All-dielectric bianisotropic metasurfaces

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Abstract – Bianisotropic all-dielectric metasurfaces are demonstrated experimentally and their properties are studied in the microwave frequency range. Such metasurfaces are composed of dielectric particles with broken symmetry that exhibit different backscattering for the opposite excitation directions. An array of dielectric bianisotropic ceramic particles is fabricated and experimentally investigated for microwaves. The measured data demonstrate that the metasurface is characterized by different reflection phases when being excited from the opposite directions. At the frequency 6.7 GHz the metasurface provides a 2π phase change in the reflection spectrum with the amplitude close to 1.

I. INTRODUCTION

Metasurfaces are two-dimensional metamaterials consisting of arrays of subwavelength unit cells. They allow to control and manipulate the properties of electromagnetic waves by employing the concepts and designs of flat optics [1]. This includes a control of a specific phase, amplitude, and polarisation of electromagnetic waves [1, 2]. Metasurfaces also inherit basic metamaterial features such as their compact dimensions, broadband operation, and ability to implement various electromagnetic properties and functionalities [2, 3].

Recently, high-index *dielectric* metasurfaces attracted a lot of attention because, when compared to the metasurfaces with metal particles, they do not suffer from detrimental effects of absorption and heating [4, 5]. In particular, it was shown that metasurfaces with both electric and magnetic dipolar responses can suppress dramatically the wave reflection, increasing significantly overall metasurface efficiency [6, 5]. A better control of electromagnetic radiation can be achieved by exploiting *magnetoelectric coupling* (or *bianisotropy*) of the metasurface elements in addition to their electric and magnetic dipolar response [7, 8]. Magnetoelectric coupling occurs whenever an electric (magnetic) response is induced by a local magnetic (electric) field [7]. This coupling leads to an asymmetric response of the metasurface when being illuminated from opposite directions [8]. Depending on the specific kind of bianisotropy, the asymmetry may occur in reflection, transmission, or in both [9, 10]. This allows in particular to polarize incident waves [10] or to make a metasurface transparent from one direction while being fully opaque from the opposite direction.

Here we demonstrate experimentally all-dielectric bianisotropic metasurface operating at microwave frequencies. We study the extinction spectra of a single bianisotropic high-index particle as well as transmission and reflection spectra of bianisotropic metasurface made from such particles in the frequency range 4-9 GHz. We experimentally demonstrate the asymmetric reflection phases for the opposite excitation directions and the possibility to achieve a 2π phase change combined with an acceptable reflection amplitude which is close to 1. The properties of the array have been theoretically studied in [8] and confirmed here experimentally in the microwave spectrum.

II. BIANISOTROPIC METASURFACE

The metasurface under study is composed of bianisotropic high-index dielectric particles that are periodically arranged on a square lattice with a period $a = 2.7$ cm. The individual particle has a form of a cylinder with a finite hole inside [see inset to Fig. 1(a)]. The cylinder has a radius of $R = 1$ cm and a height of $H = 1$ cm. The radius of the hole inside the cylinder is $R_0 = 0.5$ cm and the height is $H_0 = H/2 = 0.5$ cm. The dielectric particle permittivity $\epsilon = 10$ and loss tangent $\tan\delta = 0.0007$. The ambient material is air.

Fig. 1: (a) Experiment setup for measurement of the metasurface scattering parameters. The inset demonstrates unit cell of the metasurface. (b) Simulated forward (presented by RCS^+) and backward (presented by RCS^-) scattering of a single bianisotropic particle.

First we studied numerically and experimentally radar cross section (RCS) of the single particle excited by a plane-wave. Under the forward excitation direction, we assume that the wavevector k is co-directional with the z coordinate, and refer to this propagation direction as k^+ . Under the backward excitation direction, we assume that the wavevector k is counter directional with the z coordinate, and refer to this propagation direction as k^- .

The numerical simulation was performed by using the Time Domain Solver of CST Microwave Studio. The particle surrounded with open boundaries was excited by a plane wave that propagates in the $\pm z$ direction with an electric field polarized along the x -axis. Broadband far field monitors were defined in order to calculate the bistatic RCS. The simulated results for a single particle are shown in Fig. 1 (b). One can see that the bianisotropic particle possesses an identical forward scattering (RCS^+) for both (k^+) and (k^-) excitation directions. However, the backward scattering (RCS^-) depends on the excitation direction. This clearly confirms the bianisotropic response sustained by the particle. At the frequency 7.4 GHz, the bianisotropic particle exhibits minimum in the backward scattering RCS^- for the forward excitation direction k^+ while for the backward excitation direction (k^-) backward scattering RCS^- is close to its maximum. In other words at some particular frequency near 7.4 GHz dielectric particle re-radiates field in forward and backward direction if the field goes in z^+ direction. At the same time this particle will re-radiate field only in forward direction if the field will incident in z^- direction.

III. EXPERIMENTAL INVESTIGATION

All-dielectric bianisotropic metasurface composed of the ceramic particles studied above have been fabricated and studied experimentally [see Fig. 1(a)]. An array of 9×9 inverse particle shapes was drilled in a custom holder made of a Styrofoam material ($\epsilon \approx 1$) and filled with a ceramic powder Eccostock HiK with $\epsilon = 10$ and loss tangent $\tan\delta=0.0007$ [11]. The period was $a = 2.7 \text{ cm}$, and the total size of the metasurface was $24 \text{ cm} \times 24 \text{ cm}$. The metasurface was placed in an anechoic chamber between two horn antennas at the distance of 2 meters from each antenna. The measurement frequency range was set to 1-18 GHz. The antennas were connected to the ports of the vector network analyzer. To avoid an additional reflection from the metasurface edges and also border effects, the metasurface perimeter was surrounded by microwave absorbers. Complex S-parameters of the system were measured for the forward and backward plane wave excitations. To suppress the effects of multiple reflections between the metasurface sample and the antennas, the postprocessing of measured data by means of time-domain gating was employed [12].

The measured amplitude and phase of the transmission and reflection coefficients are shown in Fig. 2. The measured phases of the transmission coefficient S_{12} and S_{21} are equally identical due to reciprocity of the system (thus we plot only S_{21} parameter). In a contrast, since the particles have small dielectric losses, the reflection coefficient S_{11} and S_{22} amplitudes have to be different for opposite excitation directions due to the magnetoelectric coupling [13]. The phase coverage from 0 to 2π is observed in the frequency range 5-9 GHz. In particular at the frequencies with the maximum reflection coefficients amplitudes (6.6 GHz and 7.6 GHz) the reflection phases are close to 2π .

Fig. 2: Measured (solid line) and simulated (dashed line) (a) amplitude and (b) phase of the metasurface transmission and reflection coefficients.

IV. CONCLUSION

In conclusion, we have designed, fabricated, and studied experimentally the all-dielectric metasurface composed of high-index dielectric bianisotropic particles with different backward and forward scattering. We have demonstrated experimentally bianisotropic properties of the metasurface consisting of periodically arranged all-dielectric bianisotropic particles, that can behave as a reflect array with a 2π reflection phase while being excited from one side, whereas remains transparent outside this operational frequency range.

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