Chinese Journal of Electronics
vol. 33, no. 2, pp. 449–455, March 2024
https://doi.org/10.23919/cje.2022.00.121

RESEARCH ARTICLE

A Tightly Coupled Dipole Array with Diverse Element Reflection Phases for RCS Reduction

Yuewen GOU, Yikai CHEN, and Shiwen YANG

University of Electronic Science and Technology of China, Chengdu 611731, China

Corresponding author: Yikai CHEN, Email: ykchen@uestc.edu.cn
Manuscript Received May 6, 2022; Accepted February 13, 2023

Abstract — This paper proposes a novel low scattering tightly coupled dipole array (TCDA), aiming to reduce the radar cross section (RCS) of phased antenna arrays under a certain oblique incident wave. First, we build three types of antenna elements that exhibit similar radiation characteristics but diverse reflection phase differences based on the proposed theoretical analysis. The required reflection phase difference is achieved by using different dielectric superstrates for each antenna element. Then, by arranging the three types of subarrays next to each other, a low scattering TCDA (8 × 9) is designed. Meanwhile, a reference antenna array with a single type of antenna element is also constructed. To demonstrate the effectiveness of the proposed RCS reduction technique, simulated and measured results of the reference and proposed antenna array are compared. Both antenna arrays operate over the 6–18 GHz frequency band and can scan up to ±45° in the E-/H-planes. However, the proposed antenna array achieves a significant monostatic RCS reduction over 8–12 GHz, with a maximum reduction value of 7.55 dB. It indicates that this diverse element reflection phase technique is a good candidate for wideband RCS reduction.
Keywords — Phased array, Tightly coupled dipole array, Radar cross section.
Citation — Yuewen GOU, Yikai CHEN, and Shiwen YANG, "A Tightly Coupled Dipole Array with Diverse Element Reflection Phases for RCS Reduction," *Chinese Journal of Electronics*, vol. 33, no. 2, pp. 449–455, 2024. doi: 10.23919/cje.2022.00.121.

I. Introduction

Recently, the tightly coupled dipole array (TCDA) designed according to Wheeler's current sheet antenna (CSA) array [1], has become an attractive candidate for phased antenna arrays due to its wideband and low-profile characteristics. To date, researchers have investigated various approaches to enhance TCDA's radiation performance, but rarely focused on its scattering characteristics. In reality, phased antenna arrays will always contribute significantly to the total radar cross section (RCS) of a stealth platform. Thus, it is critical to suppress the scattering of phased antenna arrays.

Over the past few decades, radar absorbing materials [2], [3] and metasurfaces like artificial magnetic conductor (AMC) [4] and frequency selective surface (FSS) [5] are employed in RCS reduction of antennas. Some digital and coding metasurfaces are also exploited to achieve diffuse scattering beams [6], [7]. However, most of these techniques are designed definitely for narrow band antennas like slot antenna and microstrip patch antenna, and leave out the consideration of antenna's scanning ability. Their practical applicability in radar systems is constrained by their restricted frequency band and static radiation beams. Moreover, the compact configuration of TCDA also makes it difficult to apply these loading methods. Recently, out-of-band RCS reduction for a TCDA is realized by loading the array with polarization conversion metamaterial (PCM) [8]. Another effective technique is to introduce polarization selective metamaterial absorber (PSMA) on the surface of a TCDA [9]. But the introduction of resistive coatings reduced the peak gain of TCDA. Unfortunately, these methods inevitably increase the cost and the loading of resistive materials will impact the radiation performance more or less. More importantly, most of the mentioned works tend to focus on the case that the incident wave is coming from the normal direction. In actuality, most threats to targets are detected not just from the normal direction but also from oblique incidence angles. Therefore, it is of practical significance to reduce the RCS of a phased antenna array

Associate Editor: Prof. Wei CUI, Beijing Institute of Technology.

when incident waves are at an oblique angle.

To address the aforementioned issues, a novel low scattering TCDA with heterogeneous antenna elements is designed in this paper, aiming to reduce the monostatic RCS specifically when the incident waves illuminating from a certain oblique angle. Firstly, an element-level reflection phase diversity concept is proposed to calculate the required reflection phase difference among different antenna elements. Then, three types of TCDA antenna elements that exhibit almost the same radiation performance but diverse reflection phase is developed. Finally, a compound phased array consisting of these three kinds of antenna elements is developed for in-band RCS reduction under oblique incidence. Experiment validations for a uniform reference antenna array and the proposed low scattering array are presented to illustrate the effectiveness of the proposed RCS reduction technique. The measured results demonstrates that the proposed antenna array realizes significant RCS reduction while preserving the good radiation performance.

Following is a summary of the advantages and contribution of the proposed technique.

1) Propose a method to reduce the monostatic RCS specifically for a certain oblique incident angle, which is rarely researched in existing literatures.

2) Propose a method to create different TCDA antenna elements that perform diverse reflection phases but the same radiation performance.

3) The different types of antenna elements are designed modular, and are easy for modular antenna array fabrication.

4) The element-level reflection phase diversity technique does not introduce additional structures. As a result, it does not increase the complexity of the design, the profile height, the weight, or the radiation performance.

II. Design of the Proposed Antenna

1. Concept of element-level reflection phase diversity

As shown in Figure 1, the proposed low RCS antenna array is made up of two subarrays with various type of antenna elements. The two subarrays are uniformly ordered, thus they excite the same array factor AF. Assume that $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ are the scattering pattern of the antenna element in subarray 1 and 2, respectively. When illuminated by a plane wave with an oblique incident angle of θ, the scattering field of such an array can be expressed as

$$\boldsymbol{E}_{\rm sca} = \boldsymbol{E}_1 \cdot AF \cdot {\rm e}^{{\rm j}(2kD\sin\theta+\beta)} + \boldsymbol{E}_2 \cdot AF \tag{1}$$

where k defines the wavenumber of the wave in media, D represents the distance between contiguous subarrays along y-axis, and β represents the progressive phase shift between the antenna elements, respectively.

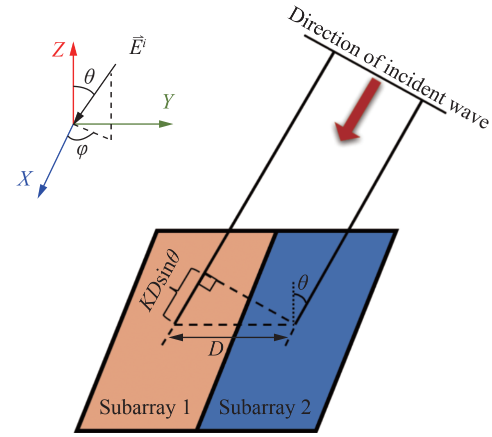

Figure 1 Generic structure of a proposed low scattering array.

Suppose the two different antenna elements in two subarrays reflect equivalent energy under incident plane waves, then $\boldsymbol{E}_1 = \boldsymbol{E}_2$. Thus, the total scattering field only depends on β. When $\beta = \pi - 2kD\sin\theta$, $\boldsymbol{E}_{\rm sca}$ will create a null in the direction of incidence. The scattering field is fully suppressed by this element-level reflection phase diversity method.

Considering radiation case, $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ are the radiation patterns. If the two kinds of antenna element induce similar radiation pattern, then $\boldsymbol{E}_1 = \boldsymbol{E}_2$. Suppose a reference array is made up of the same type of antenna elements, and the proposed array will have the same array distribution, then the two arrays will generate the same radiation fields.

Therefore, using the proposed method, a low scattering antenna array can be obtained without any deterioration of radiation performance. Evidently, the proposed concept could be extended to antenna arrays with much richer element-level reflection phase diversity. In this work, we will demonstrate the application of the element-level reflection phase diversity technique by a low RCS antenna array with three types of antenna elements.

2. Antenna element designs

In order to create a low RCS antenna array, multiple types of antenna elements must be built according to the element-level reflection phase diversity idea. Geometry of three types of antenna elements with reflection phase diversity are presented in Figure 2. The three types of antenna elements are composed of a dielectric superstrate, a dipole with overlapped arms, a folded Marchand balun, a ground plane for electromagnetic wave reflection, and a ground plane for subminiature push-on (SMP) connector soldering. The Marchand balun is printed on the outside surface of two 0.254 mm thick Rogers RO4350 dielectric sheets ($\varepsilon_r = 3.66$), while the dipole is placed between the two sheets. The copper layers of the three antenna elements have identical construction, as shown in Figure 3.

All of the three types of antenna elements have the same compact size of 6 mm × 6 mm × 15 mm. The only difference lies in the dielectric superstrates that cover the

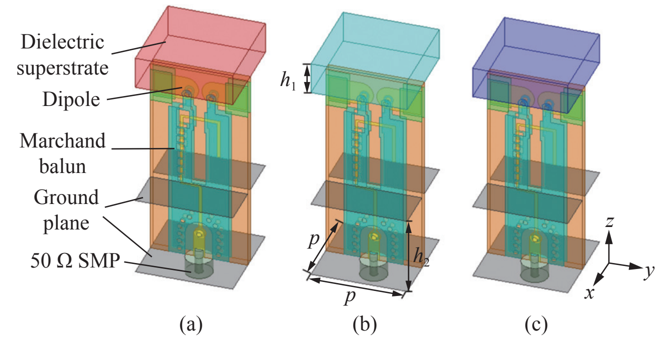

Figure 2 Geometry of the three types of antenna elements. (a) Antenna element 1; (b) Antenna element 2; (c) Antenna element 3.

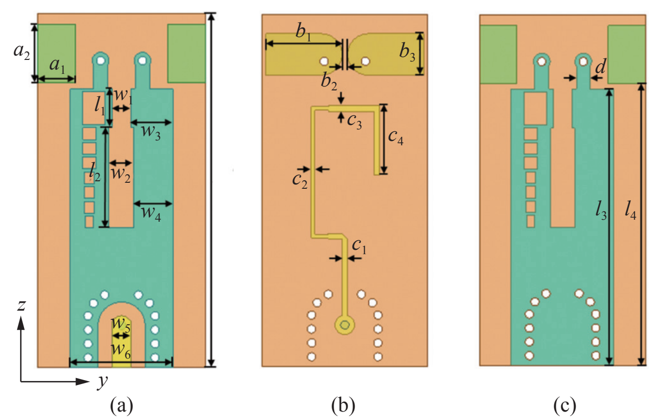

Figure 3 Copper layers in the three types of antenna elements. (a) Layer 1; (b) Layer 2; (c) Layer 3.

top surface of the antenna elements. Specifically, the dielectric superstrate of antenna element 1 is a foam ($\varepsilon_r = 1.05$), which is equivalent to the air. The dielectric superstrate of antenna element 2 is a F4BM-2 dielectric sheet ($\varepsilon_r = 2.2$), and the dielectric superstrate over antenna element 3 is a FR4 dielectric sheet ($\varepsilon_r = 4.4$). This design makes the antennas easy for modular array fabrication. Detailed dimensions of the three types of antenna elements are presented in Table 1.

Table 1 Dimensions of the antenna elements (Unit: mm)

a_1	a_2	b_1	b_2	b_3	c_1	c_2	c_3
1.35	2.1	2.75	0.2	1.5	0.2	0.13	0.2
c_4	d	h_1	h_2	h_3	l_1	l_2	l_3
2.5	0.5	2	5	13	1.4	3.6	10
l_4	p	w_1	w_2	w_3	w_4	w_5	w_6
10.2	6	1	0.9	1.5	1.4	0.7	3.7

In order to illustrate the scattering and radiation performance of these three antenna elements, simulations are performed with an infinite periodic boundary in Ansys HFSS.

The simulated VSWRs (voltage standing wave ratios) of antenna elements 1, 2, and 3 are plotted in Figure 4. As shown, all of the three types of antenna elements operate in 6–18 GHz and scan up to ±45° in E-/H-planes. Additionally, Figure 5 shows that the radiation patterns of the three antenna elements are comparable in E-plane and H-plane at 12 GHz. Thanks to the constant radiation performance, it is possible to develop an array with diverse antenna elements.

In this work, we attempt to reduce the RCS of the phased antenna array in X-band. Specifically, the plane

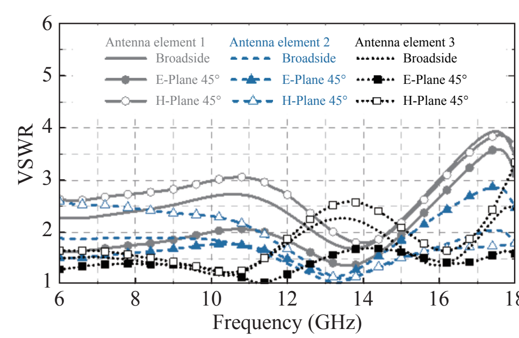

Figure 4 VSWRs of the three antenna elements.

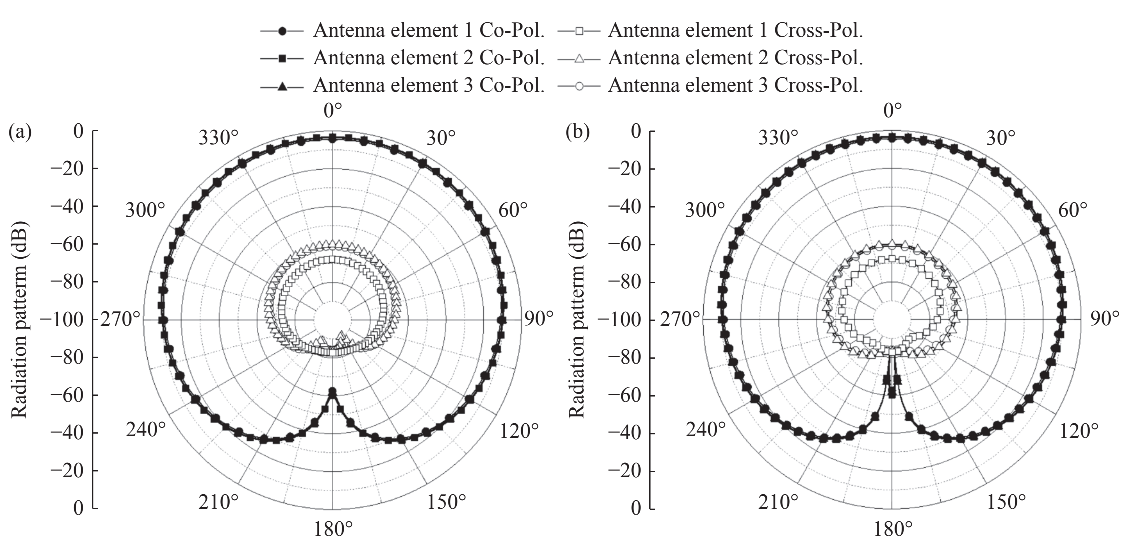

Figure 5 Simulated radiation patterns of the three types of antenna elements at 12 GHz. (a) E-plane, (b) H-plane.

wave illuminates from an oblique angle of $\theta = 30°$, and the distance between adjacent subarrays is $D = 18$ mm. According to the aforementioned theoretical analysis, to obtain the reflection phase diversity, the reflection phase difference among the antenna elements should be $\beta = \pi - 2kD\sin\theta = 36°$.

Thus, except for the similar radiation characteristics, the reflection phase of each antenna element has to satisfy the critical phase differences. In this paper, the reflection phase under oblique incidence is calculated through the method reported in [10]. 50 Ω-matched loadings are used to connect the three antenna elements. Figure 6 shows the simulated reflection phase of the three proposed antenna elements when the x-polarized incident waves coming from $\theta = 30°$. It can be seen that the reflection phases of the three antenna elements conform to the required reflection phase difference. The three substrates have different characteristic impedance, so the reflection phase will be different when electromagnetic waves are incident from free space. More complex parameter optimization approaches can be used to obtain a more stable phase difference. Low scattering is thus expected to be realized when an antenna array effectively combines the three different types of antenna elements.

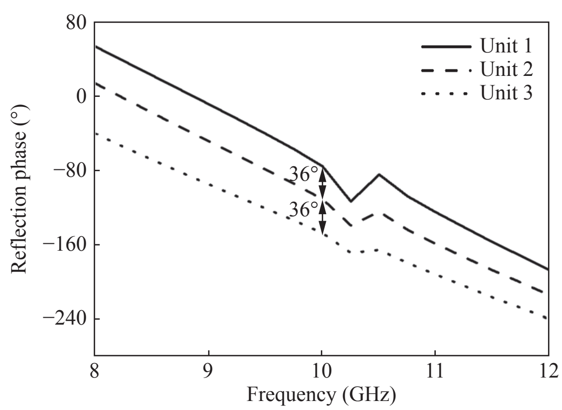

Figure 6 The reflection phase of the three antenna elements under x-polarized incident wave with 30° incidence angle.

3. Antenna array developments

Once the three antenna elements are fixed, it is possible to create a heterogeneous antenna array to achieve element-level reflection phase diversity, as shown in Figure 7(b). Each subarray consists of 3 × 8 antenna elements. To demonstrate the efficiency of the proposed method for reducing RCS, a 9 × 8 reference antenna array made up by antenna element 1 is also established, as shown in Figure 7(a). The proposed low scattering antenna array's antenna element spacing is the same as that of the reference array.

Investigations on the scattering performance of the reference and proposed arrays are conducted by full wave simulations. Figure 8 shows the monostatic RCS versus frequency under x-polarized incident waves come from the angle of $\theta = 30°$. The proposed array realized significant in-band RCS reduction over 8.5–12.5 GHz with an average value of 6.2 dB and a maximum value of 10.2 dB in 12.5 GHz.

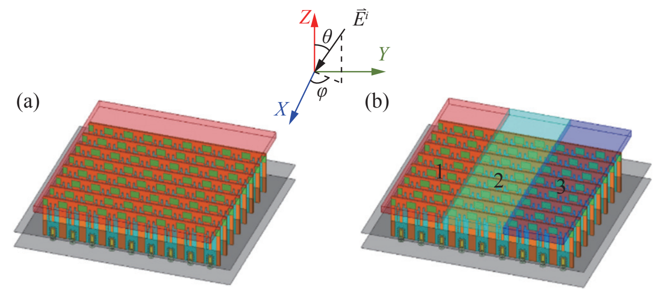

Figure 7 Geometry of the reference antenna array and the proposed antenna array. (a) Reference antenna array, (b) Proposed antenna array.

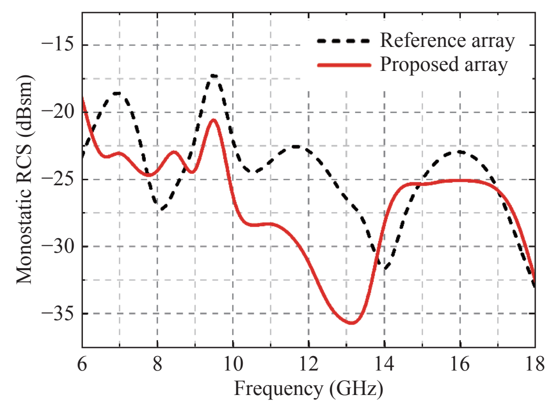

Figure 8 Simulated monostatic RCS of the proposed and reference antenna arrays under x-polarized incident plane waves with an incident angle of $\theta = 30°$.

To further explore the principle of the proposed reflection phase diversity method, the 3-D scattering patterns of the referenceand proposed antenna array under x-polarized incident plane waves with 30° incident angle are presented in Figure 9. Due to the scattering cancellation, scattering energy has been dispersed from $\theta = 30°$ to other non-threatening ranges of angles, leading to a scattering null. In this way, RCS in potential threatening angular ranges is suppressed in the proposed low scattering antenna array. Therefore, it can be seen from these simulation findings that the monostatic RCS can

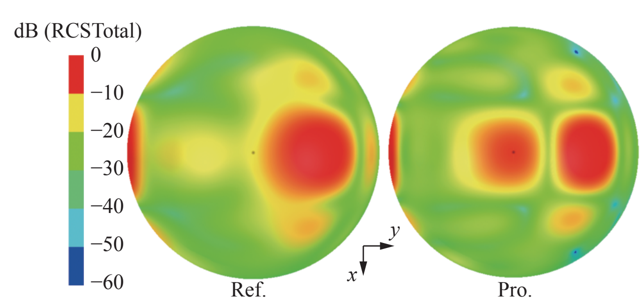

Figure 9 3-D scattering patterns of the reference (Ref.) antenna array and the proposed (Pro.) low scattering antenna array under x-polarized normal incident waves.

be effectively controlled within a certain range of angles by element level reflection phase variety.

III. Experimental Validation

The fabricated prototypes of the reference and the proposed antenna array are shown in Figure 10. The two antenna arrays share the same aperture size of 66 mm × 60 mm. Figure 11 shows the measured active VSWRs of the proposed array in E-/H-plane scanning cases. For the broadside radiation, the active VSWR is below 2.5. When scanning to 45° in the E-/H-planes, the proposed antenna array excites an active VSWR of below 3.0. It can be concluded that the proposed array provesan impedance bandwidth of 6–18 GHz.

The simulated and measured broadside realized gain for the reference array and the proposed array are shown in Figure 12. As it can be seen, the proposed array performs the same well as the reference array with no gain deterioration.The measured cross-polarization levels are higher than the simulated results due to measurement precision, whereas the measured co-polarization agrees well with the simulations. However, both of the simulated and measured results illustrate the attractive low cross-polarization (< −25 dB) property of the antenna arrays.

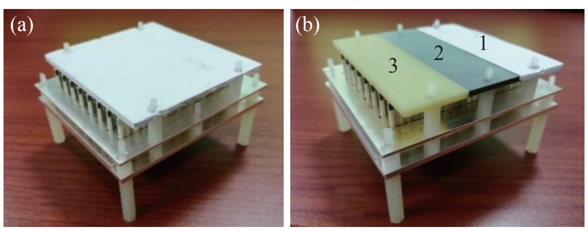

Figure 10 Fabricated prototypes of the antenna arrays. (a) The reference array; (b) The proposed low scattering array.

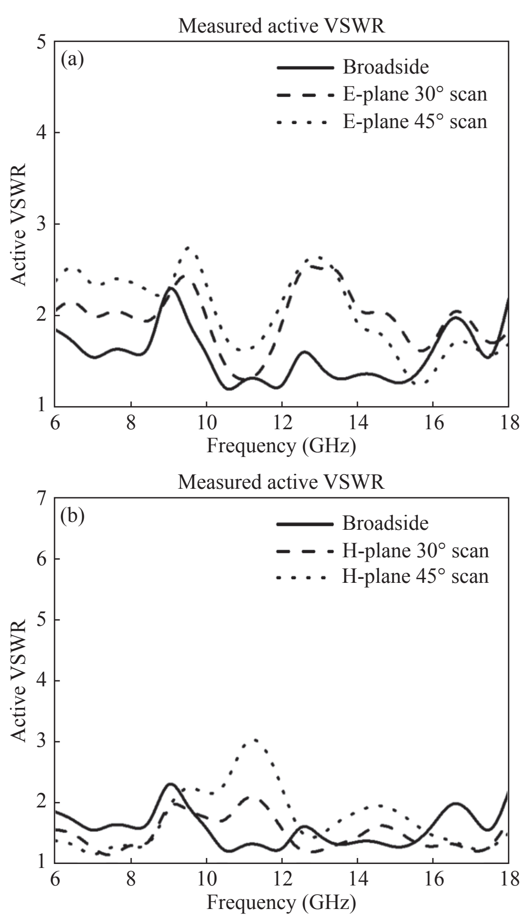

Figure 11 Measured active VSWR of the proposed array. (a) E-plane scanning cases; (b) H-plane scanning cases.

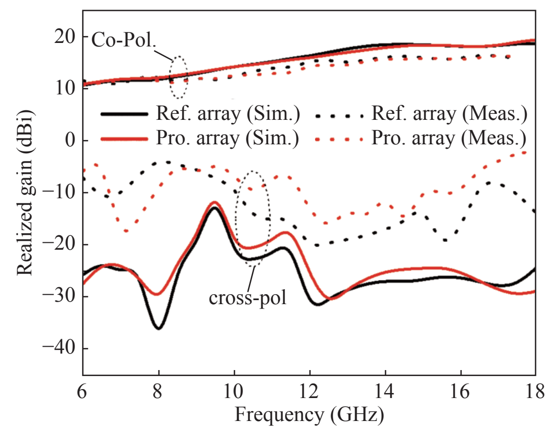

Figure 12 Measured and simulated realized gains of the reference and the proposed antenna array.

Figure 13 and Figure 14 present the simulated and measured scanning radiation patterns of the reference and the proposed arrays at 12 GHz. Both arrays achieve ±45° scanning ranges in the E-/H-plane.Again, the measured and simulated results are reasonably agreed. At large scanning angles, the surface wave is the main cause of some inaccuracies.

Figure 15(a) displays the measured monostatic RCS versus frequency for the reference and the proposed arrays over X-band under x-polarized plane waves with an incident angle of $\theta = 30°$. It illustrates that the monostatic RCS of the proposed antenna array is significantly reduced in the X-band, with a maximum reduction value of 7.55 dB. Figure 15(b) plots the simulated and measured monostatic RCS versus incidence angles along the azimuth plane and 0° elevation angle under x-polarized oblique incident waves. It can be observed that an average of 5 dB RCS reduction is achieved within the angular range from −30° to +30°. The simulated RCS agrees well with the measured one except for some conflicts, which may result from the fabrication tolerance and measurement errors. In summary, the proposed antenna array realizes wideband low RCS performance with no deterioration of radiation characteristics.

IV. Conclusion

This paper presents an element-level reflection phase diversity method to reduce the RCS of a tightly coupled phased array specifically under a certain oblique incident wave. With the theoretical analysis in this paper,

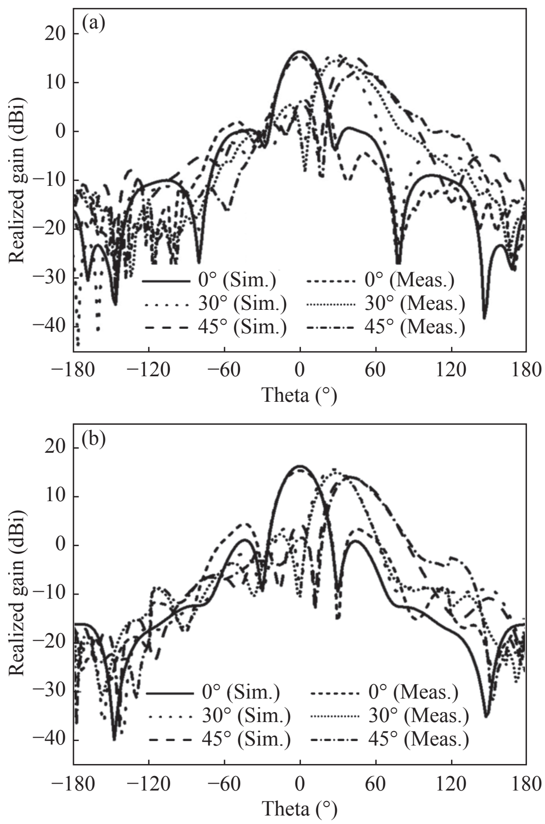

Figure 13 Measured and simulated radiation patterns of the reference antenna array. (a) E-plane scanning, (b) H-plane scanning.

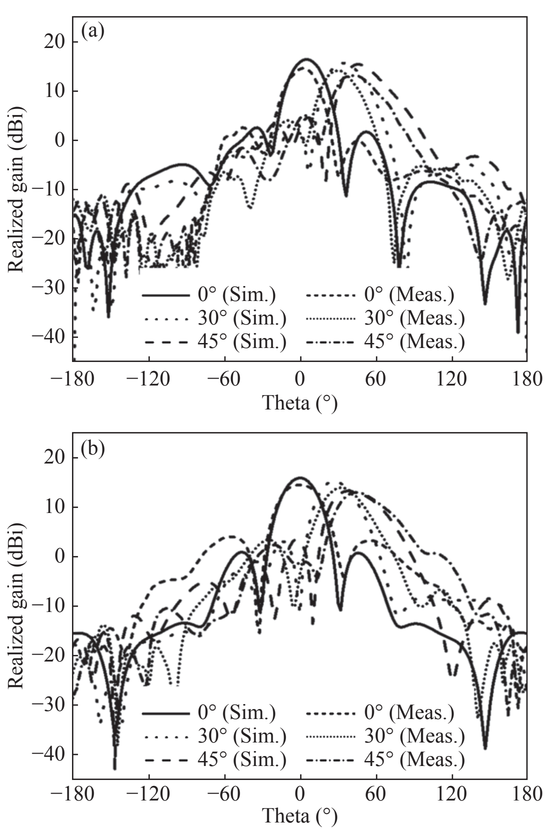

Figure 14 Measured and simulated radiation patterns of the proposed antenna array. (a) E-plane scanning, (b) H-plane scanning.

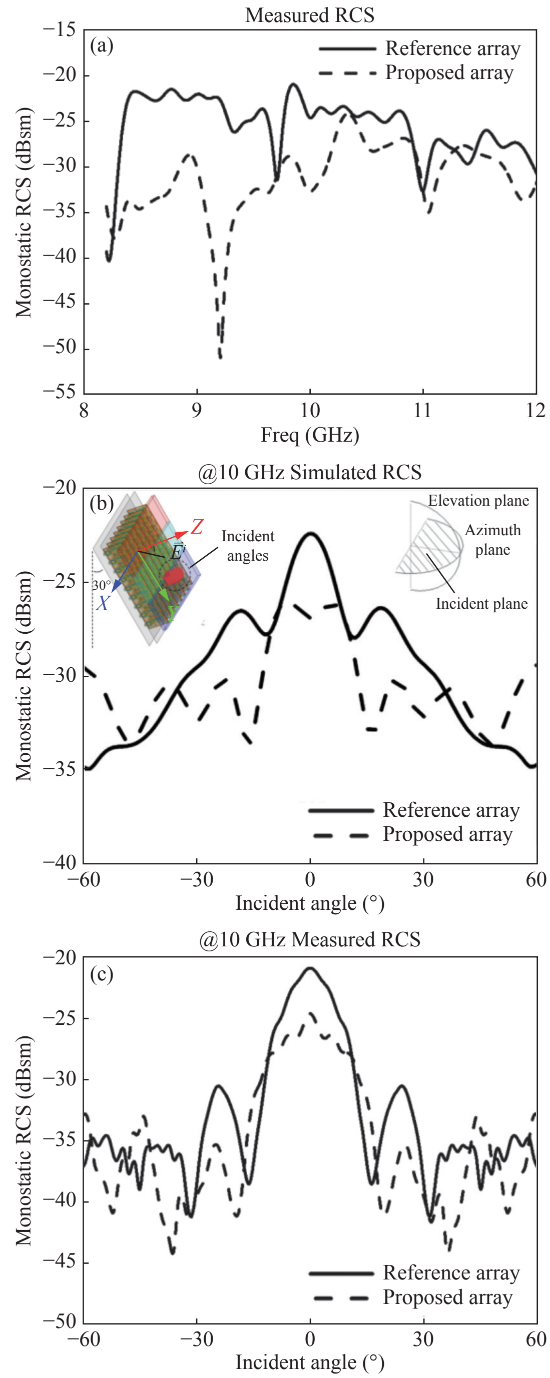

Figure 15 Monostatic RCS of the reference and the proposed antenna arrays under x-polarized plane waves. (a) Measured monostatic RCS versus frequency for plane waves with 30° incidence angle. (b) Simulated and (c) measured monostatic RCS versus incidence angles along azimuth plane.

three different kinds of TCDA antenna elements are proposed to obtain the identical radiation performance and diverse reflection phase difference. The low scattering antenna array is then proposed by combining the three types of subarrays together, with a uniform reference array as a contrast. For validation, protypes of the 8 × 9 reference and proposed TCDA arrays are fabricated and measured. The simulated and measured results demonstrate that the proposed array radiates over 6–18 GHz within the scanning range of ±45° in E-/H-plane. Moreover, the proposed array achieves significant monostatic RCS reduction with a maximum value of 7.55 dB in X-band. It is suitable for the modern stealthy platform in military applications.

References

[1] H. Wheeler, "Simple relations derived from a phased-array antenna made of an infinite current sheet," *IEEE Transactions on Antennas and Propagation*, vol. 13, no. 4, pp. 506–514, 1965.

[2] T. Liu, X. Y. Cao, J. Gao, *et al.*, "RCS reduction of waveguide slot antenna with metamaterial absorber," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 3, pp. 1479–1484, 2013.

[3] Y. H. Liu and X. P. Zhao, "Perfect absorber metamaterial for designing low-RCS patch antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 1473–1476, 2014.

[4] Y. T. Jia, Y. Liu, S. X. Gong, *et al.*, "A low-RCS and high-gain circularly polarized antenna with a low profile," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2477–2480, 2017.

[5] Y. T. Jia, Y. Liu, H. Wang, *et al.*, "Low RCS microstrip antenna using polarisation-dependent frequency selective surface," *Electronics Letters*, vol. 50, no. 14, pp. 978–979, 2014.

[6] H. Y. Sun, C. Q. Gu, X. L. Chen, *et al.*, "Broadband and broad-angle polarization-independent metasurface for radar cross section reduction," *Scientific Reports*, vol. 7, no. 1, article no. article no. 40782, 2017.

[7] X. Liu, J. Gao, L. M. Xu, *et al.*, "A coding diffuse metasurface for RCS reduction," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 724–727, 2017.

[8] S. W. Xiao, S. W. Yang, H. Y. Zhang, *et al.*, "A low-profile wideband tightly coupled dipole array with reduced scattering using polarization conversion metamaterial," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 8, pp. 5353–5361, 2019.

[9] Z. C. Zhang, M. Huang, Y. K. Chen, *et al.*, "In-band scattering control of ultra-wideband tightly coupled dipole arrays based on polarization-selective metamaterial absorber," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 12, pp. 7927–7936, 2020.

[10] G. B. Wu, S. W. Qu, C. Ma, *et al.*, "Reflectarray antenna design with arbitrary incident and reflection beam angle," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 11, pp. 5964–5973, 2018.

Yuewen GOU was born in Xi'an, China, in 1996. She received the the B.E. degree in electromagnetics and microwave technology and the B.A. degree in translation from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2018, where she is currently pursuing the Ph.D. degree in electronic science and technology. Her current research interests include ultra-wideband phased antenna arrays, low-scattering antenna arrays, and metasurface. (Email: beckygyw@163.com)

Yikai CHEN was born in Hangzhou, China, in 1984. He received the B.E. and Ph.D. degrees in electromagnetics and microwave technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2006 and 2011, respectively.

From 2011 to 2015, he was a Research Scientist with the Temasek Laboratories, National University of Singapore, Singapore. In 2015, he joined UESTC, as a Full Professor. He has authored or co-authored over 200 peer-reviewed articles and over 70 patents/patent disclosures. He has co-authored the book entitled *the Characteristic Modes: Theory and Applications in Antenna Engineering* (John Wiley, 2015), and one book chapter to *Differential Evolution: Fundamentals and Applications in Electrical Engineering* (IEEE Wiley, 2009). His current research interests include ultra-wideband phased antenna arrays, RCS reduction techniques, 5G base station antenna arrays, characteristic mode theory, and time modulation techniques for antenna array systems.

Dr. Chen is a member of the Applied Computational Electromagnetics Society (ACES). He was a recipient of the National Excellent Doctoral Dissertation Award of China in 2013. He serves as an Associate Editor for the *Electronics Letters* and the *Chinese Journal of Electronics*, the review boards of 20 journals, and has also served many international conferences as TPC Members, Session Organizers, and Session Chairs. (Email: ykchen@uestc.edu.cn)

Shiwen YANG was born in in Langzhong, China, in 1967. He received the B.S. degree in electronic science and technology from East China Normal University, Shanghai, China, in 1989, and the M.S. degree in electromagnetics and microwave technology and the Ph.D. degree in physical electronics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 1992 and 1998, respectively.

From 1994 to 1998, he was a Lecturer with the Institute of High Energy Electronics, UESTC. From 1998 to 2001, he was a Research Fellow at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. From 2002 to 2005, he was a Research Scientist with Temasek Laboratories, National University of Singapore. Since 2005, he has been a Full Professor with the School of Electronic Engineering, UESTC. Since 2015, he has been a Chang-Jiang Professor with UESTC nominated by the Ministry of Education of China. He has authored or coauthored more than 300 technical papers. His current research interests include antennas, antennas arrays, optimization techniques, and computational electromagnetics.

Dr. Yang was the recipient of the Foundation for China Distinguished Young Investigator presented by the National Science Foundation of China in 2011. He is the Chair of the IEEE Chengdu AP/EMC Joint Chapter and serves as an Associate Editor for *IEEE Transactions on Antennas and Propagation*. (Email: swnyang@uestc.edu.cn)