PAPER

Absorbing properties of metamaterial dihedral corner reflector

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Abstract

In this paper, the absorbing property of metal-cross shaped metamaterial dihedral (MCMD) and cross-cross shaped metamaterial dihedral (CCMD) with the same parameters are investigated. In TE mode, the absorptivities are 91.1% at 9.17 GHz for MCMD and 99.7% at 9.20 GHz for CCMD. For MCMC and CCMD, the absorptivities are 90.5% and 99.8% at 9.2 and 9.17 GHz respectively for the TM polarized incident wave. The results of simulation and measurement show that CCMD has better multi-band absorption performance and lower radar cross-section than MCMD. Experiments have demonstrated the reflection coefficient can be utilized to analyze the electromagnetic characteristics of dihedral corner as well. The study of dihedral corner reflector is of great importance as it is used in modeling many areas such as stealth technology, electromagnetic compatibility and target recognition.

1. Introduction

Metamaterials (MMs) [1, 2] are artificial effective electromagnetic structures with subwavelength scale cells. It obtains the properties which cannot be found in nature, such as negative refraction index [3], cloaks [4], superlens [5] and extraordinary optical transmission [6]. Metamaterial perfect absorbers (MPA) have been proposed at microwave by Landy et al in 2008 [7]. MPA can be applied in many fields, such as solar energy [8, 9], plasmonic sensors [10], bolometers and photo-detectors [3]. During the last years, many kinds of metamaterial absorbers have been extensively investigated: the stair-like 3D structure [11], multi-metallic-layers structure [12], flexible and lightweight substrate [13, 14], planner structure [15], transparently curved metamaterial [6] and so on.

The dihedral corner, as a potential application of metamaterial absorber [16–18], has been rarely investigated. Dihedral corner [19–21], which is often formed between the plane’s tails or between the naval ships and the water surface, could degrade the target’s stealth performance. Dihedral corner is one of the corner reflectors with strong multiple scattering characteristics. Besides, its wide scattering pattern makes it a typical scattering structure. Most traditional studies have focused on the enhancement or reduction of Radar Cross section (RCS) in dihedral corner reflector. For instance, the fractal structure [22] or metasurface to enhance and reduce RCS has been proposed through the corner reflector [23]. A method is presented to calculate the scattering characteristics of the dielectric coated corner reflector [24–26]. It is analyzed in [19] that RCS characteristics of dihedral corner reflectors caused by length is slighter than the effects caused by width. A major ignorance of traditional dihedral corner research is that many kinds of research focus on the RCS of dihedral corner but neglect the absorption property.

This paper deals with the study of the absorbing characteristics of different dihedral corner structures. The dihedral corner absorbers exhibit a high absorption rate at different polarization incidences compared with a flat plate. Firstly, the absorptivity of different dihedral corner reflectors with an open background has been
calculated using the Finite Integration Technique. The absorption characteristics of the different polarization angles with TE and TM modes are verified by experiments. The second part deals with the RCS of different dihedral corner reflectors loaded with a cross-shaped metamaterial structure. At last, the resonance frequency of RCS is compared with the absorption frequency to validate the method.

2. Simulation and experiment

Figure 1 (a) shows the schematic diagrams of the flat plates loaded with cross-shaped metamaterial absorber (CMA). The unit cell of the upper metallic layer consists of two perpendicular metal wires, the middle layer is the dielectric plate, the metal is deposited on the bottom layer to eliminate the transmitted wave. The optimized geometrical parameters of metamaterial absorber are \( a = b = 10 \text{ mm}, \ c = 8 \text{ mm} \) and \( d = 0.5 \text{ mm} \). The substrate is FR-4 with a thickness of 0.8 mm, with a relative dielectric constant of 4.3 and the loss tangent of 0.025. The thickness of the copper is 0.035 mm.

The whole experimental sample is made into a unit size of \( 20 \times 20 \text{ mm} \times 200 \text{ mm} \) and a part of the sample is shown in figure 1(b). Four flat plates of the same structure are composed of two dihedral corner reflector, whose middle gap are attached with copper film and the corner angle can be varied freely. The metal-cross shaped metamaterial dihedral (MCMD), cross-cross shaped metamaterial dihedral (CCMD) of the experimental samples and the measurement set-up are shown in figures 1(c), (d) and 2(b), respectively. The simulation results are acquired by simulation software, CST Microwave Studio, which is based on the Finite Integration Time (FIT) domain method [27]. In the CST simulation, two waveguide ports are added for transmitting and receiving electromagnetic waves. In the boundary condition setting, the x and y directions are set as \( H_t = 0 \) or \( E_t = 0 \) and z directions as an open (add space) respectively to obtain the reflection coefficient under two different polarization modes.

The absorption \( A \) of the metamaterial absorber is defined as \( A = 1 - T - R \), in which \( T = |S_{21}|^2 \) and \( R = |S_{11}|^2 \). \( T \) and \( R \) represent the transmission and reflection coefficients. \( S_{11} \) and \( S_{21} \) are the scattering parameters of the reflection and transmission respectively. The transmission can be eliminated by containing the
copper in the bottom layer. In a microwave anechoic chamber, two standard gain horn antennas were connected to an Agilent E8362B vector network analyzer to get the reflection coefficient curves.

Firstly, the absorption behavior of the flat plates metamaterial absorber under the normal incidence wave was investigated. The $S_{11}$ (Reflection coefficient) of the CMA in the TE polarization from 3.0 to 20.0 GHz are depicted in figure 2(a). Clearly, the absorption rate is greater than 98% at 9.2 GHz, while the absorbing hardly exists in other frequencies. The measured results in the frequency band of 3.0–17.0 GHz are presented in figure 2(a) due to limited experimental conditions. The measured results also validate the effectiveness of the absorbing behavior and achieve a higher absorption.

The results of the same geometric parameters of MCMD and CCMD are plotted in figure 3. Some excited phenomena have been observed especially dihedral corner metamaterial’s absorption under two polarization modes. Due to the CMA forms the dihedral corner reflector, which composes the overall symmetrical structure of the absorber, the composed dihedral corner reflectors metamaterials have better absorption characteristics. However, the absorption of the TE wave and TM wave vary greatly with the dihedral corner reflectors at normal incidence.

Figures 3(a), (b) shows different absorption behaviors that emerges when the incident electric field is perpendicular or parallel to the MCMD ridge (TE or TM mode), respectively. The $S_{11}$ (Reflection coefficient) of the MCMD drops sharply at 9.2 GHz for both TE (figure 3(a)) and TM (figure 3(b)) modes, and for TM mode it also decreases greatly at 17.8 GHz and 18.92 GHz. For TE mode of the MCMD, in figure 3(a), there is the same absorption point for the planner and the dihedral corner structure. Figure 3(a) show that the simulated absorption peak is up to 91.1% at 9.17 GHz for the MCMD. Accordingly, as figure 3(b) indicates, the absorptivity are 90.5%, 78.6% and 88.2% at 9.2 GHz, 17.8 GHz and 18.92 GHz respectively for the TM polarized mode of the MCMD. For the CCMD, the absorption can reach above 99.7% at 9.2 GHz. Following figure 3(d), about 99.8%, 93% and 98% of the TM polarized incident electromagnetic energy are absorbed at 9.17 GHz, 18.1 GHz and 19.1 GHz respectively. Both of the two dihedral corner structures generate multi-band absorption in TM polarization mode. The high absorption rate means that most of the incident electromagnetic waves are consumed at the dihedral corner reflectors. It denotes that the reflection is quite weak and high absorptions can be achieved [12].

Especially, the maximum absorption is almost equal to unity in the vicinity frequency of 9.17 GHz and 19.1 GHz, which denotes that the incident wave completely absorbs to its dihedral corner reflectors after
transmission from the standard gain horn. The simulated results of MCMD and CCMD are slightly different from the experimental results at the resonance frequency point. There is a certain angle between the two gain horn antennas during the measurement, which does not exist in the simulation. The insufficient precision of the manufacturing process leads to the bending of the experimental sample, which is also an important cause of frequency shift.

3. Results and discussion

3.1. The backscattered plots with frequency for TE and TM Polarization

In this section, the Radar Cross section (RCS) verifies the absorption behavior of the dihedral corner reflector. RCS simulation of dihedral corner reflectors mainly focus on different structures of the RCS characteristics with a series of parameters changing is analyzed [8]. Figure 4 presents the simulated results of the radar cross-section spectra of CMA, MCMD and CCMD under normal incident wave (the wave travels along -z-axis).

Figure 4(a) shows that there is only one maximum reduction in backscattered power of about 18.46 dB in the vicinity of 9.5 GHz. It is noteworthy that due to the CMA symmetric structure, the RCS has nothing to do with the polarization mode of the incident wave and CMA is polarization insensitive. More interestingly, the maximum RCS reduction is almost equal to 19 dB in the vicinity of 9.5 GHz, which denotes the scattering properties completely with the absorption behavior of the CMA. However, in other frequency ranges the copper plate and the CMA exhibit the same characteristics for scattering. It fully shows the frequency selection characteristic of CMA.

In figures 4(b) and (c), it conducted an analysis of the relationship of different TE and TM in the MCMD and CCMD. The comparison of different polarization modes investigated that the difference between horizontal polarization and vertical polarization is minor, regardless of frequency.

In addition, it can also be concluded that the same absorption frequency will be obtained under TM polarization incidence due to the corner reflector symmetric property, and the maximum reduction in RCS will also be generated when the TM polarized wave is normally incident to the CCMD. It is found that the main reduction frequency in RCS is overlap basically with absorption frequency point under two polarized waves to the MCMD and CCMD. It can be seen that the frequency-shift of the maximum reduction in RCS is less than 0.3 GHz in the two polarization modes, and the simulated results of the absorbing frequency are basically consistent with the measured.

3.2. 3D bistatic scattering patterns

In the plentiful work of RCS for dihedral corner reflectors, relatively little attention is given to analytic solutions of the 3D bistatic scattering patters problem. Figure 6 shows the 3D scattering patterns with different structures at different frequencies, which can intuitively observe the intensity of scattering from the color. The dihedral scattering responses in [21, 28] and the total scattered field in [29] are given by a single transmitter that exemplifies each illumination case and a single frequency.

The simulated results of the scattering patterns are shown in figure 5 for the MCMD and CCMD. The incident wave illuminates the MCMX with TE polarization mode (shown in figure 4(b)). The RCSs are $-7.8$ dB and $-24.2$ dB at 4.8 and 9.5 GHz respectively. In the case of TE polarization mode illumination, the 3D scattering patterns response obtained is in good agreement with the absorption characteristics of the dihedral corner reflector. When the incident wave is illuminated to the sample at 9.5 GHz, the resonance is most intensive and the absorption is the highest and the backscattered power is minimum. Meanwhile, the structural symmetry of the CCMD leads to the better absorption and the backscattered power is minimum ($f = 9.5$ GHz). It denotes that the reflection energy of CCMD is quite weak and high absorptions can be achieved.
3.3. Variation of backscattered power with the angle of incidence for different structure

For investigating the absorption rate of the proposed dihedral corner reflectors, a Mono-static RCS is simulated on the dihedral corner ($\alpha = 90^\circ$).

As shown in figure 6, the RCSs of the dihedral corner copper (DCC), MCMD and CCMD using uniform size are compared at 9.5 GHz. Compared with the DCC, the RCS of the MCMD is 41.5 dB lower at 19° and the CCMD is 9.5 dB lower at 10° in TE polarization mode. Depending on the different angle of incidence wave, the reflected field from metamaterial absorber plate may partially or fully illuminate the other plate, resulting in asymmetry RCS curves of the different plates dihedral corner reflectors. These large echoes from the different structures arise from multiple reflections between the two mutually orthogonal flat plates dominating the backscattered pattern in forward region, forming a high reduction for RCS. In the case of electromagnetic wave incidence, the change with theta angle of the MCMD from 10 to 80 degree, the RCS curve typically increase in an asymmetrical state (shown in figure 6(b)). On the whole, RCS of dihedral corner reflectors in different polarization mode has oddly affected by the copper plate of dihedral corner reflectors for MCMD; RCS of dihedral corner reflectors in different polarization modes up trend with the angle of dihedral corner reflectors and remain asymmetric; when theta angle reaches 90 degrees, the RCS reached its maximum.

It is observed from figures 6(b) and (d) that the different dihedral corner reflectors have a better RCS reduction effect than the dihedral corner copper with uniform sizes for the angles from 10° to 80°. In this result, the turning points are distributed at the incident angles of 10° and 80° and the rest is the effect of the dihedral corner. For the normal incident on CCMD with theta = 45°, the absorptive performance is the symmetry with each other for TE wave and TM wave, which have been demonstrated in figure 6(d). The RCS simulated results of different dihedral corner reflector for MCMD and CCMD have been presented as proof of the concept of the absorption behavior in the same frequency points. Although the RCS of a dihedral corner reflector can be reduced by using the CCMD with uniform unit cells, the RCS can be further reduced by using the proposed MCMD metamaterial absorber.
Figures 4–6 show the simulated RCS results of the different structures on the dihedral corner. These graphs indicate our previous absorption behavior that the electromagnetic properties of the dihedral corner reflector by three aspects can be analyzed. The coincidence of the maximum RCS reduction is obtained for two polarization modes which indicates that the absorption behavior for calculating an effective reflection coefficient is also applicable to our dihedral corner. As expected, the proposed dihedral corner reflectors in the TE polarization mode show a high absorption rate and RCS reduction than flat plates at 9.5 GHz. When compared with the flat plate and MCMD, the RCS of the CCMD is dramatically reduced at different polarization modes.

4. Conclusion

The absorption characteristics of two kinds of metamaterial dihedral corners MCMC and CCMD are analyzed elaborately with simulation and experiment results. By using the simulation of $S_{11}$ (Reflection coefficient), RCS and 3D bistatic scattering patterns, the MCMC and CCMD are proved to be useful in improving absorptivity and reducing the backscattered power. Like the flat plates CMA, the absorptivities of MCMC and CCMD are almost perfect at a lower frequency in the TE and TM polarization. Different from CMA, MCMC and CCMD produced a strong multi-band absorption at higher frequency in TM polarization. The MCMC and CCMD can be applied in certain devices such as sensors, power splitter, and stealth technology.

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