Magnet-free nonreciprocal bianisotropic metasurfaces

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Abstract

Tellegen and moving metasurfaces are two promising classes of non-reciprocal bianisotropic metasurfaces which offer extended functionalities for electromagnetic wave manipulation. However, in order to realize these metasurfaces, ferrite-based unit-cells have been utilized which need to be biased by an external magnetic field. Inspired by recent works on magnet-free non-bianisotropic non-reciprocal building blocks, we introduce new designs for magnet-free Tellegen and moving metasurfaces.

1 Introduction

To engineer an electromagnetic wavefront, one needs to control the phase, amplitude, and polarization of the wave. In conventional quasi-optical and optical components, this is achieved by propagating the electromagnetic wave through a bulk material over a distance which is typically much larger than the wavelength of radiation. In this manner, changes to the wave are gradually accumulated along the optical path. The same scenario holds for three-dimensional metamaterials, e.g., in transformation optics, a bulk medium is engineered to tailor an electromagnetic wave [1, 2]. Recent advances in metasurfaces, electrically-thin composite layers of sub-wavelength polarizable unit-cells, have enabled precise control of electromagnetic waves across sub-wavelength thicknesses. These artificial surfaces have been used to tailor electromagnetic waves in unprecedented ways [3–9]. A metasurface can offer drastically different functionalities depending on the electromagnetic characteristics of its constituent elements. Allowing non-reciprocity in a metasurface, namely breaking its time-reversal symmetry, can give rise to a set of fascinating functionalities which are not possible with reciprocal metasurfaces. Non-reciprocal responses have traditionally been realized using magnetic gyrotropy (non-reciprocal components based on ferrites) [10] or electric gyrotropy (non-reciprocal components based on magnetized plasmas) [11]. Along the same lines, non-reciprocal metasurfaces based on ferrites or magnetized plasmas have been recently proposed [12–15]. However, these structures require an external static magnetic field bias, which complicates their design and implementation. In order to address this issue, different approaches have been put forward to realize non-reciprocal metasurfaces, which utilize non-gyrotropic components in their building blocks [16–19]. Although these structures circumvent the limitations associated with gyrotropic

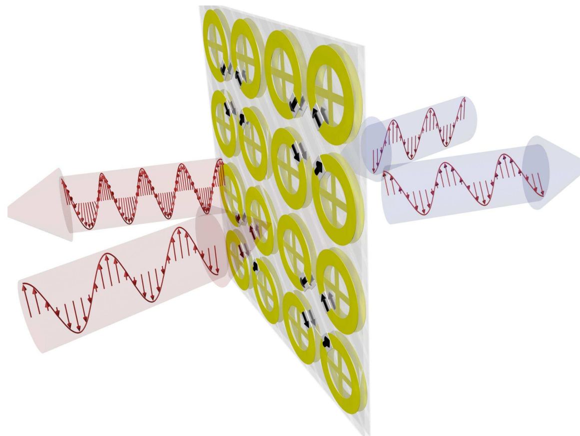
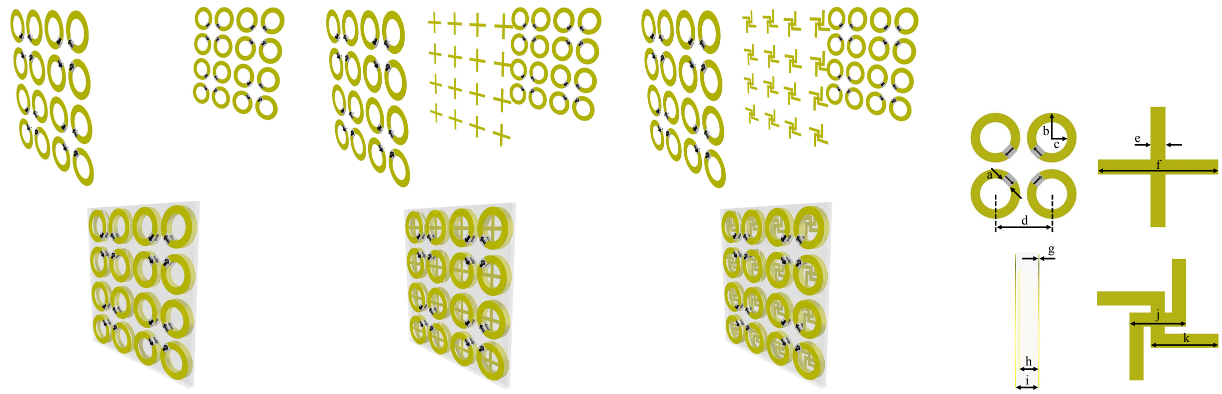


Figure 1: Schematic of a generic non-reciprocal bianisotropic uniaxial metasurface. This generic bianisotropic metasurface can behave asymmetrically for incident waves hitting its different sides. Depending on its bianisotropic coupling, this asymmetric behavior can happen in forward or backward scattering resulting in different transmissions or reflections for waves illuminating its different sides.

metasurfaces, only a limited set of functionalities have been explored. In most of these designs, non-reciprocal effects result from the surface effective electric and/or magnetic polarizabilities of these metasurfaces not being symmetric. However, non-reciprocity in a metasurface can also result from non-reciprocal electromagnetic coupling. Recently, it was shown that metasurfaces possessing different classes of non-reciprocal bianisotropic coupling (Tellegen and moving coupling) offer novel functionalities and opportunities to tailor electromagnetic wavefronts [12,20]. In this paper, we will present metasurface designs that exhibit magnet-free non-reciprocal Tellegen and moving coupling. We utilize the non-reciprocal, non-bianisotropic building block proposed in [16], and propose new magnet-free metasurfaces which possess the different classes of non-reciprocal bianisotropic coupling.

2 Effective polarizability dyadics of particles in periodic arrays

Before describing the proposed metasurface designs in detail, it is beneficial to review the scattering properties of a generic metasurface composed of densely spaced sub-wavelength polarizable particles. Let us consider a metasurface formed of a periodic array of electrically dense unit cells. Such a metasurface can be adequately characterized by its effective surface polarizabilities. For a generic metasurface, the electromagnetic response due to a normally incident electromagnetic plane wave can be modeled utilizing the linear relations between the induced electric dipole moments $\mathbf{p}$, magnetic dipole moments $\mathbf{m}$, and the incident electromagnetic fields



(a) (b) (c) (d)

Figure 2: Schematics of the magnet-free non-reciprocal (a) non-bianisotropic metasurface (b) bianisotropic Tellegen metasurface, (c) bianisotropic moving metasurface. (d) Designed dimensions: a=0.5 mm, b=2.65 mm, c=1.65 mm, d=6 mm, e=1 mm, f=4.7 mm, g=0.035 mm, h=0.77 mm (for the Tellegen metasurface) and 0.026 mm (for the moving metasurface), i=0.9 mm (for the non-bianisotropic metasurface and the Tellegen metasurface) and 0.39 mm (for the moving metasurface), j=2 mm, and k=4.35 mm. For all the designs the dielectric used between arrays is Rogers RO3006 ($\epsilon_{\rm r}$=6.15 and $\tan\delta$=0.002). Note that in all our simulations we use ideal isolators with zero insertion loss, infinite isolation, and zero transmission phase shift. Since the metasurfaces are periodic, we simulate a single unit-cell with periodic boundary condition.

$\mathbf{E}_{\rm inc}$ and $\mathbf{H}_{\rm inc}$ at the location of the unit-cells

$$\begin{bmatrix} \mathbf{p} \\ \mathbf{m} \end{bmatrix} = \begin{bmatrix} \overline{\overline{\widehat{\alpha}}}_{\rm ee} & \overline{\overline{\widehat{\alpha}}}_{\rm em} \\ \overline{\overline{\widehat{\alpha}}}_{\rm me} & \overline{\overline{\widehat{\alpha}}}_{\rm mm} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{E}_{\rm inc} \\ \mathbf{H}_{\rm inc} \end{bmatrix}. \tag{1}$$

Here, $\overline{\overline{\widehat{\alpha}}}_{\rm ee}$, $\overline{\overline{\widehat{\alpha}}}_{\rm mm}$, $\overline{\overline{\widehat{\alpha}}}_{\rm em}$, and $\overline{\overline{\widehat{\alpha}}}_{\rm me}$ are the effective electric, magnetic, electromagnetic, and magnetoelectric polarizabilities of the metasurface, respectively. It should be noted that throughout the paper, the symbols with bars above (both with hat and without hat) are 2×2 matrices and the symbols without bars are scalars. Throughout the paper, we will consider uniaxial metasurfaces, isotropic in the plane of the sheet. Such a metasurface functions for arbitrary polarized incident plane waves. We assume the metasurfaces under study are positioned along the **xy**-plane, and are illuminated by normally incident plane waves. The uniaxial symmetry allows only an isotopic response and rotation around the axis **z**. Thus, all the polarizabilities in (1) take the form:

$$\begin{aligned} \overline{\overline{\widehat{\alpha}}}_{\rm ee} &= \widehat{\alpha}_{\rm ee}^{\rm co}\overline{\overline{I}}_{\rm t} + \widehat{\alpha}_{\rm ee}^{\rm cr}\overline{\overline{J}}_{\rm t}, & \overline{\overline{\widehat{\alpha}}}_{\rm mm} &= \widehat{\alpha}_{\rm mm}^{\rm co}\overline{\overline{I}}_{\rm t} + \widehat{\alpha}_{\rm mm}^{\rm cr}\overline{\overline{J}}_{\rm t}, \\ \overline{\overline{\widehat{\alpha}}}_{\rm em} &= \widehat{\alpha}_{\rm em}^{\rm co}\overline{\overline{I}}_{\rm t} + \widehat{\alpha}_{\rm em}^{\rm cr}\overline{\overline{J}}_{\rm t}, & \overline{\overline{\widehat{\alpha}}}_{\rm me} &= \widehat{\alpha}_{\rm me}^{\rm co}\overline{\overline{I}}_{\rm t} + \widehat{\alpha}_{\rm me}^{\rm cr}\overline{\overline{J}}_{\rm t}, \end{aligned} \tag{2}$$

where indices 'co' and 'cr' refer to the symmetric and anti-symmetric parts of the corresponding polarizabilities, respectively. Here, $\overline{\overline{I}}_{\rm t} = \overline{\overline{I}} - \mathbf{z}_0\mathbf{z}_0$ is the two-dimensional unit dyadic, and

$\overline{\overline{J}}_{\rm t} = \mathbf{z}_0 \times \overline{\overline{I}}_{\rm t}$ is the vector-product operator. The corresponding matrix forms for these dyadics in the Cartesian coordinate system read

$$\overline{\overline{I}}_{\rm t} : \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \overline{\overline{J}}_{\rm t} : \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}. \tag{3}$$

In the following sections, effects resulting from the different classes of electromagnetic coupling present in bianisotropic metasurfaces will be studied. Therefore, it is convenient to separate the electromagnetic/magnetoelectric coupling coefficients responsible for reciprocal and non-reciprocal bianisotropic coupling processes:

$$\begin{aligned} \overline{\overline{\widehat{\alpha}}}_{\rm em} &= (\widehat{\chi} + j\widehat{\kappa})\overline{\overline{I}}_{\rm t} + (\widehat{V} + j\widehat{\Omega})\overline{\overline{J}}_{\rm t}, \\ \overline{\overline{\widehat{\alpha}}}_{\rm me} &= (\widehat{\chi} - j\widehat{\kappa})\overline{\overline{I}}_{\rm t} + (-\widehat{V} + j\widehat{\Omega})\overline{\overline{J}}_{\rm t}. \end{aligned} \tag{4}$$

There are certain constrains imposed by reciprocity on the polarizabilities of a metasurface:

$$\overline{\overline{\widehat{\alpha}}}_{\rm em} = -\overline{\overline{\widehat{\alpha}}}_{\rm me}^{\rm T}, \quad \overline{\overline{\widehat{\alpha}}}_{\rm ee} = \overline{\overline{\widehat{\alpha}}}_{\rm ee}^{\rm T}, \quad \overline{\overline{\widehat{\alpha}}}_{\rm mm} = \overline{\overline{\widehat{\alpha}}}_{\rm mm}^{\rm T}. \tag{5}$$

According to these conditions, there are two reciprocal classes (chiral $\widehat{\kappa}$ and omega $\widehat{\Omega}$) and two non-reciprocal classes (moving $\widehat{V}$ and Tellegen $\widehat{\chi}$) [21]. Note also that for a reciprocal uniaxial metasurface (isotropic in the plane of the metasurface) the electric and magnetic polarizabilities $\overline{\overline{\widehat{\alpha}}}_{\rm ee}$ and $\overline{\overline{\widehat{\alpha}}}_{\rm mm}$ are always symmetric dyadics meaning that $\widehat{\alpha}_{\rm ee}^{\rm cr} = 0$ and $\widehat{\alpha}_{\rm mm}^{\rm cr} = 0$.

Metasurfaces possessing different classes of bianisotropic electromagnetic coupling may behave differently for incident waves hitting their different sides. The reflection and transmition coefficients for a $-\mathbf{z}$-directed normally impinging incident wave on a generic bianisotropic metasurface reads [22]

$$\begin{aligned} \overleftarrow{R} &= -\frac{j\omega}{2S}\left[\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm co} + j2\widehat{\Omega} - \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm co}\right)\overline{\overline{I}}_{\rm t} + \left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm cr} - 2\widehat{\chi} - \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm cr}\right)\overline{\overline{J}}_{\rm t}\right] = R_{\leftarrow}^{co}\overline{\overline{I}}_{\rm t} + R_{\leftarrow}^{cr}\overline{\overline{J}}_{\rm t} \\ \overleftarrow{T} &= \left[1 - \frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm co} + 2\widehat{V} + \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm co}\right)\right]\overline{\overline{I}}_{\rm t} - \frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm cr} - j2\widehat{\kappa} + \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm cr}\right)\overline{\overline{J}}_{\rm t} = T_{\leftarrow}^{co}\overline{\overline{I}}_{\rm t} + T_{\leftarrow}^{cr}\overline{\overline{J}}_{\rm t} \end{aligned} \tag{6}$$

and for a $+\mathbf{z}$-directed incident wave, the scattering parameters are

$$\begin{aligned} \overrightarrow{R} &= -\frac{j\omega}{2S}\left[\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm co} - j2\widehat{\Omega} - \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm co}\right)\overline{\overline{I}}_{\rm t} + \left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm cr} + 2\widehat{\chi} - \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm cr}\right)\overline{\overline{J}}_{\rm t}\right] = R_{\rightarrow}^{co}\overline{\overline{I}}_{\rm t} + R_{\rightarrow}^{cr}\overline{\overline{J}}_{\rm t} \\ \overrightarrow{T} &= \left[1 - \frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm co} - 2\widehat{V} + \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm co}\right)\right]\overline{\overline{I}}_{\rm t} - \frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee}^{\rm cr} + j2\widehat{\kappa} + \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm cr}\right)\overline{\overline{J}}_{\rm t} = T_{\rightarrow}^{co}\overline{\overline{I}}_{\rm t} + T_{\rightarrow}^{cr}\overline{\overline{J}}_{\rm t} \end{aligned} \tag{7}$$

where ω, η_0, and S are the angular frequency, free space wave impedance, and metasurface unit-cell area, respectively. Here "$\leftarrow$" and "$\rightarrow$" are used to distinguish between scattering parameters due to $-\mathbf{z}$- and $+\mathbf{z}$-directed incident waves. It can be seen from these two sets of equations that the bianisotropic electromagnetic coupling is the main reason an isotropic metasurface behaves asymmetrically for incident waves hitting its different sides. Depending on the class of bianisotropic coupling a metasurface possesses, this asymmetric behavior shows up in co- and/or cross-polarized reflection and/or transmission from the metasurface [see Fig. 1]. From the scattering parameters of a metasurface, we can obtain its surface-averaged effective polarizabilities:

$$\frac{j\omega}{S}\begin{bmatrix} \eta_0\widehat{\alpha}_{\rm ee}^{\rm co} & \widehat{\Omega} \\ \widehat{\kappa} & \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm co} \end{bmatrix} = \begin{bmatrix} 1-\frac{1}{2}\left(R_{\leftarrow}^{co}+R_{\rightarrow}^{co}+T_{\leftarrow}^{co}+T_{\rightarrow}^{co}\right) & \frac{1}{j2}\left(-R_{\leftarrow}^{co}+R_{\rightarrow}^{co}\right) \\ -\frac{1}{j2}\left(-T_{\leftarrow}^{cr}+T_{\rightarrow}^{cr}\right) & 1+\frac{1}{2}\left(R_{\leftarrow}^{co}+R_{\rightarrow}^{co}-T_{\leftarrow}^{co}-T_{\rightarrow}^{co}\right) \end{bmatrix} \tag{8}$$

$$\frac{j\omega}{S}\begin{bmatrix} \eta_0\widehat{\alpha}_{\rm ee}^{\rm cr} & \widehat{V} \\ \widehat{\chi} & \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}^{\rm cr} \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\left(R_{\leftarrow}^{cr}+R_{\rightarrow}^{cr}+T_{\leftarrow}^{cr}+T_{\rightarrow}^{cr}\right) & \frac{1}{2}\left(-T_{\leftarrow}^{co}+T_{\rightarrow}^{co}\right) \\ -\frac{1}{2}\left(-R_{\leftarrow}^{cr}+R_{\rightarrow}^{cr}\right) & \frac{1}{2}\left(R_{\leftarrow}^{cr}+R_{\rightarrow}^{cr}-T_{\leftarrow}^{cr}-T_{\rightarrow}^{cr}\right) \end{bmatrix} \tag{9}$$

With this formulation, we can now study magnet-free, non-bianisotropic non-reciprocal metasurfaces and introduce new bi-anisotropic non-reciprocal metasurfaces.

3 Non-reciprocal electric and/or magnetic metasurfaces

As noted earlier, different approaches have been recently proposed for designing non-reciprocal metasurfaces based on non-gyrotropic unit cells. One of the most widely reported methods relies on utilizing unidirectional active circuit elements embeded within metasurfaces [16,17]. To help explain the proposed magnet-free, bianisotropic metasurfaces, we turn to the design proposed by Kodera et al. [16], shown in Fig. 2(a). The metasurface is an array of pairs of rings loaded with ideal isolators. These isolators are perfectly matched electrical components which allow the flow of electric current in one direction only. These isolators can be realized using common-source field effect transistors [16]. Due to the presence of the isolators, traveling waves are supported around the rings, which result in a rotating radial magnetic moment. This rotating magnetic moment resembles the rotating magnetic moment in magnetic gyrotropic materials, that occures due to electron spin precession in the presence of external static magnetic field [23]. Therefore, the structure provides Faraday rotation without the need for an external magnetic bias. Normalized surface-averaged effective polarizabilities for this layer are shown in Fig. 3. A few important points can be drawn from these polarizabilities. The first point is that all the bianisotropic coupling polarizabilities are negligible, meaning that the metasurface is non-bianisotropic. The metasurface exhibits an asymmetric behavior (due to the non-reciprocal, off-diagonal component of the magnetic polarizability) for waves hitting its different sides. However the set of functionalities enabled by this asymmetry is quite limited (e.g., asymmetry

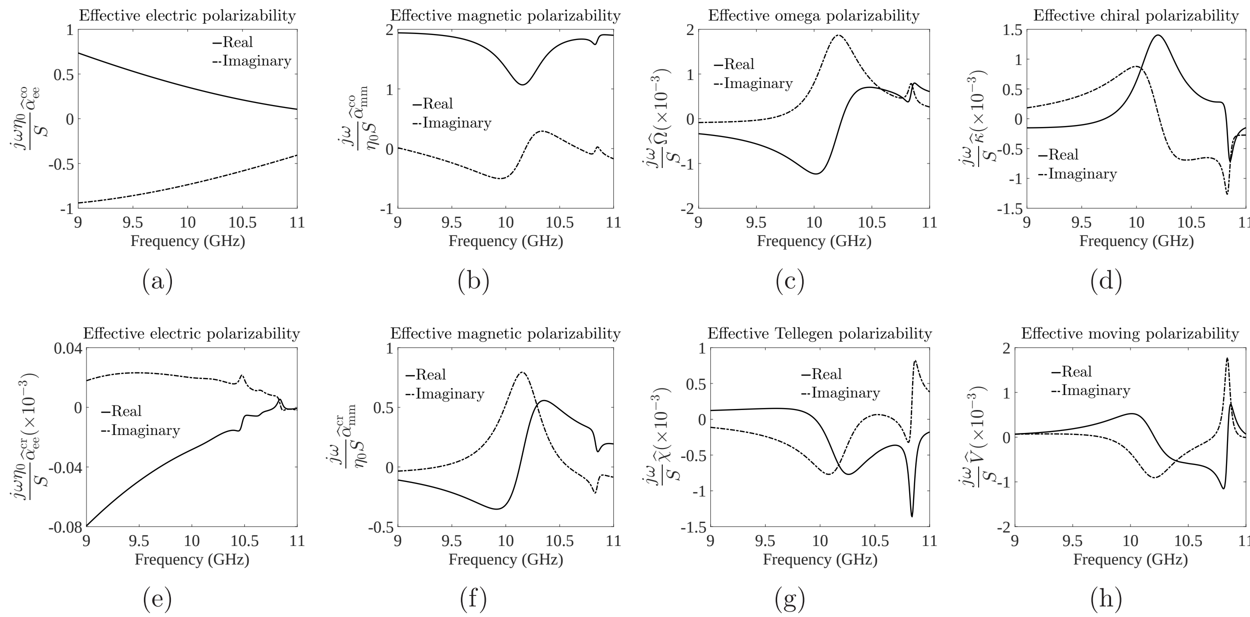


Figure 3: Normalized surface-averaged effective (a) co-polarized electric, (b) co-polarized magnetic, (c) omega, (d) chiral, (e) cross-polarized electric, (f) cross-polarized magnetic, (g) Tellegen, and (h) moving polarizabilities for the non-bianisotropic metasurface shown in Fig. 2(a).

in polarization rotation angle for waves illuminating different sides of the metasurface [see (6) and (7)]). The second point is that $\widehat{\alpha}_{\rm mm}^{\rm cr}$ is considerably large while $\widehat{\alpha}_{\rm ee}^{\rm cr}$ has a negligible value. This means that non-reciprocity in this structure is due to the off-diagonal component of the magnetic polarizability. This response resembles that of conventional non-reciprocal components based on magnetic gyrotropy (e.g., magnetized ferrite). Magnet-free non-reciprocal metasurfaces with nonreciprocity due to off-diagonal components of electric polarizabilities have also been reported [17, 24]. Such metasurfaces have a dominant large $\widehat{\alpha}_{\rm ee}^{\rm cr}$ and quite small $\widehat{\alpha}_{\rm mm}^{\rm cr}$, emulating non-reciprocity in conventional non-reciprocal components based on electric gyrotropy (e.g., magnetized plasma). However, non-reciprocity in a metasurface can be due to non-reciprocal bianisotropic coupling present in the metasurface building blocks. In this paper, we will propose two new designs for magnet-free, non-reciprocal bianisotropic metasurfaces. It will be shown that, by introducing different classes of non-reciprocal bianisortopic coupling in a metasurface, we can explore new possibilities to design asymmetric metasurfaces.

4 Bianisotropic non-reciprocal metasurfaces

4.1 Tellegen metasurfaces

Bianisotropic Tellegen coupling is one of the main classes of non-reciprocal electromagnetic coupling. It can be seen from equations (6) and (7) that the presence of Tellegen coupling in a metasurface makes it to scatter asymmetrically for waves hitting its different sides. Here, to

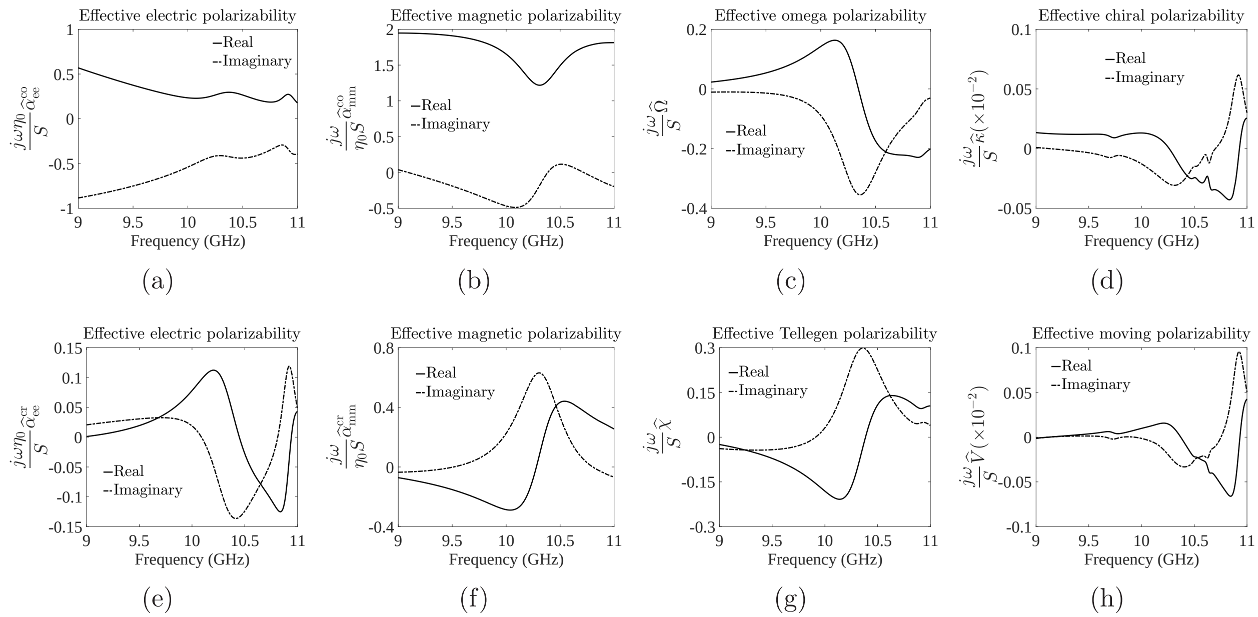
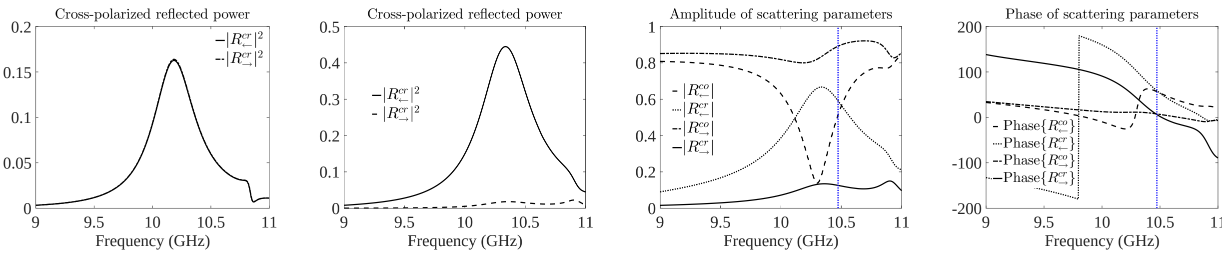


Figure 4: Normalized surface-averaged effective (a) co-polarized electric, (b) co-polarized magnetic, (c) omega, (d) chiral, (e) cross-polarized electric, (f) cross-polarized magnetic, (g) Tellegen, and (h) moving polarizabilities for the bianisotropic Tellegen metasurface shown in Fig. 2(b).

realize a magnet-free Tellegen metasurface, we propose the structure shown in Fig. 2(b). In this design a periodic array of cross dipoles is positioned between the two arrays of rings, but closer to one of them. The scattered fields due to the rotating radial magnetic moments between the two ring layers excite electric currents on the cross dipoles. The electric currents on the cross dipoles produce secondary scattered fields. This process results in Tellegen coupling in the metasurface. Figure 4 shows the normalized surface-averaged effective polarizabilities for this metasurface. It can be seen that the metasurface possesses strong non-reciprocal Tellegen coupling. In addition, the metasurface also possesses reciprocal omega coupling which is due to the asymmetrical position of the cross-dipole array. Furthermore, bianisotropic chiral coupling and moving coupling are negligible.

As it can be seen from (6) and (7), Tellegen coupling can enable a metasurface to behave asymmetrically in cross polarized reflection for incident waves hitting its different sides (i.e., $R^{cr}_{\leftarrow} \neq R^{cr}_{\rightarrow}$). Figure 5(a) and 5(b) compare $R^{cr}_{\leftarrow}$ and $R^{cr}_{\rightarrow}$ for the non-bianisotropic metasurface shown in Fig. 2(a), and the bianisotropic Tellegen metasurface presented in this section [see Fig. 2(b)]. It can be seen that introducing Tellegen non-reciprocity allows different cross-polarized reflection for waves hitting metasurface's different sides. For example figures 5(c) and 5(d) show the reflection and transmission coefficients for a metasurface which reflects waves differently, depending on which side is illuminated. The metasurface imposes a polarization rotation of 48° for a wave hitting one side and 8° for a wave hitting the other.



(a) (b) (c) (d)

Figure 5: Co- and cross-polarized reflected power for (a) non-bianisotropic metasurface shown in Fig. 2(a) and (b) bianisotropic Tellegen metasurface shown in Fig. 2(b). (c) Amplitudes and (d) phases of co- and cross-polarized reflections for the bianisotropic Tellegen metasurface shown in Fig. 2(b).

4.2 Moving metasurfaces

It has been known for a long time that a medium in motion exhibits non-reciprocity [25]. It has been shown that the constitutive relations similar to those of a medium in motion can be achieved using stationary, artificially engineered particles [26]. In fact, these artificial particles are at rest, but mimick the electromagnetic properties of a medium that is moving. In order to behave electromagnetically as a medium in motion, these stationary particles must possess a special type of non-reciprocal electromagnetic coupling called bianisotropic moving coupling. In [12, 20], it was shown that a metasurface formed by an array of these inclusions can present unprecedented properties. However these particles have used magnetized ferrites which complicates their implementation. Here, we propose an alternative design for a moving metasurface [see Fig. 2(c)]. The choice of an array of rotated cross dipoles can be understood from the definition of moving coupling in (4), and its role in scattering from the metasurface [see (1), (6), and (7)]. As it can be seen from these equations, in a bianisotropic metasurface an incident magnetic (electric) field should contribute in creation of an electric (magnetic) moment in the metasurface which is orthogonal to the incident magnetic (electric) field. It is necessary to emphasize once more that by a moving metasurface we mean a metasurface which mimics the electromagnetic properties of a real moving medium while remaining stationary. The normalized surface-averaged effective polarizabilities for this layer are shown in Fig. 6. It is evident that the proposed metasurface possesses considerably strong bianisotropic moving coupling. From (6) and (7), it is clear that bianisotropic moving coupling can make a metasurface behave asymmetrically in terms of co-polarized transmission coefficient for waves hitting its different sides. Figures 7(a) and 7(b) compare $T^{co}_{\leftarrow}$ and $T^{co}_{\rightarrow}$ for this metasurface and the non-bianisotropic metasurface shown in Fig. 2(a). Introducing bianisotropic moving coupling into the metasurface clearly makes it behave asymmetrically for waves hitting its different sides.

Figure 6 shows that in addition to bianisotropic moving coupling, all the other forms of electromagnetic couplings are present in the proposed metasurface. This is a very interesting point, which deserves further attention. Let us think of a generic bianisotropic metasurface (for the sake of clarity we name different sides of the metasurface: A and B). First, suppose side

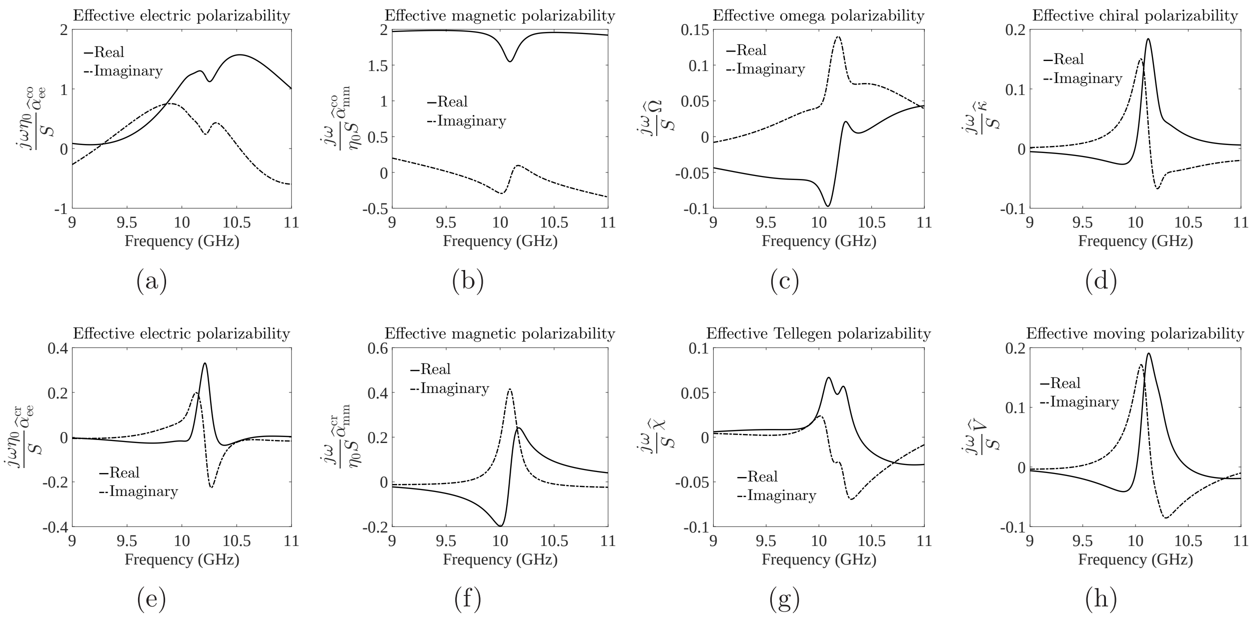


Figure 6: Normalized surface-averaged effective (a) co-polarized electric, (b) co-polarized magnetic, (c) omega, (d) chiral, (e) cross-polarized electric, (f) cross-polarized magnetic, (g) Tellegen, and (h) moving polarizabilities for the bianisotropic moving metasurface shown in Fig. 2(c).

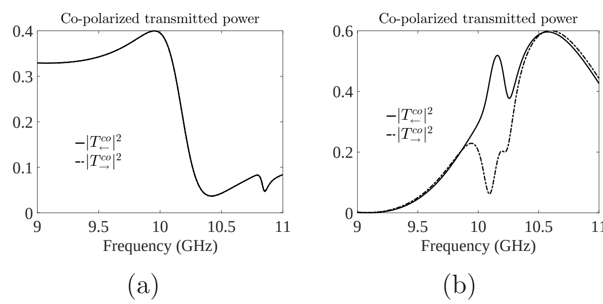


Figure 7: Co- and cross-polarized transmitted power for (a) non-bianisotropic metasurface shown in Fig. 2(a) and (b) bianisotropic moving metasurface shown in Fig. 2(c).

A of the metasurface is normally illuminated with a plane wave. The metasurface may start to scatter four different possible channels: co-polarized backward, cross-polarized backward, co-polarized forward, and cross-polarized forward waves. Equations (6) and (7) show that the same metasurface can scatter differently when illuminated from its B-side, depending on the class of bianisotropic coupling present in the metasurface. A metasurface possessing all four different classes of bianisotropic coupling can behave asymmetrically in terms of co- and/or cross-polarized reflection and/or transmission coefficients, when illuminated from its different sides. Such a metasurface can provide a very powerful platform for manipulating electromagnetic wavefronts. It could allow providing two different functionalities for waves hitting its opposite sides.

5 Conclusions

Two novel designs for magnet-free, non-reciprocal bianisotropic metasurfaces were proposed. These designs are based on the non-gyrotropic, non-reciporocal, magnetic metasurface proposed in [16]. However the same concept can be applied to any of the recently proposed magnet-free, non-reciprocal metasurfaces (e.g., [17]). The concept proposed in this paper takes us one step closer to designing next generation metasurfaces capable of tailoring co- and/or cross-polarized scattering (forward and/or backward scattering) independently for waves hitting their opposite sides.

Acknowledgments

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