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## The development of double-sided nonreflecting absorber of the terahertz waves on the basis of metamaterials

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**Abstract.** The paper aimed to study the interaction of the THz range electromagnetic waves with metamaterials, consisting of rectangular omega elements, as well as to develop a one-sided and double-sided “ideal” THz wave absorber based on such structures.

The theory and means of implementing electromagnetic radiation absorbers have a long history. There are a large number of such devices, especially in the microwave range [1-3]. However, most of these devices have the absorbent structure on a reflective metal surface, since the most common purpose of creating such devices is to reduce the reflection of waves from metal surfaces.

Electrically thin absorbers can be implemented in various ways, but only some of them have been studied recently. One of the ways is to combine two thin layers of metamaterials with contrasting material parameters [4]. Another way is to combine a thin conducting sheet with an array of resonant open rings, which creates the necessary magnetic response [5], as well as multilayer absorbing structures with a metal substrate [6, 7]. The paper considers the simplest option – a single-layer absorber. This choice allows us to call the thickness of the absorber extremely thin, since the thickness of the layer cannot be less than the thickness of one layer of the particles constituting the metamaterial. This paper deals with the implementation of a single-layer metamaterial that would completely absorb the incident electromagnetic waves in the THz frequency range, being low reflective at the same time.

The conditions for the complete absorption of a normally incident plane wave by an infinite periodic array of electric and magnetic dipoles are known from antenna theory [7]. The period of an infinite array is equal to  $p$  (the value of  $p$  is less than the radiation wavelength in the surrounding space); each cell of the array contains one uniaxial electrically polarizable particle and one uniaxial magnetically polarizable particle. Also not without interest is the absorption coefficient for both normal and oblique incidence of waves on the absorber. Traditional absorbers, consisting of at least two layers, have certain thickness. As a result, when the incidence angle deviates from the normal, the resonant frequency of the array shifts. This is because the effective thickness of the absorbing layer varies for waves falling at different angles. However, this type of absorber is an extremely thin layer, so a heavy change in the resonant frequency is expected not to be observed when the angle of wave incidence changes. A change in the angle of incidence will nevertheless influence the interaction of waves in the structure and, consequently, the absorption efficiency.

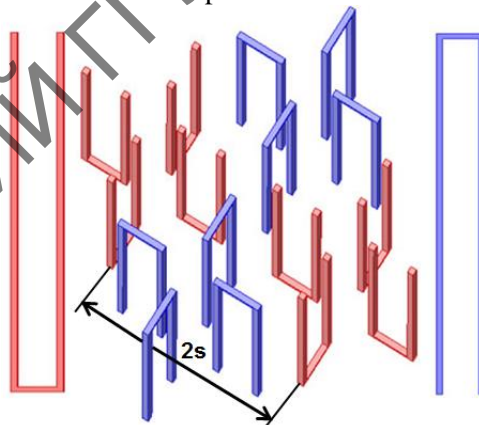


It is known that while approximating electrically small dimensions it is possible to achieve a balance of polarizabilities for a single uniaxial omega resonator, formed from a conductive material [1]. At the same time, the condition of obtaining zero reflection from the electromagnetic material will be satisfied when electric and magnetic dipoles are simultaneously induced in the resonator at the same resonant frequency. Therefore, it is necessary to find the polarizability of a single  $\Omega$ -particle and make sure that its properties satisfy the balance conditions [1].

Using the analytical approach described in [2], it is possible to determine the desired polarizabilities components of an electrically small conductor of arbitrary shape. The use of this approach and computer simulation, based on the finite element method, made it possible to determine the scattered fields and, consequently, the desired components of the polarizability tensors of the omega resonator.

The structural parameters of the rectangular  $\Omega$ -resonator and its polarizability for the THz frequency range have been obtained in this paper. By changing the structural parameters of the omega element, a balance of polarizabilities has been achieved. This  $\Omega$ -resonator is balanced and shows resonant properties near the frequency of 1 THz, since the induced electrical and magnetic dipole moments are equally significant and contribute equally to the radiation of an electromagnetic wave. It should be noted that the electromagnetic and magnetoelectric polarizabilities are also approximately equal to each other with a high degree of accuracy. Hence, this  $\Omega$ -resonator with balanced polarizabilities fully satisfies the condition for the absence of terahertz wave reflection.

Figure 1 shows a unit cell of a metamaterial based on balanced  $\Omega$ -resonators, developed using computer simulation. The location of the resonators is such as to compensate for the omega-coupling (electromagnetic and magnetoelectric coupling), as required by the condition for complete absorption [3]. The unit cell of the proposed absorber consists of 16 omega resonators. The metamaterial subcell consists of four  $\Omega$ -resonator blocks, as shown in Fig. 1. The blocks containing four resonators, ends of which are oriented in one direction, are staggered in the unit cell. This design uses  $\Omega$ -resonators made of titanium with a conductivity of  $1.82 \cdot 10^6$  Sm/m, which provides the required level of dissipative losses. The inter-element distance and the lattice period are denoted as  $2s$  and  $p$  ( $p = 4s$ ), respectively.

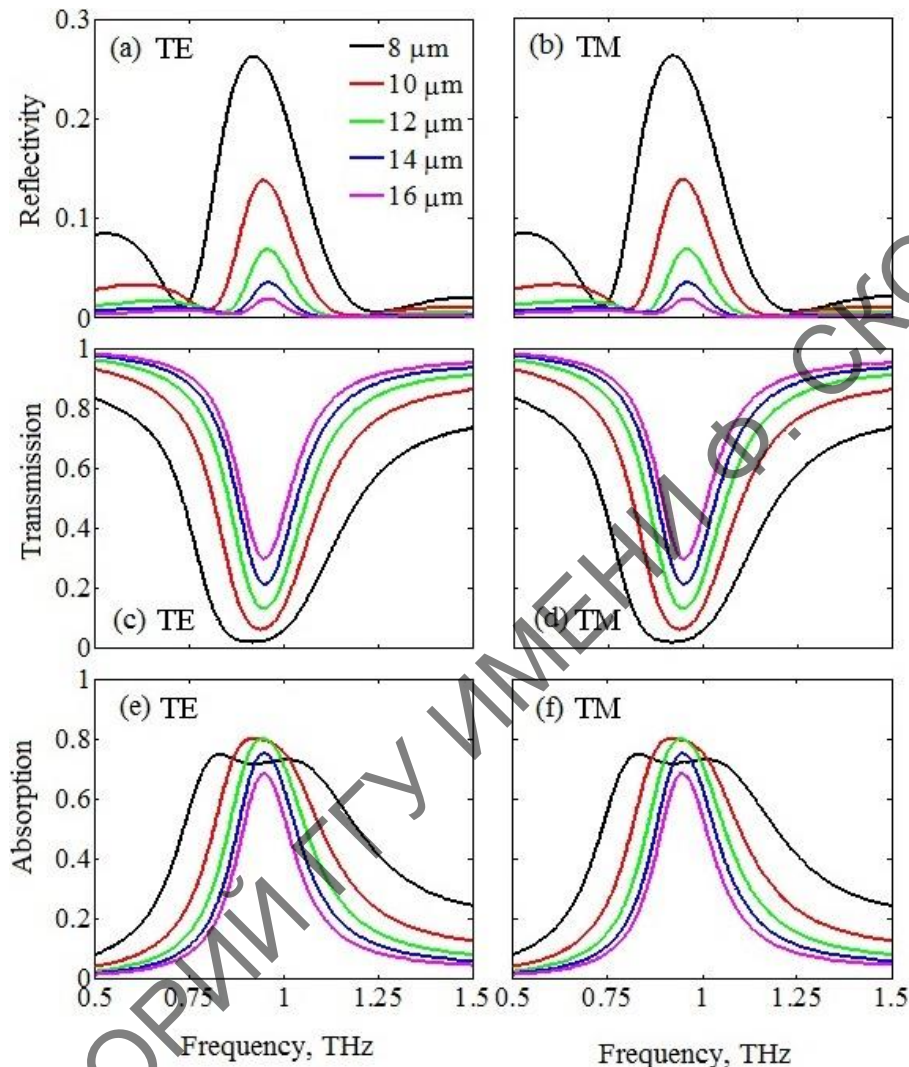


**Figure 1.** A schematic of the metamaterial unit cell based on balanced  $\Omega$ -resonators with the opposite direction of the ends

To determine the electromagnetic properties of the proposed structure, the reflection ( $R$ ), transmission ( $T$ ) and absorption ( $A$ ) coefficients of the absorber were simulated on the basis of balanced  $\Omega$ -resonators depending on the frequency at a different lattice period ( $p = 4s$ ), at different polarization of the incident wave (TE and TM), with different values of the conductor diameter and the angles of incidence.

Figure 2 shows the simulation results: reflectivity ( $R$ ), transmission ( $T$ ) and absorption ( $A$ ) coefficients of an absorber based on balanced  $\Omega$ -resonators depending on the frequency for different lattice periods ( $p = 4s$ ) and for different polarization of the incident wave (TE and TM). The

absorption coefficient is calculated from the reflection and transmission coefficients as follows:  
 $A=1-R-T$ .



**Figure 2.** Reflectivity (a, b), transmission (c, d) and absorption (e, f) coefficients at a different lattice period ( $p = 4s$ ) for the normal incidence of TE and TM waves

The use of computer simulations resulted in finding optimal metamaterial parameters. The spectra are shown not to depend on the polarization of the incident waves. The absorption coefficient reaches a maximum value of 82% at a resonant frequency of 0.95 THz, while the reflection coefficient does not exceed 7% in the frequency range from 0.5 to 1.5 THz. The value  $p = 12 \mu\text{m}$  is the optimal period of the structure (see the green line). It is also shown that the wave passes completely through the metamaterial outside the resonant frequency band. Therefore, the proposed absorber on the basis of balanced  $\Omega$ -resonators exhibits insignificant reflective properties in the frequency range under study and, at the same time, demonstrates effective resonant absorption.

For many absorber applications, it is especially important to absorb electromagnetic waves not only at normal incidence, but also with oblique incidence of waves. The study of the transmission coefficient depending on the frequency and the angle of incidence for the TE and TM waves has been done. It is shown that the transmission remains almost unchanged with an increase in the angle of incidence to 60°. Absorption is more stable up to 40°. It should be noted that the proposed absorber

based on  $\Omega$ -resonators exhibits good efficiency and angular stability under oblique excitation for TE and TM polarizations of incident waves.

It can be concluded that such a unique property as zero reflection in a wide frequency range in combination with frequency-selective absorption provides new opportunities in various applications, for example, when creating electrically thin multi-frequency filters of electromagnetic radiation, as well as “invisible” sensors in THz frequency range.

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