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Broadband Radar Cross-Section Reduction for Microstrip Patch Antenna Based on Hybrid AMC Structures

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Abstract—Two different kinds of artificial magnetic conductors (AMCs) are used to reduce the out-of-band radar cross section (RCS) of microstrip patch antenna. The principle of this method is based on the high impedance characteristic of the AMC structures. The simulated results show that out-of-band RCS of the proposed patch antenna is much lower than that of the reference antenna over the frequency range of 5–12 GHz. The in-band scattering characteristic of the microstrip patch antenna is analyzed, and two slots are cut on the patch antenna to reduce in-band RCS. Prototypes of the reference and designed antennas are manufactured and tested, and the measured and simulated results of the two antennas are in good agreement.

1. INTRODUCTION

With the development of stealth technology, radar cross-section reduction (RCSR) has received more and more attention, especially for the military platform. As a kind of special scatter, antenna's scattering makes great contribution to the main RCS of a low observable platform, so the RCSR for antenna is practical and urgent. Some solutions have been proposed for the RCSR of antenna, such as changing the basic structure of original antenna, loading radar absorbering materials (RAMs) and using passive or active cancelation technology.

Shaping is widely used to reduce RCS of antenna and other stealth targets. With this technique, RCS can be reduced by changing the structures of the original antennas [1, 2]. Radome technology [3, 4] is used to protect the antenna and reduce the out-of-band RCS of the antenna. References [5, 6] proposed a new method for antenna RCSR based on the bionics. In fact, this new method is still based on the shaping technology. RAMs is another important approach for antenna RCSR. Several RAMs based on EBG and frequency selective surface (FSS) structures have been discussed in [7–11]. An EBG absorber using conducting polymer to reduce the out-of-band RCS of a patch antenna was developed, which had little influence on the antenna's radiation characteristics [7]. In [9], an ultra-thin EBG RAM consisting of lumped resistance was used to reduce RCS of ridged waveguide slot antenna array. However, such a design is in narrowband, and the use of many lumped element resistors makes the absorber complex and expensive. Furthermore, the antenna's radiation characteristic degraded significantly. Another ultrathin and broadband radar absorber comprising single-layer resistive FSS was investigated in [10], and this absorber has a broadband absorption bandwidth. In recent years, AMC structures based on the passive cancelation theory are applied to antenna RCSR. The so-called mushroom-like EBG structures, which is proposed by Sievenpiper et al. [12], consists of a periodic array of metallic patches. Each patch with an element is connected to the perfect electric conductor (PEC) ground plane by metallic vias. This EBG exhibits in-phase reflection band-gap at the resonant frequency, working as artificial magnetic conductor. Therefore, it can be used to cancel out reflected energy from antenna at the specific frequency within specific angular. In [13], the mushroom-like EBG was used to reduce

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RCS of the patch array antenna, and one UC-EBG acted as the ground plane of printed dipole antenna to reduce out-of-band RCS in [14]. A combination of two AMC structures with overlapped operation bandwidths was used to cancel out the backscatter energy in [15], and this method is based on the coupling resonances phenomena [16]. However, these approaches are shown to work well in the normal direction over a relative narrowband. In order to broaden the operating bandwidth, two different AMC unit cells operating at different resonance frequencies with 180° phase difference were implemented to reduce RCS over a broad frequency range [17]. Although this design can reduce the metal plate RCS over a broad frequency range, it is not suitable for antenna's RCSR. Other techniques, such as loading pin diodes, implementing distributed load, using ferrite substrate [18–20], are also applied to RCSR of antennas successfully.

In this paper, Hybrid AMC (HAMC) technique is presented for patch antenna's RCSR over the out-of-band frequency range of 5–12 GHz without compromising radiation characteristics. In order to overcome the intrinsic narrow bandwidth of AMC structure, two AMC structures based on [16, 17] are designed, which operate at two different resonance frequencies without overlapped operation bandwidths. The chessboard configuration is used to arrange the AMC unit cells in [15] for reducing the RCS of metal plate, which is different from the design in this paper. The proposed antenna resonant at 4.5 GHz and HAMC structures in this paper cannot cover the operating bandwidth of the patch antenna. In order to reduce the in-band RCS, two narrow slots are cut on the patch antenna. The rest of the paper is organized as follows. in Section 2, the design procedures and mechanisms are discussed. In Section 3, the simulated results are exhibited, and two prototypes of the reference and proposed antennas are fabricated and measured for the sake of verifying our design strategies

2. DESIGN PROCEDURE

2.1. HAMC Elements Design

Two different dimensions of AMC structures are designed in order to reduce the out-of-band RCS in this section. As we all know, AMC structures can only reduce the RCS over a narrow frequency range. To overcome this drawback, two AMC structures are utilized to reduce RCS over a broad band efficiently. Because the size of the ground plane of the patch antenna is limited, the miniaturized AMC element consisting of spiral inductors is designed in this paper. The resonant frequency of AMC element can be attuned by changing the length of spiral so that an expected RCS reduction frequency range can be obtained. As shown in Figure 1 and Figure 2, the size of the first AMC element is larger than that of the second AMC element, and the first AMC element has lower in-phase reflection band-gap than the second AMC element. The thickness of FR-4 substrate is $h = 2.5$ mm with a relative permittivity of 4.4 for both AMC elements in this design. According to [21, 22], the uniplanar AMC and EBG structures have different properties and operating bandwidths. In order to obtain the in-phase reflection band-gap, the periodic boundary condition is used to design the AMC element in the process of simulation, which

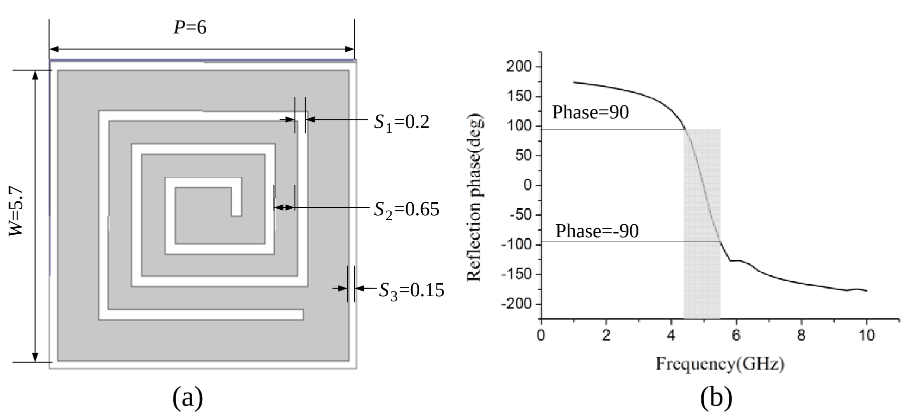

Figure 1. (a) Structures of AMC element 1 and (b) reflection phase variation versus frequency.

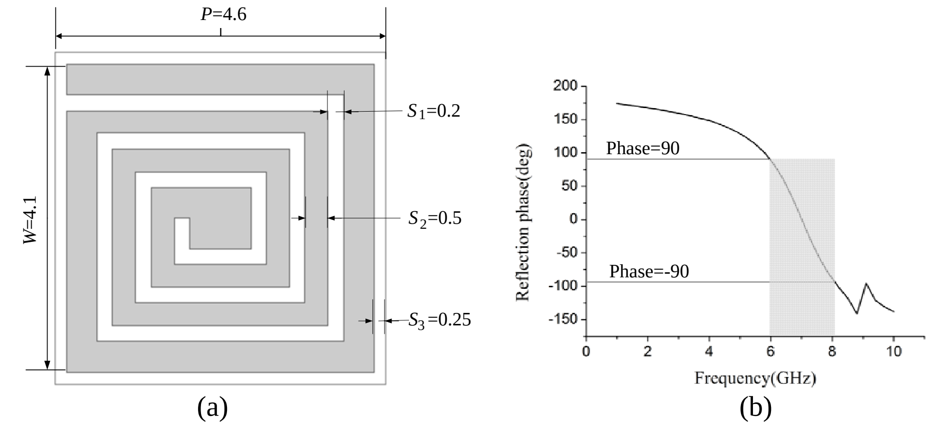

Figure 2. (a) Structures of AMC element 2 and (b) reflection phase variation versus frequency.

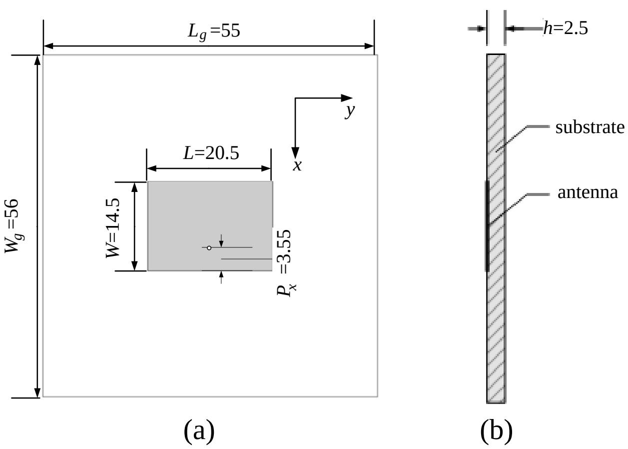

Figure 3. The structures of reference antenna (unit: mm). (a) Top view. (b) Side view.

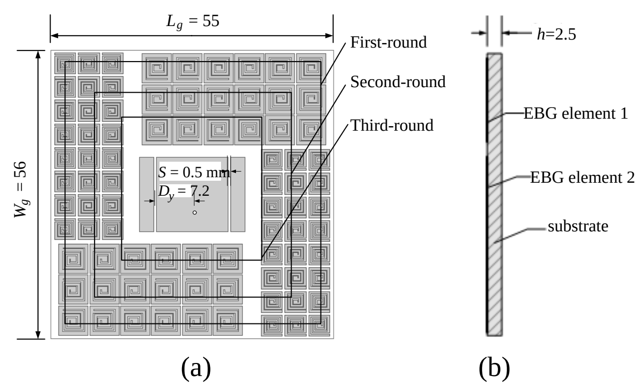

Figure 4. The structures of proposed antenna (unit: mm). (a) Top view. (b) Side view.

is based on the Bloch-Floquet theory and on the finite element. The parameters of AMC element 1 (unit: mm) and corresponding refection phase are shown in Figure 1.

Just as mentioned above, the AMC element 2 is also designed using the same method, and the optimization result is plotted in Figure 2. The parameters of element 2 (unit: mm) are depicted in Figure (a), and the reflection phase versus frequency is shown in Figure (b). Comparing Figure 1 and Figure 2, the AMC element 1 resonant frequency is 5 GHz and that of AMC element 2 is 7 GHz. The reflection phase from 90° to −90° of two AMC structures is not overlapped, and a broadband RCS reduction can be obtained by arranging these AMC unit cells properly around the patch antenna [16].

2.2. Design of Reference and Proposed Antennas

Figure 3 shows the reference antenna with a central frequency of 4.5 GHz. The patch antenna is fed by coaxial probe and printed on the substrate of FR-4 with a thickness of 2.5 mm and relative permittivity of 4.4. The parameters of the reference antenna are illustrated in Figure 3.

Figure 4 shows the proposed antenna with the same size as the reference antenna, and HAMC structures are used to cover the partial substrate around patch antenna. Just as discussed above, the HAMC structures are used to reduce the out-of-band RCS of patch antenna, and different arrangements of HAMC structures will result in different RCSR results. The numbers of the AMC unit cells and the distance between the antenna and the AMC unit cells have great effect on the RCS of the antenna but little influence on the antenna radiation performance. Therefore, both the parameters need to be simulated carefully. The arrangement in Figure 4 gives relatively better performance after simulation. Although the in-phase reflection band-gap of HAMC can be designed to cover the in-band and out-of-band of patch antenna simultaneously, the in-band RCS reduction is not very noticeable. To further reduce the in-band RCS, two slots are added to the patch antenna. In order to reduce the impact on the radiation performance of antenna, the width of slots should be as narrow as possible, and the distance between the two slots is about half of a wavelength at the resonant frequency.

3. NUMERICAL AND EXPERIMENTAL RESULTS

3.1. The Radiation Characteristics for Reference and Proposed Antennas

To validate the design strategies above, prototypes of the reference and proposed antennas are manufactured and tested. Figure 5 shows photographs of the reference and proposed antennas. The simulated and measured radiation characteristics are compared in this section.

Figure 6 shows the S_{11} parameters of the reference and proposed antennas, from which we can see that the measured results are in good agreement with the simulations. Compared with the reference antenna, the simulated central frequency of the proposed antenna shifts to the lower while the measured central frequency moves higher slightly. Both the reference and proposed antennas cover 4.4–4.6 GHz with S_{11} less than -10 dB.

Comparison of radiation patterns of the reference and proposed antennas is given in Figure 7. In the E-plane (phi = 0 deg), the simulated and measured results are accordant. In the H-plane (phi = 90 deg), the measured results of reference and proposed antennas are slightly different, and the measured gain is

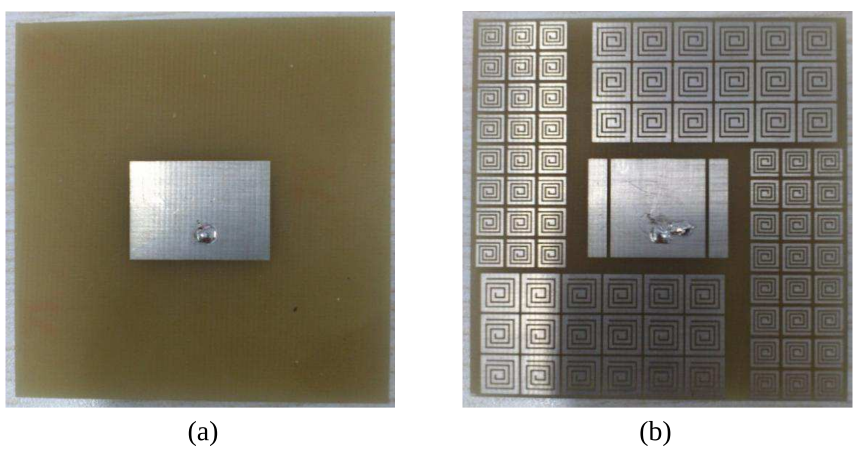

Figure 5. Photographs of (a) the reference antenna and (b) proposed antenna.

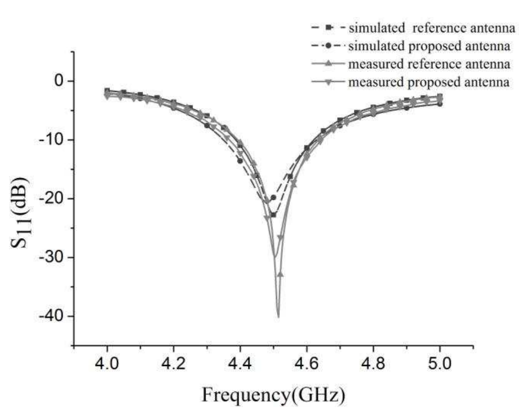

Figure 6. Comparison of S_{11} parameters of the reference and proposed antennas.

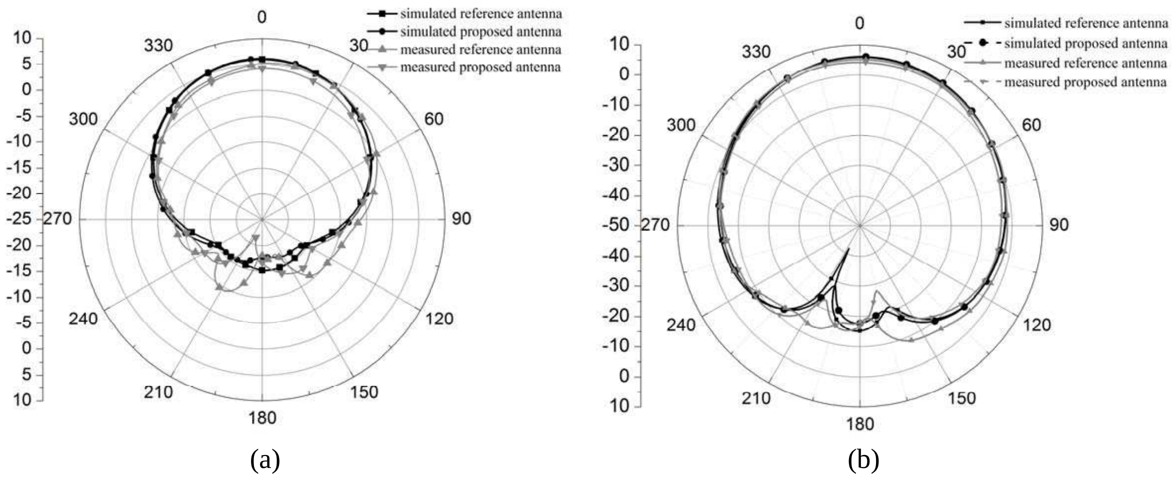

Figure 7. Comparison of radiation patterns of the reference and proposed antennas. (a) *E*-plane. (b) *H*-plane.

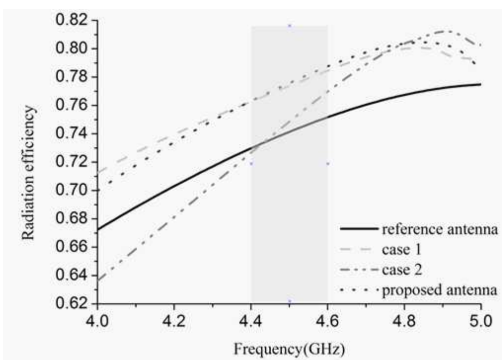

Figure 8. The radiation efficiency of antenna variation versus the number of the AMC structures.

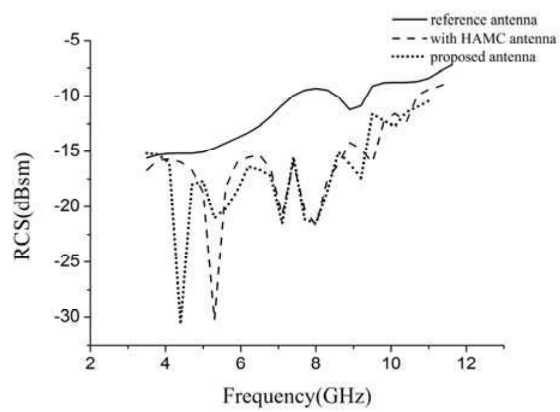

Figure 9. Comparation of monostatic RCSs of three different antennas.

lower than that of simulation. The result is reasonable considering the fabrication and the measurement errors. The above results show that the HAMC structures have little influence on the performance of the patch antenna.

Figure 8 shows that the antenna radiation efficiency varies with the number of the AMC unit cells within the operating frequency band. Referring to Figure 4(a), there are three round AMC structures around the antenna, and case 1 means that only the third-round unit cells are reserved. Similarly, case 2 means that both the third-round and second-round structures are reserved. It is shown that the radiation efficiency of antenna varies slightly in different arrangements. Compared to the reference antenna, the combined AMC structures can enhance the radiation efficiency.

3.2. The Scattering Characteristics for Reference and Proposed Antennas

In this section, the monostatic RCSs of the reference and proposed antennas are discussed. Firstly, the HAMC structures consisting of two different AMC elements are loaded around the patch antenna to verify the validity of the HAMC structures. The phi-polarized incident wave which is normal to the surface of patch antenna is implemented during the process of simulation. The monostatic RCSs of the reference antenna and the antenna with HAMC structures are shown in Figure 9. The backward RCSs have been reduced as much as 15 dB at the frequency of 5.2 GHz. Besides, Figure 9 also shows that the designed HAMC can only reduce the out-of-band RCS. However, the in-band RCS is still large compared with the reference antenna.

To further reduce the in-band RCS based on the antenna with HAMC structures, two slots, which have little influence on the out-of-band RCS, are added to the patch antenna. The proposed antenna with HAMC structures and slots is given. It is found that out-of-band RCS of the proposed antenna changes slightly compared with the antenna with HAMC structures while the in-band RCS is much lower. This means that the slots do reduce the in-band RCS.

To illustrate the variation of in-band RCS versus the theta angle, the low, central and high frequency points are chosen, respectively. The phi-polarized incident wave impinging from the direction of phi = 0 deg is implemented in the process of simulation. Figure 10(b) shows that the in-band RCS can be reduced as much as 15 dB at 4.5 GHz in the normal direction. It is also shown that the RCSs have been effectively reduced within the angular ranges [−25°, 25°]. Besides, Figure 10 shows that the in-band RCS of the proposed antenna increases within the angular ranges [30°, 100°] and [−100°, 30°]. This is because the slots can be excited within the specific angular ranges. When the theta angle exceeds a specific value, the slots cannot work, and the discontinuous structures will result in two large RCS peaks. It is well known that the direction of the slots cut on the patch antenna is related to the polarization of incident plane wave, so the slot in this paper can only reduce RCS of the patch antenna under the phi-polarization plane wave.

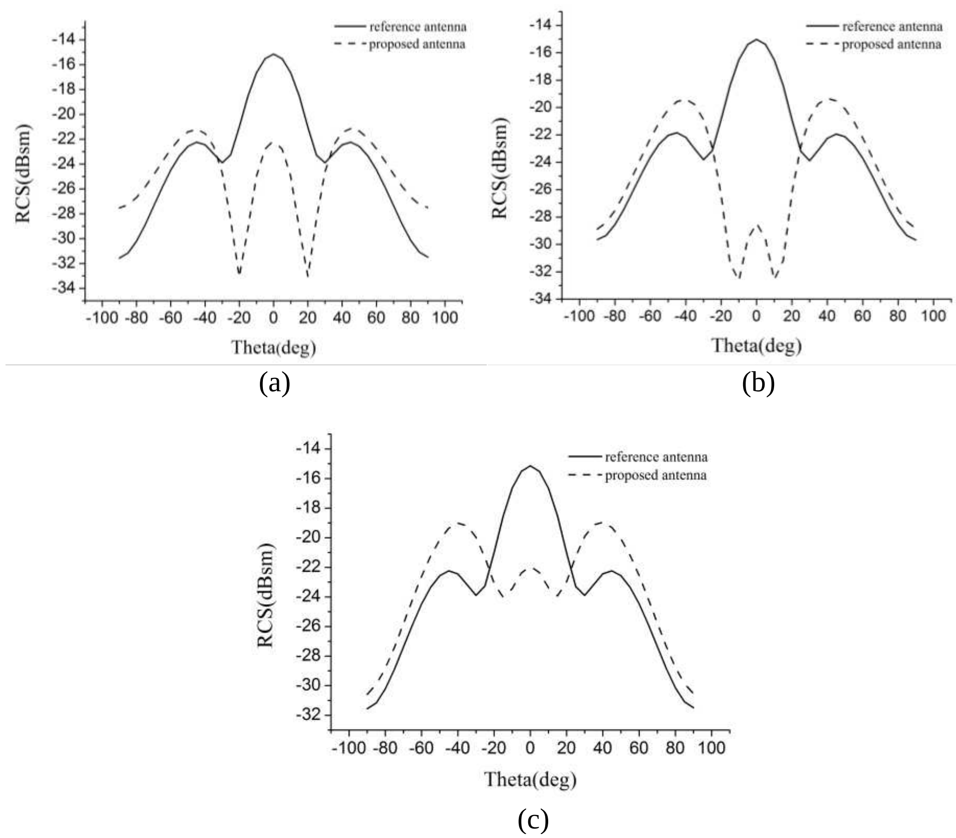

Figure 10. The in-band RCS variation versus the theta angle. (a) $f = 4.4$ GHz. (b) $f = 4.5$ GHz. (c) $f = 4.6$ GHz.

4. CONCLUSION

This paper proposes a low RCS microstrip patch antenna, and two different AMC structures are loaded around the microstrip patch antenna to reduce the out-of-band RCS. Two narrow slots are added to the patch antenna to reduce the in-band RCS. The simulated results show that the monostatic RCS of the proposed antenna can be reduced significantly over the frequency range of 5–12 GHz, and the in-band RCS has been reduced up to 15 dB at 4.5 GHz. Furthermore, the simulated and measured results have demonstrated that the HAMC structures and slots have little influence on the radiation performance of the patch antenna. The in-band and out-of-band RCSs of the patch antenna are reduced over the frequency range of 4–12 GHz, so this design provides a solution for the patch antenna RCSR.

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