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Design, fabrication and characterization of stacked layers planar broadband metamaterial absorber at microwave frequency

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ABSTRACT

The design, simulation, fabrication, and measurement of an ultra-wide spectral band metamaterial absorber were investigated in this paper. The unit cell consisting of three loop copper layers were printed on FR-4 epoxy dielectric substrate, and the top layer was Teflon. By stacking a number of one-layer structures on top of each other, a multi-layered structure was generated with a thickness of 3.7 mm. Results of the recursive method and the simulations showed a high absorption for wide angle of incidence up to 60° at TM and TE modes. The absorption at normal incidence was strong in the frequency range of 5.64–21.16 GHz numerically. The proposed structure was fabricated. The experimental results showed a good correspondence with the simulated results. Importantly, the design can be extended to other frequencies, such as terahertz, infrared, and optical frequencies.

1. Introduction

After the demonstration of first perfect metamaterial absorber (MA) in spectra microwave by Landy et al. [1], the design, fabrication, and characterization of MAs have been broadly explored in broadband spectra which covers microwave [2,3], terahertz [4,5], infrared [6,7], and optical bands [8,9]. In recent years, metamaterial-based absorber has been paid much attention in the microwave and terahertz band which can be easily accomplished by a proper design due to their potential applications and a perfect absorption. An ideal MA should be polarization-insensitive, ultra-thin, broadband, and have wide incident angle in addition to exhibiting the near-perfection absorption.

Unfortunately, the bandwidth in MAs is fairly narrow, and there is not an enough progress toward the design and implementation of broadband MAs. Recently, MAs which exhibit great performance within single-band [10,11,22], dual band [12,13,22], and triple band [14–16,23] have been reported, but these MA types indicate multiple absorption peaks at various frequency bands. Moreover, the absorption bandwidth of such designed MAs is narrow. In particular applications, broadening the absorption bandwidth are also of significance [2,17,18,31]. In general, there exist two kinds of assembling for structures with different geometrical parameters. The first one is the MAs with the structures of different geometrical parameters which are positioned co-planar to make certain that the resonant frequencies could be close to each other [12,32]. The second is the MAs with different geometrical parameters which are staked in multi-layered structures [13,33].

For expanding the absorption, wide bandwidth [19–26] has been reported, but such MA types are thick, difficult to fabricate, expensive, and fragile. First used by Xiong et al., the ultra-broadband MA has above 90% absorptivity at normal incidence in the frequency range of 8.37–21 GHz with thickness of 3.65 mm [26], and is composed of multi-layered structures. In this paper, however, instead of using the Rogers TMM4 substrate ($\varepsilon_r = 2.1$, loss $\tan\delta = 0.001$), structure was simulated, optimized, and fabricated on lossy FR-4 epoxy dielectric substrate ($\varepsilon_r = 4.3$, loss $\tan\delta = 0.022$). As a result, the loss mechanism differed from the report in Ref. [26]. On the contrary, for confirming MA's real world response, the sample of structures was designed, fabricated and tested in the laboratory. The results of simulation and measurement were in good agreement with each other. In Ref. [26], only the simulations are reported. Due to structural changes made by the researcher in the structure of Ref. [26], bandwidth was increased and the absorption spectrum became better.

In this paper, a metamaterial absorber with improved bandwidth performance operating around 5.796–20.732 GHz is presented. The structure of the paper is as follows. In Section 2, the researchers presented the geometry of the proposed designs. In addition, the simulation results were compared with the results of recursive method. In Section 3, the fabricated metamaterial surface

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was experimentally characterized and the results were discussed. Finally, a conclusion was drawn in Section 4.

2. Design and simulation of unit cell

The structure was composed of three loop copper layers (conductivity of $\sigma = 5.96 \times 10^7$ S/m, thickness of copper $t_2 = 0.017$ mm) which were separated by a $t_1 = 1$ mm thick FR-4 epoxy dielectric substrate ($\varepsilon_r = 4.3$, loss $\tan\delta = 0.022$). The bottom layer was completely copper laminated, and the transmission was equal to zero, thus, the absorptivity can be figured out from $A(\omega) = 1 - R(\omega)$. The top layer was Teflon ($\varepsilon_r = 2.1$, loss $\tan\delta = 0.001$). Between them, layers of adhesive with thickness of 0.06 mm were employed. The values were optimized for structures, where the periodicity was $p_x = p_y$=6.6 mm, $h_1 = h_2 = h_3 = 1$ mm, $h_4 = 0.7$ mm, $d_1 = 0.2$ mm, $d_2 = d_3 = 0.3$ mm, $d_4 = 0.7$ mm, $d_5 = 0.5$ mm, $d_6 = 0.4$ mm, $L_1 = 1.7$ mm, $L_2 = 3.6$ mm, $L_3 = 5$ mm.

In this paper, two theoretical methods have been utilized. The proposed structure as shown in Fig. 1 was first simulated using CST Microwave Studio 2012, then the recursive method was used and finally their results were compared. The MA is the periodic boundary conditions extension of the unit cell in both x and y directions.

A polarized transverse electromagnetic (TEM) wave impinges upon this structure with the TM and TE modes. The structure will have only a reflection coefficient due to a metallic ground plate. Absorption curve's numerical simulation result under normal and oblique incidence is displayed in Fig. 2a and b at TM and TE modes, respectively.

It can be seen that there are four close to unity absorption peaks at $f = 7.88$ GHz, 10.76 GHz, 16 GHz and 19.88 GHz, with absorption rates of 99.00%, 99:99%, 99.90% and 98.90%, respectively. One obvious absorption dip is achieved at 6.56 GHz, which the absorption is about 68.3%. This design provides a bandwidth of approximately 15.52 GHz. For both linear polarizations, there is a same behavior. But as can be seen, the MA absorbs more TM-polarized light than the TE case. The angle θ is defined as the angle between the propagation vector of the incident wave and the z-axis over the yz-plane. The results of simulation indicate that absorption spectrum remains nearly unchanged up to $\theta = 60^\circ$. Beyond 60°, there is a sudden drop in the absorptivity. It is due largely to the incident magnetic flux between the sandwiched structure's layers, getting less and less with the increase of incidence angle [27].

On the contrary, the structure has been explored utilizing a recursive method. In a multi-layered structure, for either the TE or the TM polarization, the total reflection and transmission coefficients are given as follows for layer i [27]:

$$R_i = \frac{r_{i+1,i} + R_{i-1}e^{\pm j2\varphi_i}}{1 + r_{i+1,i}R_{i-1}e^{\pm j2\varphi_i}} \tag{1}$$

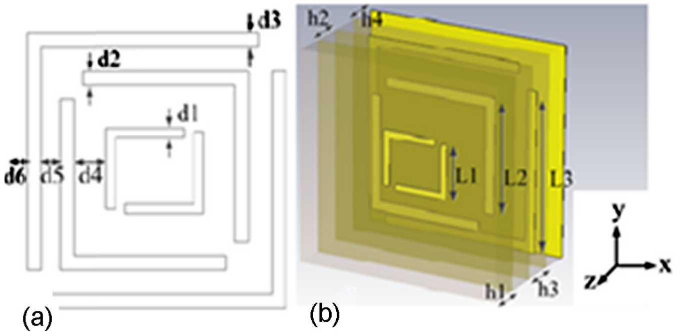

Fig. 1. Perspective of MA unit cell, (a) top view (b) side view.

$$T_i = \frac{t_{i+1,i}T_{i-1}e^{\pm j\varphi_i}}{1 + r_{i+1,i}R_{i-1}e^{\pm j2\varphi_i}} \tag{2}$$

where, the phase φ_i connected with slab i is preceded by a +sign for a metamaterial and by a −sign for a dielectric material. For transverse electric mode, the interface reflection and transmission coefficients are given by [27]:

$$r_{ij}^{\mathrm{TE}} = \frac{k_{zi} - k_{zj}}{k_{zi} + k_{zj}} \tag{3}$$

$$t_{ij}^{\mathrm{TE}} = \frac{2k_{zi}}{k_{zi} + k_{zj}}. \tag{4}$$

For transverse magnetic mode, the interface reflection and transmission coefficients are given by [27]:

$$r_{ij}^{\mathrm{TM}} = \frac{k_j \cos\ \theta_i - k_i \cos\ \theta_j}{k_j \cos\theta_i - k_i \cos\ \theta_j}. \tag{5}$$

$$t_{ij}^{\mathrm{TM}} = \frac{2k_i \cos\ \theta_i}{k_j \cos\theta_i - k_i \cos\ \theta_j} \tag{6}$$

where, $k_i = \omega\sqrt{\varepsilon_i\mu_i} = \omega n_i/c$, $\phi_i = k_{zi}d_i$ and θ_i is the acute angle between the normal and the wave-normal.

On the other hand, retrieval procedure is one of the most common characterization tools for the metamaterial structures [28]. It is widely employed for computing the effective parameters of the metamaterial under investigation. The effective permittivity and permeability values were then derived from the transmission and reflection coefficients [29].

$$Z = \eta_0\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{7}$$

$$n = \frac{1}{kt}\cos^{-1}\left[\frac{1}{2S_{21}}(1 - S_{11}^2 + S_{21}^2)\right] \tag{8}$$

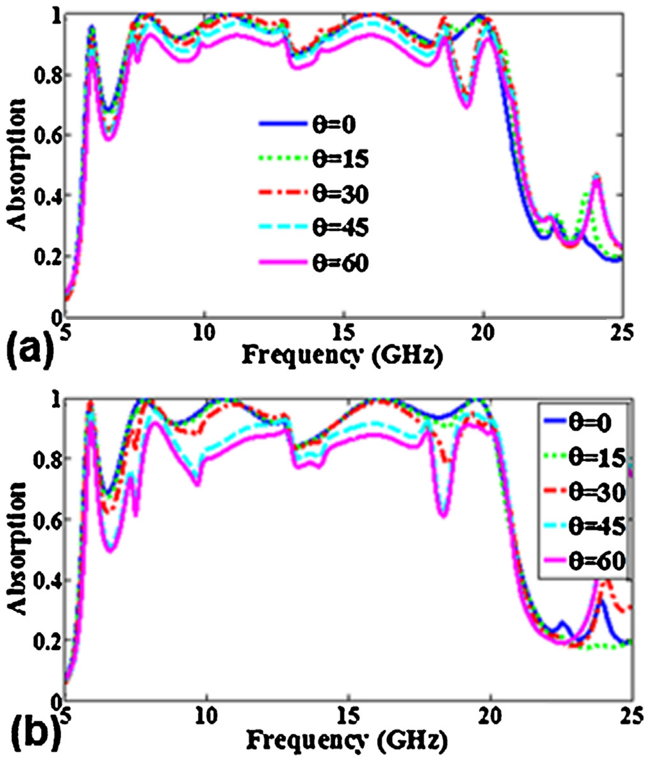

Fig. 2. The simulated results of the MA under normal and oblique incidence wave for (a) TM and (b) TE modes.