Progress In Electromagnetics Research Letters, Vol. 95, 99–105, 2021

An Efficient Technique for Wide Band RCS Reduction of Patch Antenna Array Using Rectangular Cavity Walls and Phase Cancellation Principle

Xiaoyuan Zhang, Xiaoxiang He, Yang Yang*, and Chenyue Xu

Abstract—The rectangular cavity is investigated and applied in the field of the radar cross section reduction (RCSR) of patch antennas for the first time. An integrated and efficient design technique is presented which uses both a slotted rectangular cavity and reflective phase cancellation by a simple artificial magnetic conductor (AMC) element. On condition that ensuring the radiation performance of the patch antenna does not deteriorate, the in-band radar cross section (RCS) of the antenna can be reduced by 12.2 dB at 7.6 GHz just relying on a type of phase-regulated AMC elements. On this basis, the rectangular cavity walls were first loaded surrounding the above-mentioned low-RCS patch antenna. The relative bandwidth (in which RCS was reduced by more than 8 dB) went from 3.33% to 50% in the RCSR of the antenna. Meanwhile, the RCS could be reduced by an additional 5 dB at its working frequency (7.6 GHz).

1. INTRODUCTION

Due to the urgent demands of modern information warfare, the RCSR of the antennas has always been a hot topic for experts in recent years. Patch antennas have a wide range of applications in radar detection because of their unique advantages such as simple structure, convenient processing, and light weight. Therefore, the stealth design of patch antennas is very necessary. It is a effective method of RCSR for patch antennas which change the current distribution on the antenna structure to reduce the reflected power. The technique of etching slots on the ground plane was applied in RCSR [1]. However, RCS was reduced a little at its working frequency. In order to achieve energy cancellation at a specified frequency, the chessboard structure has been widely used. The reflected wave will cancel out when the two parts are placed in a chessboard. However, the difficulty in current design is designing two kinds of AMC elements with equal reflection amplitude and 180 degree difference in reflection phase in wide frequency band. At the same time, the structure usually has a defect that it will increase the original area of the antenna [2–4]. To simplify the design and avoid this disadvantage, a polarisation-dependent frequency selective surface (PDFSS) structure was proposed [5]. However, its total RCS was not going to go down very much. Then polarization conversion units were added around the antenna [6], but they also increased the area of the antenna. Another simple AMC is absorbing material which could be used as part of the ground plane of the antenna to reduce the reflection waves of the ground [7], but its RCS could be reduced only within a narrow bandwidth. Therefore, the traditional simplex design method can hardly meet the current requirements. This letter presents a simple and general technique for RCSR of patch antennas while ensuring the normal radiation performance of the antenna. The in-band RCS is reduced by 12 dB without adding extra area to the antenna just through a kind of AMC element replacing the ground plane. By means of the designed slotted rectangular cavity walls surrounding the

Received 27 October 2020, Accepted 21 December 2020, Scheduled 23 December 2020
* Corresponding author: Yang Yang (eeyy@nuaa.edu.cn).
The authors are with the Nanjing University of Aeronautics and Astronautics, Jiangsu, Nanjing 211106, China.

antenna, RCS can be reduced at wider band, and RCS can go even lower at its working frequency: The relative bandwidth (in which RCS was reduced by more than 8 dB) went from 3.33% to 50% in the RCSR of the antenna. Meanwhile, the RCS could be reduced by an additional 5 dB at its working frequency (7.6 GHz).

2. DESIGN AND SIMULATION OF THE LOW-RCS ANTENNA

A low-RCS patch antenna is proposed as in Fig. 1. Two AMC elements are arranged around the patch to cancel the reflection wave on the ground rather than expanding the ground of the antenna. To prevent the AMC units from affecting the radiation performance, an L-shaped slot (1.05 mm wide) which can cut off the current distribution was added to the ground. Based on the principle of phase cancellation, the RCSR method of the cavity is applied. Four metal walls (medium thickness: 0.3 mm) are added around antenna 1 vertically. At the same time, a 0.5 mm thick dielectric plate with four grooves used to weld the coaxial connector is added below it.

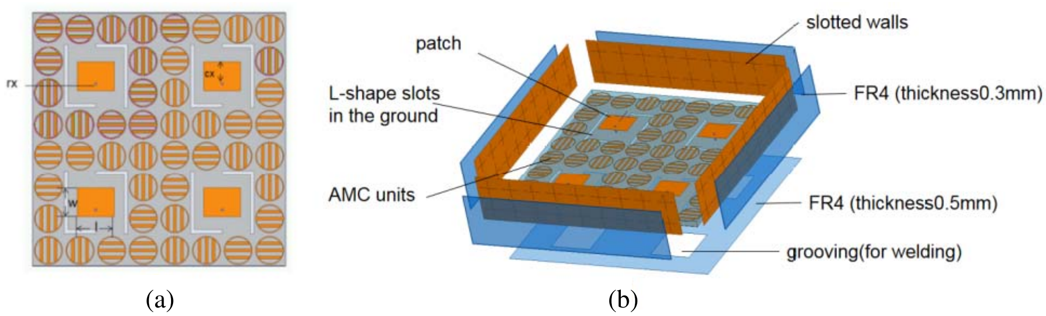


Figure 1. The proposed antenna.

As shown in Fig. 2, a polarity-dependent AMC element is proposed in this letter. In order to improve scattering performance for general patch antennas, the upper layer of the unit is inserted into the middle of the two FR4 layers, so that the elements and the antenna can share the ground floor. The dimensions for the AMC unit and the antenna are shown in Table 1.

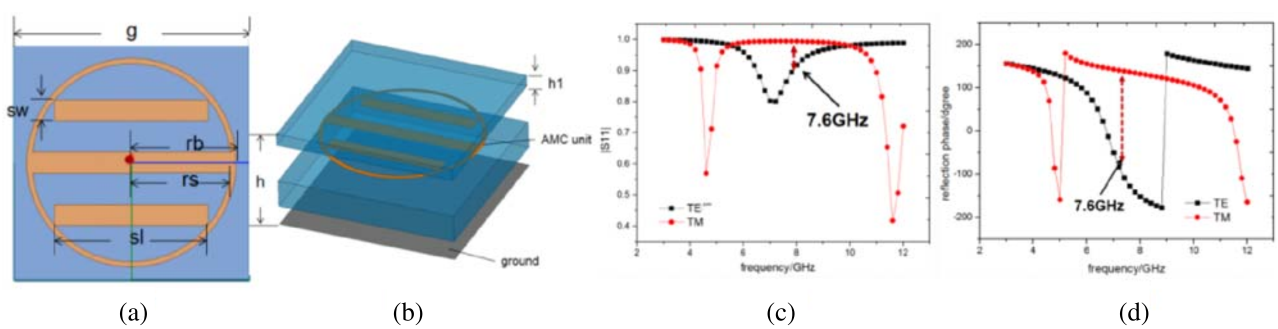
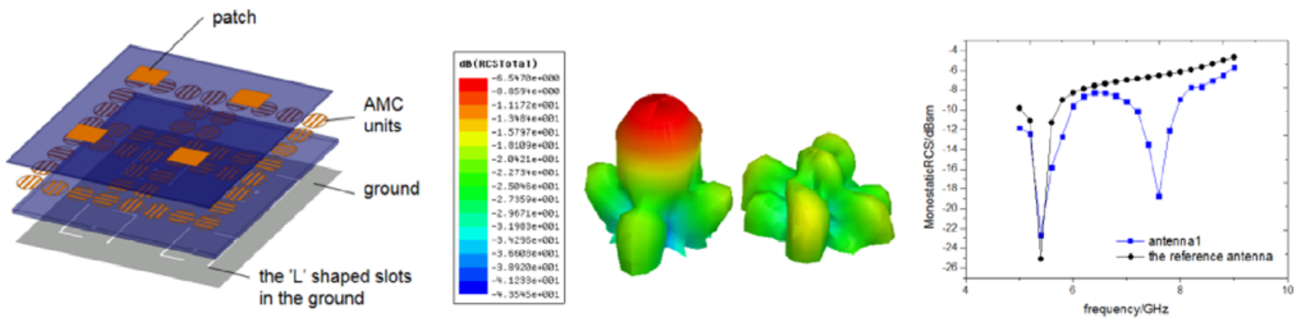


Figure 2. The polarity-dependent AMC unit. (a) The top view of the unit, (b) the 3-d view of the unit, (c) reflection magnitudes, (d) reflection phases.

Table 1. Dimensions for the AMC unit and the antenna.

Parameters	sw	sl	rb	rs	g	h	$h1$	l	w	cx	rx
Value/mm	0.8	7.8	4	3.8	9	2	0.5	10.5	8.2	6.25	0.3

As shown in Fig. 2, the two modes of this element have the same reflection amplitude and 180 degrees of phase difference at 7.6 GHz. Therefore, the unit is rotated 90 degrees to obtain another unit, and the two elements can form a 180 degree phase difference in both modes at 7.6 GHz. Antenna 1 is proposed using the two AMC elements and L-shaped slots. As shown in Fig. 3, the original main scattered beam is directed into other angles.



(a) (b) (c)

Figure 3. Antenna 1 and simulation results. (iwavephi = 0, iwavetheta = 0). (a) The model of antenna 1, (b) 3-D scattering pattern of y-polarized incident wave at 7.6 GHz of the reference antenna and antenna 1, (c) the monostatic RCS of the antenna 1 and the reference antenna.

Many researchers have predicted the RCS of a cavity and been able to calculate the peaks and zeros of the RCS in the past [8–10]. And a lot of research has been done on corner reflectors, cylinders, and metallic edges [11–15]. Therefore, we can similarly use a rectangular cavity to reduce the RCS of a metal plate and patch antenna. As shown in Fig. 4, four metal walls (height: 16 mm) are added vertically around a metal plate which has the same size as antenna 1 (72 mm-by-72 mm), and the RCS of the plate is reduced in 5–9 GHz. The energy in the plane of the electric field of the incident wave will be transferred to other angles. Antenna 2 is proposed by adding four metal walls vertically around antenna 1 (medium thickness: 0.3 mm). The L-shaped slots could prevent the antenna performance from being affected by the AMC, but the slots will also change the integrity of cavity, so a 0.5 mm thick dielectric plate with four grooves is added below it like Fig. 1. In this way, the antenna can obtain a scattering frequency point at 7.5 GHz while obtaining a wide-band RCS reduction as shown in Fig. 5. It can be seen that antenna 2 achieves RCS reduction of more than 8 dB between 6.4 and 7.9 GHz, and the relative bandwidth of RCSR goes from 3.33% to 50%.

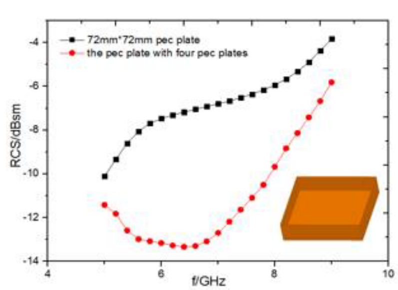
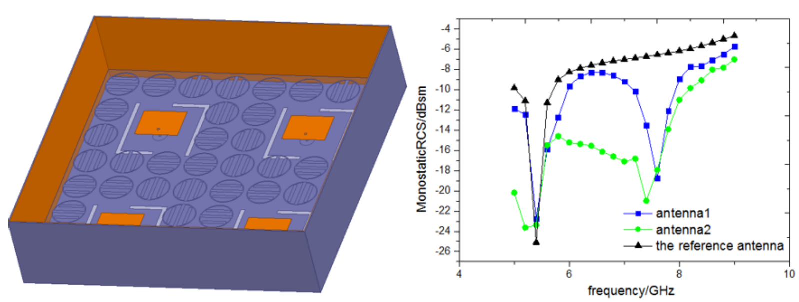


Figure 4. The monostatic RCS of the metal plate surrounded with four metal walls of y-polarized incident wave (iwavephi = 0, iwavetheta = 0).



(a) (b)

Figure 5. Antenna 2 (with AMC units and rectangular cavity walls). (a) The structure of antenna 2, (b) the monostatic RCS of antenna 2 of y-polarized incident wave (iwavephi = 0, iwavetheta = 0).

3. MEASURED AND RESULTS OF THE ANTENNA WITH SLOTTED RECTANGULAR CAVITY WALLS

A slotted rectangular cavity is proposed to be loaded around antenna 1 in Fig. 6, and the slot is 6.1 mm long and 0.8 mm wide. The height of the wall around the antenna is 16 mm. The comparisons of the antennas in monostatic and bistatic RCS are shown in Fig. 8. Antenna 3 (with slotted rectangular cavity) can better guarantee the scattering phase cancellation at 7.6 GHz and also reduce the RCS like a metal cavity in 6–7 GHz. Meanwhile, the radiation performance of antenna 3 is basically the same as that of the reference antenna in Fig. 7. Table 2 shows the comparison of the three antennas in radiation and scattering performance. The measured results are shown in Fig. 9, and the reason that they have some discrepancies is that there are some errors caused by processing and testing. However, the validity of the design method is proved by the results.

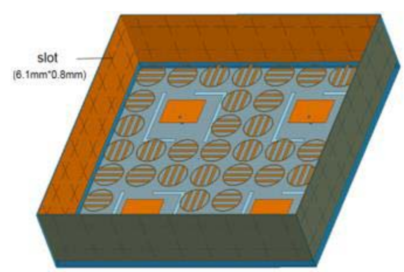


Figure 6. The structure of antenna 3.

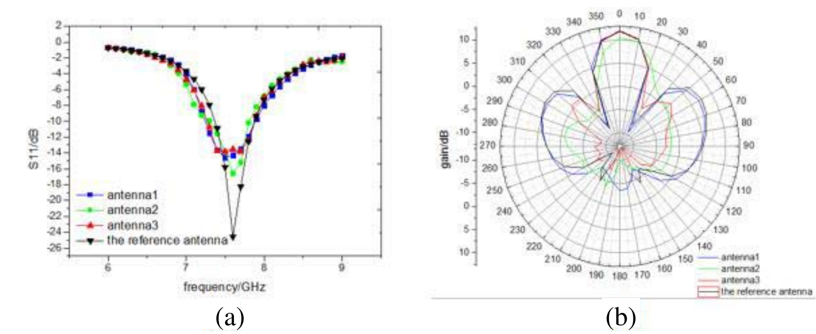


Figure 7. Radiation performance comparison diagram of four antennas. (a) S_{11} parameters, (b) radiation patterns at 7.6 HGz.

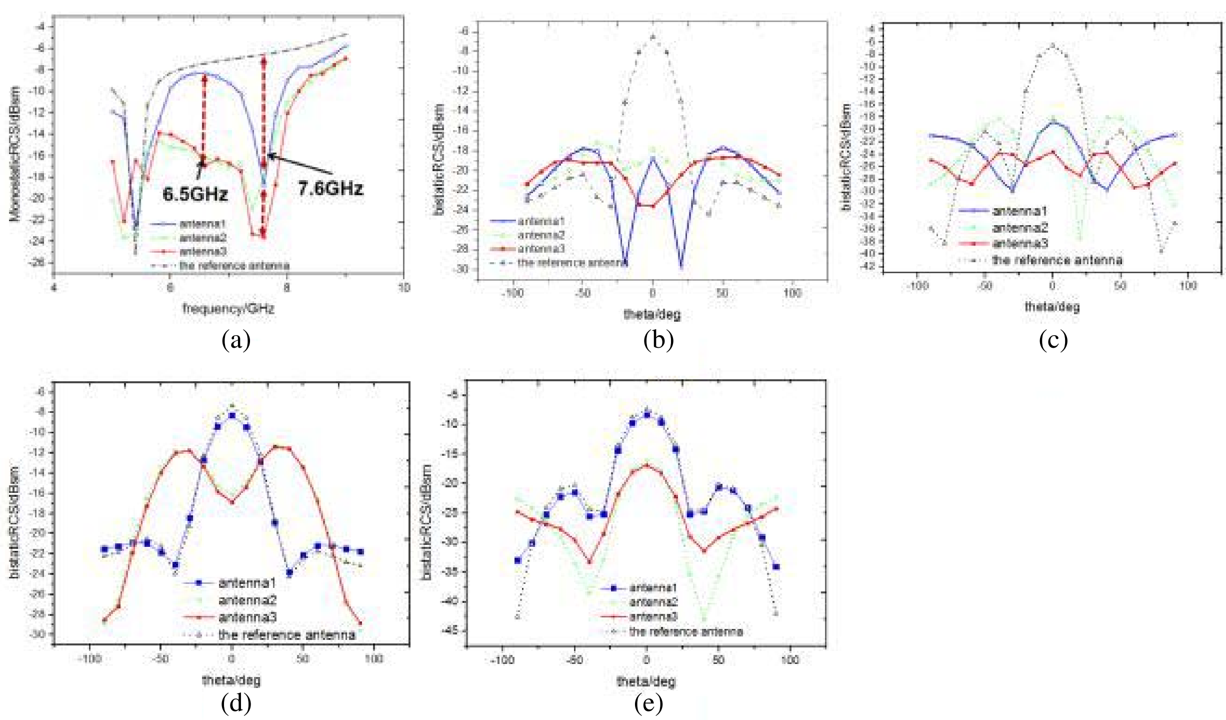
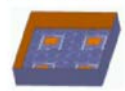
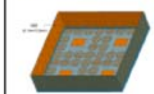
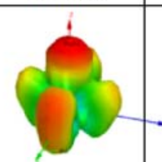
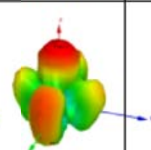
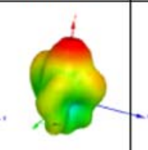
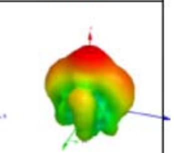
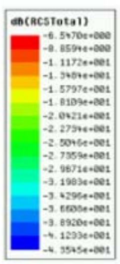
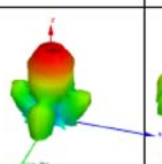
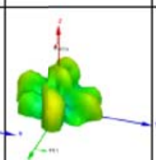
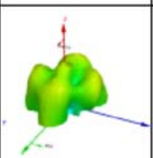
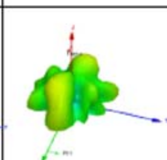
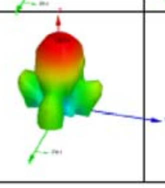
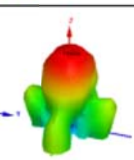
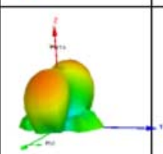
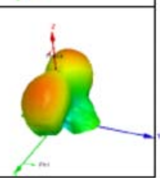
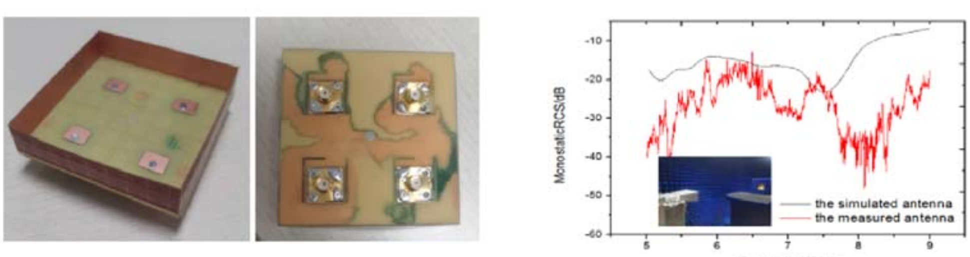


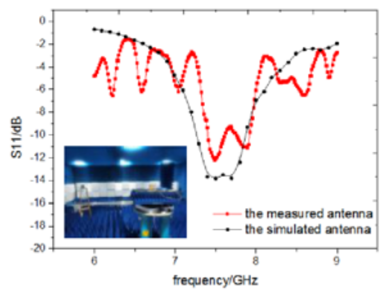
Figure 8. Scatter performance comparison diagram of four antennas of y-polarized incident wave (iwavephi $= 0$, iwavetheta $= 0$). (a) Monostatic RCS of four antennas, (b) Bistatic RCS of XOZ-plane at 7.6 GHz, (c) Bistatic RCS of YOZ-plane at 7.6 GHz, (d) Bistatic RCS of XOZ-plane at 6.6 GHz, (e) Bistatic RCS of YOZ-plane at 6.6 GHz.

Table 2. Comparison of radiation and scattering performance of four antennas.

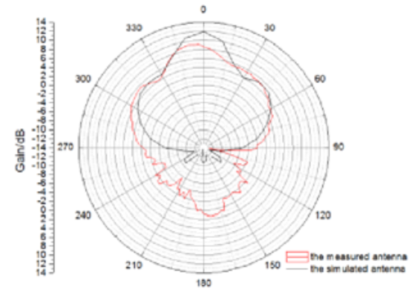
		The reference antenna 	antenna1 (loaded AMC units) 	antenna2 (loaded metal cavity around antenna 1) 	antenna3 (loaded slotted metal cavity around antenna1) 
Radiation performance 	The center frequency point	7.6GHz	7.5GHz	7.6GHz	7.6GHz
	-10dB frequency band	7.35-8.85GHz	7.25-7.9GHz	7.3-7.8GHz	7.25-7.85GHz
	Gain at 7.6GHz	12.04dB	11.92dB	10.52dB	11.86dB
	3d Gain at 7.6GHz				
Scattering performance 	The frequency band where RCS can be reduced by 3dBsm	——	7.2 - 7.8GHz	5.6 - 8.4GHz	5.6 - 8.6GHz
	relative bandwidth of effective reduction (reduced by 8dBsm)	——	7.5-7.6GHz 3.33%	6.4-7.9GHz 50%	6.4-7.9GHz 50%
	3D RCS at 7.6GHz				
	3D RCS at 6.5GHz				



(a) (b)



(c)



(d)

Figure 9. Measure result of antenna 3. (a) The pictures of the antenna, (b) comparison of monostatic RCS of the antennas, (c) comparison of S_{11} of the antennas, (d) comparison of gain of the antennas.

4. CONCLUSION

In this letter, an efficient technique for wide band RCS reduction of patch antenna array using rectangular cavity walls and phase cancellation principle is proposed. The first step is to design a simple phase-controlled AMC element according to the working frequency of the patch antenna. When substituting the AMC units for the ground plane of the patch antenna, the in-band RCS of the antenna can be reduced by 12.2 dB. Then this letter presents that the rectangular cavity can be applied in RCSR for the first time. After simulation and testing, its RCS can be reduced even more at wider band: the RCSR relative bandwidth can go from 3.33% to 50% (reduced by 8 dB), and the RCS can shrink by an additional 5 dB at its working frequency (7.6 GHz). The integrated technique provides a new way for future researchers in RCSR.

REFERENCES

1. Li, Y., Y. Liu, and S.-X. Gong, "Microstrip antenna using ground-cut slots and miniaturization techniques with low RCS," *Progress In Electromagnetics Research Letters*, Vol. 1, 211–220, 2008.
2. Liu, T., C. Zhou, X. He, et al., "A low RCS microstrip antenna based on broadband AMC structures," *2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 1–3, 2018.
3. Al-Nuaimi, M. K. T., Y. He, and W. Hong, "In-band and out-of-band RCS reduction of a patch antenna using anisotropic unit cell," *2019 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 1–3, 2019.
4. Zhang, C., J. Gao, et al., "Low scattering microstrip antenna array using coding artificial magnetic conductor ground," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 5, 869–872 2018.
5. Jia, Y., Y. Liu, H. Wang, et al., "Low RCS microstrip antenna using polarisation-dependent frequency selective surface," *Electronics Letters*, Vol. 50, No. 14, 978–979, 2014.
6. Liu, Y., Y. Hao, K. Li, et al., "Radar cross section reduction of a microstrip antenna based on polarization conversion metamaterial," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 80–83, 2016.
7. Costa, F., S. Genovesi, and A. Monorchio, "A frequency selective absorbing ground plane for low-RCS microstrip antenna arrays," *Progress In Electromagnetics Research*, Vol. 126, 317–332, 2012.
8. Ling, H., R.-C. Chou, and S.-W. Lee, "Shooting and bouncing rays: Calculating the RCS of an arbitrarily shaped cavity," *IEEE Transactions on Antennas and Propagation*, Vol. 37, No. 2, 194–205, 1989.
9. Xu, L., J. Tian, and X.-W. Shi, "A closed-form solution to analyze RCS of cavity with rectangular cross section," *Progress In Electromagnetics Research*, Vol. 79, 195–208, 2008.

10. Wang, T. M., A. Cuevas, and H. Ling, "RCS of a partially open rectangular box in the resonant region," *EEE Transactions on Antennas and Propagatio*, Vol. 38, No. 9, 1498–1504, 1990.
11. Valagiannopoulos, C. A., "Arbitrary currents on circular cylinder with inhomogeneous cladding and RCS optimization," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 5, 665–680, 2007.
12. Griesser, T. and C. A. Balanis, "RCS analysis and reduction for lossy dihedral corner reflectors," *Proceedings of the IEEE*, Vol. 77, No. 5, 806–814, 1989.
13. Valagiannopoulos, C. A., "On smoothening the singular field developed in the vicinity of metallic edges," *International Journal of Applied Electromagnetics and Mechanics*, Vol. 31, No. 2, 67–77, 2009.
14. Lee, S., K. Y. Jung, H. Choo, et al., "Scattering analysis of modulated corrugations in a conducting circular cylinder and study of RCS reduction," *IEEE Transactions on Antennas and Propagation*, Vol. 67, No. 11, 7162–7167, 2019.
15. Valagiannopoulos, C. A., "Closed-form solution to the scattering of a skew strip field by metallic PIN in a slab," *Progress In Electromagnetics Research*, Vol. 79, 1–21, 2008.