A Thin Magnetic-Type Absorber for Wide Incidence Angles and Both Polarizations Using Dipole-Arrays

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Abstract. A thin microwave radar absorber with metallic dipole arrays incorporated into magnetic polymer composite is proposed to operate over a wide range of incidence angles for both TE and TM polarizations. Owing to the impedance characteristics, the magnetic absorber (MA) without dipoles cannot hold oblique-incidence-absorption for TM polarization. By introducing dipoles, the incorporated MA exhibits a broad bandwidth for reflection equal or less than -10 dB for incidence angle up to 60° for TM polarization, and remains excellent oblique-incidence absorption for TE polarization. The improvement of oblique-incidence absorption for TM polarization is related to LC resonance caused by the embedded dipoles. The experimental results show that the proposed MA with a thickness of 2.0mm provides wide bandwidth (5.0 GHz ~15.7 GHz for normal incidence and 4.5 GHz ~14.8 GHz for incidence angle of 45°) for TM polarization, which is agreement with the simulated results.

1. Introduction
The design of electromagnetic (EM) absorbers for radar cross section reduction (RCSR) is a challenging task [1]. Most investigations of the traditional structures for EM absorbers including Salisbury, Jaumann and Dallenbach absorbers [2] mainly considered with normal angle of incidence [3]. Only a few design methods considering oblique angle of incidence were published. However, the demands of oblique incidence absorption with emphasis on the applications in solving EM pollution problems such as electromagnetic interference (EMI) and electromagnetic compatibility (EMC) have been an increasing concern. EM absorbers with good oblique incidence performance for both transverse electric (TE) and transverse magnetic (TM) polarizations are badly needed in EMI and EMC.

Two main fundamental questions for oblique incidence performance of EM absorbers are frequency stability and absorption bandwidth for both polarizations with a fixed thickness [3]. In previous papers, several design methods [3]-[8] have been proposed to enhance the oblique incidence performance. In Ref. 3, the high permittivity dielectric layers were found to be essential for frequency compensations and bandwidth increases. This design method can improve oblique incidence performance significantly but is limited to Jaumann absorber. In Ref. 4, A. Kazemzadeh et al. have developed a design procedure for multilayered Jaumann absorbers and capacitive circuit absorber with a stable frequency response up to 45° incidence for both polarizations and an ultrawide bandwidth of 26GHz. However, the main drawback of the above mentioned two design methods is the increase of the thickness of EM absorbers. Ref. [5]-[8] have introduced high-impedance surfaces to create electrically thin electromagnetic absorbers to improve oblique incidence performance, but the improvement is limited to TM polarization.

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In this paper, a simple method to realize the stable absorption for both TE and TM polarizations over a wide incidence angle range at a limited thickness was introduced. Firstly, based on the impedance matching characteristics, the magnetic absorber (MA) without metallic dipole arrays achieved good oblique-incidence absorption and stable resonance frequency for TE polarization. Secondly, by embedding dipole arrays into the MA (MAWDA), the oblique-incidence performance for TM polarization was improved, while the performance of MAWDA for TE polarization was almost non-deteriorated. Both impedance characteristic and surface current distributions of MAWDA were proposed to explain the effect of dipole arrays in oblique incidence. Finally, the experimental results show that MAWDA with smaller thickness (2.0mm) and wider bandwidth (5.0 GHz ~15.7 GHz for normal incidence and 4.5 GHz ~14.8 GHz for incidence angle of 45°) for TM polarization compared to Ref. [6-8] excites multiple resonances and therefore obtains a broadband absorption.

2. Design and simulation results

A single unit cell of the absorber based on magnetic absorbing sheet is illustrated in Fig. 1(a). The 2.0 mm-thick-magnetic absorbing sheet is backed by a metal ground. The MAWDA has dipoles incorporated into the magnetic absorbing sheet. As shown in figure 1(b) and 1(c), each unit cell with a period of $a=6.0$ mm contains only one dipole. The optimized parameters of dipole are as follows: the length $l=4.0$ mm, the width $w=1$ mm and the position of dipole arrays $t_1=1.0$ mm. The magnetic absorbing sheet used in this work was prepared by polymer composite filled with FeCo alloy powders (at the weight ratio of 1:6) as described in Ref. [9] and [10]. The measured relative permittivity and permeability of the magnetic sheet material are shown in figure 2.

![Figure 1. Schematic of the proposed MAWDA: (a) Single unit cell of the MAWDA, (b) perspective view and (c) sectional view of the absorber with metallic dipole. Each unit cell contains only one dipole.](image)

![Figure 2. Relative permittivity ($\varepsilon$) and permeability ($\mu$) of the magnetic absorbing sheet material as a function of frequency.](image)
Figure 3. TE and TM plane wave incident on the MAWDA. The electric (magnetic) field of the TE-polarized (TM-polarized) incident wave is along $y$-axis, and $\theta$ is the incidence angle.

Numerical simulations were performed using the finite difference time domain (FDTD) solver CST Microwave Studio. We simulated a single unit cell with periodic boundary 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 sheet as shown in figure 3. In simulation, the material settings of the aluminum dipole were chosen as lossy metal with an electrical conductivity of $3.72 \times 10^7$ S/m and PEC, respectively. Note that, there is not transmission because the bottom of the absorber is a PEC plate. Thus, the absorption can be determined only by the reflection.

The simulated results are presented in figure 4. In the case of TE polarization, with electric field propagates along the $y$-axis direction [see in figure 3], figure 4(a) demonstrates very stable operation frequency but reduced maximum absorption with incident angle, and this performance remains even by embedding dipoles into the MA [see in figure 4(b)]. In the case of TM polarization, the operation frequency of MA shifts towards higher frequencies with increasing incident angle in figure 4(c). To fix the operation frequency, dipoles are introduced. As shown in figure 4(d), the MAWDA demonstrates two absorption peaks at about 7.6 GHz and 11.5 GHz, and an enhancement of the absorption bandwidth with the incident angle changing from 0° to 60°. At the incident angle of 45° and 60°, the -10dB absorption bandwidth is increased to 12GHz (from 6.0 GHz to 18.0 GHz).

Figure 4. Simulated reflection coefficient of the MAWDA for both TE and TM polarizations: (a) MA and (b) MAWDA for TE-polarized wave, (c) MA and (d) MAWDA for TM-polarized wave.
3. Analysis and discussion

We now give an investigation into the physical origin of the absorption for both TE and TM polarizations. The absorption characteristics remain almost consistent after embedding dipoles into the MA for TE polarization. Due to the fact that the electric field is parallel to the ground plane and perpendicular to the dipole length, it does not interact with the dipole and the dipole has negligible effect on the response of the absorber. Therefore, the MA and MAWDA are equivalent in this case [11]-[12]. The resonance absorption peak around 11.5 GHz is relevant to the ~λ/4 absorption, where λ is the effective wavelength in the magnetic absorbing sheet [13]. However, for the case of TM polarization, the incidence electric field propagating along y-axis direction, the MAWDA produces two resonance absorption peaks which have different resonance mechanisms from the TE polarization case. This can be obtained by examining the surface current distributions at the corresponding absorption frequencies.

Figure 5 shows the normal-incidence surface current distributions of the MAWDA for TM polarization at two absorption frequencies of 7.6 GHz and 11.5 GHz, respectively. It is observed that either significant magnetic or electrical response can be seen at the absorption peak frequencies. For the magnetic response, the induced current flows through the dipole antiparallel to the current on the surface of the grounded PEC plate, which creates the magnetic flux coupling with the incident magnetic field [in figure 5(a)]. For the electric response, the current on the dipole flows parallel to the incident electric field [14] [in figure 5(b)]. Therefore, these two absorption peaks relies on the magnetic and electric response.

To further clarify the absorption mechanism of the MAWDA between TE and TM polarization, quantitative analysis of the input impedance under normal incidence and 45° incidence is illustrated in detail. According to Ref. [15], the characteristic impedance of free space [see in figure 6] can be expressed by 377/cos(θ) Ohm and 377cos(θ) Ohm for TE and TM polarization, respectively. For the MA, the magnitude of reflectivity corresponding to different input impedances under TE and TM polarizations according to Ref. [16] and [17] is shown in figure 7. It is obtained that the changing trends of input impedance for matching condition are totally different between TE and TM polarization, which inevitably leads to the case that once the absorption for MA in one polarization is good then another is bad [18]-[20]. It is difficult to simultaneously improve the absorption performance of an absorber under both polarizations. However, the MAWDA can make a difference. The presence of an additional resonance with the introducing of the dipole results in notable enlargement of the absorption band under TM polarization for the incidence up to 60°[see in figure4(d)].
Figure 7. The magnitude of reflectivity as a function of input impedance and the incidence angle for MA. (a) TE polarization, (b) TM polarization

Figure 8 shows the calculated complex impedance of the absorber with incidence angle of 0° and 45°. From figure 8(b), around 7.6 GHz the imaginary part of the input impedance of the MAWDA is close to zero, which means the resonance occurs at ~7.6 GHz. The real parts of the MAWDA around two resonance frequencies is decreased and less than 377 Ohm, which is favorable to increase the bandwidth and improve the oblique-incidence performance for TM polarization. We can understand the two absorption peaks of the MAWDA for TM polarization by simply using equivalent circuit method. The dipole introduces equivalent capacitance and inductance into the equivalent circuit of MA [18]. Then the equivalent circuit introduces a LC resonance with matching capacitive and inductive parameters. The dipole acts capacitive to determine the position of the lower resonance frequency (7.6 GHz) and inductively to confirm the upper resonance frequency (11.5 GHz) [19]-[24]. According to Ref.[20], the equivalent parameters under normal incidence for TM polarization are approximately calculated by curve fitting. The equivalent capacitive and inductance are function of $\varepsilon_0(\varepsilon_r+1)/2$ and $\mu_0(\mu_r+1)/2$, where $\varepsilon_0$ and $\mu_0$ are the permittivity and permeability of the vacuum. Hence, the equivalent capacitive is about 0.0022$\varepsilon_0(\varepsilon_r+1)$pF and the equivalent inductance is about 0.0274$\mu_0(\mu_r+1)$μH. The fitting result is shown in figure 9. We can intuitively observe that the improvement of the absorption for TM polarization is related to LC resonance, and thus a wideband absorber can be achieved by designing the dimension parameters carefully.

Figure 8. Real and imaginary part of the input impedance, (a) TE polarization, (b) TM polarization
4. Experimental results

In our experiment, the considered magnetic sheets were fabricated in the form of rubber board. The aluminum dipole arrays were pasted between the top and bottom magnetic layers. The total area of the sample is 400 mm×400 mm, including more than 4000 units. An image of the MAWDA is shown in figure 10. The reflection coefficient dependence on frequency and incidence angle was measured by the United States Naval Research Laboratory (NRL) arch method [11] using vector network analyzer (Agilent 8720ET). For reflection coefficient measurement of the MAWDA structure, two 2-18GHz band horn antennas are used; one for transmission and another for reception.

For normal incidence, the structure is placed at 1.7m distance away from the antennas so that the far-field condition is amply satisfied. For incidence angle of 45°, the two horn antennas are rotated from 0° to 45°. The measured results of MA and MAWDA are shown in figure 11. For TE polarization, we can see the introducing of dipole arrays has no effect on the absorption performance for the incidence angle of 0° and 45°. However, the absorption bandwidth is improved for TM polarization from figure 11(b). The -10 dB absorption bandwidth for incidence angle of 0° is about 10.7 GHz (5.0GHz-15.7GHz), and for 45° that is about 10.3 GHz (4.5GHz-14.8GHz). The experimental results show good agreement with the simulated results, but the change in frequency for TE polarization is observed which could be attributed to the effects of the EM parameters of magnetic sheet. And the bandwidth for TM polarization is somewhat large in disagreement with the simulations, which may be caused by fabrication tolerances in the structures.

5. Conclusions

In summary, a simple design method to realize the frequency stable absorption of MA for both TE and TM polarizations has been presented. Firstly, based on the magnetic absorbing materials, the absorber
can achieve a stability of resonance frequency for TE polarization. Secondly, by introducing dipoles, we improve the performance of oblique incidence for TM polarization without deteriorating the absorption characteristics for TE polarization. Both simulated and measured results validate that the MAWDA with a thickness of 2.0 mm exhibits good oblique-incidence-performance for both TE and TM polarizations and a broadened -10dB absorption bandwidth for TM polarizations. By analyzing the surface current distribution and impedance characteristic, it is found that this feature for TM polarization is mainly related to the LC resonance ability of the absorber.

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