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Total Absorption Based On Smooth Double-Turn Helices

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Abstract. The electrically thin absorber of electromagnetic waves is under study. We proposed a new concept of the perfect absorber which consists from a single layer of the smooth double-turn helices. This allows one to design an absorber with unprecedentedly small thickness. Simple and smooth shape of the helices makes them more preferable from experimental point of view in comparison to other chiral particles. The absorber implies absence of a ground plane. High efficiency of the realized structure in the S band is demonstrated.

Introduction

Bi-anisotropic media have multiple applications due to their electromagnetic coupling effects. One example of such structure is chiral medium. It was well-studied, e. g. in [1]. Electromagnetic devices working at higher frequencies are preferable and advantageous from practical point of view. Transition to optical and even terahertz frequencies implies new technologies of fabrication of such devices which allow producing metal inclusions with dimensions about tens of micrometers and less. But minimization of the dimensions is limited by capabilities of the modern manufacture. Also the modern manufacture makes it possible to create only the inclusions with smooth shape. Recently, a significant amount of works has been devoted to electrically thin totally absorbing layers. Electrically thin absorbers mostly imply the use of a ground plane [2] limiting electromagnetic response of the structure from the opposite side. Such two-layer structures possess asymmetrical properties and do not absorb radiation from the opposite side. We realize a conceptually new kind of a perfect absorber for incident electromagnetic waves. It consists of only a single array of double-turn helices (small electromagnetic dipolar inclusions). It allows us to design an absorber with extremely small thickness ($\lambda/15$) but still which provides necessary magnetic response. The induced electric and magnetic dipole moments in the inclusions under illumination do not scatter in backward direction but in forward direction they radiate secondary plane waves destructively interfering with incident ones (providing zero transmission) [3]. The equal electric and magnetic properties are achieved due to optimal shape of the inclusions and their certain arrangement in the array [4]. The realized absorber demonstrates highly efficient performance and operates symmetrically for incident waves from the two sides.

Conditions for total absorption

Small helices are electromagnetic particles of a sub-wavelength size. A regular planar array of the particles forms an artificial single-layer metamaterial, so-called “metasurface”. Incident waves induce oscillating electric $\boldsymbol{p}$ and magnetic $\boldsymbol{m}$ dipoles in the inclusions of a metasurface. In [5] it was shown that symmetrical perfect absorption operation can be accomplished only in a metasurface which has equally significant co-polarized electric and magnetic responses but possesses no electromagnetic coupling. Therefore, the induced moments in such a metasurface are orthogonal:

the electric and magnetic dipole moments are directed along the incident electric and magnetic fields, respectively. It is well-know that helices are chiral particles.

The array of chiral particles one can model as an array of electric and magnetic dipoles excited by normal incident wave propagating along $-\vec{z}_0$ direction. We model the properties of each inclusion in terms of the effective polarizability dyadics (marked by hats) which give the particle response to the incident fields [6]:

$$\begin{bmatrix} \vec{p} \\ \vec{m} \end{bmatrix} = \begin{bmatrix} \overline{\overline{\hat{\alpha}}}_{ee} & -j\overline{\overline{\hat{k}}} \\ j\overline{\overline{\hat{k}}} & \overline{\overline{\hat{\alpha}}}_{mm} \end{bmatrix} \cdot \begin{bmatrix} \vec{E}_{inc} \\ \vec{H}_{inc} \end{bmatrix}. \tag{1}$$

Here electric $\overline{\overline{\hat{\alpha}}}_{ee}$, magnetic $\overline{\overline{\hat{\alpha}}}_{mm}$ and electromagnetic $\overline{\overline{\hat{k}}}$ polarizabilities dyadics are symmetric (the case of reciprocal chiral coupling) since we consider a uniaxial array. Here, $E_{\rm inc}$ is the incident electric field.

The oscillating moments radiate secondary waves in backward

$$E_b = \frac{-j\omega}{2S}\left(\eta_0 p - \frac{1}{\eta_0} m\right) \tag{2}$$

and forward directions

$$E_f = \frac{-j\omega}{2S}\left(\eta_0 p + \frac{1}{\eta_0} m\right), \tag{3}$$

where $S=a^2$ is the unit-cell area, $j\omega p/S$ and $j\omega m/S$ are the surface-averaged electric and magnetic currents, respectively; $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the free space wave impedance.

Choosing the dipole moments in such a way that the forward radiated secondary wave interferes destructively with the incident one and the backward radiation is absent,

$$p = \frac{-jS}{\omega\eta_0} E_{\rm inc}, \; m = \eta_0^2 p \tag{4}$$

one can achieve total absorption in the meta-atom array.

Thus, realization of a single-layer meta-atom absorber requires engineering of certain electrically and magnetically polarizability inclusions providing necessary induced dipole moments (4).

Reflected and transmitted fields from the infinite array can be found [7]

$$\vec{E}_r = -\frac{j\omega}{2S}\left[\eta_0 \hat{\alpha}_{ee}^{co} - \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right] \cdot \vec{E}_{inc}\ , \tag{5}$$

$$\vec{E}_t = \left\{\left[1 - \frac{j\omega}{2S}\left(\eta_0 \hat{\alpha}_{ee}^{co} + \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right]\overline{\overline{I}}_t \pm \frac{\omega}{S}\,\hat{\kappa}\,\overline{\overline{J}}_t\right\} \cdot \vec{E}_{inc}\ , \tag{6}$$

where $\overline{\overline{I}}_t = \overline{\overline{I}} - \vec{z}_0\vec{z}_0$ is the two-dimensional unit dyadic, and $\overline{\overline{J}}_t = \vec{z}_0 \times \vec{I}_t$ is the vector-product operator.

Substituting conditions of total absorption $\vec{E}_r = 0$ and $\vec{E}_t = 0$ in equations (5) and (6) one can easily find the necessary conditions for the effective polarizabilities of the particles

$$\eta_0 \hat{\alpha}_{ee}^{co} = \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co} = \frac{S}{j\omega}, \qquad \hat{\kappa} = 0. \tag{7}$$

From the conditions (7) one can see that electric and magnetic effective polarizabilities of the particles must be equal and purely imaginary. Also we propose to use chiral inclusions but with compensated effective chirality of the whole structure.

Perfect absorber based on double-turn helices

Equal electric and magnetic responses can be accomplished in the helical inclusions with equal electric and magnetic polarizabilities. Such balanced electromagnetic properties are achieved in a helical inclusion with the following dimensions [8]: the total length of the wire is 41.7 mm, the radius of the helix is 3.3 mm, the height is 2.3 mm, the diameter of the wire is 0.5 mm, the pitch angle of the helix is 6.33°. The material of the inclusions is nichrome Cr15Ni60 with the conductivity 10^6 S/m. The helical inclusions are embedded in a plastic foam substrate with ε = 1.03 and thickness 6.6 mm. The arrangement of the helices is illustrated in Fig. 1,b. Each unit cell consists of four helices of specific handedness located at a distance 15.1 mm from the center of the cell. "Right-" and "left-handed" unit cells are alternated in the plane of the metasurface with the interlacement 42.42 mm.

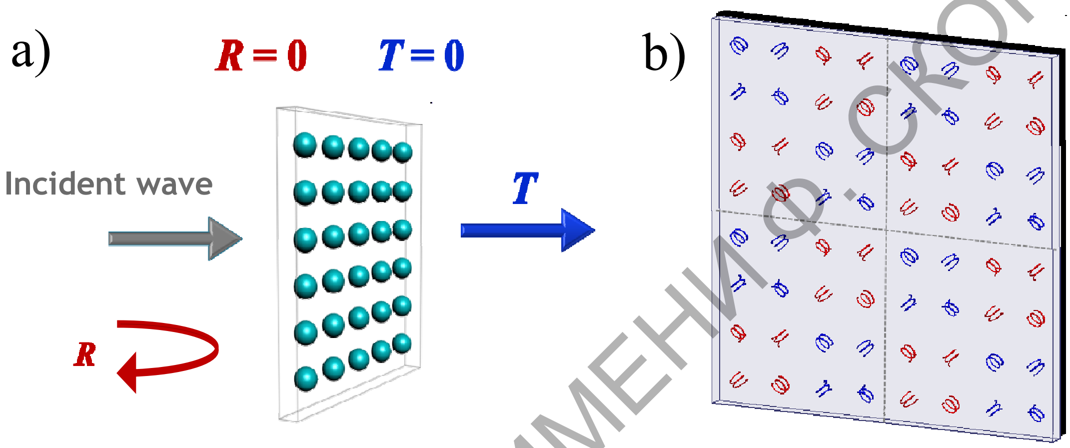

Fig. 1 The metasurface based on small dipolar inclusions: a) illustration of the total absorption; b) optimal arrangement of the double-turn helices in a metasurface

The sample was illuminated by a normally incident linearly polarized plane wave. Since the metasurface has uniaxial symmetry in the plane, it operates for arbitrary polarized plane waves. Fig. 2 shows reflection and transmission coefficients for simulated results.

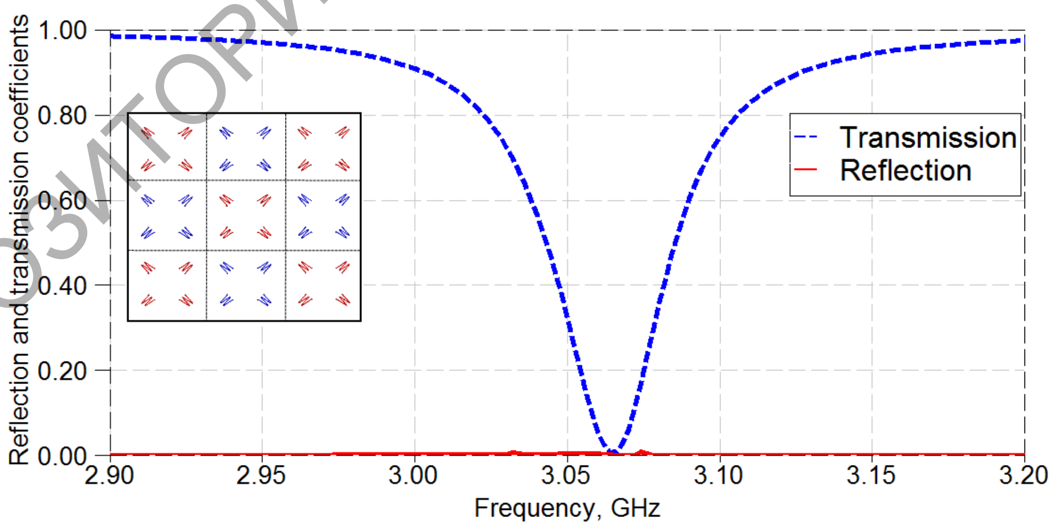

Fig. 2 Normalized intensity of the reflected and transmitted waves from the absorber (normal incidence)

One can see that at the resonance frequency 3.065 GHz the designed metasurface absorbs 99.8% of the impinging power. Therefore, perfect absorption is achieved at the resonance frequency for matasurface based on double-turn helices. The absorber symmetrically operates from the two sides. We studied by simulations also the case of oblique incidence of wave. The absorption level is quite high $\pm 80\%$ at angle from 0 to 60 degrees (Fig.3,a). On the Figure 3,b you can see how the absorption level depends on bulk conductivity of the metal of helices.

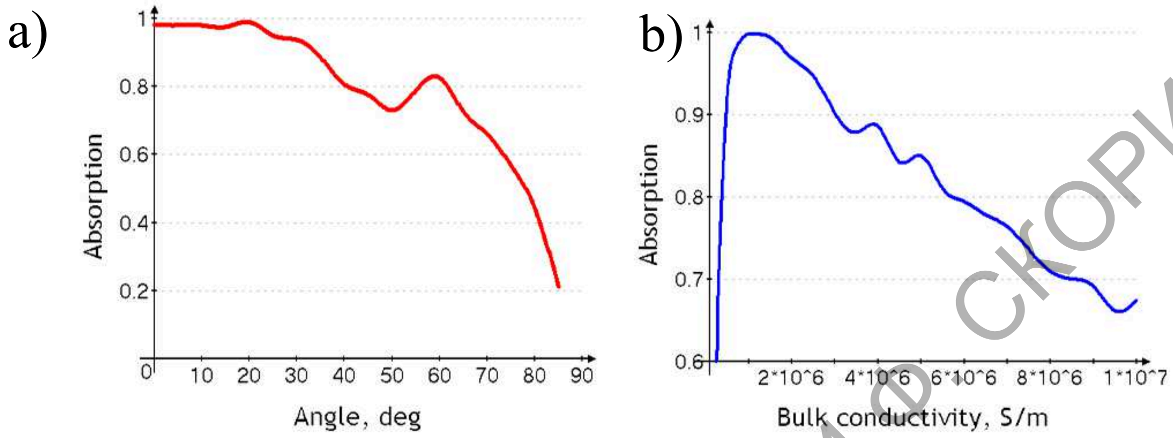

Fig. 3 Absorbing properties of the metasurface: a) the absorption in the case of oblique incident wave; b) the graph of the absorption at depends from bulk conductivity at the resonance frequency

One can see that absorption level is high in metasurface based on double-turn helices in the case of oblique incident wave. As follows from Fig. 3,b we used material with the bulk conductivity 10^6 S/m that corresponds of the maximum absorption of the incident wave.

Conclusion

We realized a new kind of electrically thin absorber of electromagnetic waves. The absorber operates with 99.8% efficiency at around 3.065 GHz. Our absorber does not have a ground plane and works for any polarization of incident wave. At the next step, the idea of a single-layer meta-atom absorber can be extended to higher frequencies opening up a possibility to create film absorbers with thickness of one molecular layer.

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