Experimental realization of three-dimensional all-dielectric photonic topological insulators

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***Abstract*— Significant progress has recently been made in the study of topological states in photonic topological systems. Being motivated by the recent theoretical proposal of three-dimensional topological structures based on high-permittivity bianisotropic particles, here we verify experimentally the concept of three-dimensional all-dielectric photonic topological insulators in the microwave frequency range. We demonstrate an excitation of topological surface states in the near field as well as their impact on the far-field radiation where the propagation direction is dictated by the excitation of a particular pseudo-spin.**

Keywords—photonic topological insulator; dielectric metamaterials; surface states

I. Introduction

Theoretical predictions and experimental realizations of photonic topological systems have demonstrated fascinating properties of their electromagnetic modes and opened avenues for their use in practical systems and devices [1]. However, most of these systems have been restricted to topological states either in one or in two dimensions [2]. Only very recently, a research on three-dimensional (3D) topological states, including photonic analogues of topological semimetals [3-5] and topological insulators (TIs) [6,7] have been proposed. One of the system is based on the concept of all-dielectric metacrystal [6] that preserve time-reversal symmetry and thus avoids the limitations imposed by magnetic materials in the alternative TI system [7]. By relying entirely on the dielectric platform - which also avoids the undesirable effects of Ohmic losses necessarily present in metallic and plasmonic structures - this concept can support 3D topological order for light.

In this contribution, we provide the first experimental verification of the concept of the 3D photonic TI by fabricating and characterizing all-dielectric microwave metacrystal. We find an excellent agreement between the experimental data and numerical results and verify experimentally the existence of the topological surface states as well as their contribution to the far-field radiation.

II. Results

The topological photonic metacrystal introduced here is schematically shown in Fig. 1. It features a hexagonal lattice of asymmetric dielectric disks with permittivity 39 embedded into a matrix with permittivity close to one. To achieve 3D topological metacrystal, one can stack these hexagonal lattices periodically in the *y*-direction.

In the case of symmetric dielectric disks (meta-atoms), their 3D periodic arrangement is designed so that the photonic band structure exhibits two overlaid 3D Dirac points near the K and K' points in the Brillouin zone. Each of the Dirac bands originates from the electric and magnetic dipolar modes of the dielectric disks. Owing to the proper design an electromagnetic duality can be restored in such a structure [6]. However, an introduction of asymmetry of meta-atoms in the vertical direction results in the coupling of the in-plane electric and magnetic modes and the opening of a complete photonic bandgap in place of the former Dirac points. This magneto-electric coupling, referred to as bianisotropy, has an effect equivalent to the spin-orbit interaction in condensed-matter systems.

The eigenmodes of the structure with bianisotropy are mi-

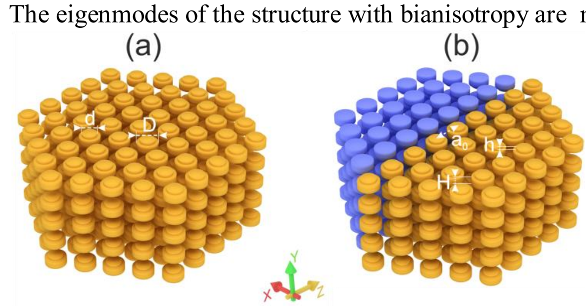

Fig.1. Three-dimensional all-dielectric metacrystals (a) without and (b) with the domain wall. Parameters are: a_0 = 41 mm, D = 29.14 mm; d = 22 mm, ε = 39, H = 9 mm; h = 3 mm, the distance between the layers is 20 mm.

xed states with in-plane electric and magnetic dipolar components which are locked in both orientation and phase. Such mixed states are referred to as pseudo spin-up and spin-down states. These new states possess topological properties which are characterized by non-vanishing spin-Chern numbers [6].

The major interest in 3D topological metacrystals lies in the fact that they support robust surface states at their interfaces. The interfaces supporting such states can be divided into two classes: i) domain walls, which represent interfaces between structures possessing different topological characteristics [Fig. 1(b)] and ii) interfaces with non-topological domains [Fig. 1(a)]. We have performed numerical simulations for the two mentioned cases using CST Microwave Studio 2017. The structures were excited by the plane wave [see Fig. 2 (a,b)]. Fig. 2 (c,d) show in-plane maps of electric field intensity for the first class of a topological interface. The two domains represent crystals with opposite orientation of the meta-atoms in the vertical direction (Fig. 1(b) and Fig. 2 (a)), thus effectively creating a topological interface. The topological surface state appears, as expected, at the domain wall. It is worth to note that the simulations show the emergence of the surface state on the external boundary with free space even in the case without the domain wall [see Fig. 2(d)].

To verify numerical results, we have fabricated metacrystals by periodically stacking ceramic disks. Each layer (total five layers) consists of 61 bianisotropic dielectric particles located on the substrate with permittivity close to 1.

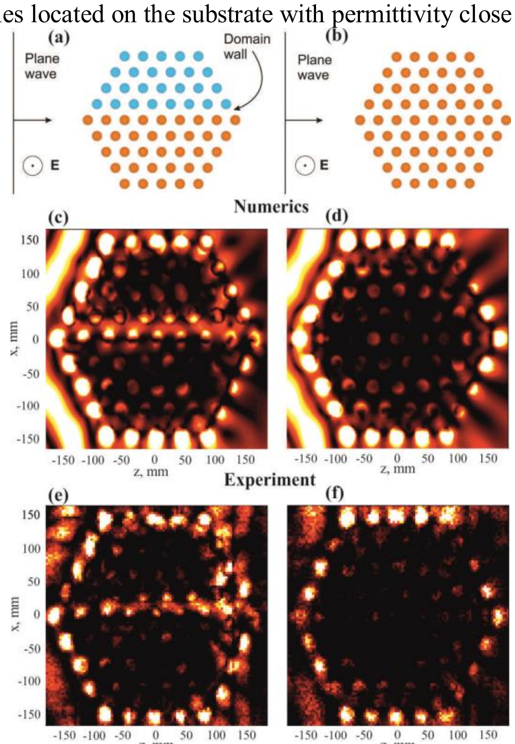

Fig. 2. Schematic representation of the models with (a) and without (b) domain wall used in numerical simulations. Numerically calculated field intensity maps obtained in the central layer of the structures (c) with and (d) without domain wall. Near-field maps measured in the vicinity of the central (third) layer for structures (e) with and (f) without domain wall.

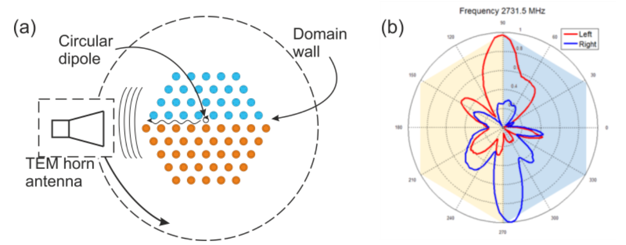

Fig.3. (a) Schematic representation of the experimental setup. The circularly polarized dipole source is located in the third layer at the domain wall almost in the center of the structure and the radiation in the far-field is collected by the horn antenna. (b) Radiation patterns, measured for the right- (blue) and left- (red) circular polarizations of the source at the frequency of 2.73 GHz.

To measure the field intensity we used an automatic mechanical near-field scanning device and an electric field probe connected to the receiving port of the analyzer and a single TEM-horn antenna as a source. The experimental results of Fig. 2 (e, f) are in excellent agreement with numerical results for both cases.

Next, we proceed to the far-field characterization of the topological surface states. By placing the dipole source in the center of the crystal at the domain wall (see Fig. 3 (a)), we performed the characterization of the radiation pattern in an anechoic chamber. The control of the polarization of the dipole antenna enables selective excitation of the mode with specific angular momentum. Thus, circular left or right polarization excites a surface state with a particular pseudo-spin locked to its propagation direction. Such directionality, combined with the lack of reflection at interfaces, resulted in a highly asymmetric direction far field radiation pattern [Fig. 3 (b)].

In summary, we have demonstrated experimentally the first implementation of 3D all-dielectric photonic topological insulators based on bianisotropic metacrystals. Our measurements have revealed the excitation of surface states in the near-field and their contribution to the directive far-field radiation defined by the polarization of the source.

Acknowledgments

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References

[1] L Lu, J.D. Joannopoulos, M. Soljačić, "Topological photonics," Nat. Photon., vol. 8, 821, 2014.

[2] A. B. Khanikaev, G. Shvets, "Two-dimensional topological photonics," Nat. Photon., vol. 11, 763, 2017.

[3] L. Lu et al., "Experimental observation of Weyl points," Science, vol. 349, 622, 2015.

[4] Jiho Noh et al., "Experimental observation of optical Weyl points and fermi arc-like surface states," Nat. Phys. vol. 13, 611, 2017.

[5] M. Xiao, Q. Lin, and S. Fan, "Hyperbolic Weyl Point in Reciprocal Chiral Metamaterials," Phys. Rev. Lett. vol. 117, 057401, 2016.

[6] A. Slobozhanyuk et al., "Three-Dimensional All-Dielectric Photonic Topological Insulator", Nat. Photon., vol. 11, 130, 2017.

[7] L. Lu et al., "Symmetry-protected topological photonic crystal in three dimensions," Nat. Phys., vol. 12, 337, 2016