Broadband RCS Reduction of Microstrip Patch Antenna Using Bandstop Frequency Selective Surface

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Abstract. *In this article, a simple and effective approach is presented to reduce the Radar Cross Section (RCS) of microstrip patch antenna in ultra broad frequency band. This approach substitutes a metallic ground plane of a conventional patch antenna with a hybrid ground consisting of bandstop Frequency Selective Surface (FSS) cells with partial metallic plane. To demonstrate the validity of the proposed approach, the influence of different ground planes on antenna's performance is investigated. Thus, a patch antenna with miniaturized FSS cells is proposed. The results suggest that this antenna shows 3dB RCS reduction almost in the whole out-of operating band within 1-20 GHz for wide incident angles when compared to conventional antenna, while its radiation characteristics are sustained simultaneously. The reasonable agreement between the measured and the simulated results verifies the efficiency of the proposed approach. Moreover, this approach doesn't alter the lightweight, low-profile, easy conformal and easy manufacturing nature of the original antenna and can be extended to obtain low-RCS antennas with metallic planes in broadband that are quite suitable for the applications which are sensitive to the variation of frequencies.*

Keywords

Bandstop FSS; microstrip patch antenna; RCS reduction; broadband.

1. Introduction

With the development of stealth technology, the Radar Cross Section (RCS) of target objects for example airborne vehicles has been reduced to a very small degree. Nevertheless, antennas, which are designed to be effective radiators, have also been the main contributors for a low observable platform. In recent years, there has been a considerable concern of methods to reduce the RCS of antennas in electromagnetic engineering. Among them, the use of Radar Absorbing Materials (RAMs) [1-3], antenna shaping [4], [5] as well as antenna coating [6], [7] are the three remarkable solutions. Actually, RAMs convert the incoming energy into heat, the shaped antennas scatter the energy away from the threatening regions, while coated antennas alter the scattering sources. However, these methods usually require a trade-off between antennas' radiation characteristics and RCS reduction effects.

Another way to reduce RCS is the application of Frequency Selective Surface (FSS) radomes to antennas [8], [9]. In this case, the FSS is transparent to electromagnetic waves in the operating band of antennas, transmission of antennas signal is not affected at all, while the signal outside the operating band is reflected. Such advantages of FSS radomes bring them to extensive practical applications. Nevertheless, in order to obtain favorable RCS reduction specifications at the premise of maintaining antenna radiation features, a complex conformal shape should be designed first and an appropriate space should be set between antenna and the FSS radome when mounting [8], which increases the complexity, bulk and costs to the whole system. What's more, unstable RCS reduction performance is easily caused by fixing errors and there are few literatures on integrated design of FSS and antenna. Recently, FSS is proposed to replace the total solid metal ground plane of reflect array antenna for RCS reduction [10]. Analogous method was used for monopoles in [11], in which RCS reduction could be obtained in the direction where the array is not able to scan. The integrated design of bandpass FSS with microstrip antenna is exploited in [12]. However, the RCS is only reduced within a narrow frequency range from 5.5 GHz to 8.5 GHz.

In this article, an approach of RCS reduction for microstrip patch antenna in ultra broad frequency band is described. This approach is presented by replacing the total metallic ground of conventional patch antenna with a hybrid ground made up of bandstop FSS cells with partial metallic plane. To reveal the superiority of the proposed approach, the influence of different ground planes on antenna's performance is investigated. Thus, a novel patch antenna is proposed. This antenna is backed by a hybrid ground plane which is composed of miniaturized FSS cells with partial metallic plane. Compared with the conventional antenna, this novel antenna exhibits almost undisturbed radiation performance and excellent out-of-band RCS reduction within 1-20 GHz for wide incident angles, which verifies the efficiency of the proposed approach. More importantly, this approach also keeps the advantages of lightweight, low-profile, easy conformal and easy manufacturing nature of the original antenna. Moreover, it can be extended to realize broadband RCS reduction of antennas with metallic planes.

2. Design Methodology

The total scattering field $\boldsymbol{E}^s(\boldsymbol{Z}_l)$ of an antenna is given by

$$E^s(Z_l) = E^s(Z_c) + E^a(Z_l) \qquad (1)$$

where $\boldsymbol{E}^s(\boldsymbol{Z}_c)$ is the structural scattering, $\boldsymbol{E}^a(\boldsymbol{Z}_l)$ is the antenna-mode scattering. When the antenna is match-loaded (Z_l=Z_c), the antenna-mode scattering equals to zero and the total RCS of the antenna can be calculated by

$$\sigma = \sigma_s = \lim_{R\to\infty} 4\pi R^2 \frac{\left|E^s\right|^2}{\left|E^i\right|^2} \qquad (2)$$

where R is the detecting distance, $\boldsymbol{E}^i$ is the incident field. In the following study, for reducing the RCS of a match-loaded antenna, only structural scattering $\boldsymbol{E}^s$ is considered.

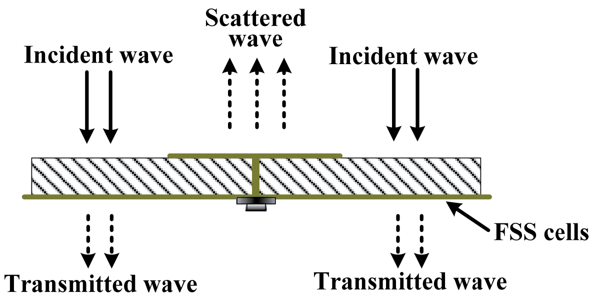


Fig. 1. RCS reduction schematic.

A conventional microstrip patch antenna is usually mounted on a substrate backed by continuous metallic ground plane. However, the ground plane contributes a lot to the total RCS while guaranteeing antenna's well radiation performance. As shown in Fig. 1, to reduce the antenna's RCS in broad frequency band, the metallic ground is substituted with bandstop FSS cells in this article. Contrary to the working mechanism of FSS radome [8], [9], these FSS cells perform bandstop characteristics and work just as a metal plate in the antenna operating band, while outside the band, these cells show broadband filtering performance, so most of the incident energy directly passes through the antenna and is absorbed by the RAM below. In this way, the scattering field $\boldsymbol{E}^s$ in expression (2) becomes very small and a broadband RCS reduction is obtained.

Nevertheless, unlike the applications of bandstop FSSs to reduce the RCS of reflectarray [10] and monopoles [11], the modified ground of microstrip patch antenna should support the propagation of quasi-TEM mode. Besides, in order to decrease as much as potential back radiation and consequent energy losses, the vertical electric fields supported by the patch antenna should be totally reflected by the portion of the ground below the patch. Consequently, we propose to replace the total metallic ground with bandstop FSS cells with partial metallic plane. Thus a low-RCS microstrip antenna with favorable radiation performance can be achieved.

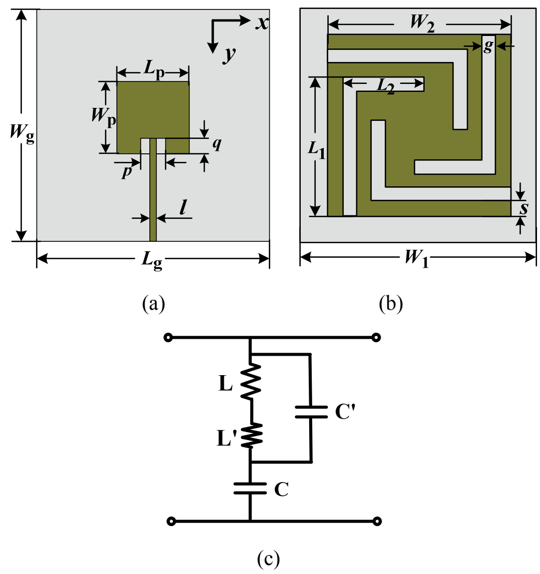


Fig. 2. (a) Geometry of microstrip patch antenna.
(b) Geometry of designed FSS unit cell.
(c) Equivalent circuit model of designed FSS.

3. Antenna Design

As an example, a patch antenna working at 5.6 GHz is studied. Its upper geometry is depicted in Fig. 2(a). The dimensions of the antenna are L_g= W_g= 60 mm, L_p= 20 mm, W_p = 15.8 mm, l = 2 mm, p = 3.6 mm, q = 5 mm.

3.1 Miniaturized Bandstop FSS Design

In this study, to achieve perfect effects, the ideal FSS should possess stable both in-band total-reflection and out-of-band passing characteristics. Furthermore, restricted by antenna dimensions, the FSS unit cell should be miniaturized first. As shown in Fig. 2(b), a novel bandstop FSS meeting these specifications is presented by introducing the technique of cutting slots [13] into traditional square FSS configuration. The corresponding equivalent circuit model is shown in Fig. 2(c), where L and C represent equivalent inductance and capacitance in the periodic square patches respectively, L' and C' represent equivalent inductance and capacitance originating from the slots. The resonant frequency of this FSS can be expressed as:

$$f = \frac{1}{2\pi\sqrt{(L+L')(C+C')}}. \qquad (3)$$

It is obvious that the resonant frequency is effectively reduced due to L' and C'. Therefore, the geometrical size of FSS unit cell decreases.

The physical parameters of the unit cell are as follows: W_1 = 6 mm, W_2 = 5.6 mm, L_1 = 4.2 mm, L_2 = 2.9 mm, $s = g$ = 0.5 mm. As seen from the numerical results in Fig. 3(a), the -10 dB stopband is from 5.1 GHz to 6.2 GHz for normal incidence, which matches the operating band of patch antenna very well. Moreover, the frequency response is quite stable for different incidence angles and polarizations. Fig. 3(b) gives the reflection phases for different cases. It can be seen that almost all of the reflection phases for different cases are 180^o at 5.6 GHz, while the reflection phases almost equal to 0^o at 8.1 GHz. These results indicate that the miniaturized FSS cells act as PEC at 5.6 GHz and perform as air at 8.1 GHz. This is advantageous to the design of a low-RCS antenna.

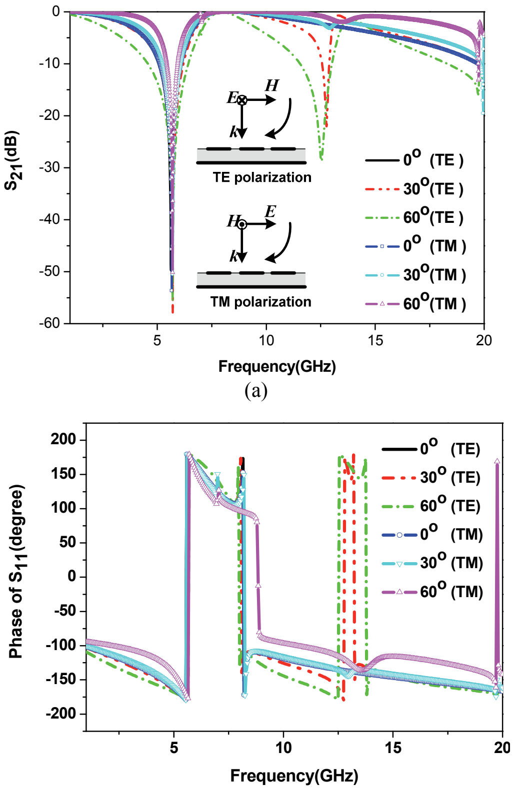


Fig. 3. Numerical results under different incidence angles: (a) transmission coefficients, (b) reflection phases.

3.2 Low-RCS Microstrip Patch Antenna Design

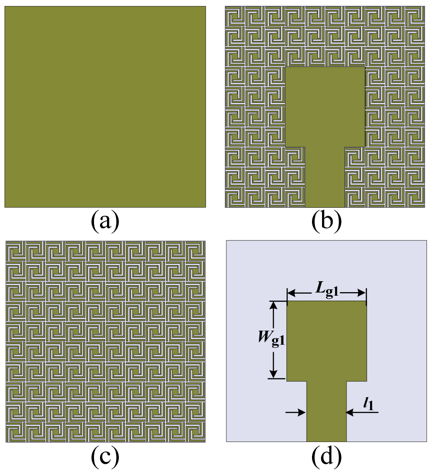


Fig. 4. Different patterns of antenna ground: (a) case A, (b) case B, (c) case C, (d) case D.

To reveal the superiority of the proposed approach, the influence of different ground planes, as shown in Fig. 4, on antenna's performance is investigated. Fig. 4(a)-(d) are respectively the conventional metallic grounded antenna (named case A, for convenience), hybrid grounded antenna (named case B), FSS grounded antenna (named case C) and minimum grounded antenna (named case D). Apparently, the set of case D is to illustrate the importance of FSS for maintaining the antenna radiation performance. To keep the integrality of FSS cells, the dimensions in case D, which are the same with that in case B, are as follows: $L_{g1} = W_{g1} = 24$ mm, $l_1 = 8$ mm.

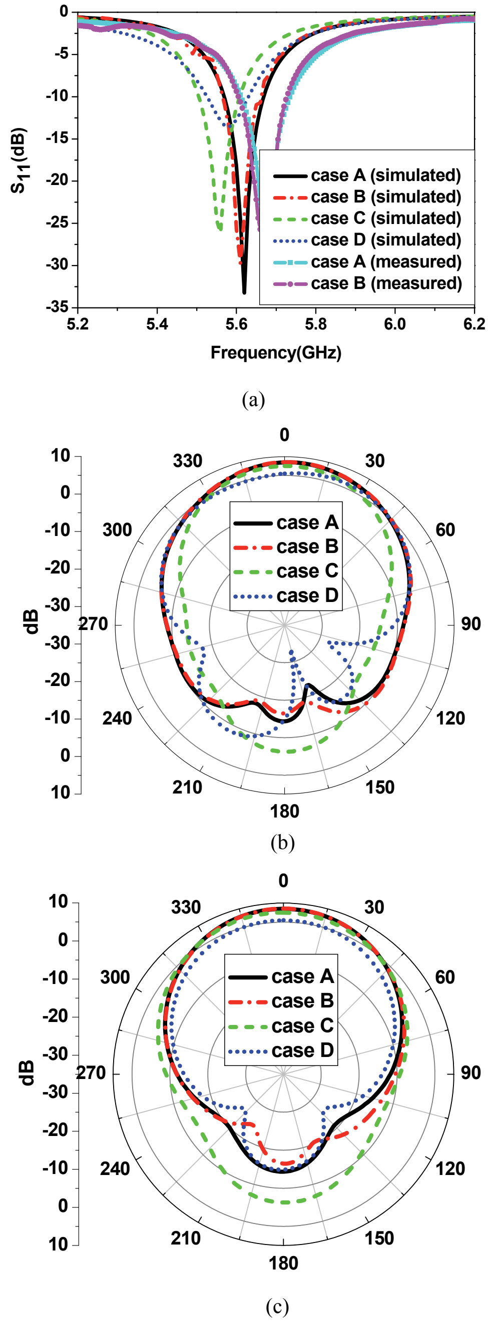


Fig. 5. Comparison among radiation performance with different cases: (a) reflection coefficients, (b) simulated radiation patterns in E-plane, (c) simulated radiation patterns in H-plane.

A full wave analysis provided by Ansoft HFSS has been carried out to simulate the radiation performance for different cases. As can be seen in Fig. 5(a), the -10 dB working band of case A and B are almost the same, nevertheless, both that of case C and D have obvious frequency discrepancies compared with case A. The results demonstrate that only the partially patterned ground can support quasi-TEM mode. As to the radiation patterns shown in Fig. 5(b)-(c), the similar conclusion can be drawn, viz., case B has the closet radiation patterns to case A, whereas case C and D have apparent peak gains decline and worse back lobes comparatively. The analysis indicates that the FSS ground and minimum ground couldn't reflect the vertical electric fields produced by the patch. As a result, the radiating field is perturbed. To sum up, only case B keeps the radiation performance, which verifies our approach.

4. Results and Discussions

To illustrate and validate the merits of our design, antennas in case A and B printed on 1 mm thick low-loss dielectric substrates ($\varepsilon_r = 2.65$, $\tan\delta = 0.0009$) were both physically fabricated and practically measured. Fig. 6 shows the fabricated antenna of case B. The input reflection coefficients measured by Agilent N5230C network analyzer are plotted in Fig. 5(a). The measured S_{11} show a small frequency shifts compared with the simulated ones. This discrepancy can be attributed to substrate errors and fabrication precision. But a reasonably good agreement between measured results of case A and B is obtained. Fig. 7 depicts the normalized measured radiation patterns at 5.66 GHz for E and H plane respectively. It can be seen that good radiation patterns are kept.

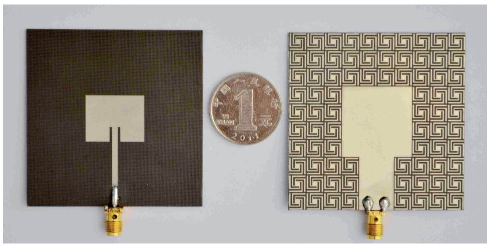
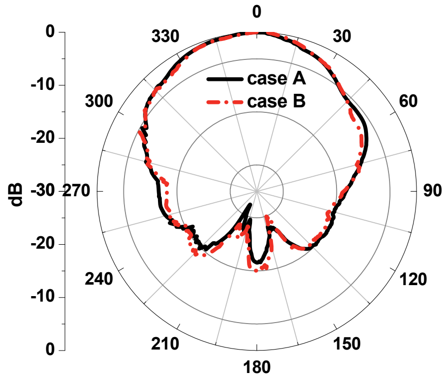
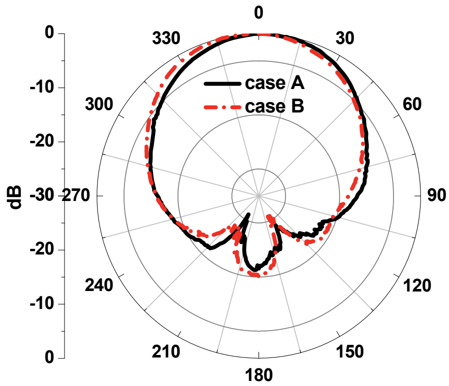


Fig. 6. Top and bottom views of the fabricated patch antenna.

Using Ansoft HFSS, both monostatic RCS (MRCS) and bistatic RCS (BRCS) of case B are compared against that of case A for different polarizations. As seen in Fig. 8(a), when the incident angle $\theta = \varphi = 0^o$, there is hardly reduction of MRCS within the antenna operating band, in contrast, a prominent RCS reduction outside the operating band, i.e., 1-4 GHz and 6.6-20 GHz, is presented for both polarizations. Fig. 8(b) shows the BRCS of reflective angle $\theta = 60^o$, $\varphi = 225^o$, corresponding to the incident angle $\theta = 60^o$, $\varphi = 45^o$. We can see that analogous RCS reduction tendency with MRCS is preserved due to the stable frequency response of the designed FSS. To make a detailed analysis of above results, Fig. 8(c)-(d) describe the M- and B-RCS at 8.1 GHz with variation of incidence angles from -90^o to 90^o, respectively. It is found that case B is characterized by over 3 dB RCS reduction for any polarized waves in wide incident angles. The peak RCS values at the boresight direction have been well suppressed. From above results, it is summarized that the RCS of the antenna is effectively reduced with the aid of such a hybrid patterned ground.



(a)



(b)

Fig. 7. Measured radiation patterns: (a) E-plane, (b) H-plane.

To better understand the behavior of the antennas, the simulated scattering field distributions above xoy plane at 8.1 GHz are shown in Fig. 9. It can be observed that the scattering field of case B is obviously smaller than that of case A. As a result, case B shows significant RCS reduction compared with case A.

A final verification is accomplished by measuring the reflectivity for perpendicular incident plane wave [12], [14], [15]. Restricted by the operating frequency range of testing antenna, the results are given from 2 GHz to 18 GHz. As is apparent in Fig. 10, case B appreciates evident reduction of reflectivity out of the antenna working band, which is in good accordance with the simulated RCS reduction effects illustrated in Fig. 8(a).

5. Conclusions

This article proposes a simple and effective approach that combines microstrip patch antenna with bandstop FSS for broadband RCS reduction. To confirm the validity of this approach, a novel antenna backed by a hybrid ground

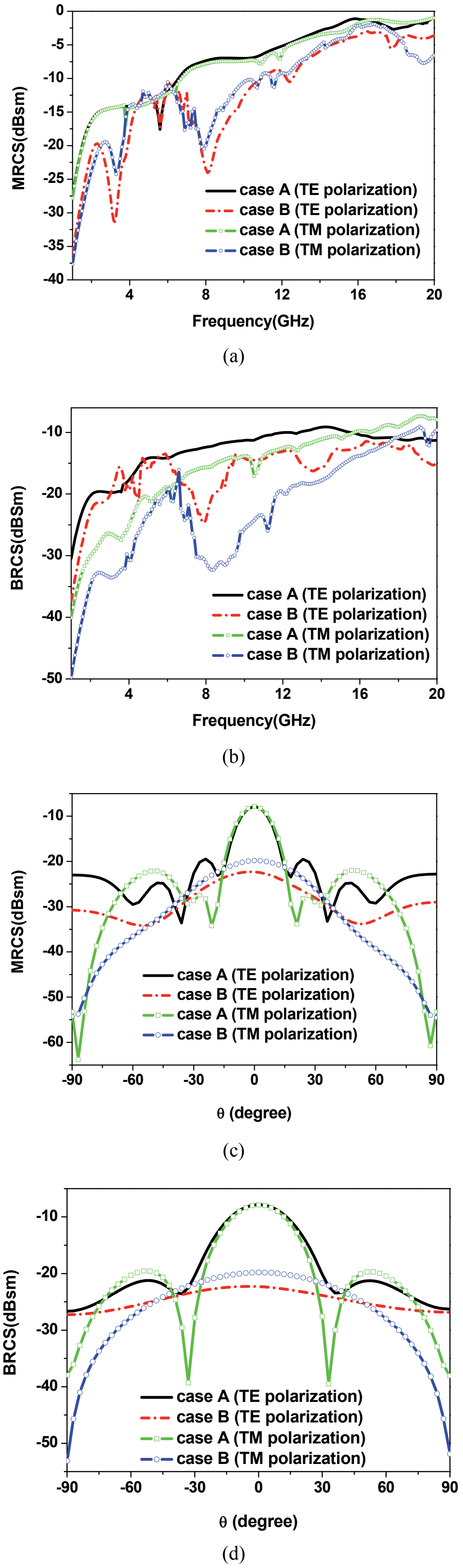


Fig. 8. Simulated RCS: (a) MRCS versus frequency (the incident angle $\theta = \varphi = 0^o$). (b) BRCS versus frequency (the reflective angle $\theta = 60^o$, $\varphi = 225^o$, the incident angle $\theta = 60^o$, $\varphi = 45^o$). (c) MRCS versus incidence angles, (d) BRCS versus incidence angles.

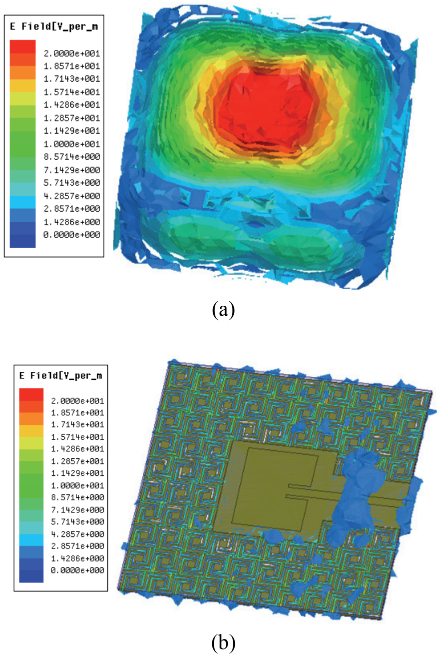


Fig. 9. Electric field distributions above the radiating patch at 8.1 GHz: (a) case A, (b) case B.

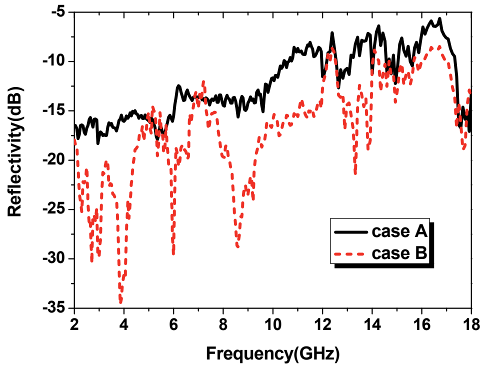


Fig. 10. Measured reflectivity.

plane consisting of miniaturized FSS cells with partial metallic plane is designed, fabricated and measured. Both simulated and measured results show that the novel antenna obtains 3 dB RCS reduction almost in the whole out-of working band within 1-20 GHz, while its in-band radiation performance is preserved favorably. Different from the previous methods, the proposed approach doesn't need a trade-off between antennas' radiation characteristics and RCS reduction effects, and on the other hand, it doesn't perturb the advantages of lightweight, low-profile, easy conformal and manufacturing nature of original antenna. Furthermore, this approach can be extended to realize broadband RCS reduction of antennas with metallic planes.

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