Bianisotropic origami metasurfaces for mechanically controlled asymmetric radiation

Min Li¹,², Yan Hu¹, Qiaolu Chen¹,², Hongsheng Chen¹,²,³,∗ and Zuojia Wang¹,²,∗

¹ Interdisciplinary Center for Quantum Information, State Key Laboratory of Modern Optical Instrumentation, ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University, Hangzhou 310027, People’s Republic of China
² International Joint Innovation Center, Key Lab. of Advanced Micro/Nano Electronic Devices and Smart Systems of Zhejiang, The Electromagnetics Academy at Zhejiang University, Zhejiang University, Haining 314400, People’s Republic of China
³ Authors to whom any correspondence should be addressed.

E-mail: zuojiawang@zju.edu.cn and hansomchen@zju.edu.cn

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Abstract
Bianisotropic metasurfaces have been attracting increasing attention due to their strong capability for magneto–electric coupling manipulation on electromagnetic fields. Bianisotropic effect is physically determined by the symmetries of structure and switching among various bianisotropic states is thus difficult by varying material properties. Here, we propose a reconfigurable bianisotropic metasurface by arranging meta-atoms in a Miura-ori lattice. The bianisotropic properties are dynamically controlled via the deformation of the Miura-ori pattern, i.e., zero bianisotropy at the unfolded state and enhanced bianisotropy in folded geometries. It is also demonstrated that asymmetric radiation performance can be flexibly controlled by changing only the folded angle of deformation. Our work provides an alternative pathway toward dynamically control over the bianisotropy of metasurfaces, which may provide potential applications for smart directional radiation and scattering.

1. Introduction
During the past decade, metamaterials [1–3] with artificially engineered atoms (meta-atoms) have been largely studied to explore novel electromagnetic (EM) properties beyond natural materials. As the two-dimensional (2D) counterparts, metasurfaces [4–7] with optically thin composite layers have shown unprecedented abilities to control and transform EM waves at the interfaces. Metasurfaces can be modeled as an infinitesimally thin sheet of electric and/or magnetic surface currents, causing both amplitude and phase jumps of the macroscopic electric and magnetic fields across the metasurface plane. Specifically, metasurfaces with magneto–electric coupling, namely magnetic (electric) polarization excited by electric (magnetic) external field, are called bianisotropic metasurfaces [8]. The bianisotropy of metasurfaces can be characterized quantitatively by the effective magneto–electric and/or electro–magnetic polarizabilities or susceptibilities [9], depending on the definition of the fields associated to the relations between the fields and the surface polarizations. Attributing to diverse magneto–electric couplings, bianisotropic metasurfaces have shown unprecedented abilities for advanced wave transformations [10–16]. Theoretical calculation infers that bianisotropy is a fundamental requirement for the design of 100% efficient anomalous refractive and reflective metasurfaces. The control over transmission and reflection amplitudes and phases offered by bianisotropic meta-atoms opens new possibilities for the design of advanced optical devices such as high-efficient lenses [17–19], low-profile antennas [20], spin-based metamirrors [21, 22] and radiation polarizer [23]. Besides, bianisotropic meta-atoms largely extend available EM properties, which are hard to be accessed by conventional artificially engineered atoms, thus enabling many novel optical phenomena, for instance, strong magnetic polarization compared to artificial magnetism and extremely asymmetric radiation [24]. Despite so many advances in this field, achieving dynamically control over the bianisotropy of metasurfaces remains a challenge.
Figure 1. Schematic of the origami-based tunable bianisotropic metasurface. Arrays of SRRs are periodically printed on a flat sheet, and a Miura-ori unit cell consists of four SRRs located at the centers of four identical parallelograms. (a) Origami metasurface at a flat state. Due to the vanished bianisotropic susceptibilities, the radiation of an emitter inside the metasurface is symmetric for forward and backward directions. The inset shows the dimensions of the unit cell of Miura-ori metasurface. (b) Origami metasurface at a folded state. The folded origami metastructure exhibits enhanced bianisotropy and the radiation of the emitter is highly asymmetric, i.e., enhanced radiation toward up while suppressed radiation toward down.

Origami and kirigami [25–27] provide a powerful platform to generate complex and elaborate three-dimensional (3D) structures from two-dimensional (2D) flat materials via engineering folding and/or cutting pattern. This design principle has stimulated a wide range of applications in the fields of optics, physics, biology, chemistry and engineering, from micro biological grippers [28] to large scale deployable solar arrays [29] and stretchable electronics [30]. Specifically, the deformable configuration techniques can provide an effective strategy for the realization of optical reconfiguration [31, 32]. 3D metasurface for tunable resonance modes [33, 34], reconfigurable chiral origami/kirigami metamaterials [35, 36], kirigami nanocomposites-based diffraction gratings [37], multifunctional metamaterials [38], origami acoustics [39] and lattice transformations [40, 41] have been demonstrated one after another in recent years. Besides, elastic vibrations of the graphene sheet enable the coupling between EM field and propagating graphene surface plasmon polaritons [42, 43].

Here, we put forward origami deformable techniques on the exploration of metasurfaces with tunable bianisotropy. The proposed tunable bianisotropic metasurface is composed of an array of split ring resonators (SRRs) that are incorporated into Miura-ori origami pattern, a special case of rigid origami with dynamically and continuously alterable shapes [25]. The bianisotropic properties of the metasurface, characterized by magneto–electric and electro–magnetic surface susceptibilities, are dynamically controlled via the deformation of the Miura-ori SRRs. As illustrated in figure 1, the origami metastructure exhibits no bianisotropy (zero bianisotropic susceptibilities) at the unfolded state. The deformation of the Miura-ori unit along the vertical direction breaks the mirror symmetry against the transverse plane, and the rearrangement of the orientations of SRRs results in greatly enhanced bianisotropy. By combining the origami metasurface with dipole antennas, we further demonstrate a controllable asymmetry radiation with its asymmetric level determined by the degree of deformation. Microwave measurements exhibit a strong asymmetry radiation at the bianisotropic mode. Our work provides an alternative pathway to the dynamically control over the bianisotropy of metasurfaces. The proposed origami structure with tunable asymmetric radiation is expected to facilitate the implementation of reconfigurable directional optical devices such as emitters and lasers and particularly origami solar cells optimized for unidirectional illumination.

2. Characterization of angularly dispersive bianisotropy

In this section, we discuss the angularly dispersive bianisotropy in origami metasurfaces and introduce a method of effective surface susceptibilities to characterize bianisotropic effects. For a general metasurface, the
Figure 2. Biaxiality of unfolded origami metasurface for TM polarization. (a) Origami metasurface at the planar state, with periodic arrays of SRRs located at $xy$ plane. The metasurface is illuminated by TM plane waves with the incident angle $\theta$. Simulated reflection and transmission spectra for: (b) incident angle $\theta = 0^\circ$ and (d) incident angle $\theta = 30^\circ$. Retrieved surface susceptibilities of electric, total equivalent tangential magnetic and magnetoelectric ones from the reflection and transmission data at: (c) incident angle $\theta = 0^\circ$ and (d) incident angle $\theta = 30^\circ$.

Surface susceptibility tensors relate the average fields to the surface polarizations and can be defined as [9, 44, 45]:

$$ P = \sqrt{\frac{\epsilon_0}{\mu_0}} \hat{\alpha}_{ee} \cdot E^{ave} + \hat{\alpha}_{em} \cdot H^{ave} $$

$$ M = \hat{\alpha}_{me} \cdot E^{ave} + \sqrt{\frac{\mu_0}{\epsilon_0}} \hat{\alpha}_{mm} \cdot H^{ave} $$

(1)

where, $\hat{\alpha}_{ee}$, $\hat{\alpha}_{em}$, $\hat{\alpha}_{me}$, and $\hat{\alpha}_{mm}$ denote surface susceptibility tensors (the surface susceptibility tensors are also denoted by $\chi$ in other published work [9]). All vectors in the form of $A^{ave}$ refer to the average fields, calculated as

$$ A^{ave} = (A^+ + A^-)/2 $$

(2)

where superscripts $+$ and $-$ correspond to the fields at the top and the bottom of the metasurface plane ($z = 0$), respectively.

Now we consider periodical arrays of SRRs printed on a flat sheet and fold the structure into a Miura-ori pattern, as shown in figure 1. In the process of deformation, the reference plane of the metasurface is fixed at $z = 0$. The geometric parameters of the Miura-ori pattern are listed as: $a = b = 10$ mm, sector angle $\gamma = 60^\circ$. The outer and inner radii of the SRR are 3.5 mm and 3 mm.
respectively, the gap size is 1 mm. Here, for simplification, we neglect the influence of the substrate and assume the SRRs are located in free space. Considering the structure is reciprocal and no polarization conversion occurs, the susceptibility tensors can be written in the form:

\[
\begin{align*}
\alpha_{xx}^{ee} & = \begin{bmatrix} \alpha_{xx}^{ee} & 0 & 0 \\
0 & \alpha_{yy}^{ee} & 0 \\
0 & 0 & \alpha_{zz}^{ee} \end{bmatrix}, & \alpha_{xx}^{em} & = \begin{bmatrix} 0 & \alpha_{xy}^{em} & 0 \\
0 & \alpha_{yy}^{em} & 0 \\
0 & 0 & \alpha_{zz}^{em} \end{bmatrix} \\
\alpha_{xx}^{me} & = \begin{bmatrix} 0 & \alpha_{yx}^{me} & 0 \\
0 & 0 & \alpha_{zy}^{me} \end{bmatrix}, & \alpha_{xx}^{mm} & = \begin{bmatrix} \alpha_{xx}^{mm} & 0 & 0 \\
0 & \alpha_{yy}^{mm} & 0 \\
0 & 0 & \alpha_{zz}^{mm} \end{bmatrix}
\end{align*}
\tag{3}
\]

with \(\alpha_{xy}^{ee} = -\alpha_{yx}^{ee}, \alpha_{yy}^{ee} = -\alpha_{xy}^{ee}\). Forward and backward reflection refer to the scenarios that the incident waves propagate along \(-z\) and \(+z\) directions, respectively. For transverse magnetic (TM) polarized waves with an incident angle \(\theta_{in}\), as shown in figure 2(a), the co-polarized reflection and transmission coefficients are given by [44]

\[
r_{\pm} = -\left( \frac{1 + a_{\pm}^i}{1 - a_{\pm}^i} - \cos \theta_{in} + b_{\pm}^i \right) \left( \frac{1 - a_{\pm}^i}{1 + a_{\pm}^i} + \cos \theta_{in} - b_{\pm}^i \right)^{-1}
\tag{4}
\]

\[
t = \left( \frac{1 + a_{\pm}^i}{1 - a_{\pm}^i} + \cos \theta_{in} + b_{\pm}^i \right) \left( \frac{1 - a_{\pm}^i}{1 + a_{\pm}^i} + \cos \theta_{in} - b_{\pm}^i \right)^{-1}
\tag{5}
\]

where

\[
\begin{align*}
a_{\pm}^i & = \frac{i \omega}{2} (\alpha_{xx}^{ee} \cos \theta_{in} \mp \alpha_{xy}^{em}), & a_{\pm}^b = \frac{i \omega}{2} (\alpha_{xx}^{ee} \cos \theta_{in} \pm \alpha_{xy}^{em}) \\
b_{\pm}^i & = \frac{i \omega}{2} (\alpha_{zz}^{mm} \sin^2 \theta_{in} \mp \alpha_{yy}^{em} \cos \theta_{in}), & b_{\pm}^b = \frac{i \omega}{2} (\alpha_{zz}^{mm} \sin^2 \theta_{in} \mp \alpha_{yy}^{em} \cos \theta_{in}).
\end{align*}
\tag{6}
\]

Note that \(r^+\) and \(r^-\) denote the reflection coefficients for the forward and the backward directions, respectively, and \(t\) is the transmission coefficient for both directions. Equations (4) and (5) include three linear equations and four unknown susceptibility parameters \((\alpha_{xx}^{ee}, \alpha_{yy}^{ee}, \alpha_{xx}^{mm} \text{ and } \alpha_{yy}^{mm})\). Four susceptibility parameters cannot be completely retrieved under one fixed incident angle. Here, we introduce a total equivalent tangential magnetic susceptibility \(\alpha_{mn}^{mm}\) given by

\[
\alpha_{mn}^{mm} = \alpha_{zz}^{ee} \sin^2 \theta_{in} \mp \alpha_{yy}^{mm}.
\tag{7}
\]

This equivalent parameter includes the joint interaction between the out-of-plane electric response and the in-plane magnetic response at an arbitrary angle of incidence. The number of parameters reduces to three and the problem described in equations (3) and (4) becomes solvable. Notably, this assumption can be further interpreted from the physical point of view. We write the Maxwell’s boundary conditions at the interface [46–48]:

\[
\begin{align*}
\mathbf{E}_{in}^+ \times \mathbf{n} - \mathbf{E}_{in}^- \times \mathbf{n} &= -i \omega \left( \mathbf{M}_{in} - \mathbf{n} \times \frac{k_{\omega}}{\omega} \mathbf{P}_{in} \right) \\
\mathbf{n} \times \mathbf{H}_{in}^+ - \mathbf{n} \times \mathbf{H}_{in}^- &= -i \omega \left( \mathbf{P}_{in} - \mathbf{n} \times \frac{k_{\omega}}{\omega} \mathbf{M}_{in} \right).
\end{align*}
\tag{8}
\]

It indicates that the discontinuity of the transverse electric (magnetic) field is caused by the tangential magnetic (electric) polarization \(\mathbf{M}_i \text{ (} \mathbf{P}_i\text{)}\) together with the normal electric (magnetic) polarization \(\mathbf{P}_{in} \text{ (} \mathbf{M}_{in}\text{)}\). Therefore, we can adopt total equivalent tangential magnetic polarization density \(\mathbf{M}_{in} = \mathbf{M}_i - (\mathbf{n} \times k_{\omega} / \omega) \mathbf{P}_{in}\) and electric surface polarization density \(\mathbf{P}_{in} = \mathbf{P}_i - (\mathbf{n} \times k_{\omega} / \omega) \mathbf{M}_{in}\) to evaluate the discontinuity of the tangential electric and magnetic fields. The total equivalent tangential magnetic susceptibility \(\alpha_{mn}^{mm}\) well characterize the contribution of normal electric susceptibility \(\alpha_{zz}^{ee}\) and tangential magnetic susceptibility \(\alpha_{yy}^{mm}\) in field manipulation. The equivalent parameters can be derived
from equations (4), (5) and (7), and expressed as

$$\alpha_{xx}^{\text{em}} = \frac{-2i}{\omega} \left[ \frac{1 - \Delta}{\cos \theta_{\text{in}}} \right]$$

$$\alpha_{tt}^{\text{em}} = \frac{-2i}{\omega} \left[ \frac{1 - \Delta}{\cos \theta_{\text{in}}} \right]$$

$$\alpha_{xy}^{\text{em}} = \frac{-2i}{\omega} \left[ \frac{r_+ - r_-}{2} \right]$$

where parameter $\Delta$ denotes

$$\Delta = \frac{2}{(1 + t)^2 + \left( \frac{r_+ - r_-}{2} \right)^2}.$$  

The susceptibilities under normal incidences i.e., $\theta_{\text{in}} = 0^\circ$, are identical with the results presented in previous work [9]. The retrieved susceptibilities of $\alpha_{xx}^{\text{em}}$, $\alpha_{tt}^{\text{em}}$ and $\alpha_{xy}^{\text{em}}$ for origami metasurface at the planar state are given in figure 2. The transmission and reflection amplitudes shown in figures 2(b) and (d) suggest a strong resonance around 6.9 GHz. We may not explicitly claim magnetic and/or electric polarizations from only the reflection or transmission data. However, this can be clearly distinguished by referring to the retrieved susceptibilities in figures 2(c) and (e). Indeed, the electric susceptibility exhibits a significant resonance and is nearly by four orders of magnitude higher than magnetic and magneto-electric ones. The symmetric reflection (both the amplitude and the phase shift) for the illumination from both directions indicates a vanished bianisotropic term $\alpha_{yy}^{\text{em}}$ in the metasurface before folding, which is further verified via the small magneto-electric susceptibility in figures 2(c) and (e). We can conclude that electric susceptibility $\alpha_{xx}^{\text{em}}$ of planar origami metasurface is less sensitive to the incident angle.

Next, transverse electric (TE) polarized illumination is excited to retrieve the rest of the susceptibilities given in equation (3), as depicted in figure 3(a). The co-polarized reflection and transmission coefficients for TE incidence are [44]:

$$r^+ = \left( \frac{1 + a_1^+}{1 - a_1^+} \cos \theta_{\text{in}} + b_1^+ \right) \left( \frac{1 - a_2^+}{1 - a_2^+} \cos \theta_{\text{in}} - b_2^+ \right)^{-1}$$  \hspace{1cm} (11)

$$t = \left( \frac{1 + a_1^+}{1 - a_2^+} \cos \theta_{\text{in}} + b_1^+ \right) \left( \frac{1 - a_2^+}{1 - a_2^+} \cos \theta_{\text{in}} - b_2^+ \right)^{-1},$$  \hspace{1cm} (12)

where

$$a_1^\pm = \frac{i\omega}{2} \left( \alpha_{xx}^{\text{em}} \cos \theta_{\text{in}} \pm \alpha_{xy}^{\text{me}} \right), \quad a_2^\pm = \frac{i\omega}{2} \left( \alpha_{xx}^{\text{em}} \cos \theta_{\text{in}} \mp \alpha_{xy}^{\text{me}} \right)$$

$$b_1^\pm = \frac{i\omega}{2} \left( \alpha_{zz}^{\text{em}} \sin^2 \theta_{\text{in}} + \alpha_{yy}^{\text{me}} \mp \alpha_{xy}^{\text{me}} \cos \theta_{\text{in}} \right)$$

$$b_2^\pm = \frac{i\omega}{2} \left( \alpha_{zz}^{\text{em}} \sin^2 \theta_{\text{in}} + \alpha_{yy}^{\text{me}} \pm \alpha_{xy}^{\text{me}} \cos \theta_{\text{in}} \right).$$  \hspace{1cm} (13)

Similar to the TM case, we introduce total equivalent tangential electric susceptibility $\alpha_{tt}^{\text{ee}}$ to replace $\alpha_{zz}^{\text{em}} \sin^2 \theta_{\text{in}} + \alpha_{yy}^{\text{ee}}$ in $b_1^\pm$ and $b_2^\pm$, yielding to

$$\alpha_{tt}^{\text{ee}} = \alpha_{zz}^{\text{em}} \sin^2 \theta_{\text{in}} + \alpha_{yy}^{\text{ee}}.$$  \hspace{1cm} (14)

Solving equations (11), (12) and (14) leads to:

$$\alpha_{xx}^{\text{em}} = \frac{-2i}{\omega} \left[ \frac{1 - \Delta}{\cos \theta_{\text{in}}} \right]$$

$$\alpha_{tt}^{\text{ee}} = \frac{-2i}{\omega} \left[ \frac{1 - \Delta}{\cos \theta_{\text{in}}} \right]$$

$$\alpha_{xy}^{\text{me}} = \frac{2i}{\omega} \Delta \left( \frac{r_+ - r_-}{2} \right)$$

where the parameter $\Delta$ has the same form expressed in equation (10). The retrieved susceptibilities of $\alpha_{xx}^{\text{em}}$, $\alpha_{tt}^{\text{ee}}$ and $\alpha_{xy}^{\text{me}}$ for the origami metasurface before folding are given in figure 3. At normal incidences, the reflection and transmission spectra in figure 3(b) have no resonant mode in the frequency band of interest. Accordingly, the retrieved susceptibilities are pretty small as illustrated in figure 3(c). However, the
Figure 3. Biaxiosropy of unfolded origami metasurface for TE polarization. (a) Origami metasurface at the planar state, with periodic arrays of SRRs located at xy plane. The metasurface is illuminated by TE plane waves with the incident angle $\theta$. Simulated reflection and transmission spectra for: (b) incident angle $\theta = 0^\circ$ and (d) incident angle $\theta = 30^\circ$. Retrieved surface susceptibilities of magnetic, total equivalent tangential electric and EM ones from the reflection and transmission data at: (c) incident angle $\theta = 0^\circ$ and (d) incident angle $\theta = 30^\circ$.

Biaxiosropy effect changes for oblique incidences because the magnetic field passes through the planes of SRRs, leading to strong magnetic responses along z direction. A strong resonant feature arises up around 7 GHz due to the magnetic susceptibility of z component $\alpha_{zz}$, with its value four order of magnitude higher than those of $\alpha_{xx}$ and $\alpha_{xy}$. The symmetric reflection (both amplitude and phase shift) performance for both directions indicates no biaxiosropy effect ($\alpha_{xy}$ approaches zero), in agree with the retrieved susceptibility shown in figures 3(c) and (e).

We then discuss the EM responses of the origami metamaterials at folded states. Here, the flat sheet shown in figure 2(a) is compressed to 45°, following to the folding principle of Miura-ori pattern. Compared with the unfolded flat one, the folded origami metasurface shows the same amplitude modulation yet different phase accumulation in reflection (figure 4(a)), namely, asymmetric reflection for forward and backward directions. Hence, enhanced biaxiosropy appears. Quantitatively, magneto–electric susceptibility for the folded origami metasurface in figure 4(b) is by three orders of magnitude higher than that for planar state in figure 2(c). Besides, the total equivalent tangential magnetic susceptibility $\alpha_{tt}$ increases by five orders of magnitude compared to the planar state. At oblique incidences, an extra dip arises up as shown in figure 4(c). This dip is caused by the so-called ‘dark mode’ [49], which can be excited by electric field along z direction. Therefore, the total equivalent tangential magnetic susceptibility $\alpha_{tt}$...
Figure 4. Bianisotropy of the folded origami metasurface for TM polarization. Simulated reflection and transmission spectra for: (a) incident angle $\theta_{in} = 0^\circ$ and (c) incident angle $\theta_{in} = 30^\circ$. Retrieved surface susceptibilities of electric, total equivalent tangential magnetic and magneto–electric ones from the reflection and transmission data at: (b) incident angle $\theta_{in} = 0^\circ$ and (d) incident angle $\theta_{in} = 30^\circ$.

Figure 5. Dipole moments unraveling the underlying mechanism of the bianisotropy induced asymmetric reflection of the Miura-ori metamaterials. Illumination is along (a) the $+z$ and (b) $−z$ direction. For clarity, only dipole moments generated due to bianisotropic coupling are shown. The insets depict the radiation patterns of the effective total dipole moments. Only one half of each pattern is shown. Total backscattered (reflected) field from the metasurface is different for different illuminations.

extracted from oblique incidence in figure 4(d) has an extra resonant feature compared to that from normal incidence in figure 4(b).
Figure 6. Extracted bianisotropic susceptibilities of the origami metasurface at various folding state. (a) Magneto–electric susceptibility $\alpha_{em}^{xy}$. (b) Electro–magnetic susceptibility $\alpha_{me}^{xy}$.

In the following, we will investigate the underlying mechanism of the bianisotropy induced asymmetric reflection of the Miura-ori metamaterials. Geometric asymmetry in structures is the basis of bianisotropy in EMs and Willis coupling in acoustics (the analog of bianisotropy in EMs) [16]. The Miura-ori induced deformation along $z$ direction breaks the mirror symmetry of the metastructure. The incident magnetic field passes through the planes of SRRs and induces the electric dipole moments, thus generating magneto–electric coupling responses. To reveal the underlying mechanism of bianisotropy induced asymmetric reflection of the Miura-ori metamaterials, we consider the origami metamaterials, illuminated by plane waves with the $y$-oriented electric field propagating along the $+z$ and $-z$ direction respectively. For simplicity of the analysis, we consider only those parts of the dipole moments which are created due to bianisotropic polarizabilities $\alpha_{em}$ and $\alpha_{me}$. The other dipole contributions due to polarizabilities $\alpha_{ee}$ and $\alpha_{mm}$ always generate the same reflected waves regardless of the illumination direction (as in the case of a simple layer of an isotropic magnetodielectric) [10]. Figure 5 shows the orientations of the induced dipole moments on the four split-ring resonators due to the bianisotropic coupling under two illuminations. The total electric and magnetic dipole moments are represented by $p_{eff}$ and $m_{eff}$. The dipole moments radiate plane waves with the same linear polarizations (see the radiation patterns in the insets; for clarity, only one half of each radiation pattern is shown). The backscattered fields for both scenarios can be determined. Comparing figures 5(a) and (b), it is seen that the backscattered field has the opposite signs in the two scenarios: $jE_{sc}$ and $-jE_{sc}$. This results in the asymmetry of the total reflected field (created by the total dipole moments) when the metasurface is illuminated from the $+z$ and $-z$ directions.

The bianisotropic susceptibilities at various folded states are illustrated in figure 6. As the metasurface deforms, the resonance of bianisotropic susceptibility undergoes a redshift due to the decreased periodicities along $x$ and $y$ directions, which are determined by the geometric properties of Miura-ori pattern. The
3. Controllable asymmetric radiation

The bianisotropic properties of the origami metasurface can be employed to achieve dynamically control on the radiation direction of antennas [50]. For an electrically thin electric (magnetic) slab, a parallel electric (magnetic) dipole inside it can only induce parallel electric (magnetic) polarization. The induced effective dipole is in parallel to the excitation dipole. Therefore, any single dipole antenna located inside an ordinary electrically slab always generates symmetric radiation on both sides. If magneto–electric coupling is introduced at the interface, an electric (magnetic) dipole source can induce additional magnetic (electric) polarization. A pair of electric and magnetic dipoles perpendicular to each other can efficiently produce asymmetric radiation toward a single side [10]. Based on this mechanism, we employ the origami metasurface to realize controllable asymmetric radiation for dipole antennas. Two types of dipoles oriented along y direction have been designed with two different lengths. Their resonant frequencies are around 5.4 GHz (dipole 1) and 7.3 GHz (dipole 2), respectively. The return loss of the two antennas is presented in figure 7(a). At the resonant frequencies, two dipole antennas match well and exhibit high radiation efficiencies. Next, dipole 1 and dipole 2 are located at the center of the origami layer with the folded states at 85° and 45° respectively. Considering the small layer thickness and its periodicities in the x and y directions, there is no obvious boundary for waves coming from the ±z directions. As a result, the radiation
performances of dipoles are mainly dominated by the bianisotropic susceptibility of the origami layer. The simulated radiation patterns for folded states are plotted in figures 7(b) and (c) respectively. Here, we focus on the radiation in the $zx$ plane and the coordinate axis is defined in figure 1. Although the radiation power pattern at both cases shows asymmetric behaviors for forward and backward directions, the power gain contrast is higher for the folded state of $85^\circ$. A recent work has also demonstrated enhanced asymmetric radiation, enabled by metasurfaces and thin films consisting of only one layer of asymmetric constituents [24]. Since the bianisotropic properties of the origami metastructure are reconfigurable, controllable asymmetric radiation is expected. It is noticed that an origami-based tunable acoustic radiator is demonstrated in previous work [39]. However, the underlying physics is different. In that work, each acoustic radiator locates on the parallelogram facet of the origami. When the origami deforms, the location of the radiator will be altered with reduced radiating angles that contribute to the far field pressure point, resulting in variation of far-field radiation. The power gain contrast between forward and backward radiation are shown in figure 7(d). To characterize the asymmetric radiation performance of the antenna system, we calculate the radiation asymmetry defined as $G_{\text{forward}}/G_{\text{backward}}$, where $G_{\text{forward}}$ and $G_{\text{backward}}$ refer to the gain of forward ($-z$ direction) and backward ($+z$ direction) radiation respectively. The value of radiation asymmetry directly embodies the asymmetric radiation performance of the antenna, i.e., symmetric radiation with unitary radiation asymmetry and extremely asymmetric radiation with radiation asymmetry approaching zero. As illustrated in figure 7(d), the radiation asymmetry can be dynamically controlled via the deformation of the Miura-ori pattern. The asymmetric radiation performance of the antenna begins with zero at the unfolded state (radiation asymmetry equals to 1:1), gradually increases under deformation and reaches the maximum (radiation asymmetry reaches up to 1:33) in extremely folded geometries. This can be explained by the greatly enhanced electro–magnetic susceptibility $\alpha_{xy}$ when the origami is at large-folded geometries as illustrated in figure 6(b). We further investigate radiation asymmetry of Miura-ori with various sector angle $\gamma$. The increased sector angle will reduce the relative density of the Miura-ori metamaterial [36] (see the inset) and simultaneously attenuate the asymmetric radiation performance of the antenna system as demonstrated in figure 7(d).

Miura-ori metasurfaces have been fabricated and characterized in the microwave region. Copper SRRs (thickness 0.035 mm) are periodically printed on a halogen free frame-resistant type polyimide film.
(thickness 0.05 mm) with a permittivity of 3.5. Reflection and transmission properties of the metasurface have been measured in an anechoic chamber with a setup of two wideband antennas connected to a vector network analyzer. The experiment setup is shown in figure 8(a). One of the horn antennas serves as the source to illuminate incidence plane waves to the sample. Another horn antenna acts as a receiver to record the reflection and transmission intensities. The reflection amplitude is normalized by the reflection intensity measured with a same-size copper plate, while the transmission is normalized by the direct transmission intensity without the sample. For the planar state of the Miura-ori metasurface, the measured reflection and transmission amplitudes under normal incidence are plotted in figure 8(b). S11, S22 and S12 denote forward reflection, backward reflection and transmission respectively. The phase difference between forward and backward reflection is presented in figure 8(c), indicating symmetric reflection for illumination along opposite directions. Figures 8(d) and (e) show the measured results for origami metasurface in its folded state at 65°. By contrast, an obvious phase difference between forward and backward reflection can be observed in figure 8(e), implying asymmetric EM responses resulting from the enhanced bianisotropy of the metasurface. The radiation pattern of the folded structure has been measured as well. In measurements, the system was fed by a monopole connected to the coaxial feed cable and was kept stable with the aid of a foam slab. Another horn antenna was used as the receiver moving along the arc track, in order to measure the scattered fields at various radiation angles. The experimental set up for far-field measurement is shown in figure 8(f). The measured radiation pattern is plotted in figure 8(g). At the folded state of 65°, asymmetric radiation can be observed at the frequency of 6.9 GHz and 7.5 GHz, while symmetric radiation kept at 6.5 GHz. It should be noted that the substrate will introduce a slight frequency shift in experiments because the permittivity of the substrate will increase the capacitance induced at the gap of each split-ring resonator.

4. Conclusion

In summary, we have proposed an origami approach to dynamically control the bianisotropy of metasurfaces. The proposed tunable bianisotropic metasurface is composed of arrays of SRRs incorporated into a Miura-ori pattern. The bianisotropic properties of the metasurface, characterized by bianisotropic susceptibilities, are dynamically controlled via the deformation of the Miura-ori SRRs. The deformation of the Miura-ori unit along vertical direction breaks the mirror symmetry against the transverse plane and induces the misalignments of the SRRs orientations, leading to greatly enhanced bianisotropy. With the aid of the proposed tunable bianisotropic metasurface, we further demonstrate a controllable asymmetric radiation and the asymmetric level is determined by the deformation of the metastructure. Our work provides an alternative pathway to dynamically control the bianisotropy of the metasurfaces. Due to the scaling properties of Maxwell’s equations, the design principle proposed here is scale-independent and can be extended to terahertz, infrared, and even optical frequencies. Therefore, it is expected that origami structures with tunable asymmetric radiation can facilitate the implementation of reconfigurable directional optical devices such as emitters and lasers and particularly origami solar cells optimized for unidirectional illumination.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Hongsheng Chen https://orcid.org/0000-0003-3573-3338

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