

Research Article

Research on the Scattering Characteristics and the RCS Reduction of Circularly Polarized Microstrip Antenna

W. Jiang, T. Hong, and S. X. Gong

National Laboratory of Antennas and Microwave Technology, Xidian University, Xi'an, Shaanxi 710071, China

Correspondence should be addressed to T. Hong; tok_hong@126.com

Received 20 March 2013; Revised 20 June 2013; Accepted 21 June 2013

Academic Editor: Hon Tat Hui

Copyright © 2013 W. Jiang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Based on the study of the radiation and scattering of the circularly polarized (CP) antenna, a novel radar cross-section (RCS) reduction technique is proposed for CP antenna in this paper. Quasi-fractal slots are applied in the design of the antenna ground plane to reduce the RCS of the CP antenna. Both prototype antenna and array are designed, and their time-, frequency-, and space-domain characteristics are studied to authenticate the proposed technique. The simulated and measured results show that the RCS of the prototype antenna and array is reduced up to 7.85 dB and 6.95 dB in the band of 1 GHz–10 GHz. The proposed technique serves a candidate in the design of low RCS CP antennas and arrays.

1. Introduction

Circularly polarized (CP) transmitting and receiving antennas are less sensitive to their respective orientations, which leads to that the CP antennas are suitable to various wireless systems such as global positioning system (GPS), radio frequency identification (RFID), wireless local area network (WLAN), and modern radar. Microstrip patch antenna, spiral antenna, dielectric resonator antenna, and slot antenna are the typical types of CP antennas [1–6].

The radiation of CP antenna has been analyzed a lot because of its wide usage. Recently, much attention has been paid to antenna scattering since it is the main contribution to the total radar cross-section (RCS) of low-observable platforms. Antenna is a special scatter whose scattering is related with both its loading condition and structure, which embarrasses the design of CP antenna with low RCS and good radiation performances simultaneously [7, 8]. The low RCS antenna is pivotal to the antenna array on low-observable platforms, which makes the design of antennas with low RCS pressing.

Scattering characteristics of several kinds of antennas have been reported. In [8], the bistatic RCS of a microstrip patch antenna, including the effect of the feed termination impedance, has been calculated. In [9], the bistatic RCS of UWB antenna is studied. Several antennas with low RCS have also been reported. In [10], the insect tentacle structure is proposed to design a low RCS ultrawideband (UWB) antenna. In [11], the fractal slotted patch is applied to reduce the RCS of a microstrip antenna.

Up to now, much more attentions have been paid to the radiation performances of the CP antennas while the RCS reduction is rarely reported. Considering the application of the low RCS CP antennas in the low-observable platforms, the scattering performances of the CP antenna are studied and a novel low RCS L-band CP microstrip antenna is proposed in this paper.

2. Theoretical Analysis

The configuration of antenna scattering is shown in Figures 1(a) and 1(b). It is well known that an antenna is a special scatter whose scattering is related with its feed termination impedance. The antenna scattering consists of structural mode scattering (in this case a matched load is connected to the antenna feed port, and there is no reflective power form the load), and antenna mode scattering (in this case, part of the received energy would be reflected by the load and reradiated to the space). Therefore, antenna RCS (σ) can



FIGURE 1: Antenna scattering configuration.



FIGURE 2: Geometry of GFSA.

be divided into two categories: structural mode RCS (σ_s) and antenna mode RCS (σ_a). Their relationship is given by

$$\sigma = \left| \sqrt{\sigma_s} + \sqrt{\sigma_a} e^{j\phi} \right|^2, \tag{1}$$

where ϕ is the phase difference between these two modes [4].

The structural mode RCS depends on the structural characteristics of the target antenna such as the metal surfaces, corners, and edges. While the antenna mode RCS is related to the radiation characteristics of the target antenna. Therefore, the structural mode scattering remains constant, while the antenna mode scattering changes when the impendence of the load of the target antenna changes. The expression of the scattering field $\mathbf{E}^{s}(Z_{l})$ of the target antenna terminated with arbitrary load is given by [12]

$$\mathbf{E}^{s}\left(Z_{l}\right) = \left[\frac{\left(1-\Gamma_{a}\right)\mathbf{E}^{s}\left(\infty\right)+\left(1+\Gamma_{a}\right)\mathbf{E}^{s}\left(0\right)}{2}\right] + \left[\frac{\Gamma_{l}}{1-\Gamma_{l}\Gamma_{a}}\frac{1-\Gamma_{a}^{2}}{2}\left(\mathbf{E}^{s}\left(\infty\right)-\mathbf{E}^{s}\left(0\right)\right)\right].$$
(2)

In (2), the expression between the first square brackets is the structural mode scattering field and that between the second square brackets is the antenna mode scattering field. The scattering fields of the two modes can be expressed by the scattering fields $\mathbf{E}^{s}(\infty)$ and $\mathbf{E}^{s}(0)$ of the antenna that is opencircuited and short-circuited loads terminated respectively. Γ_{l} and Γ_{a} are the reflection coefficients of the load and the antenna.



FIGURE 3: VSWR curves of GFSA and REF.



FIGURE 4: AR curves of GFSA and REF.

Involving in the polarization, the basic formulation of antenna scattering is given by [12, 13]

$$\mathbf{E}^{s}(Z_{l}) = \mathbf{E}^{s}(Z_{c}) + \frac{\Gamma_{l}}{1 - \Gamma_{l}\Gamma_{a}}b_{0}^{m}\mathbf{E}_{1}^{t},$$

$$b_{0}^{m} = -j\lambda C \left[\mathbf{A}\left(\mathbf{k}\right) \cdot \mathbf{u}^{*}\right],$$

$$\mathbf{E}_{1}^{t} = \sqrt{Z_{c}}\mathbf{A}\left(\mathbf{k}\right)\frac{e^{-jkr}}{r},$$
(3)

where $\mathbf{E}^{s}(Z_{c})$ are the scattering fields of the target antenna with matched load Z_{c} ; b_{0}^{m} is the amplitude of the wave scattered by the target antenna matched loaded; \mathbf{E}_{1}^{t} is the radiation field of the target antenna excited by a unit amplitude source; **u** and **U** are the polarization vectors of the incident plane wave and the target antenna, respectively.

Let \mathbf{v} be the polarization of the receiver antenna, then the scattering field from the target antenna can be expressed as follows:

$$E_{\nu}^{s} = \mathbf{E}^{s} (Z_{l}) \cdot \mathbf{v}^{*}$$

= $\mathbf{E}^{s} (Z_{c}) \cdot \mathbf{v}^{*} + \frac{\Gamma_{l}}{1 - \Gamma_{l}\Gamma_{a}} b_{0}^{m} \mathbf{E}_{1}^{t} (Z_{c}) \cdot \mathbf{v}^{*}.$ (4)

Using (3), the \overline{v} polarized scattering field can be expressed as follow

$$E_{\nu}^{s} = \left[\mathbf{E}^{s}\left(Z_{c}\right) \cdot \mathbf{v}^{*}\right] + \left[\frac{-j\lambda\Gamma_{l}}{1 - \Gamma_{l}\Gamma_{a}}C\left(|\mathbf{A}\left(\mathbf{k}\right)|\mathbf{U}\cdot\mathbf{u}^{*}\right) \times \sqrt{Z}\left(|\mathbf{A}\left(\mathbf{k}\right)|\mathbf{U}\cdot\mathbf{v}^{*}\right)\frac{e^{-jkr}}{r}\right].$$
(5)

Here the polarizations of the incident plane wave, the receiver antenna, and target antenna are taken into account synchronously. In (5), the expression between the first square brackets is the structural mode scattering field and that between the second square brackets is the antenna mode scattering field. The fact can be concluded that the antenna mode scattering field could be adjusted by changing the parameters Γ_l , Γ_a , $|\mathbf{A}(\mathbf{k})|$, \mathbf{U} , \mathbf{u} , and \mathbf{v} .

For the monostatic scattering case shown in Figure 1(b),

$$\mathbf{u} = \mathbf{v}.\tag{6}$$



FIGURE 5: Measured and simulated LHCP radiation patterns.





Then, the partial gain of the target antenna can be expressed by [13]

$$g_1(\mathbf{k}, \mathbf{u}) = 4\pi |\mathbf{A}(\mathbf{k}) \cdot \mathbf{u}^*|^2 = pG_1(\mathbf{k}), \qquad (7)$$

$$p = \left| \mathbf{U} \cdot \mathbf{u}^* \right|^2,\tag{8}$$

$$G_{\mathrm{I}}(\mathbf{k}) = \left(1 - \left|\Gamma_{a}\right|^{2}\right) G_{2}(\mathbf{k}), \qquad (9)$$

where p is the polarization efficiency; $G_1(\mathbf{k})$ is the realized gain of the target antenna when the reflection from the target antenna is involved; $G_2(\mathbf{k})$ is the gain of the target antenna.

Using (7) and (9), (5) can be rewritten as

$$E_{u}^{s} = \left[\mathbf{E}^{s}\left(Z_{c}\right) \cdot \mathbf{u}^{*}\right] + \left[\frac{\Gamma_{l}}{1 - \Gamma_{l}\Gamma_{a}} b_{0}^{m} \mathbf{E}_{1}^{t}\left(Z_{c}\right) \cdot \mathbf{u}^{*}\right]$$
$$= \left[\mathbf{E}^{s}\left(Z_{c}\right) \cdot \mathbf{u}^{*}\right] + \left[\frac{-j\Gamma_{l}}{1 - \Gamma_{l}\Gamma_{a}} \frac{\lambda}{4\pi} p\left(1 - \left|\Gamma_{a}\right|^{2}\right) G_{2}\left(\mathbf{k}\right) \frac{e^{-jkr}}{r}\right].$$
(10)

Here the first and the second parts of (10) represent the \overline{u} polarized structural mode and antenna mode scattering field. This equation provides us with possibilities to control



FIGURE 7: Bistatic RCS with observe angle.



FIGURE 8: Bistatic RCS with incident frequency.

the scattering field of the target antenna. For instance, if the incident wave is polarization mismatched with the target antenna, that is, p = 0, the antenna mode scattering field is equal to zero. While if the incident wave is polarization matched with the target antenna, that is, p = 1, the antenna mode scattering reaches maximum. If p = 1, the antenna mode scattering will be maximum. The signs of the deduction above are accordant with those of the literature [13].

3. Antenna Study

3.1. Antenna Structure. The geometry of the proposed antenna (ground fractal slotted antenna, GFSA) is shown in Figure 2. It consists of radiator, ground plane, and feed port



FIGURE 10: Axial ratio curves of PA and RA.



FIGURE 11: Measured and simulated LHCP radiation patterns.

which are printed on the top and bottom surfaces of an FR-4 substrate with relative permittivity of 4.4. GFSA is fed by a coaxial cable through the feed port whose position on the radiator can be calculated by

$$R_{\rm in} = R_{\rm in}^0 \cos^2\left(\frac{\pi y_0}{L}\right),\tag{11}$$

where R_{in}^0 is the input resistance of the antenna side-fed by microstrip line. R_{in} is the input resistance of the antenna probe-fed. *L* is the side length of the radiator. y_0 is the distance of the feed port from the radiator edge.

CP radiation can be implemented by two degenerated modes with orthogonal polarizations. Corner-cut rectangular radiator is a commonly used implementation method. As shown in Figure 2, the corner-cut square patch radiator is printed on the top surface of the substrate to implement the left-hand circularly polarized (LHCP) radiation. In order to avoid the edge effect between the radiator and the ground plane, the ground plane should be properly lager than the ground plane. 8 quasi-fractal patche is etched on the extra part of the ground plane on the other side of the substrate. Each quasi-fractal patches are connected by the metal strips. The detailed structural parameters are given in Figure 2.

In order to demonstrate the superiority of GFSA in RCS reduction, a reference antenna (REF) which is not slotted is also studied.

3.2. Radiation Performances. Measured and simulated VSWR curves of the two antennas are shown in Figures 3(a) and 3(b), respectively. It can be seen that the curves are well fitted, and GFSA's measured operating band is 1.97 GHz–2.06 GHz (about 2.3% relative band width) under the condition of VSWR < 2. Between the measured and

TABLE 1: LHCP gains of GFSA and REF.

	1.96 GHz	1.97 GHz	1.98 GHz	1.99 GHz
GFSA	2.73 dB	2.96 dB	2.91 dB	2.77 dB
REF	2.74 dB	2.92 dB	2.90 dB	2.72 dB

simulated curves of GFSA, there is about 40 MHz frequency offset which is caused by the machining error and the effect of the experimental environment.

The axial ratio curves of the two antennas are shown in Figure 4. GFSA's operating band is 1.958 GHz–1.982 GHz and REF's operating band is 1.964 GHz–1.988 GHz, under the condition of AR < 3 dB. There is about 6 MHz frequency offset between the two antennas which is caused by the quasi-fractal structure on the ground plane. From Figures 3 and 4, we can see that the two antennas have similar operation band.

Antenna radiation pattern measurement of GFSA has been performed in an anechoic chamber at 1.97 GHz in both *x-z* plane and *y-z* plane. LHCP radiation patterns are normalized with respect to the maximum in their crossing points. As seen in Figures 5(a) and 5(b), good agreement between simulations and measurements is obtained, and the maximum radiation is perpendicular to the radiator surface. As shown in Table 1 are the measured LHCP gains of the two antennas. It can be seen that the gains of the two antennas are similar, and the LHCP gains of GFSA and REF have reached 2.96 dB and 2.92 dB, respectively, at 1.97 GHz.

From the analysis above, the fact can be concluded that GFSA and REF have similar radiation performances, and the LHCP gain of GFSA is slightly increased.

3.3. Scattering Performances. Time-domain analysis is an effective method for antenna scattering analysis because it is



FIGURE 12: Bistatic RCS with incident frequency.

much easier than the frequency-domain analysis to separate the antenna scattering into the antenna mode and structural mode scattering. The time-domain scattering characteristics of GFSA are studied. The configuration of the simulation is shown in the inset of Figure 6(a). As shown in Figure 6(a), the probe signal of GFSA which is short circuit and open circuit loaded when a normalized pulse is used as the incident wave. The previous signal is the incident pulse, and the following signal is the backward scattering wave. The time delay between the incident and scattering signal indicates the round trip of the signal. The scattering signals are shown in Figure 6(b) when the antenna is open circuit and short circuit loaded. It can be seen that the curves are almost coincidence between 2 ns and 6.8 ns and then a time difference of 1/2 period appears. From the definitions of the scattering modes in Section 2, the conclusion can be made that the previous

waveform is the structural mode scattering wave, and the following waveform is the antenna scattering wave.

As shown in Figures 7(a) and 7(b) are the space-domain RCS curves of GFSA and REF. The incident wave propagates on the negative direction of *z*-axis (perpendicularly) and is *x*-polarized which means that the direction of the incident electric field is parallel to the *x*-axis. In *x*-*z* plane, the RCS of GFSA is lower than that of REF in the angular region of $[-107^{\circ}, 97^{\circ}]$ and $[-62^{\circ}, 62^{\circ}]$. In *y*-*z* plane, the RCS of GFSA is well reduced in the 360° angular region. From Figures 7(a) and 7(b), we can see that the bistatic RCS of GFSA is well reduced in *x*-*z* plane and *y*-*z* plane, especially on the direction of $\theta = 0^{\circ}$ (maximum radiation direction of the antenna) by the degree of 1.72 dB. However, the reduction of 1.72 dB is not quite enough which will be discussed together with the array case later.

TABLE 2: LHCP gains of PA and RA.

	1.97 GHz	1.98 GHz	1.99 GHz	2 GHz
PA	7.3 dB	7.37 dB	7.4 dB	7.41 dB
RA	7.41 dB	7.5 dB	7.6 dB	7.5 dB

The frequency-domain scattering characteristic of GFSA is shown in Figure 8. The RCS curves of GFSA and REF are basically in coincidence below 1.68 GHz, and the RCS reduction is not impressive, while the distance of the two curves is enlarged soon as the frequency increased.

4. Array Study

4.1. Radiation Performances. Microstrip antenna is commonly used as a part of the array to realize the patterns of array. In this section, a linearly arranged 4-unit array is designed based on GFSA and REF. The proposed array (PA) is shown in Figure 9. The axial ratio curves of PA and the reference array (RA) are shown in Figure 10. Under the condition of AR < 3 dB, the operating band of PA is 1.974 GHz– 1.999 GHz and that of RA is 1.974 GHz–2.001 GHz. About 2 MHz offset occurred between the arrays which is due to the slots on PA. The measured axial ratio at 1.99 GHz on the radiation direction is 2.56 dB which is 0.63 dB larger than the simulated result 1.93 dB. It is believed that the error of the handmade coaxial feed line leads to the output phase differences between the feed ports of the array in the measurement.

The simulated and measured radiation patterns at 1.99 GHz are shown in Figures 11(a) and 11(b). LHCP radiation patterns are normalized with respect to the maximum in their crossing points. The simulated and measured curves fit well in the angle of $[-20^{\circ}, 20^{\circ}]$ in both *x*-*z* and *y*-*z* planes. The radiation directions of the simulated and measured curves are coincident with each other and are all perpendicular to the radiator surface. As shown in Table 2 is the measured LHCP gains of the two arrays. It can be seen that the gain of the PA is slightly lower than that of PA, and the LHCP gains of PA and RA are 7.4 dB and 7.6 dB, respectively, at 1.99 GHz.

4.2. Scattering Performances. The bistatic RCSs of the arrays are studied when they are lit by the incident wave perpendicularly. The incident wave is x-polarized. The changes of antenna bistatic RCS with incident wave frequency when the observe angles are $\theta = 0^\circ$, $\theta = 10^\circ$, and $\theta = 20^\circ$, are shown in Figures 12(a)-12(c). As shown in Figure 12(a), the RCS curves of the two arrays are practically coincident in the 1 GHz-1.5 GHz band. This phenomenon reminds us the problem left above. It is caused by the same reason analyzed above that the array is electrically small target to the incident wave in this band, so the Rayleigh scattering characteristic (low frequency scattering characteristic) is dominant which means that the scattering level of the array is determined by the size of the array instead of the detail structure of the array. With the increasing of the frequency of the incident wave, the array is larger and larger comparing to the wavelength

of the incident wave, and the detail structure of the array is more and more influential to the scattering. So the RCS of PA is largely reduced in the band of 1.5 GHz–10 GHz. In Figures 12(b) and 12(c), the RCS curve of PA is getting close to that of RA with the observe angle increasing which means that the effect of the proposed technique is getting weaker. However, the RCS curves of the PA are still lower than those of RA.

5. Conclusion

A novel RCS reduction technique is proposed for CP antenna and array in this paper. In order to suppress the scattering wave of CP microstrip antenna and array, quasi-fractal slots are etched on the ground planes. The prototypes are studied by being compared to the reference ones, and the measured and simulated result shows that the RCS of the prototypes is effectively reduced in the band of 1.5 GHz–10 GHz while the gains and the patterns hold.

Acknowledgments

The authors would like to thank the National Natural Science Foundation of China (no. 61201018), the Fundamental Research Funds for the Central Universities (K5051202010), and Specialized Research Fund for the Doctoral Program of Higher Education (20120203120011) for their financial support.

References

- I. Nicolaescu, "Improvement of stepped-frequency continuous wave ground-penetrating radar cross-range resolution," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 1, pp. 85–92, 2013.
- [2] S. Yang, A. Kishk, and K. Lee, "Wideband circularly polarized antenna with L-shaped slot," *IEEE Transactions on Antennas* and Propagation, vol. 56, no. 6, pp. 1780–1783, 2008.
- [3] S.-H. Chang and W.-J. Liao, "A novel dual band circularly polarized GNSS antenna for handheld devices," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 2, pp. 555–562, 2013.
- [4] S. H. Zainud-Deen, H. A. El-Azem Malhat, and K. H. Awadalla, "A Single-feed cylindrical superquadric dielectric resonator antenna for circular polarization," *Progress in Electromagnetics Research*, vol. 85, pp. 409–424, 2008.
- [5] S. A. Razavi and M. H. Neshati, "Development of a low-profile circularly polarized cavity-backed antenna using HMSIW technique," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 3, pp. 1041–1047, 2013.
- [6] Nasimuddin, Z. N. Chen, and X. Qing, "Slotted microstrip antennas for circular polarization with compact size," *IEEE Antennas and Propagation Magazine*, vol. 55, no. 2, pp. 124–137, 2013.
- [7] E. F. Knott, J. Shaeffer, and M. Tuley, *Radar Cross Sectioned*, SciTech, Raleigh, NC, USA, 2nd edition, 2004.
- [8] D. M. Pozar, "Radiation and scattering from a microstrip patch on a uniaxial substrate," *IEEE Transactions on Antennas and Propagation*, vol. 35, no. 6, pp. 613–621, 1987.
- [9] S. Hu, H. Chen, C. L. Law et al., "Backscattering cross section of ultrawideband antennas," *IEEE Antennas and Wireless Prop*agation Letters, vol. 6, pp. 70–73, 2007.

- [10] W. Jiang, Y. Liu, S. X. Gong, and T. Hong, "Application of bionics in antenna radar cross section reduction," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1275–1278, 2009.
- [11] Y. Liu, S. X. Gong, and H. B. Zhang, "A novel fractal slot microstrip antenna with low RCS," in *Proceedings of IEEE Antennas and Propagation Society International Symposium*, pp. 2603–2606, July 2006.
- [12] S. X. Gong and Y. Liu, *Prediction and Reduction of Antenna Radar Cross Section*, XDUP, Xian, China, 2010.
- [13] Y. T. Lo and S. W. Lee, Antenna Handbook, Chapman & Hall, New York, NY, USA, 1993.

