Near-field manipulations with microwave metamaterials in order to design highly efficient novel devices

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***Abstract*— Microwave metamaterials are prominent candidates for the development of a new generation of the devices which will possess a different functionality. This is due to the fact that the unit cells dimensions of the metamaterials have to be much smaller than the operational wavelength of the device and therefore it simpler to develop it in microwave frequency range rather than in the visible spectrum. Here we employ the unique properties of metamaterials to manipulate and sculpt the electromagnetic near-field. The latest gives an opportunity to design novel devices for different applications, including topologically protected metamaterials for loss-free communications and metamaterial based resonators for enhancement of Magnetic Resonance Imaging characteristics**

***Index Terms*—Metamaterials, Magnetic Resonance Imaging, Topological Photonics**

I. INTRODUCTION

THE extensive fundamental research in the area of metamaterials in the past 15 years has created a foundation for the next stage of developing metamaterial applications. The general idea of this project was to employ the unique properties of metamaterials to manipulate and sculpt the electromagnetic near-field. In particularly I was focused on two main directions: (i) topologically protected metamaterials for loss-free communications and (ii) metamaterial based resonators for enhancement of Magnetic Resonance Imaging (MRI). Below, I summarized the main results of this project.

II. TOPOLOGICALLY PROTECTED METAMATERIALS FOR LOSS-FREE COMMUNICATIONS

The study of the spin-orbit interaction of light has been a driving force for the development of many concepts of topological photonics [1] dealing with photons instead of electrons and revealing optical analogies of the scattering immune surface states. In this project, we show experimentally and numerically how to engineer two-, and three-dimensional topologically nontrivial electromagnetic structures based on subwavelength metallic meta-atoms and all-dielectric components.

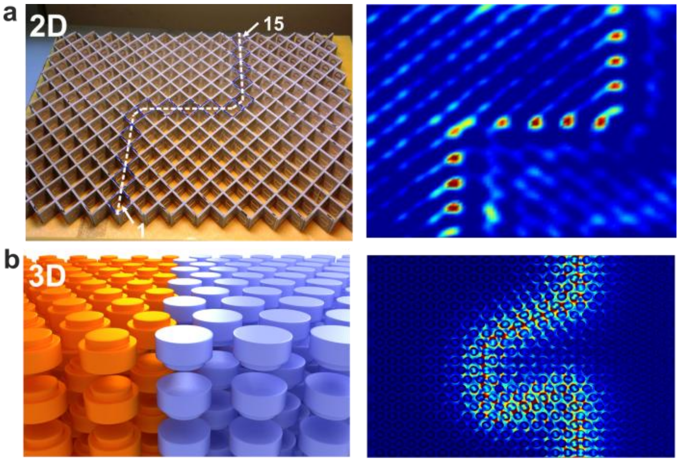

Fig. 1. (a) Experimental two-dimensional metacrystal and the observation of topological edge modes. (b) Three-dimensional all-dielectric metacrystal with the vertical domain wall formed by the reversal of the mass term induced by bianisotropy (left panel). Topological robustness of surface states propagating along a sharply curved two-dimensional domain wall formed in the middle of the all-dielectric three-dimensional topological insulator (right panel).

We consider the bianisotropic metacrystals [2] which is a very important system to explore topologically nontrivial states. These metacrystals allow emulating the quantum spin Hall effect directly. The method relies on the engineering of material parameters restoring spin/polarization degeneracy of electromagnetic waves followed by the engineering of the spin-orbit interaction, which leads to the appearance of topologically nontrivial photonic states with exceptional properties [2]. We have performed the first experimental demonstration of topologically nontrivial bianisotropic metamaterials [3]. We have suggested and realized a new type of engineered metasurface with an interface, supporting the propagation of topologically protected electromagnetic waves and demonstrated guiding around sharp corners and no backscattering (Figure 1a, left panel). By employing near field scanning techniques, we were able to directly map topologically nontrivial electromagnetic modes flawlessly guided around sharp corners in different open, two-dimensional photonic systems, including all-dielectric metasurfaces (Figure 1a, right panel).

Also, we have suggested a way to design three-dimensional

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all-dielectric photonic topological metacrystals. Our design is based on a 3D hexagonal lattice of dielectric disks, where the duality symmetry, which is typically broken by an uneven material's response to electric and magnetic fields, is restored for the in-plane components thanks to its careful design, and the inversion symmetry is broken by removing part of the dielectric disks (see Figure 1b). We numerically demonstrated that helical electromagnetic excitations supported by the proposed topologically nontrivial metamaterial are tolerant to sharp bends and propagate without reflection in three-dimensions (Figure 1b, right panel). Electromagnetic radiation in the form of topological surface modes flows unimpeded along arbitrary contours defined by the synthetic gauge field, which envisions implementation of topologically robust three-dimensional photonic circuitry from microwave frequencies to the optical domain [4].

III. METAMATERIAL BASED RESONATORS FOR ENHANCEMENT OF MAGNETIC RESONANCE IMAGING

We reveal that the unique properties of ultrathin metasurface resonators can improve dramatically MRI characteristics [5]. We have realized a metasurface as an array of 14×2 wires. The studied biological sample has been placed on the metasurface structure, embedded inside the water phantom and placed in a 1.5 T MR scanner, that has operating frequency 63.8 MHz. First, we have made experimental measurements of the signal to noise ratio (SNR) in the region of interest under the metasurface. We determined the ratio $\mathrm{SNR}_2/\mathrm{SNR}_1 \approx 2.7$, where SNR_2 corresponds to the ratio with the metasurface inside the phantom and SNR_1 corresponds to the ratio for the empty phantom. The enhancement of the SNR with addition of metamaterial (Figures 2a) is due to the resonant coupling to electromagnetic modes of the metasurface. The SNR enhancement effect is observed up to 7 cm of the scan depth from the surface (Fig. 2(b)). Figures 2(c,d) show numerically calculated specific absorption rate (SAR) value. The Food and Drug Administration specified that average SAR value should not exceed 4 W/kg for a whole body scan. In Figs. 2(c,d) we estimated the so-called safe – "object" region (marked as black dashed rectangle), where the SAR value for applied continuous power of 16.6 W is smaller than 4 W/kg in the presence of the metasurface. This region is equal to 68% of the metamaterial length. Moreover, it should be mentioned that if the object is placed near the central part of the metasurface, the SAR values are even smaller than without the metasurface. This happens due to the specific resonant mode structure of the metamaterial with the region of minimum value of radiofrequency electric field. It is important to note that the SNR enhancement effect in the metasurfaces has been further advanced in in-vivo imaging and spectroscopy of the human brain at 7T [6].

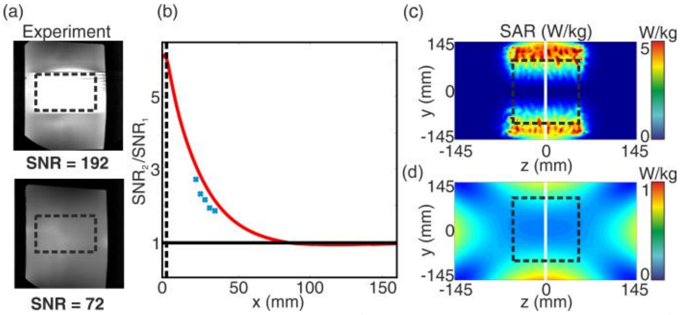

Fig. 2. (a) MRI images and SNR values for the phantom with the presence of metasurface (upper figure) and without it (bottom figure). The black dashed rectangle corresponds to the safe – "object" – zone. (b) Numerically calculated (red curve) and experimentally measured (blue symbols) ratio between SNR with the metasurface and without it in depth (along the x direction). SAR (10g) map calculated in the phantom (c) near the metasurface and (d) without it.

IV. CONCLUSION

The results of this project bridges a gap between the fundamental ideas of metamaterials and applications spanning the research fields from electromagnetic engineering of highly efficient topologically protected microwave and optical components (e.g. waveguides) to medical diagnostics.

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