Improvement of Oblique Incidence Performance for a Microwave Absorber Based on Magnetic Polymer Composites

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Abstract— This paper presents a microwave absorber combining together the frequency selective surfaces (FSSs) and magnetic absorbing sheet for stable absorption under both TE and TM polarizations. The proposed absorber is constructed of magnetic absorbing substrate embedded with a periodic array of cross pattern composing a series of circular-metal-disks, and a bottom metal plane. The absorption characteristics of the magnetic absorbing substrate under both TE and TM polarizations are tuned and improved by introducing the circular-metal-disks. After optimizing the dimensions of the circular-metal-disks, the absorber with a thickness of 2.4 mm achieves a reflection coefficient less than −10 dB from 4.8 GHz to 11.0 GHz with a stable frequency response up to 30° for both polarizations. Meanwhile, the absorber has a wide bandwidth of 10.8 GHz with the incidence angle from 45° to 60° under TM polarization. The study of the current indicates that the improvement of the absorption characteristics is due to both the electric resonance and magnetic resonance.

1. INTRODUCTION

In recent years, there has been an increasing interest in the application of metamaterial absorbers. Most investigations of absorbers like Jaumann and circuit analog absorbers consider normal angle of incidence only [1]. There are a few of published information on oblique incidence performance of absorbers. However, the demand of good oblique incidence performance for various kinds of absorbers with emphasis on the applications in solving electromagnetic pollution problems such as electromagnetic interference (EMI) and electromagnetic compatibility (EMC) has been an increasing concern. Absorbers with good performance at oblique incidence for both transverse electric (TE) and transverse magnetic (TM) polarizations are badly needed.

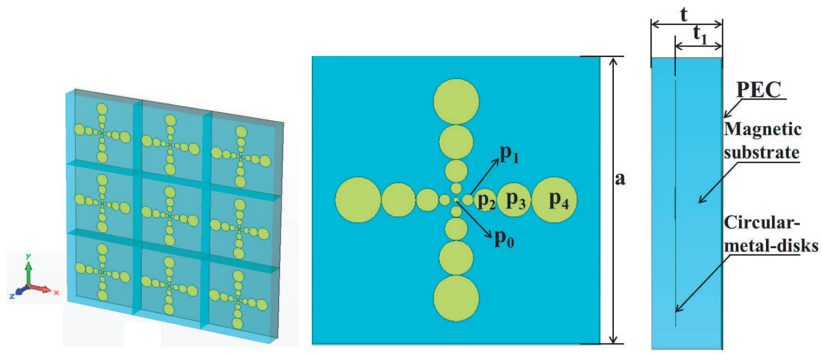
Previous methods [2–7] have been proposed to enhance the oblique incidence performance. In Ref. [2], high permittivity dielectric layers are essential for frequency stability and increase of bandwidth. This design method can improve oblique incidence performance significant but is limited to Jaumann absorber. A. Kazemzadeh et al. have developed a design procedure for multilayered Jaumann absorbers with a stable frequency response up to 45° incidence for TE and TM polarizations and an ultrawide bandwidth [3]. However, the thickness of EM absorbers is greatly increased. Refs. [4–7] have introduced high-impedance surfaces to create electrically thin electromagnetic absorbers to improve oblique incidence performance, but the improvement is limited to TM polarization.

In this paper, a broadband magnetic MA is designed by embedding circular-metal-disks into magnetic absorbing sheet. Numerical computations show that the proposed absorber achieves a reflection coefficient less than −10 dB from 4.8 GHz to 11.0 GHz with a stable frequency response up to 30° for both polarizations. Meanwhile, the absorber has a wide bandwidth of 10.8 GHz with the incidence angle from 45° to 60° under TM polarization. Finally, the impedance characteristic and the current indicate that the improvement of the absorption characteristics is due to both the electric resonance and magnetic resonance.

2. METHODOLOGY

As shown in Figs. 1(a) and (b), the proposed absorber consists of a 2-D periodic array of circular-metal-disks embedded in a magnetic sheet. An electric conductor plat is placed at the bottom of the absorber. The magnetic sheet was prepared on the basis of polymer composite filled with FeCo alloy powder described in Ref. [8] and [9] at the weight ratio of 1:3. The relative permittivity and relative permeability of the magnetic sheet material are shown in Fig. 2.

We used the finite difference time domain (FDTD) solver CST Microwave Studio to mimic the problem shown in Fig. 1(a). The program simulated a single unit cell with appropriate boundary



(a) (b) (c)

Figure 1: Geometry of the radar absorber based on a magnetic substrate with circular-metal-disks. (a) Perspective picture of MA. (b) Front view of the structure (p_0, p_1, p_2, p_3, and p_4 represent diameter of the disks, respectively. $p_0 = 0.2\,\mathrm{mm}$, $p_1 = 0.4\,\mathrm{mm}$, $p_2 = 0.8\,\mathrm{mm}$, $p_3 = 1.2\,\mathrm{mm}, p_4 = 1.6\,\mathrm{mm}$.). (c) Cross section schematic of the fundamental structure. a is the period of MA, t is the thickness of the magnetic substrate, and t_1 is the position of the circular-metal-disks.

conditions, as perfect electric conductor (PEC) boundary on two opposite sides and perfect magnetic conductor (PMC) boundary on the other two opposite sides. A linearly polarized plane wave was incident on the surface of the magnetic absorbing sheets with either TE or TM polarization, as shown in Fig. 3. In the simulation, the material settings of the aluminum patches and the metal plane were lossy metal with an electrical conductivity of $3.72 \times 107\,\mathrm{S/m}$ and PEC, respectively. Note that, there is not transmission because the bottom of the absorber is a PEC plate.

For oblique incidence, frequency stability and reflection coefficient are necessary for both TE and TM polarizations. The reflection coefficient, based on the transmission line theory [10], is calculated as a function of input impedance of MAs. According to Ref. [16], the input impedance of MAs for both polarizations at oblique incidence can be calculated by a recurrence formula.

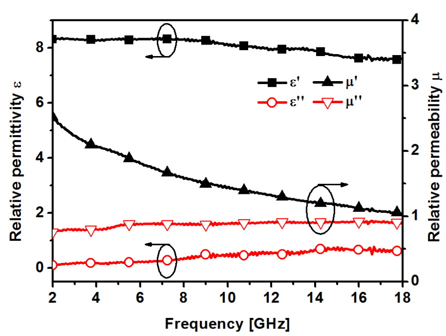


Figure 2: Relative permittivity (ε) and permeability (μ) of the magnetic absorbing sheet material as a function of frequency.

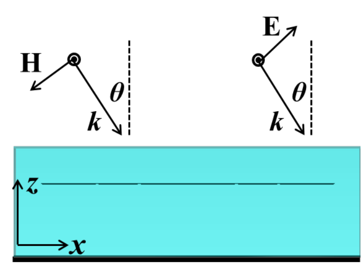


Figure 3: TE and TM plane wave incident on the MA. The electric (magnetic) field of the TE-polarized (TM-polarized) incident wave is along y-axis, and θ is the incidence angle.

$$Z_{in(\mathrm{TE})} = Z_{(\mathrm{TE})} \tanh(\nu_2 \cdot d) \tag{1}$$

$$Z_{in(\mathrm{TM})} = Z_{(\mathrm{TM})} \tanh(\nu_2 \cdot d) \tag{2}$$

$$Z_{(\mathrm{TE})} = \frac{\eta\sqrt{\mu_r/\varepsilon_r}}{\cos(\theta_2)} \tag{3}$$

$$Z_{(\mathrm{TM})} = \eta\sqrt{\mu_r/\varepsilon_r} \cdot \cos(\theta_2) \tag{4}$$

where $Z_{(\mathrm{TE})}$, $Z_{(\mathrm{TM})}$ are the characteristic impedance of absorbing layer for TE and TM polarization, respectively. $\eta \approx 377\,\Omega$ is the wave impedance of the free space, $\nu_0$is the propagation constant of the free space, θ_2 represents the angle of transmission in the magnetic composite sheet, $\nu_2 = \nu_0\sqrt{\mu_r/\varepsilon_r}\cdot\cos(\theta_2)$ is the propagation constant along the plane normal of the substrate layer. The value of $\cos(\theta_2)$ is given by Snell's law:

$$\cos(\theta_2) = \sqrt{1 - \frac{\sin^2(\theta_1)}{\mu_r\varepsilon_r}} \tag{5}$$

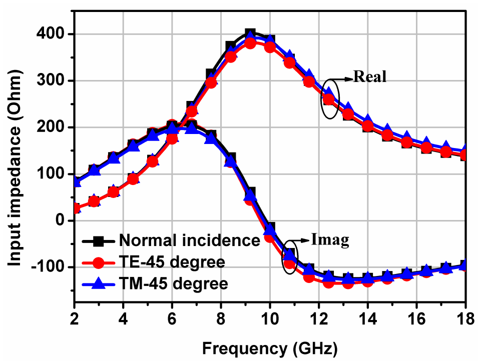


Figure 4: The input impedance of the MA without circular-metal-disks for the incidence angle of 0° and 45° under TE and TM polarization.

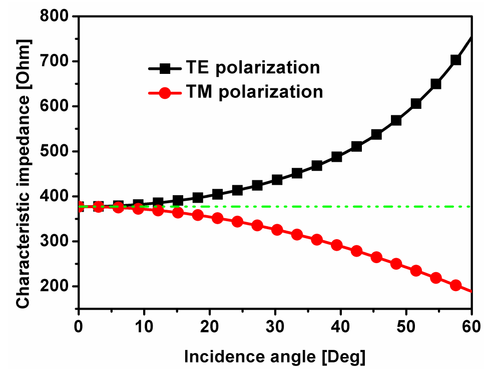


Figure 5: The variation of impedance of free space with angle of incidence at both TE and TM polarizations.

According to above formulas, the input impedance of the magnetic absorber is calculated and shown in Fig. 4. It is obtained that the input impedances vary slightly with oblique incidence angles compared to that at normal incidence. Therefore, the input impedance for different incidence angles can appropriate that for normal incidence angle as follows:

$$Z_{in} = Z_{(TE)} = Z_{(TM)} = \eta\sqrt{\mu_r/\varepsilon_r}\tanh(\nu_0\sqrt{\mu_r/\varepsilon_r}) \tag{6}$$

Then, the reflection coefficient with oblique incidence of plane wave at the angle of θ_1 for both polarizations can be calculated as [11]:

$$\Gamma(\mathrm{TE}) = \frac{Zin - \eta/\cos(\theta_1)}{Zin + \eta/\cos(\theta_1)} \tag{7}$$

$$\Gamma(\mathrm{TM}) = \frac{Z_{in} - \eta\cdot\cos(\theta_1)}{Z_{in} + \eta\cdot\cos(\theta_1)} \tag{8}$$

The characteristic impedance of free space [see in Fig. 5] can be expressed by $\eta/\cos(\theta_1)$ Ohm and $\eta\cdot\cos(\theta_1)$ Ohm for TE and TM polarization, respectively [12]. It is obtained that the totally different changing trends of characteristic impedance of free space inevitably leads to the case, that once the oblique incidence performance for MA in one polarization is good then another is bad [13–15]. It is difficult to simultaneously improve the oblique incidence performance of an absorber under both polarizations. Therefore, the introduction of the circular-metal-disks can be better to improve the oblique incidence performance.

3. NUMERICAL RESULTS AND DISCUSSIONS

Figure 6 shows the reflection coefficient of the absorber with and without circular-metal-disks. Figs. 6(a) and 6(b) demonstrates very stable operation frequency with incidence angle increases, and this performance remains even by embedding circular-metal-disks into MA [see in Figs. 6(c) and 6(d)]. In the case of TE polarization, −10 dB absorption bandwidth of the proposed MA is increased at least by 5.7% compared that of MA without circular-metal-disks from the incidence angle of 0° to 30°. In the case of TM polarization, −10 dB absorption bandwidth of the proposed MA is increased by 17%, 36% and 168% for the incidence angle of 30°, 45°, and 60°, respectively.

We now give an investigation into the physical origin of the absorption peaks at both TE and TM polarization. Figs. 7(a) and 7(b) show the normal incidence surface current distributions of

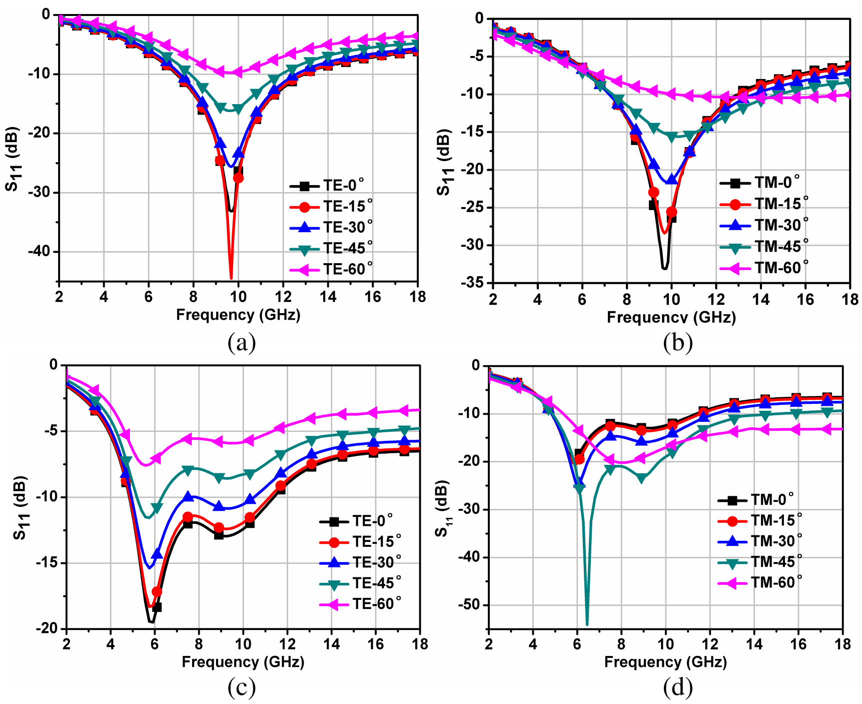


Figure 6: Simulated reflection coefficient of the proposed MAs for TE and TM polarizations: (a) MA without circular-metal-disks for TE-polarized wave, (b) MA without circular-metal-disks for TM-polarized wave, (c) MA with circular-metal-disks for TE-polarized wave, (d) MA with circular-metal-disks for TM-polarized wave.

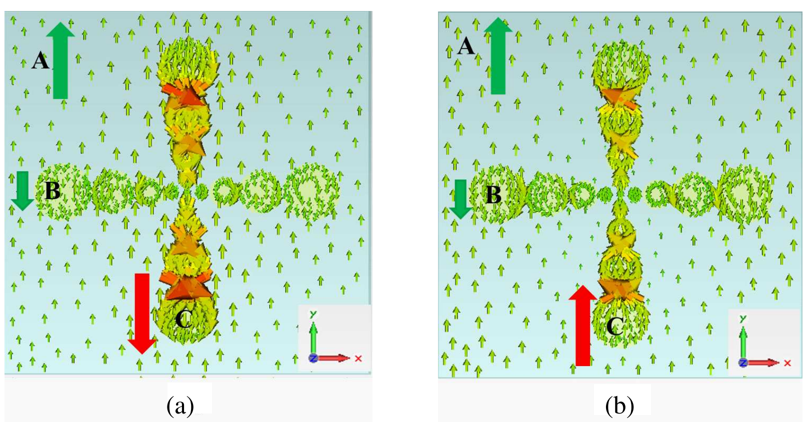


Figure 7: Surface current distributions (the electric field of the incident wave is along y-axis) of the MA with circular-metal-disks at two resonance frequencies for normal incidence (A, B, and C respect the current of different region of PEC, circular-metal-disks along x-axis, and circular-metal-disks along y-axis.). (a) 6.0GHz, (b) 9.5 GHz.

the proposed MA at two absorption frequencies of 6.0 GHz and 9.5 GHz, respectively. From the result in Fig. 5(a), only magnetic resonance can be at the absorption peak of 6.0 GHz. However, with regard to the other absorption peak at 9.5 GHz, both magnetic and electric resonances can be observed. For the magnetic resonance, the backed metal layer and the circular-metal-disks along x-axis carry electrical charges with opposite signs leading to a circulating current, which creates the magnetic flux coupling with the incidence magnetic field. At the electrical resonance, the induced current flows through the circular-metal-disks along y-axis parallel to the incidence field. Therefore, these two absorption peaks relies on the magnetic and electrical resonances.

4. CONCLUSION

A broadband magnetic absorber for realizing stable absorption under both TE and TM polarizations has been presented. By introducing circular-metal-disks, we improve the oblique incidence performance of the MA. Simulated results demonstrate that the optimized MA with a thickness of 2.4 mm exhibits good oblique incidence performance for both TE and TM polarization and a broadened −10 absorption bandwidth. By analyzing the distribution of the surface current of the proposed MA, it is found that this feature is mainly related to the magnetic and electric resonance.

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