cells. Under the RCP illumination, the axial intensity profile of the transmitted E-field is shown in Figure 6b, where non-diffracting propagation behaviour is clearly observed. Figure 6c shows the simulated intensity profile at $z = 6$ mm. The intensity distribution of doughnut type is clearly visible, which is the intensity characteristic of typical vortex beam. For the LCP illumination, the incident field is

randomly scattered in various directions in Figure 6e and the designed scattering phase profile is shown in Figure 6d. In the same colour bar as Figure 6b, there are few bright spots to be seen in Figure 6e. This is also reflected in the cross section of Figure 6f.

4 Conclusion

In summary, we propose a novel kind of all-silicon coding metasurfaces to achieve the function similar to chirality by spin decoupling. We can freely design the function of two orthogonal CP light. Here we only arrange some interesting functions in one polarization channel, such as direct transmission, superposition state of vortex beam and Bessel vortex beam, and the light from the other orthogonal channel is scattered randomly. And some experimental verifications are carried out. These two polarization channels can also be exchanged flexibly by swapping the phase distribution of the two CP states, just like the conversion of chiral enantiomers. Such simpler and versatile approach provides a new option for implementing tunable chirality. These planar coding metasurfaces pave the way for the miniaturization and integration of optical devices, which may find applications in pragmatic photonic device applications such as cryptographic nanoprints and anti-counterfeiting holograms.

5 Experimental section

5.1 Numerical characterizations

All numerical simulations are performed using CST Microwave Studio. Specifically, the time domain solver is used in the simulations. The transmission amplitudes and phase shifts are obtained by studying a single meta-atom with periodic conditions in x - and y -directions and open condition along the z -direction. In order to monitor the E-field and far-field distributions, the boundary conditions are set to open conditions along the x -, y - and z -directions, and the E-field and far-field monitors are set in 1.3 THz.

5.2 Sample fabrication

Standard ultraviolet lithography and inductively coupled plasma (ICP) etching were used to fabricate these all-silicon metasurfaces. First, the silicon wafer (4 inches in

diameter, 500 μm thick) was cleaned, the positive photoresist (AZ4620) was spin-coated, and the photoresist film was prepared by prebaking. Then, the mask was aligned and exposed to the silicon wafer, and then developed. The image on the mask was transferred to the photoresist after these operations. This was followed by post-baking and removal of photoresist. After that, the silicon exposed after development was etched with an ICP ion etching machine (ASE-HRM, STS). Finally, the photoresist was removed with acetone, cleaned and dried.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was supported by the National Natural Science Foundation of China (Nos. 61675147, 61735010 and 91838301), National Key Research and Development Program of China (No. 2017YFA0700202), Basic Research Program of Shenzhen (JCYJ20170412154 447469).

Conflict of interest statement: The authors declare no conflict of interest.

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Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2020-0622>).