Effective control of electromagnetic waves through topological microwave metamaterials

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***Abstract*— Studying topological properties of electromagnetic systems discloses an exceptional control on electromagnetic waves propagation, robust against disorder and structural imperfections. In this report, we summarize the latest results of the awardee's Ph.D. project related to electromagnetic topological structures. We employ the concept of metamaterials to experimentally realize three-dimensional photonic topological insulators and higher-order photonic topological insulators in the microwave frequency range. Their investigations unveil advanced possibilities to engineering novel topologically-protected low-loss devices and show promises for a wide range of microwave applications.**

***Index Terms*—Topological photonics, metamaterials, higher-order topological insulators**

I. Introduction

Topological photonics [1] is a rapidly developing research area promising a powerful platform for applications in microwaves and photonics. Significant progress in studying electromagnetic topological systems reveals plenty of ways, which are usually counterintuitive, to manipulate electromagnetic waves [2-3].

The most common approach to realize electromagnetic topological systems is based on metamaterials that are artificial periodic structures with extraordinary properties unreachable in nature. The goal of this project is to experimentally investigate two directions of topological photonics: (a) three-dimensional (3D) and (b) higher-order electromagnetic topological structures based on metamaterials platform.

II. Three dimensional photonic topological insulators

Theoretical studying of topological properties in electromagnetic systems gave rise to electromagnetic analogs of topological insulators demonstrated fascinating properties of their electromagnetic states [3]. However, the main focus of the research was directed on two-dimensional topological systems [4]. Recently, research on three-dimensional electromagnetic topological insulating structures has been proposed [5,6] and realized [7]. In this part of the project, we have experimentally realized three-dimensional *all-dielectric* photonic topological insulators based on the theoretical model [6].

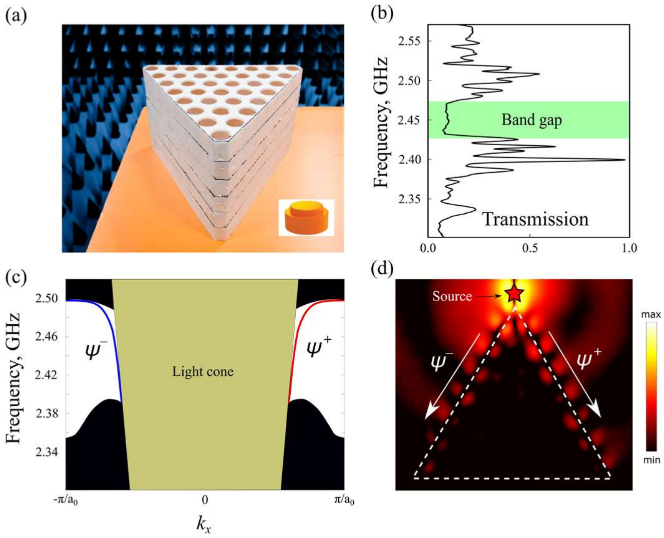

Fig. 1. Three-dimensional photonic topological system: (a) photo of the sample, where the inset shows the unit-cell of the structure, (b) measured transmission coefficient, (c) band structure for topological boundary states on the metacrystal/air interface, black areas are bulk bands colored lines are boundary states (d) measured near-field profiles of photonic topological boundary states.

A three-dimensional all-dielectric photonic topological insulator is shown in Fig.1a. The structure represents a 3D hexagonal lattice composed of bianisotropic cylindrical meta-atoms with dielectric constant equals to 39. Bianisotropy, which plays the role of effective spin-orbit interaction, opens a complete photonic topological bandgap [6]. We optimized the geometry to obtain the bandgap in the microwave frequency range. The measured transmission between two sub-wavelength dipole antennas is shown in the Fig.1b demonstrating the bandgap 2.43-2.48 GHz.

The consequence of the topological insulating phase is the emergence of edge states on the interface between topologically distinct systems. In contrast to previous studies, we considered 3D topological meta-crystal in air surrounding and observed for the first time the emergence of topological boundary states on the side surfaces. The numerically calculated band structure of

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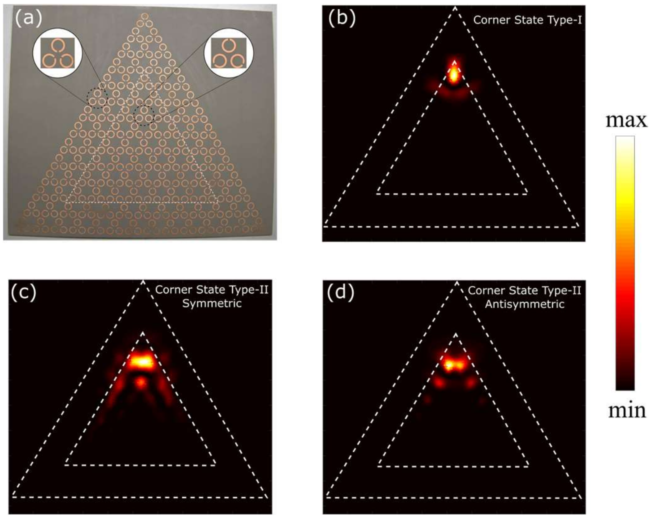

Fig. 2. Higher-order photonic topological system: (a) photo of the sample, where the insets show the unit-cells of the adjacent domains, (b-d) measured near-field profiles of higher-order photonic topological states. Dashed white lines show boundary of the different domains.

these states is shown in Fig.1 (c). It turns out that the boundary states are one-way and circularly polarized (left ψ^- and right ψ^+as shown in Fig.1c,d) and counter-propagating modes characterized by opposite polarizations. We verify our theoretical predictions experimentally using near-field scanning technique in microwaves (Fig.1d).

III. Higher-order photonic topological insulators

Recent advances in condensed matter physics gave rise to a new class of topological systems, called higher-order topological insulators [8], that support boundary modes two or more dimensional lower than the system itself. They provide advanced opportunities to control topological states. In this part of the project, we bring a new approach to engineer HO electromagnetic topological states and experimentally realize HO photonic topological insulator based on bianisotropic metasurfaces.

The considered HO topological structure is shown in Fig.2a. It represents a metasurface composed of split-ring resonators (SRR) located at the nodes of the Kagome lattice. The structure consists of two domains with different orientations of the SRR slits, as shown in the insets of Fig.2a. Importantly, the orientation affects on topology making the outer domain topologically trivial and the inner one topologically non-trivial what ensures the emergence of topological states on their interface.

We have fabricated HO topological structure using PCB-technique with the bulk band gap in microwave frequency range and studied it using near-field scanning technique. Inside the band gap we observe topological edge state (not shown here) and higher-order topological corner states of the type-I (Fig.2b). Additionally, the experimental data demonstrates the emergence of symmetric (Fig.2c) and antisymmetric (Fig.2c) higher-order topological corner states of type-II that were predicted in our recent paper [9]. Importantly, those type-II states emerge due to long-range interactions specific to electromagnetic systems.

IV. Conclusion

In the first part of the project, we have realized and studied experimentally three-dimensional all-dielectric photonic topological insulator based on bianisitropic metamaterials. We experimentally observed the emergence of one-way circularly polarized topological boundary states on the side surfaces of the structure in air surrounding. Our findings uncover the possibilities to investigate topological phenomena at open boundaries.

In the second part of the project, we have demonstrated a new design of higher-order photonic topological structures based on bianisotropic metasurfaces. We observed experimentally the emergence of higher-order photonic topological corner states of both type-I and type-II. This approach can be extended to engineer three-dimensional higher-order topological structures.

The results of both parts of the work are in preparation to be submitted in high-impact journals.

Acknowledgment and career plans

I would like to thank IEEE MTT-S for choosing me as a recipient of the Graduate Fellowship. The Award extremely helped me during doctoral school and owing to it I have recently defended my Ph.D. thesis. The receipt of the Fellowship gave me confidence in myself and granted the opportunity to expand my knowledge in electromagnetic topological structures.

Currently, I am working in the academia and continuing the research on advanced electromagnetic topological structures. The MTT-S Fellowship motivated me to start interacting with industry in the field of topologically robust waveguides that I am already doing.

Finally, I am thankful to Prof. Alexander Khanikaev, Dr. Alexey Slobozhanyuk, and Dr. Maxim Gorlach for their support during my doctoral studying.

References

[1]. T. Ozawa, *et al.*, "Topological photonics," *Rev. Mod. Phys.* 91, 015006, 2019.
[2]. Z. Wang, *et al.* "Observation of unidirectional backscattering-immune topological electromagnetic states," *Nature* 461, 772–775, 2009.
[3]. A. B. Khanikaev *et al.*, "Photonic topological insulators," *Nat. Materials*, vol. 12, 233, 2013.
[4]. A.B. Khanikaev & G. Shvets, "Two-dimensional topological photonics." *Nat. Photon.* 11, 763–773, 2017.
[5]. L. Lu, *et al.*, "Symmetry-protected topological photonic crystal in three dimensions," *Nat. Phys.* 12, 337–340, 2016.
[6]. A. Slobozhanyuk, et al., "Three-dimensional all-dielectric photonic topological insulator," Nat. Photon. 11, 130–136, 2017.
[7]. Y. Yang, *et al.*, "Realization of a three-dimensional photonic topological insulator," *Nature* 565, 622–626, 2019.
[8]. W. A. Benalcazar, B. A. Bernevig, and T. L. Hughes, "Quantized electric multipole insulators," *Science* 357, 61, 2017.
[9]. M.Li *et al.*, "Higher-order topological states in photonic kagome crystals with long-range interactions," *Nat. Photon.* 14, 89-94, 2020.

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