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A polarization-dependent wide-angle three-dimensional metamaterial absorber

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ABSTRACT

In this paper, a polarization-dependent wide-angle three-dimensional metamaterial absorber with a near-unity absorbance was presented. The metamaterial absorber structure is composed of coplanar electric and magnetic resonators. By carefully adjusting the structural dimensions, less-than-unity ε and/or μ can be realized. To match the impedance of free space, the structural dimensions were adjusted so that $\varepsilon = \mu$, which guarantees minimum reflection. Since the resonance-based structure is made of metallic resonators and lossy substrates, the imaginary part of refractive index is large, which guarantees strong absorption of transmitted waves. Full-wave simulations confirmed the effectiveness of the proposed three-dimensional metamaterial absorber.

1. Introduction

In 1968, Veselago [1] investigated the characteristics of media with simultaneously negative ε and μ. But because there is no such material in natural world, his work was neglected for almost 30 years. In 1999, Pendry et al. [2] showed that negative ε can be realized by using conducting wires and negative μ by split-ring resonators (SRRs). In 2000, Smith et al. [3] constructed the wire/SRR structure and demonstrated its negative ε and μ at microwave frequencies. From then on, materials with less-than-unity ε and/or μ have been a hot issue in many research fields and such materials were termed metamaterials.

To date, the research on metamaterials mainly focuses on the realization of left-handed pass-band and negative regractive index and many novel left-handed unit cells, like S-shaped unit cell [4], Ω-shaped unit cell [5], coplanar magnetic and electric resonator unit cell [6], have been proposed with an aim to expand the left-handed pass-band and to reduce loss. Meanwhile, the wave-absorption property of metamaterials has been almost neglected, although the use of metamaterials will potentially enhance the performance of absorbers. Due to the diffraction limit, the thickness of conventional absorbers cannot be made thin enough, so the reduction of the electrical thickness of the absorber is one of the challenging aspects in designing such components. Moreover, there is always a metallic backing plate in conventional absorbers [7], which may bring about many problems in applications such as stealth. As a result, there is an urgent need to design innovative absorbers to overcome the above two disadvantages of conventional absorbers. Kern and Werner [8] proposed an ultra-thin absorber based on frequency selective surfaces (FSS) and their absorber can be made as thin as $\lambda/10$. In their design, the metallic backing plate is necessary. To get rid of metallic backing plate problem, Bilotti et al. [9] proposed a SRR-based absorber by arranging SRR arrays behind a resistive sheet. The SRR-based absorber can be used in stealth technology, due to the absence of metallic backing plates. However, the resistive sheet used to match the impedance of the free space is necessary in such a design. Landy et al. [10,11] proposed a one-dimensional metamaterial absorber composed of magnetic and electric resonators. There is no metallic backing plate and resistive sheet in their metamaterial absorber. Both the impedance matching and the absorption can be achieved by such an absorber. This opens a brand-new way to the design of smaller and more applicable absorbers.

In this paper, we proposed a polarization-dependent wide-angle three-dimensional metamaterial absorber. Unit cell of the metamaterial is composed of coplanar magnetic and electric resonators. The mechanism of realizing strong absorption was illustrated by monitoring field distributions and retrieving the effective parameters of the metamaterial. By numerical

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simulations, the absorbance of one layer of infinite metamaterial absorber slab under different incident angles was obtained. The results show that under the desired polarization, the three-dimensional metamaterial absorber can realize near-unity absorption within a wide range of incident angles.

2. Design

The unit cell of the three-dimensional metamaterial absorber is shown in Fig. 1. On each of the six sides of the substrate cube etched the metallic patterns of an electric resonator and two C-shaped metal strips. The electric resonator is on the center part of each side, while the two C-shaped metal strips enclose the electric resonator symmetrically. The two C-shaped metal serve as a magnetic resonator. The lossy substrate cube is made of FR4 whose relative dielectric constant is $\varepsilon_r = 4.9$ and loss angle tangent $\tan\delta = 0.025$. The metal of metallic patterns is Copper whose electric conductivity is $\sigma = 5.8\times10^7$ S/m. The geometrical dimensions are: $a = 3.5$ mm, $b_1 = 3$ mm, $b_2 = 1.8$ mm, $l = 0.4$ mm, $c = 0.6$ mm and $d = 0.05$ mm. The electric resonator and the two C-shaped metal strips couples to electric and magnetic fields of the incident EM waves, respectively. By properly adjusting their geometrical dimensions, less-than-unity μ and/or ε can be realized in the same frequency range.

An absorber must meet two necessary requirements to effectively absorb EM waves, one of which is that the impedance should match that of the free space, i.e., $\mu = \varepsilon$, to minimize the reflection and the other of which is that the imaginary part of refractive index should be large to ensure that the absorber should absorb intensely the transmitted EM wave energy. By carefully adjusting the geometrical dimensions of the unit cell, the permittivity ε and permeability μ can be tuned to meet $\mu = \varepsilon$. Since that the structure is made of metallic resonators and lossy substrates and that it is based on resonances, the imaginary part of the refractive index is large in the left-handed region, which guarantees strong absorption of transmitted EM waves. Thus, the proposed unit cell is expected to be a good candidate as a three-dimensional metamaterial absorber.

3. Near-unity absorbance and mechanism

3.1. Near-unity absorbance under normal incidence

In order to testify our predictions, computer simulations were performed using CST Microwave Studio. Polarization of the incident plane waves is shown in Fig. 1. The impinging wave is incident normally on the front side of the cube, with the electric vector perpendicular to the up and bottom sides and magnetic vector perpendicular to the left and right sides. The up and bottom as well as the left and right sides were set to be periodic boundary conditions, so the absorber can be regarded as a layer of infinite metamaterial slab with one-unit-cell length in the propagation direction. Fig. 2 gives the simulated magnitudes of S_{11} and S_{21} parameters. As clearly shown in Fig. 2, both the reflection and transmission are very low near 15.1 GHz, which indicates a strong absorption.

According to magnitudes of S_{11} and S_{21} parameters in Fig. 2, we plotted the reflectance $|S_{11}|^2$, transmission $|S_{21}|^2$ and absorbance

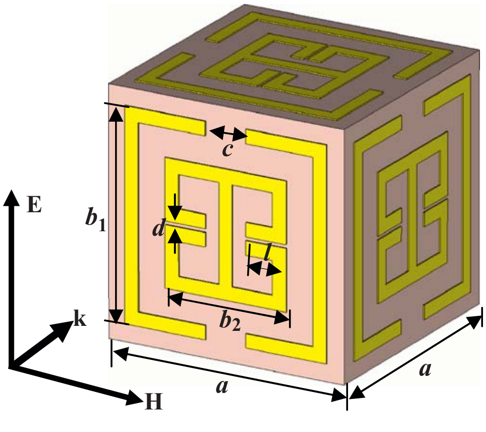

Fig. 1. Unit cell of the three-dimensional metamaterial absorber and polarization of incident EM waves.

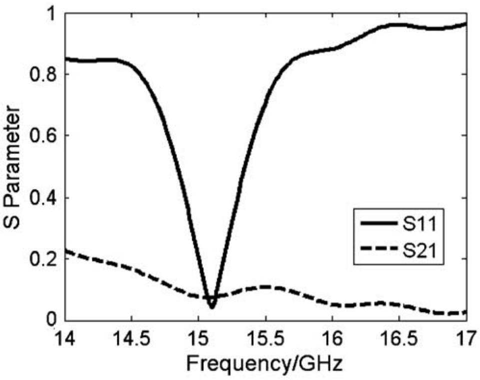

Fig. 2. Amplitudes of simulated S_{11} and S_{21} of one unit cell along the propagation direction.

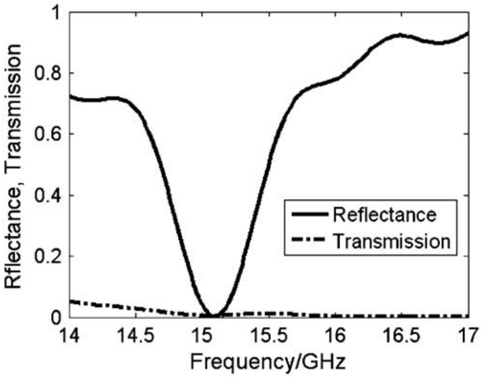

Fig. 3. Reflectance (solid) and transmission (dashed) per unit cell.

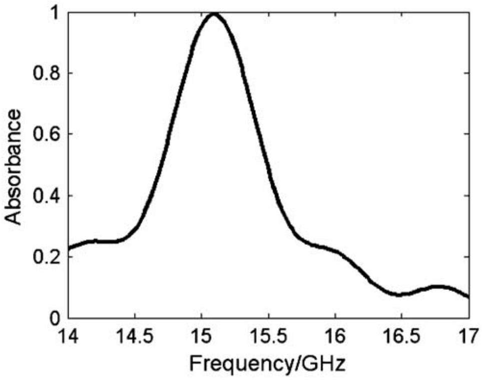

Fig. 4. Absorbance per unit cell.