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Design of a wide-band nearly perfect absorber based on multi-resonance with square patch

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ABSTRACT

A multi-resonance structure design of nearly perfect absorber (PA) was proposed based on square patch at microwave frequencies. One-layer square patch metamaterial has an absorption of 99.9%. The multi-layer metamaterials can extend the bandwidth of nearly perfect absorber. By stacking several such structural layers with different geometrical dimensions, the bandwidth of this strong absorption can be effectively enhanced due to the hybridization of magnetic polarizations in different layers. Numerical simulations reveal that the multi-layer metamaterials with different resonance frequencies can extend the absorption bandwidth. The full bandwidth at half-maximum (FWHM) bandwidth is improved to 2 GHz with 4-layers square patch structure. The simulated and experimental results are coincided well. The mechanism of nearly perfect absorption is explained in detail.

1. Introduction

Metamaterials are artificial composites materials that exhibit superior properties that are not observed in the constituent materials in nature. In fact, the term “metamaterial” is also a novel idea for material design. This idea is to break through the restriction of apparent nature rule by the order structure in certain key physical scale in order to obtain exceptional material function [1]. Smith et al. designed artificial materials based on Pendry's theoretical model, and experimentally demonstrated negative permittivity and negative permeability simultaneously at microwave frequencies [2,3]. From then on, many exotic electromagnetic properties of metamaterials have been demonstrated [4,5] and applied in many fields, such as negative refraction [6], perfect lens [7], invisibility cloak [8,9], and so on. Some applications of metamaterials are required to minimize losses, and the existence of losses could deteriorate the performance of some devices. On the other hand, many applications would be desirable to maximize the metamaterial losses, the metamaterial absorber (MA) is a typical example.

The MA was first demonstrated by Landy et al. [10], which has become an important aspect in the research of metamaterials. The first MA consisted of a sandwiched structure of electric ring resonators, dielectric substrate, and metal cut-wires, which overcome the quarter-wavelength thickness limitation and demonstrated the absorption of 88% in experiments. Since then, many kinds of sandwiched structures MA have been proposed and demonstrated high absorption from microwave to optical frequencies [11–15]. By manipulating the magnetic resonance and electric resonance independently, it is possible to achieve $\varepsilon = \mu$, matching the impedance to free space and resulting in perfect absorbance for incident electromagnetic (EM) wave. The high absorption of the MA is mainly due to local EM resonance and the losses of dielectric slab [16]. However, the absorption of those designed is often narrow, typically no more than 10% with respect to the center frequency. This narrow bandwidth feature of the resonant absorption limits the device applications of these absorbing structures.

In this paper, we present a design of a wide-band nearly perfected absorber with square patch. Numerical simulation demonstrates an absorption of 99.9%. We numerically studied the bandwidth of the perfected absorber with multi-square patches structure of different geometrical parameters. When these resonant peaks are closely positioned, the resonant peaks are merged in the absorption spectrum, the bandwidth of nearly perfected absorber is extended. The special frequency between two resonant peaks is explained in detail in this paper.

2. Design and simulation

In our design, the square patch sandwiched with metallic square patch, dielectric substrate and continuous metallic film was selected as resonator, which is concise and convenient to adjust. This structure

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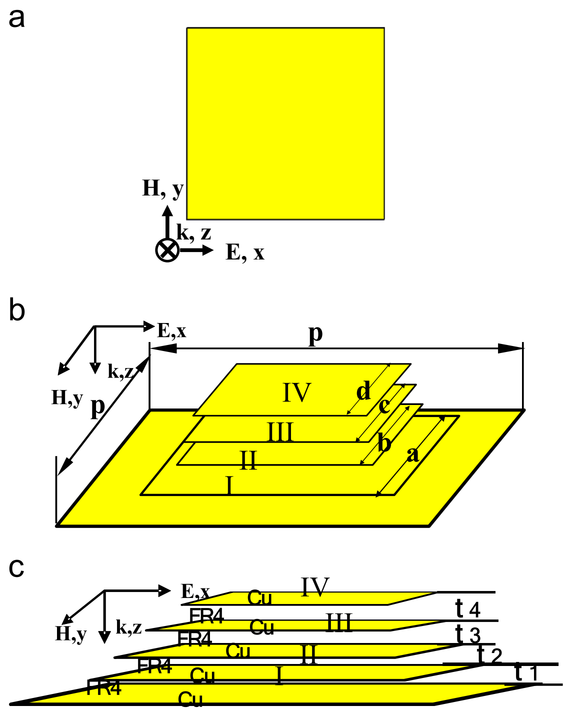

Fig. 1. (Color online) (a) Scheme of single unit cell of the MA; (b) and (c) the single unit cell of broadband MA of 4-layer square patches structure.

can drive strong magnetic response, and this symmetry of the structure also indicates its coupling to a magnetic field [12]. The multi-layer sandwich structures have metallic square patch, dielectric substrate and metallic square patch; the continuous metallic film was selected as the bottom resonator. The square patch and metallic film contain 0.02 mm thickness copper (the conductivity of the copper is $\sigma = 5.8 \times 10^7$ S/m), the substrate is FR-4 (epoxy glass, the relative dielectric constant $\varepsilon_r = 4.4$, and the loss tangent is 0.02).

The simulation has been performed based on the standard finite difference time domain (FDTD) method by CST Microwave Studio software. The top and bottom as well as the left and right sides were set to be periodic boundary conditions, so the structure simulated could be regarded as a metamaterial slab that is infinite in the (x, y) plane. Fig. 1(a) shows the coordinate axis with the wave polarization and propagation direction, the electric field polarized in the x direction, the magnetic field polarized in the y direction. Fig. 1(b) displays the schematic diagram of a 4-layer square patches structure; Fig. 1(c) was set to be periodic boundary conditions for multi-layer and the FR-4 substrate thickness is t.

For a EM plane wave normal incidence, there is no transmission to be examined, as it is blocked off by the continuous metallic film. Thus, only the reflectance needs to be examined in our simulations. The complex frequency dependent S parameter: S_{11} is corresponding to the reflection coefficient, thus the absorptivity is calculated from the reflection and expressed by the S_{11} parameter as $A(\omega) = 1 - |S_{11}|^2 = 1 - R(\omega)$.

3. Results and discussion

3.1. Narrowband metamaterial absorber of 1-layer sandwiched square patch structure

First we numerically study a simple composite structure that is made of metallic square patch positioned on a glossy FR4 dielectric and a continuous metallic film. The single unit cell is shown in Fig. 1 (a) and the optimized geometrical parameters exhibited in 1-layer is tabulated in Table 1. The absorption result of one square patch structure is shown in Fig. 2. From Fig. 2(a), we can see clearly that the reflection is near zero, the corresponding absorption is 99.9% at 8.1 GHz. To understand the origin of the spectral characteristics, the distributions of the y component magnetic field magnitude $|H_y|$ is in the plane $y = 0$, the resonance Ia is primarily associated with the excitation of magnetic polarization in the first layer, which is caused by the electric dipole coupling between the I-layer square patch and the metallic film.

The polarization insensitive for normal incident EM waves is simulated. The absorption was obtained under normal incidence. Fig. 2 shows the simulated absorption at various angles of oblique incidence for TE and TM cases. For the TE case as shown in Fig. 2 (b), the absorption peak monotonously decreases with increasing angle of incidence, but still remains higher than 80% for an incident angle (θ) smaller than 60°. Beyond 60°, there is a sudden decrease in the absorptivity, as the y component of the incident magnetic field decreases rapidly to zero and can no longer efficiently excite this magnetic polarization [17]. In Fig. 2(c), the peak value of absorption will be nearly unchanged and the center frequency of the absorption peak has a slight blueshift with the increase of incidence angle. This angle-insensitive absorption of the TM wave is mainly due to the composite structure can be effectively excited by the magnetic field. The numerical simulation results show that our nearly perfect absorber could be operated at a wide range of incident angles.

3.2. Broadband absorption of a multi-layer structure

The above mentioned structure of perfect absorber is much thinner. However, the absorption band is very narrow and the FWHM bandwidth is about 0.4 GHz. We try to increase the bandwidth of the absorption by using a multi-layer structure that can support resonant modes closely positioned in the absorption spectrum. As we know, the resonance frequency of the absorption will be changed with the variation of the geometrical parameters of the square patches. The resonance frequency is $f_m = 1/\sqrt{LC} \sim 1/a$, and a is the side length of each patch [18]. Thus, multi-square patches with different geometrical parameters are positioned on multi-layer to ensure that the resonance frequencies could be close to each other. Then, each single unit cell can be impedance-matched to the free space at each resonant frequency by tuning the FR-4 substrate thickness (t). We studied the broadband absorption of nearly perfect absorber with two square patches structure, three square patches structure, and four square patches structure assembling in the multi-layer. The II square, III square, and IV square are behalf of different assembling sandwiched structures (see Fig. 3). The a, b, c, and d represent the side lengths of each square patch in different single unit cells of nearly perfect absorber. The optimized geometrical parameters of different nearly perfect absorber structures are shown in Table 1.

We first study the case of two square patches that are sandwiched with FR-4 substrate and continuous metallic film. As shown in the inset in Fig. 3(a), two closely positioned resonances with absorption up to 99.0% are clearly observed. One peak value

Table 1
Optimized parameters (mm) for I, II, III, and IV-layers of the square patch and substrate structures.

Layer	a	b	c	d	t_1	t_2	t_3	t_4
I-Layer	8	–	–	–	0.43	–	–	–
II-Layer	8	7.86		–	0.25	0.38	–	–
III-Layer	8	7.86	7.44	–	0.075	0.13	0.53	–
IV-Layer	8	7.76	7.44	7.2	0.118	0.22	0.3	0.5