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Low RCS Microstrip Antenna Array with Incident Wave in Grazing Angle

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Abstract—In this paper, a novel microstrip antenna array with reduced radar cross-section (RCS) is proposed and studied. We define that the grazing angle θ of radar incident wave ranges from 80° to 90°. Under the condition that the incident wave is in grazing angle, a microstrip antenna designed by the techniques of miniaturization and ground-cut slots is given firstly. Compared with a traditional rectangle microstrip antenna, the RCS peaks of the proposed antenna are efficiently controlled over the frequency range of 4∼16 GHz. Based on the design above, the proposed antenna is chosen as an element to design a 2×2 antenna array. Analysis and optimization of the arrangement of the array is made to achieve more RCS reduction. The measured results of radiation performance accord with the simulated ones, which indicate that the proposed method is feasible.

1. INTRODUCTION

Antennas and arrays on stealth platform are the main contributors to the total Radar Cross Section. So it is an important problem to reduce the RCS of antennas in the field of stealth technologies [1–3]. Generally speaking, radar wave coming from grazing angles poses threat to the military aircraft. Therefore, it is essential to do some research in this aspect. Microstrip antennas are widely used on aircraft due to the fact that they are lightweight, conformal, uncomplicated and inexpensive to fabricate [4, 5]. However, microstrip antenna is a resonant structure with narrow bandwidth, which results in a large radar cross section at the resonant frequency.

In the practical applications, antenna arrays are usually employed in the military aircraft, which makes it urgent for us to reduce the RCS of antenna arrays. However, the RCS of a single antenna has a significant relationship with that of the antenna arrays. Therefore, it is necessary to design a single antenna with low RCS. In recent years, available methods to reduce the RCS of microstrip antenna are complex. In [6], minimization technique and ground-cut slots technique are used to reduce the RCS of a microstrip antenna. With slots cut on the patch, a genetic algorithm (GA) is employed to the design of low radar cross section patch antennas in [7]. Different from the method of shaping the patch, a novel method of using PIN attenuator diodes to reduce the radar cross section is proposed in [8, 9]. For the RCS reduction of antenna arrays, the author designs a low RCS antenna array which uses a frequency selective absorbing ground plane [10]. In [11], electromagnetic band-gap (EBG) structure is used to reduce the radar cross section of the patch array antenna. However, most of the methods to reduce the RCS are under the condition that the incidence angle is $\theta = 60°$ or $\theta = 0°$. To the best of my knowledge, there is little research on the RCS reduction of antenna when the incident wave is in grazing angle [12–14]. In this paper, an effective method to solve this problem is proposed on purpose.

A novel shape of patch which can minimize the microstrip antenna is analyzed and applied to the antenna design. Meanwhile, ground slots are cut to change the surface current of the antenna.

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In comparison, a traditional rectangular microstrip antenna which operates at the similar resonance frequency is chosen as the standard antenna. Both of the antennas are fabricated and measured under the same test condition. The results show that the RCS of proposed antenna is greatly reduced over almost the frequency range of 4∼16 GHz with little degradation of the radiation performance. Based on the research above, a 2×2 antenna array with low RCS units and optimized arrangement has been designed. The results of RCS reduction of the proposed array are also considerable in a relative wide frequency band.

2. LOW RCS MICROSTRIP ANTENNA DESIGN AND RESULTS

The total scattering field of antenna includes structural mode scattering and antenna mode scattering field. The antenna mode scattering field is mainly caused by the radiation of the reflected power from the receiving channel which is caused by the impedance mismatch. When the incidence angle θ of radar wave is in grazing angle, the mode scattering field of the broadside antenna is quite small. This mainly due to the fact that the received power from the antenna will be extremely small when the antenna gain at grazing is even low. Therefore, the antenna mode scattering field will be extremely small resulting from the little reflected power from the receiving channel. On the contrary, the structural mode scattering field makes a main contribution to the total scattering field of antenna.

For a microstrip antenna with incident wave in grazing angle, the structural mode scattering field is mainly radiated because of the induced current excited by the incident wave's reflecting continually between the patch and ground plane. Based on the analysis above, we can reduce the RCS by minimizing the patch and changing direction of the induced current.

The standard antenna and proposed antenna are shown in Figure 1. For the proposed antenna, a novel shape is designed to minimize the patch and change the direction of induced current. By turning the two edges of the patch into arc-shaped edges and cutting two semi-circles on both sides, the induced current excited by the incident wave is greatly changed.

The physical parameters of antenna have a great effect on the structural mode scattering field. Therefore, the novel shape of patch, of which the area is about 55% smaller than the standard antenna, can reduce the structural mode scattering field effectively.

As we all know, ground plane slots can change the impedance characteristics of the microstrip antenna and the induced current flow path of the patch surface, which has impact on the scattering characteristics [7]. In order to balance both the radiation and scattering performance, two rectangle slots on the ground plane are cut as shown in Figure 1(b). As we all know, it is inevitable to achieve lower RCS by reducing the size of the ground plane. However, gain loss of the proposed antenna will increase at the same time.

Prototypes of the standard and proposed antennas are fabricated and measured in order to validate the effectiveness of the design strategies. The configuration of the two antennas is shown in Figure 1. The thickness of the substrate of the two antennas are both 1.5 mm and the relative permittivity $\varepsilon_r = 2.5$.

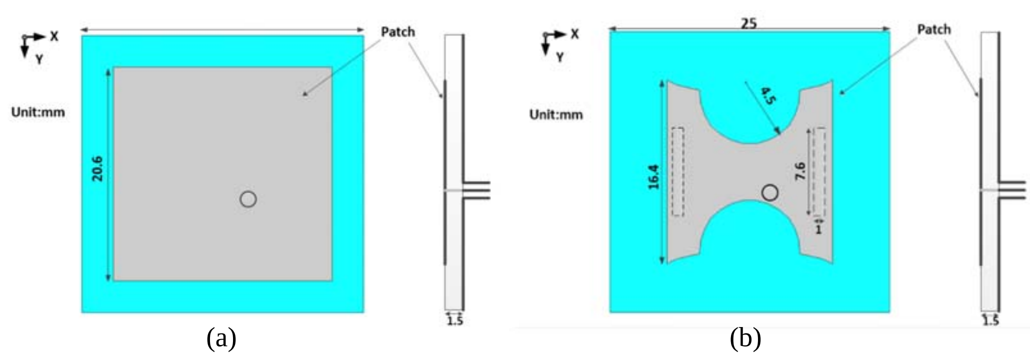


Figure 1. Antenna structures and detailed dimensions of two antennas. (a) Standard antenna. (b) Proposed antenna.

The proposed antenna is fed by coaxial line with 50 ohm in the position of (1.2, 1.2, 0).

Commercial software HFSS 14.0 based on the finite element method (FEM) is used to simulate and optimize the antennas. The simulated and measured $|S_{11}|$ of the two antennas are shown in Figure 2. The resonant frequency of the proposed antenna is 4.3 GHz and the bandwidth narrows a

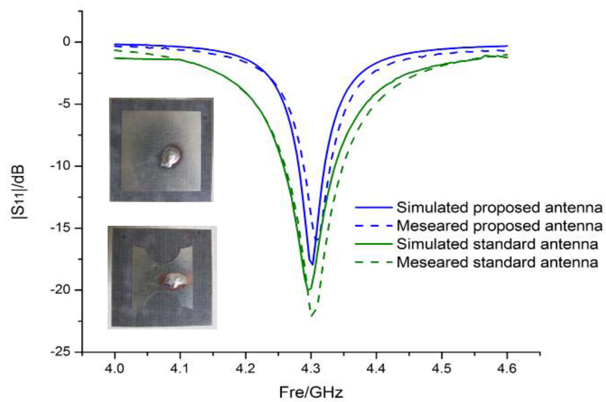
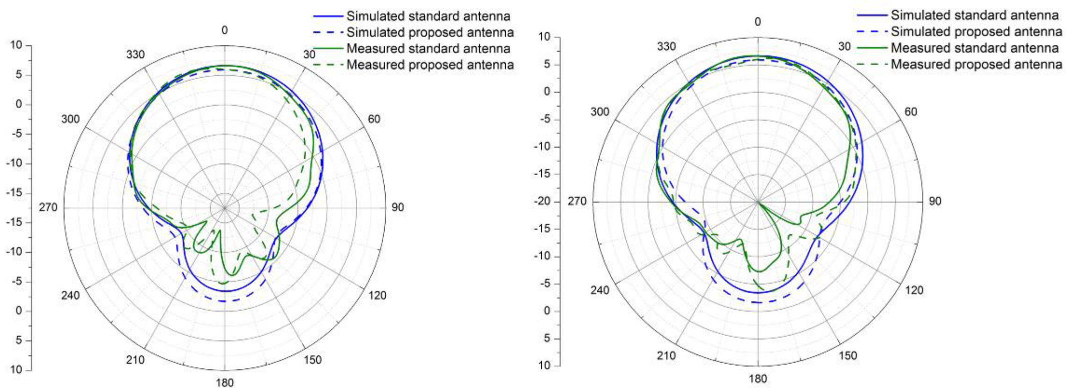


Figure 2. Simulated and measured $|S_{11}|$ of two antennas.



(a) (b)

Figure 3. Simulated and measured radiation patterns of two antennas. (a) $\varphi = 0°$. (b) $\varphi = 90°$.

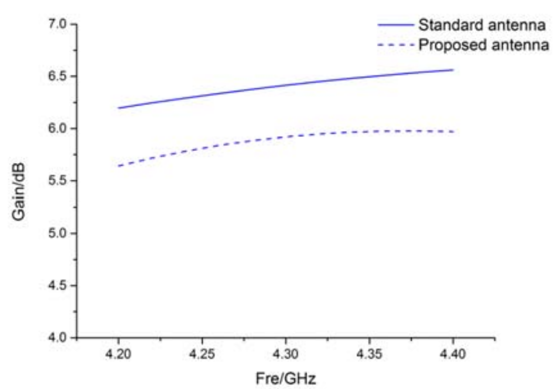
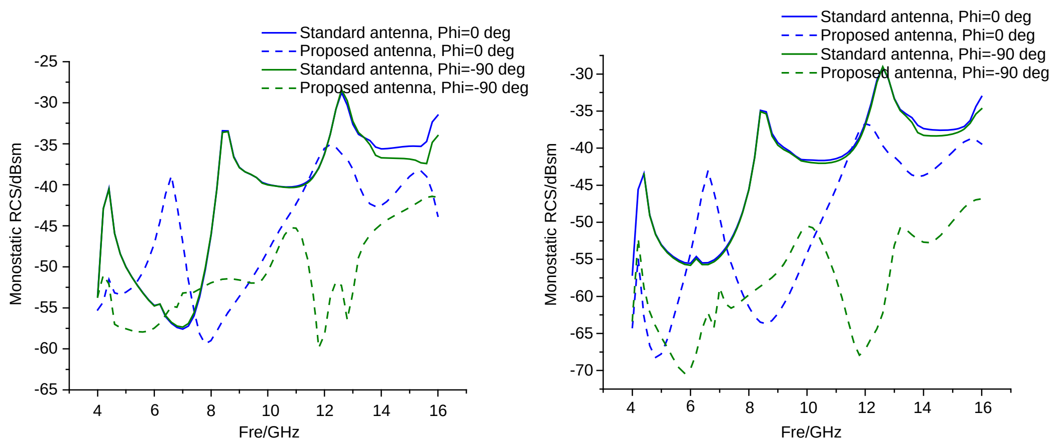


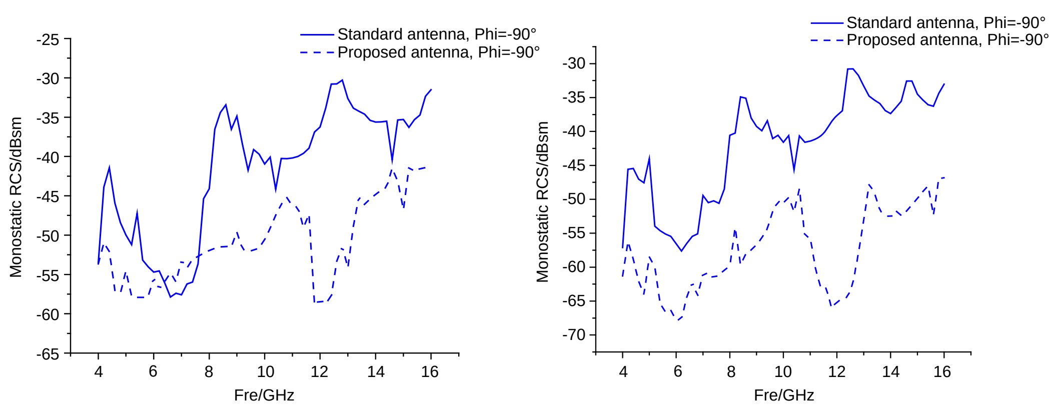
Figure 4. Measured gain with frequency for both antenna cases.

little compared with that of the standard antenna. The simulated and measured radiation patterns of $\varphi = 0°$ and $\varphi = 90°$ are shown in Figure 3. Figure 4 shows the measured gain with frequency for both antenna cases. It can be seen that the two antennas have similar radiation performance. However, due to the minimized patch and ground-cut slots, the gain of the standard antenna at resonant frequency decreases from 6.6 dB to 5.9 dB. However, the gain loss is acceptable in the purpose of reducing RCS of antenna.



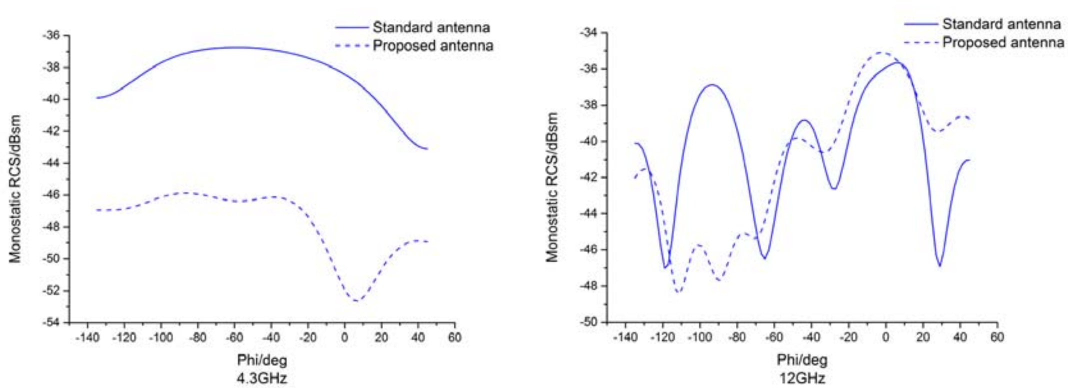
(a) (b)

Figure 5. Simulated RCS of two antennas. (a) θ=80°. (b) $\theta = 90°$.



(a) (b)

Figure 6. Measured RCS of two antennas. (a) $\theta = 80°$. (b) $\theta = 90°$.



(a) (b)

Figure 7. Simulated RCS of two antennas when phi ranges from $-135°$ to $45°$.

Figure 5 shows the RCS of two antennas with θ polarized plane wave incident from ($\theta = 80°$, $\varphi = 0°$), ($\theta = 80°$, $\varphi = -90°$), ($\theta = 90°$, $\varphi = 0°$) and ($\theta = 90°$, $\varphi = -90°$). It can be seen that RCS peaks of the proposed antenna get significant reduction of 26 dB at the frequency of 12.9 GHz when the incidence angle ($\theta = 80°$, $\varphi = -90°$) in Figure 5(a). Moreover, about 12 dB RCS reduction is achieved

Table 1. average RCS reduction effect (unit: dBsm).

Fre/GHz	4.3	6	8	10	12	14
Standard antenna	−38.1	−41.9	−48.3	−38.5	−39.4	−38.5
Proposed antenna	−47.3	−47.6	−49.1	−47.8	−39.5	−43.1

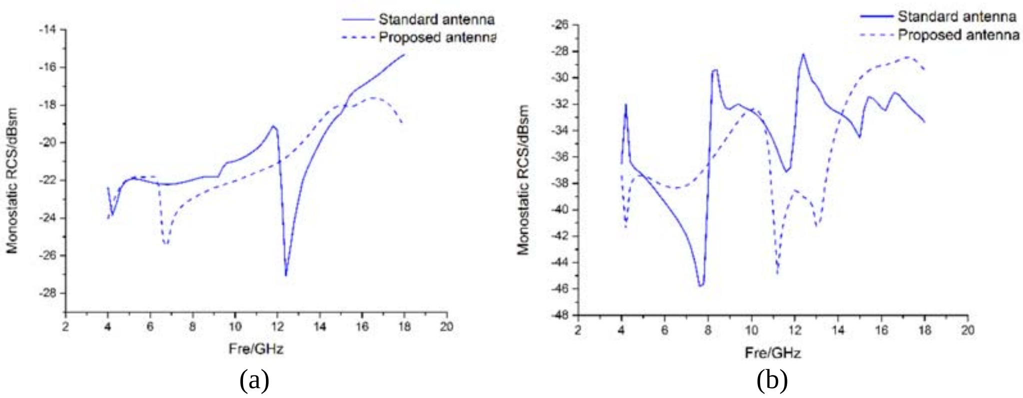


Figure 8. Simulated RCS of two antennas at other incident angles. (a) $\theta = 0°$, $\varphi = 0°$. (b) $\theta = 60°$, $\varphi = -90°$.

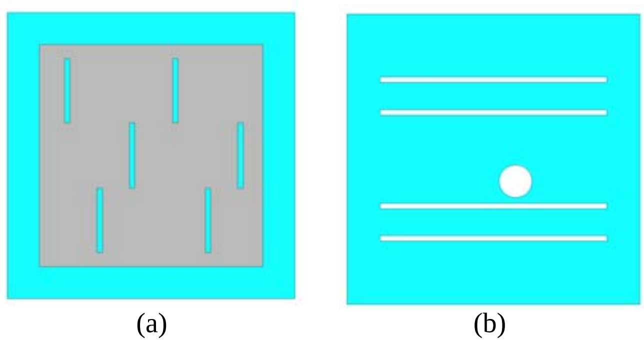


Figure 9. Conventional slotted patch antenna. (a) Top view. (b) Bottom view.

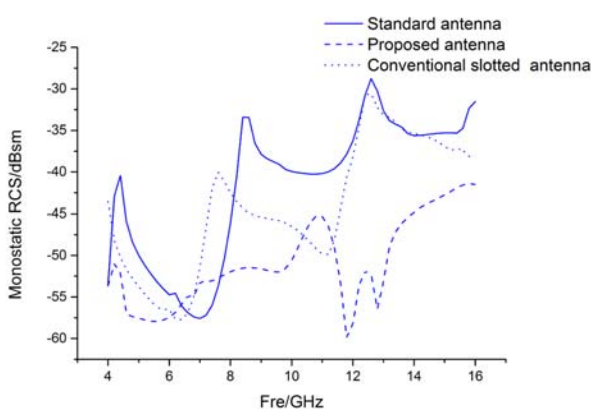


Figure 10. Simulated RCS of these three antennas.

at resonant frequency. In Figure 5(b), the results of RCS reduction are even considerable with the wave incident from $\theta = 90°$. The simulation results of the RCS curves are validated with measurements as shown in Figure 6. The average RCS when the incident wave at grazing and phi ranges from $-135°$ to $45°$ at several frequencies is evaluated to assess that a reduced RCS has been achieved in Table 1.

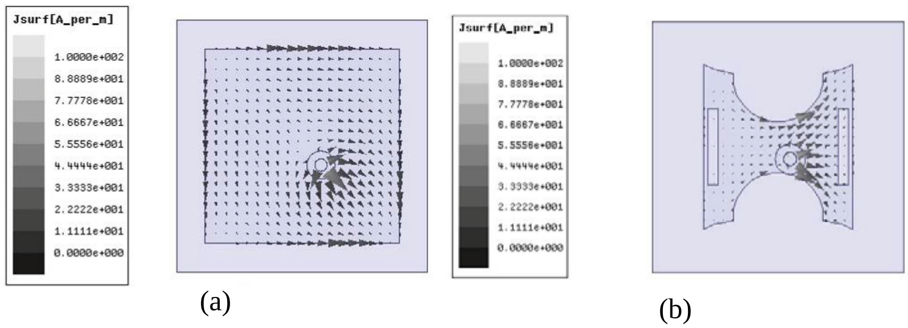


Figure 11. Surface current of the two antennas working at 4.3 GHz. (a) Standard antenna. (b) Proposed antenna.

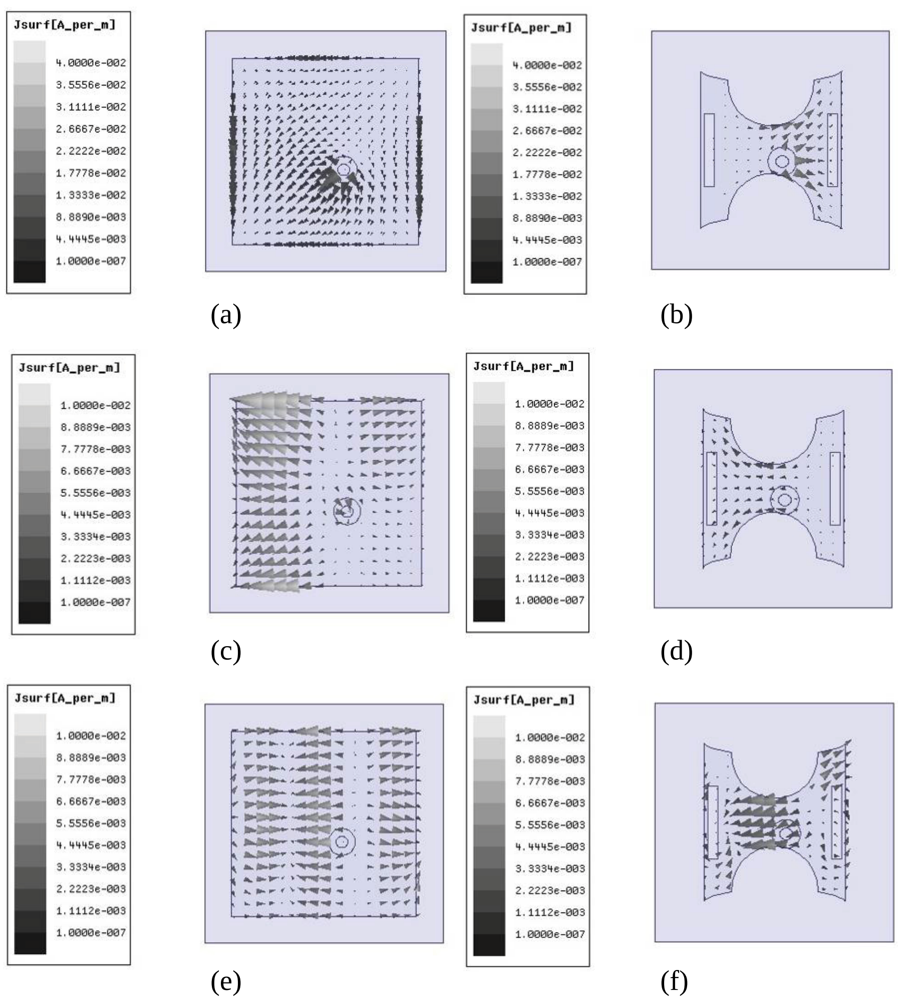
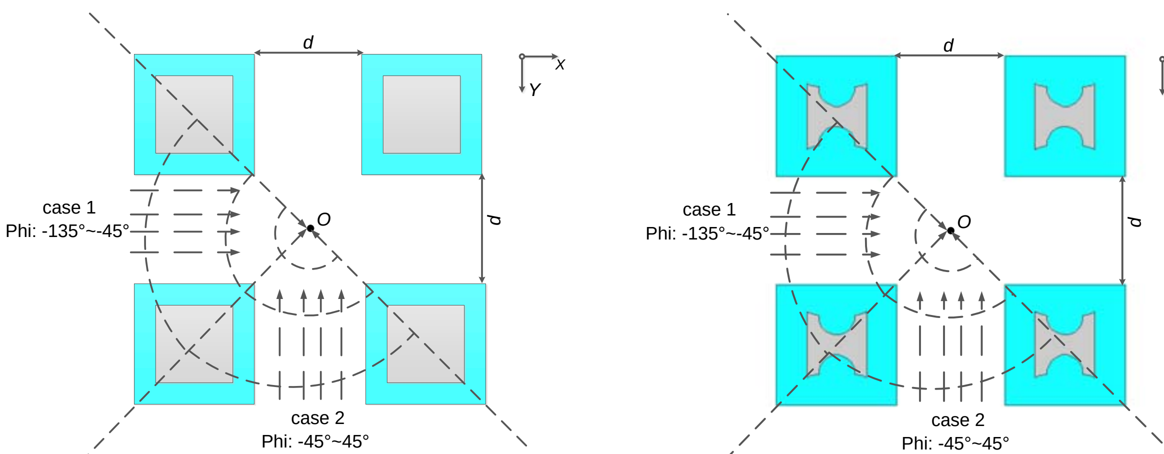


Figure 12. Surface current of (a), (c), (e) the standard antenna and (b), (d), (f) the proposed antenna. (a), (b) 4.3 GHz. (c), (d) 9 GHz. (e), (f) 13 GHz.

Figure 7 shows the simulated RCS of two antennas with phi ranges from $-135°$ to $45°$ at frequency of 4.3 GHz and 12 GHz. The RCS reduction can be obtained in the whole range of phi at 4.3 GHz, while significant difference occurs when the frequency increases. Unlike the RCS curves of standard antenna, it can be seen that there's significant different effects when the incident angle φ ranges from $-90°$ to $0°$. However, the radiation of proposed antenna almost remains unchanged. Therefore, the above results can guide us to adjust the arrangement of proposed antenna to avoid the threatening angular domain of radar detection. As shown in Figure 8, it can be easily seen that the RCS of the proposed antenna at other incidence angles basically doesn't get worse over the frequency range of 4∼16 GHz.

A conventional slotted patch antenna has been designed which has a RCS reduction when the incident wave is oblique ($\theta = 60°$) as shown in Figure 9. It can be seen that this conventional method cannot work that good when the wave is in grazing angle ($\theta = 80°$) as shown in Figure 10. However, the results of RCS reduction among these three antennas can easily clarify the effectiveness of the proposed method.

The surface current of the two antennas working at 4.3 GHz are shown in Figure 11. The surface current of the two antennas excited by the grazing incident wave at 4.3 GHz, 9 GHz and 13 GHz are shown in Figure 12. It can be seen that three substrate surface modes, TM_{10}, TM_{20} and TM_{30} could be excited by an incident wave at grazing. Therefore, multiple RCS peaks occur at these frequencies as shown in Figure 5.



(a) (b)

Figure 13. Two cases corresponding to different arrangement of the antenna array. (a) Standard array. (b) proposed array.

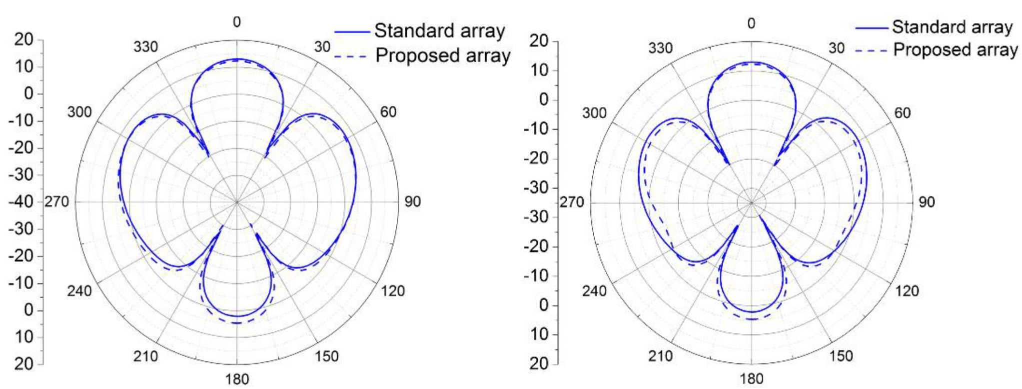


Figure 14. Simulated radiation patterns of two arrays.

3. ANTENNA ARRAY DESIGN AND DISCUSSION

In the purpose of designing a low RCS antenna array, to design a unit with low RCS is the key step. Therefore, the proposed low RCS antenna has been chosen as the unit to design a 2×2 antenna array. In addition, the arrangement of the array is analyzed and optimized to achieve more RCS reduction. Due to the asymmetry of the proposed antenna, the RCS differs greatly with the increase in the incident angle φ. We can draw the conclusion that that we can change the arrangement of array on the platform to avoid the threatening angular domain of radar detection.

The standard and proposed antenna array is shown in Figure 13. The radiation patterns of $\varphi = 0°$ and $\varphi = 90°$ of two arrays are shown in Figure 14. It can be seen that the two arrays have similar radiation patterns.

Figure 15 shows the RCS of two antenna arrays with θ polarized plane wave incident from ($\theta = 80°$, $\varphi = 0°$), ($\theta = 80°$, $\varphi = -90°$), ($\theta = 90°$, $\varphi = 0°$) and ($\theta = 90°$, $\varphi = -90°$). The results of RCS reduction are quite satisfactory over almost the frequency range of 4∼16 GHz and RCS peaks of the proposed array are efficiently controlled. When the incident angle φ ranges from $-90°$ to $0°$, the results of RCS reduction differs greatly over the frequency band of 6∼14 GHz.

The nose cone of an aircraft is one of the most threatening area and antenna in this area has large backscattering when the incident waves are in the grazing directions. For the range of incidence angle φ, we propose two cases corresponding to different arrangements of the proposed array which are shown in Figure 13. The case 1 represents that the incidence angle φ varies from $-135°$ to $-45°$ and the case 2 shows the variation range of $-45°$ to $45°$. In the two cases, the incidence angle $\theta = 85°$ is taken into account.

The RCS of proposed array in the two cases are shown in Figure 16. The analyzed frequencies of the incident wave include 4 GHz, 7 GHz, 9 GHz, and 12 GHz. It can be seen that the RCS curves in the two cases are almost the same at lower frequency. It can be explained that the structural details of the whole antenna array are not so important when the wavelength of the incident wave is much longer than the size of the array. It's the size of the array that really influences the RCS of the whole antenna array. Therefore, it makes no sense to change the arrangement of the array.

However, it can be found that the difference between the RCS curves of the two cases occurs when the frequency increases. It is apparent that the RCS curves of proposed antenna array in case 1 are lower than those of the array in case 2 when the frequency is higher than 7 GHz. Unlike the situation when the frequency is relatively low, different arrangements of the array have a great influence on the RCS. Therefore, the conclusion that the proposed array can avoid the threatening angular domain of radar detection by change the arrangement on the platform is proven to be effective.

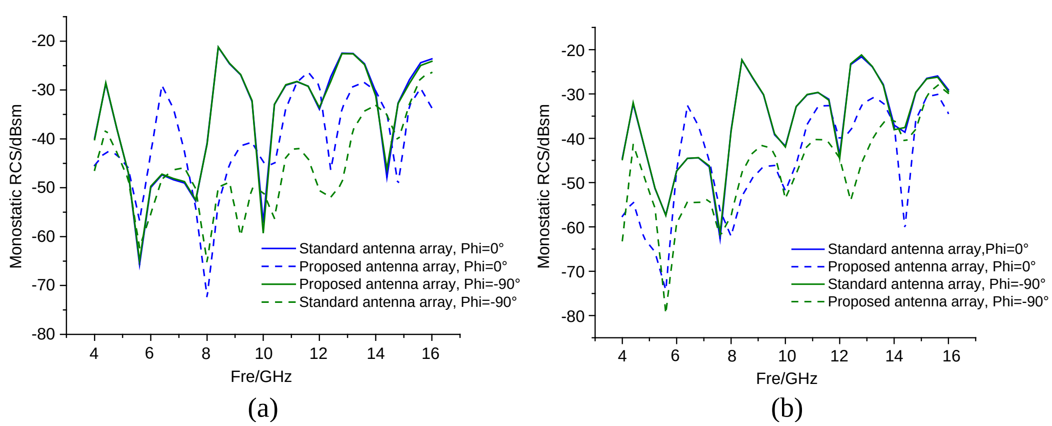


Figure 15. Simulated RCS of two arrays. (a) θ=80°. (b) $\theta = 90°$.

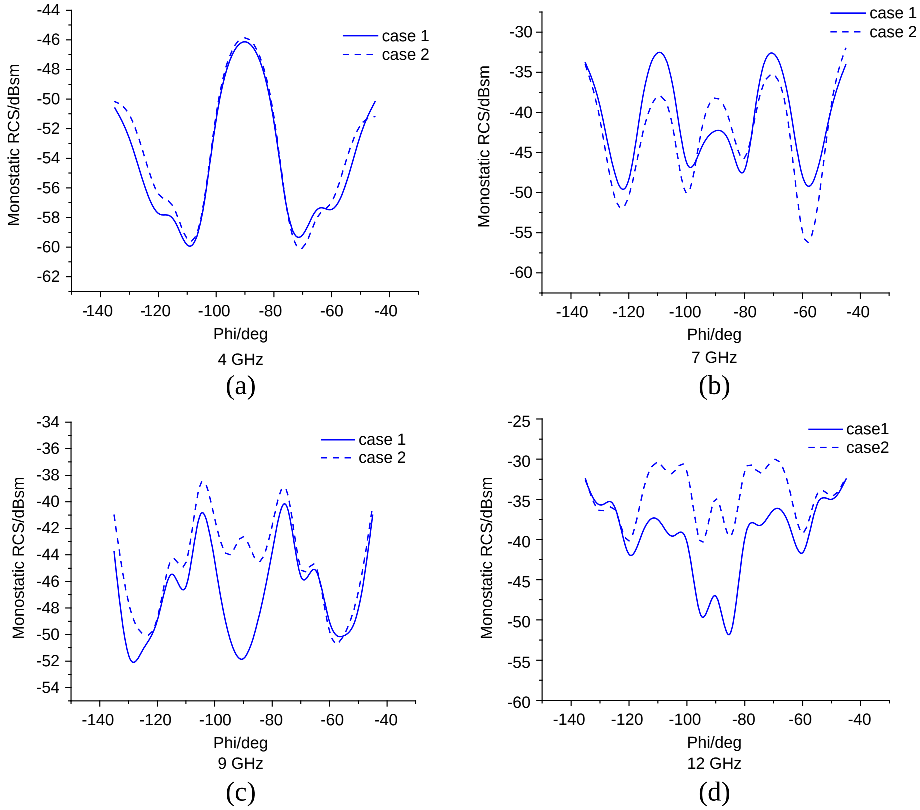


Figure 16. Simulated RCS of the proposed array in two cases.

4. CONCLUSION

Aiming at the RCS reduction of antenna array when the incident wave at grazing angle (θ ranges from 80° to 90°), a low RCS microstrip antenna array is designed in this paper. For the unit of the array, a novel shape of patch and ground-cut slots for miniaturization are analyzed and proved to be effective in the RCS reduction. By optimizing of the arrangement of the proposed array on the platform, we can achieve more reduction of RCS. The simulated and measured results show that the proposed antenna array can realize rather considerable RCS reduction with little degradation of antenna performance.

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