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Engineering coupling in electromagnetic topological models via staggered bianisotropy

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Abstract. Magneto-electric coupling known also as bianisotropy plays a fundamental role in time-reversal-invariant photonic topological metamaterials being responsible for opening of a topological bandgap. To further uncover the fundamental link between bianisotropy and photonic topological states, we investigate scattering of light from the individual bianisotropic disk and reveal polarization dependence of scattering which provides a photonic analogue of spin Hall effect originating from the coupling between electric and magnetic responses of the disk. Based on the field patterns from the individual meta-atom, we further design a linear array of such bianisotropic disks. Employing coupled-dipole model, we demonstrate that local modification of the disk bianisotropy translates into the modification of coupling constants in the effective photonic Hamiltonian thus opening an avenue to engineer electromagnetic topological states via the staggered bianisotropy pattern. To confirm our findings, we realize a representative example of such one-dimensional array experimentally and detect the interface states at the domain wall.

1. Introduction
Photonic topological structures open up a diversity of intriguing phenomena including one-way propagation of light and enhanced robustness to disorder and imperfections [1, 2]. Two major classes of photonic topological insulators include structures with broken time-reversal symmetry and time-reversal-invariant topological systems, the latter being especially promising for scaling down to optical wavelengths. One of the key strategies to realize such time-reversal-invariant systems is based on the concept of bianisotropic metamaterials, in which case careful design of the structure ensures the degeneracy of TE and TM modes, whereas magneto-electric coupling is responsible for the opening of a topological bandgap [3, 4] playing the role analogous to spin-orbit coupling in Kane-Mele model for solid state systems [5].

Therefore, bianisotropy has a crucial role in the formation of photonic topological states. However, it still remains unclear whether spatial variation of bianisotropy can enable novel types of photonic topological structures. In this work, we approach this fundamental problem in the following way: first, we investigate the scattering of light by a single bianisotropic disk with magneto-electric coupling enabled by the broken inversion symmetry. Second, combining such disks into an array and analyzing the patterns of the field from the disks, we propose

a mapping of such electromagnetic eigenmode problem onto the eigenvalue problem for the effective Hamiltonian. Our key finding is that the coupling amplitudes in the obtained effective Hamiltonian are controlled by the *local* bianisotropic responses of the two neighboring disks. This finding has far-reaching implications for the design of photonic topological structures. To support our claims further, we design a linear one-dimensional array of bianisotropic disks and observe interface states at the boundary between the two domains of the array with inverted sign of magneto-electric coupling.

2. Polarization-dependent scattering from a single disk

First we analyze the scattering of a plane wave from a single disk. Breaking mirror symmetry of the disk in Oxy plane results in the emergence of magneto-electric polarizabilities $\hat{\alpha}^{\mathrm{em}}$ and $\hat{\alpha}^{\mathrm{me}}$ with nonzero xy component. In the other words, x (y) component of electric field can induce magnetic dipole moment along y (x) direction, whereas x (y) component or magnetic field gives rise to electric dipole moment along y (x) axis. The interplay of electric and magnetic responses of the disk supplemented by bianisotropic response causes polarization-dependent scattering which results in the dependence of the disk scattering diagram on polarization of impinging wave.

We have carried on numerical simulations in CST Microwave Studio software package for the geometry of disk illumination shown in Fig. 1(a). The results of simulation suggest that the maximum of the disk scattering diagram rotates in Oxy plane when the linear polarization of the wave quantified by the angle ψ is continuously varied [Fig. 1(b)]. In fact, such polarization-dependent routing of light can be interpreted as photonic analogue of spin Hall effect, where magneto-electric coupling plays the role analogous to spin-orbit coupling in condensed matter systems.

Quite importantly, flipping of the disk over results in the change of its scattering diagram since magneto-electric coupling reverses the sign under spatial inversion. A direct consequence of this is the dependence of field overlap for the two disks on their local bianisotropic responses.

3. Array of bianisotropic disks with alternating bianisotropy

To provide a clear demonstration that the staggered pattern of bianisotropy allows one to engineer the coupling between the disks, we design a linear array of equidistant disks shown in Fig. 1(c). The effective coupling between the two disks is governed by the overlap of their near fields, which in turn depends on local bianisotropic responses of the neighboring disks. Therefore, one could expect that electromagnetic eigenmode problem for the array depicted in Fig. 1(c) can be mapped onto the tight binding problem illustrated schematically at the bottom part of Fig. 1(c). Of course, such mapping is not exact and holds only provided the radiation losses are small enough and the coupling of the next nearest neighbors can be neglected.

To verify these qualitative arguments, we have constructed an experimental sample consisting of 12 dielectric disks made of high-permittivity ceramics with $\varepsilon = 39$ having electric and magnetic dipole resonances for dipoles in plane Oxy at frequencies $2.4 - 2.5$ GHz.

Fabricated structure was excited by the two dipole antennas placed symmetrically at some distance from the domain wall to ensure the proper symmetry of excitation. The distribution of the near fields in the array was further examined with a probe antenna. Most importantly, a significant localization of the field at the domain wall has been observed, whereas no edge or interface states has been detected in the case of a linear array of equidistant disks with the same magnitude of bianisotropy parameter.

To provide a theoretical interpretation of the observed interface states, we developed a model based on coupled dipole approach and proved that in the limit of strong bianisotropy the eigenmode problem can indeed be restated as a simple tight-binding model with the pattern of couplings shown in Fig. 1(c). Furthermore, deriving the effective photonic Hamiltonian, we
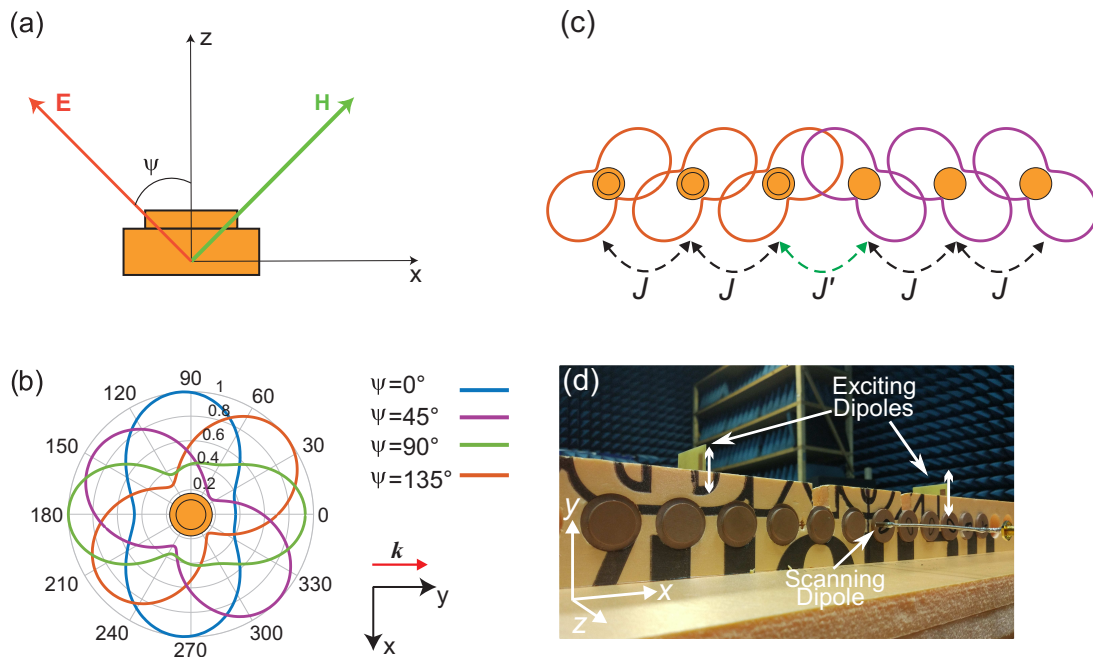
Figure 1. Illustration of polarization-dependent scattering from a single bianisotropic disk and eigenmodes of a one-dimensional array of such disks. (a) Geometry of illumination of a single disk. Incident wave propagates along y axis. Bianisotropy of the disk response is ensured by breaking the mirror symmetry in Oxy plane. (b) Scattering diagrams for different polarizations of impinging plane wave quantified by the angle ψ. (c) Illustration of the idea to modify coupling parameters in the effective photonic Hamiltonian by local modification of the disk bianisotropy. (d) Photograph of experimental structure used to prove the existence of the interface states which provide photonic realization of Jackiw-Rebbi states. Each of meta-atoms is made of two coaxial ceramic disks with the diameters $d_1 = 29.1$ mm and $d_2 = 22.0$ mm and heights $h_1 = 9.0$ mm and $h_2 = 3.0$ mm, respectively. The period of the lattice is $R = 36$ mm. White arrows show the polarization of dipole antennas used for the structure excitation.

have proved that it has the Dirac-type form and thus the interface states serve as photonic analogue of Jackiw-Rebbi states.

We believe that our findings provide a feasible option to engineer effective photonic Hamiltonians via the modification of local bianisotropic responses thus enabling new types of photonic topological states not only in one-dimensional structures, but also in the systems of higher dimensionality.

Acknowledgments

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