Progress In Electromagnetics Research Letters, Vol. 107, 103–110, 2022

Passive 2-D Retro Directive Array Antenna with Adjustable Reflection Angle

Mohammadreza Fallah, Nima Mokary Bahar, and S. Hassan Sedighy*

Abstract—In this paper, a planar passive array antenna is proposed with capability of reradiating the incoming incident wave to predetermined θ and φ reflection angles (2-D). This purpose is achieved by differentiating array elements' phases with the help of inter-connecting transmission lines. Incident and reradiated signal paths are isolated through two orthogonal polarizations used in the array structure. The idea is realized with a 2×2, microstrip, dual linearly polarized antenna array in 2 GHz operating frequency on the Ro5880 substrate with 1.2 mm height. Nonlinear nature of the theory behind this idea leads to some limitations in choosing the angles of incident and reflected signals which is thoroughly investigated.

1. INTRODUCTION

Retro-directive array antennas (RDAs) have captured the attention of researchers during past decades because of their advantages upon smart antennas in terms of simplicity and functionality. These arrays can perform smart antennas functionalities (beam-tracking and beam-forming in most of the cases), needless of using phase shifters and other bulky and complex steering systems behind the array [1–12]. They can automatically reflect the incoming signal toward its source direction without any prior knowledge about signal direction of arrival (DOA). Since there is no need for extra signal computation in their structure, RDAs perform significantly faster than smart antennas. These features make RDAs suitable pointing and tracking candidates for a lot of wireless applications including transponders [13], satellite communications [4, 14, 15], radiofrequency identification (RFID) [16], microwave power transmission [17–19], solar power satellites (SPSs) [20], etc. [21–23].

Generally, RDAs can be divided into two categories. The first one known as Van Atta array was primarily proposed by Van Atta in 1960 [24, 25], which is basically a uniform and evenly distributed linear array with connected symmetric element pairs with respect to origin. This arrangement leads to reflecting the incident signal toward its source location automatically. Power amplifiers can be used through inter-connecting elements in order to also increase the reflected signal strength [26, 27]. The dependence of the array parameters on its radiator elements such as directivity and bandwidth can be named as the main restrictions in Van Atta arrays.

The second category, named phase conjugation arrays, uses heterodyne techniques in each array element to reflect the incoming wave into its source direction [28]. In this approach, the incoming signal is mixed with a secondary signal produced by a local oscillator. In this way, the conjugated phase of incoming signal can be produced in each element leading to reradiating incident signal to the source direction. System complexity and interfering signals are the main problems of this architecture.

In this work, a rectangular 2×2 array antenna with inter-connecting elements at operation frequency of 2 GHz is proposed which is able to reradiate the incoming signal to a predetermined θ and φ reflection angle (2-D). Although a linear array with the capability of reradiating an incoming

Received 25 August 2022, Accepted 18 October 2022, Scheduled 2 November 2022
* Corresponding author: Seyed Hassan Sedighy (sedighy@iust.ac.ir).
The authors are with the Iran University of Science and Technology, Iran.

signal to a predetermined angle in one dimension (θ) has been proposed in [29], the 2D array with this capability (adjustable reflection angle) is discussed here for the first time. Initially, the theory behind this idea is thoroughly developed for an arbitrary $M \times N$ rectangular array, and then, as a case study, M and N are considered 2 for simplicity. The patch antenna is chosen to be used as the radiating element, also. In addition, dual orthogonal linear polarizations are used in the structure to isolate the incoming and outgoing signals. Since using low-loss substrate plays a critical role in the array structure [30], RO5880 is considered for this. The elements and array dimensions are calculated and simulated in CST Studio software. Then, several incident waves are considered to be applied on the structure to prove its performance. Bistatic RCS method is used to observe the reflection pattern of the array [31]. According to design consideration, this array should be able to reflect an arbitrary incident signal with $10°$ reflection shift at θ-plane (as an example) in orthogonal polarization of the incident signal. Finally, some limitations in design procedure which are mostly behind the theory are investigated.

This paper is organized as follows. Section 2 presents the theory behind the proposed system. Array design and simulation results are discussed in Section 3. Section 4 is devoted to limitations in design procedure. Finally, Section 5 concludes the paper.

2. THEORY

A uniform planar $M \times N$ (M and N are even) array is considered as shown in Fig. 1. The array factor (AF) of this rectangular array can be realized through following equation [32]:

$$\begin{aligned} AF = AF_x \times AF_y &= \sum_{m=-(p-1)}^{p} \sum_{n=-(q-1)}^{q} \omega_{mn} \cdot e^{j\frac{(2m-1)}{2}S} e^{j\frac{(2n-1)}{2}C} \\ C &= kd_x \sin\theta \cos\varphi, \\ S &= kd_y \sin\theta \sin\varphi \end{aligned} \tag{1}$$

where ω_{mn} is the (m, n)-th element weight; $k = 2\pi/\lambda$ (λ: free space wavelength at operating frequency), $p = M/2$, $q = N/2$; d_x and d_y are the space between adjacent elements at x and y directions, respectively; and (φ, θ) are spatial angles.

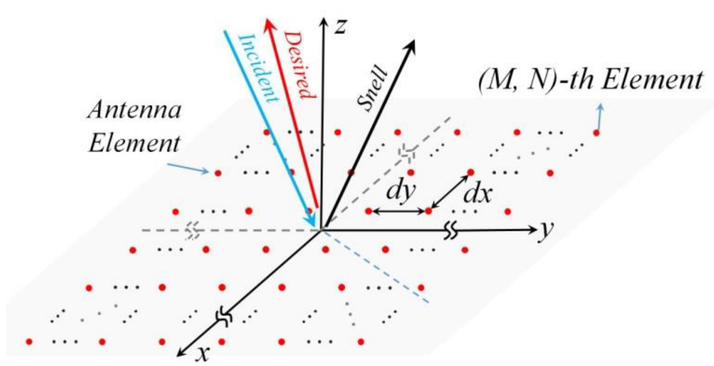

Figure 1. General $M \times N$ rectangular planar array.

For the realization of retro-directive performance, the symmetric elements with respect to origin coordination should be connected to each other through transmission lines which are named as inter-connecting elements in this paper. In other words, the transmitted signal for the (m, n)-th element is the received signal for the $(-m, -n)$-th one. Considering these inter connections, the weighting coefficients can be expressed as

$$\begin{aligned} \omega_{mn} &= \sum_{m=-(p-1)}^{p} \sum_{n=-(q-1)}^{q} e^{-j\frac{(2m-1)}{2}S_0} e^{-j\frac{(2n-1)}{2}C_0} \\ C_0 &= kd_x \sin\theta_0 \cos\varphi_0, \\ S_0 &= kd_y \sin\theta_0 \sin\varphi_0 \end{aligned} \tag{2}$$

where (φ_0, θ_0) are the spatial angles of incident wave.

In order to make a desired spatial shift in the reflection angle, the inter-connecting elements should have specific phase differences which are achievable with the help of transmission lines or adjustable analog/digital phase shifters. These phase differences can be considered in the array factor as:

$$AF = AF_x \times AF_y = \sum_{m=-(p-1)}^{p} \sum_{n=-(q-1)}^{q} \omega_{mn} \cdot e^{j\frac{(2m-1)}{2}S} e^{j\frac{(2n-1)}{2}C} \times e^{-j\frac{\delta_{(2m-1),(2n-1)}}{2}} \qquad (3)$$
$$(\delta_{i,j} = -\delta_{-i,-j})$$

where $\delta_{(2m-1),(2n-1)}$ is the phase shift at each element. Since all of the array elements are connected to their corresponding pair with respect to origin, the elements with symmetric indexes in δ terms represent the inter-connecting elements (ex. $\delta_{-3,1}$ and $\delta_{3,-1}$). It is obvious that these inter-connected pairs have odd functionality with respect to each other ($\delta_{i,j} = -\delta_{-i,-j}$).

Since the developed array factor shows symmetry in its exponential terms, the Euler's identity can be utilized to simplify it ($e^{j\kappa} + e^{-j\kappa} = 2\cos(\kappa)$)

$$AF = AF_x \times AF_y = 2 \sum_{m=-(p-1)}^{p} \sum_{n=1}^{q} \cos\left\{\frac{2m-1}{2}(S - S_0) + \frac{2n-1}{2}(C - C_0) - \frac{1}{2}\delta_{(2m-1),(2n-1)}\right\} \qquad (4)$$

In order to achieve proper values for δ terms in (4) to realize the retro-directive performance, this procedure should be followed: first, the incident wave parameters (φ_0, θ_0) are put in C_0 and S_0 terms. Then the desired reflection parameters (φ, θ) are put in C and S terms. Since the AF is supposed to be its maximum value in the desired reflection angle, the arguments inside cosine terms should be considered zero. In this way, the phase differences (δ terms) can be appropriately extracted.

3. DESIGN AND SIMULATION

3.1. System Design

This work is based on a 2×2, equally spaced array (Fig. 2). Hence, in (4) M and N should be considered 2 and $d_x = d_y = d$. With these assumptions the array factor become:

$$AF = 2\cos\left\{\frac{1}{2}\left[C + S - (C_0 + S_0) - \delta_{1,1}\right]\right\} + 2\cos\left\{\frac{1}{2}\left[C - S - (C_0 - S_0) + \delta_{-1,1}\right]\right\} \qquad (5)$$

where $\delta_{1,1}$ and $\delta_{-1,1}$ are the phase differences between $(1, 4)$ and $(2, 3)$ element pairs in Fig. 2, respectively.

The array factor (4) will be maximum in desired reflection angle if the arguments inside trigonometric terms equal zero. Thus:

$$\begin{aligned} \delta_{1,1} &= [C + S - (C_0 + S_0)] \\ \delta_{-1,1} &= [C_0 - S_0 - (C - S)] \end{aligned} \qquad (6)$$

So, the phase differences between $(1, 4)$ and $(2, 3)$ element pairs can be realized through equations mentioned in (6).

It is assumed that the proposed system should be able to reflect any arbitrary incoming signal with 10° shift in θ-plane in cross-polarization of incident signal. A dual linearly polarized microstrip antenna array with inter-connecting elements through microstrip lines is chosen and designed in CST studio software to prove the idea (Fig. 2). Dual polarizations are used because of isolation between incoming and outgoing signals. General system parameters are listed in Table 1.

Quarter wavelength matching method is utilized for matching considerations of array elements. Also, in order to achieve suitable values of inter-connecting microstrip lines, an incident plane wave in $(\varphi, \theta) = (270^\circ, 15^\circ)$ is considered to be applied on the structure. Hence, the desired reflected signal should be observed in $(\varphi, \theta) = (270^\circ, 25^\circ)$ according to system assumptions. By applying incident and reflected signals on (6), the phase difference between element pairs turns out -35.38° for both $(1, 4)$ and $(2, 3)$ pairs. Since negative lengths are not practicable, this result has to be added to 360° which makes it 324.62°.

Table 1. System parameters.

Parameter	Value
Frequency	2 GHz
Polarization	Dual-Linear
Substrate Material	RT-5880
Substrate Height	1.2 mm
Substrate Permittivity	2.2

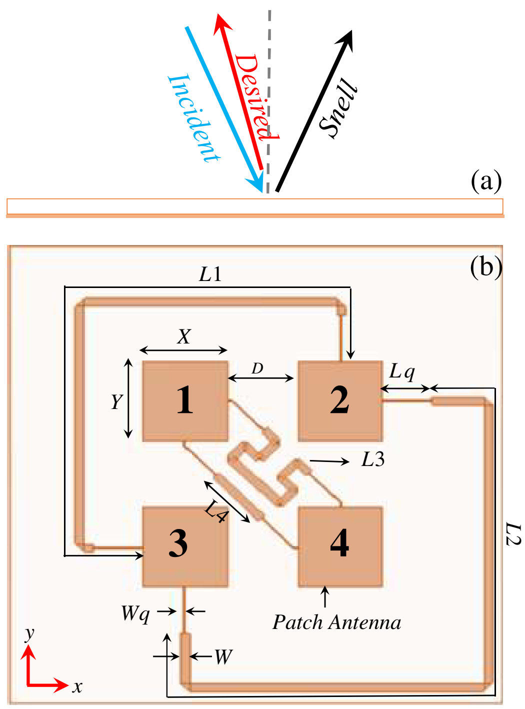

Figure 2. Proposed array which produces 10-degree shift in θ angle of incident signal in the orthogonal polarization, (a) side view, (b) top view.

According to system parameters mentioned in Table 1, the given electrical length (324.62°) can be transformed to physical length (≈ 98 mm). All of the system dimensions are listed in Table 2.

3.2. Simulation Results

Several incident plane waves with different incoming angles are considered to be applied on the proposed array to prove its performance. Bistatic RCS sweep method is used to observe the reflected signals in both co-polarization and cross-polarization of incident signal. The RCS measured in cross-polarization plane should be directed on desired reflecting angle (10° shift from incident wave in θ-plane). The applied incident waves and desired reflecting signal specifications are listed in Table 3.

Figure 3 shows the results of bistatic RCS sweep (reflection signals or scattering patterns) in both orthogonal polarizations for all incident signals mentioned in Table 3. This figure shows two scattering patterns (RCSs) derived from the proposed array. The black one is reflection pattern which is the usual behavior of any flat, reflective surface against incoming plane waves. This interaction is called Reflection Law which is one of the Snell's law derivations. For brevity, these curves (in black) are named Snell in Fig. 3. The red curves (called desired patterns) are the scattering patterns of the array in the orthogonal polarization with respect to that of incoming wave. In fact, red curves show the array performance in

Table 2. Antenna dimensions.

Parameter	Value
D	$0.6\ \lambda_0$
X, Y	48.9 mm
$L1$	309 mm
$L2$	407 mm
$L3$	136 mm
$L4$	38 mm
Lq	28.6 mm
W	4.8 mm
Wq	0.6 mm

Table 3. Incident and expected reflection waves specifications.

Incident angle (φ, θ)	Polarization	Expected reflection angle (φ, θ)	Polarization
(270°, 5°)	Horizontal	(270°, 15°)	Vertical
(270°, 15°)	Horizontal	(270°, 25°)	Vertical
(270°, 25°)	Horizontal	(270°, 35°)	Vertical
(285°, 5°)	Horizontal	(285°, 15°)	Vertical
(285°, 15°)	Horizontal	(285°, 25°)	Vertical
(285°, 25°)	Horizontal	(285°, 35°)	Vertical
(300°, 5°)	Horizontal	(300°, 15°)	Vertical
(300°, 15°)	Horizontal	(300°, 25°)	Vertical
(300°, 25°)	Horizontal	(300°, 35°)	Vertical

different conditions (different angles of incident waves). The incident wave is a plane wave which is defined with its predetermined specifications in the software to be applied to the structure in order to read its RCS and examine its performance. As it is clear in this figure, the reflected signal angles (red graphs) are properly pointed on expected values. It can be seen in Fig. 3 that the reflected patterns' levels are smaller than those of incident ones. However, it cannot be assumed as a problem because the incident and reflected signals are isolated through orthogonal polarizations and do not interfere each other.

3.3. Limitations in Design Procedure

If the graphs in Fig. 3 are observed more meticulously, it can be seen that although the reflection patterns resulting from incident waves with $\varphi = 270°$ are decently pointed on expected angles, there are some mismatches when it comes to incident waves with $\varphi = 285°$ and $\varphi = 300°$. For example, considering incident signal located at $(\varphi, \theta) = (300°, 15°)$ (Fig. 3(h)), according to system considerations the reflection signal should be pointed at $(\varphi, \theta) = (300°, 25°)$. However, the corresponding simulation result shows that the reflection signal pointed at $(\varphi, \theta) = (300°, 33°)$. In fact, as the incident signal angle gets away from the first assumption ($(\varphi, \theta) = (270°, 15°)$), this mismatch error increases. This result is firstly due to the nonlinear nature of the theory behind the idea. It means that this theory is based on every single incoming and expected outgoing signal angles (not their difference) in the array. Hence, if we want to design the structure in an absolute exact manner, any incoming and desired reflected signal angle leads to different corresponding phase shifts in the inter-connected array elements. In this way, we have to propose a new structure for any initial design parameters, which is not applicable.

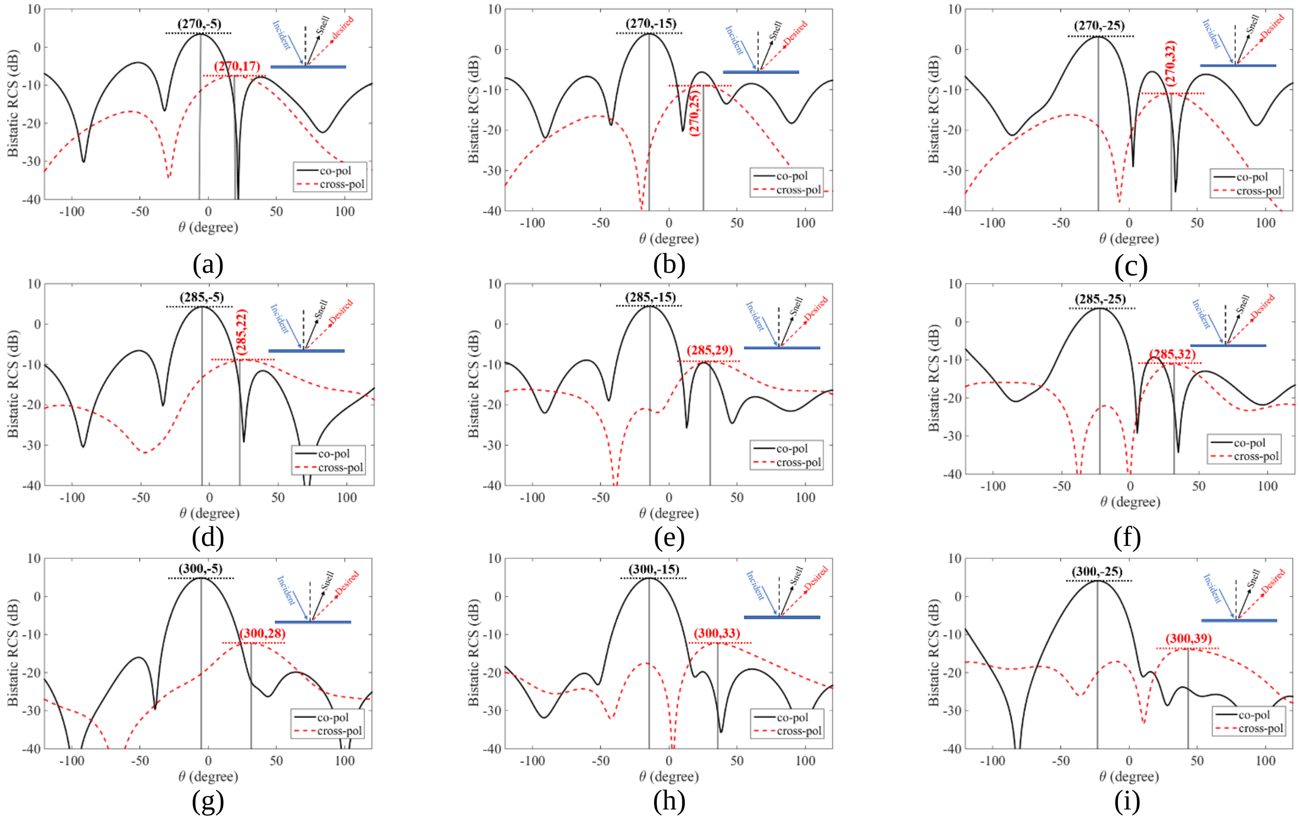

Figure 3. Scattering patterns of proposed array in two orthogonal polarizations. Incident wave angles (φ, θ) are (a) $(270°, 5°)$, (b) $(270°, 15°)$, (c) $(270°, 25°)$, (d) $(285°, 5°)$, (e) $(285°, 15°)$, (f) $(285°, 25°)$, (g) $(300°, 5°)$, (h) $(300°, 15°)$, (i) $(300°, 25°)$.

However, with the initial angles close enough to the first assumption, the deviation from the initial design is negligible, and the proposed design can be utilized in that angles' interval. These slight phase shift deviations lead to slight deviations in desired reflected angles as the incident wave gets away from the first assumption. Considering this problem in the structure, it is clear that the proposed array performance is acceptable when the incident signal angles are close enough to the first assumption.

Figure 4 shows the different electrical lengths needed for 10-degree spatial shift in θ-plane with

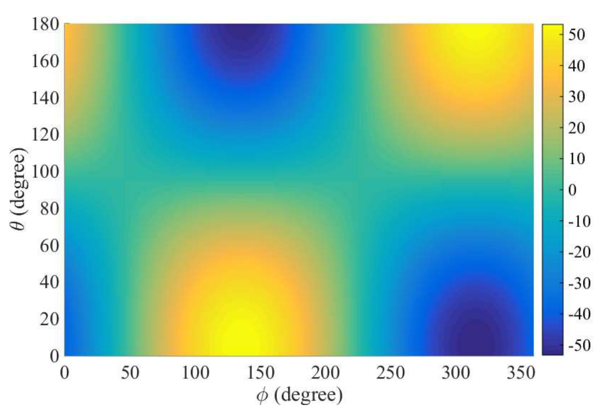

Figure 4. Electrical phase differences between element pairs in (φ, θ) coordination for $10°$ spatial shift in θ-plane.

respect to incident angle in all of the (φ, θ) coordinates resulting from (6). Since the first assumption led to the electrical length of -35.38°, the acceptable zones, at which incident signal can be applied, are those near enough the first assumption (-30° to -40° in the color bar). Furthermore, it is obvious that those acceptable zones located in $90^\circ \leq \theta \leq 180^\circ$ cannot be applied on the structure because their locations lie beneath it. Hence, the angles with $270^\circ \leq \varphi \leq 300^\circ$ and $5^\circ \leq \theta \leq 30^\circ$ will lead to decent results in this structure.

4. CONCLUSION

In this paper, a planar passive microstrip retrodirective antenna array is proposed with the capability of reradiating the incoming signal to a predetermined spatial angle in θ and φ planes. Based on the theory, a specific spatial shift was chosen, and corresponding electrical and physical lengths for interconnecting elements were calculated, applied on the structure and simulated to prove the idea and array performance. Two orthogonal polarizations were considered in the array structure in order to make isolation between incoming and reradiating signals. Finally, some limitations in the theory behind the idea were investigated which need to be considered in design procedure. Further work is expected to be focused on enhancing the array performance in terms of increasing the reradiated signal level in desired angle, accepting wider range of incoming signal angles, decreasing the non-radiating surfaces and so on.

REFERENCES

1. Goshi, D. S., K. M. Leong, and T. Itoh, "Recent advances in retrodirective system technology," *2006 IEEE Radio and Wireless Symposium*, 459–462, IEEE, 2006.
2. Leong, K. M., R. Y. Miyamoto, and T. Itoh, "Moving forward in retrodirective antenna arrays," *IEEE Potentials*, Vol. 22, No. 3, 16–21, 2003.
3. Miyamoto, R. Y. and T. Itoh, "Retrodirective arrays for wireless communications," *IEEE Microwave Magazine*, Vol. 3, No. 1, 71–79, 2002.
4. Shiroma, W., B. Murakami, J. Roque, S. Sung, G. Shiroma, and R. Miyamoto, "Progress in self-steering antennas for small-satellite networks," *Space 2004 Conference and Exhibit*, 5943, 2004.
5. Shiroma, W. A., et al., "Progress in retrodirective arrays for wireless communications," *2003 IEEE Topical Conference on Wireless Communication Technology*, 80–81, IEEE, 2003.
6. Chepala, A., V. Fusco, and N. Buchanan, "Active circular retro-directive array," *IEEE Transactions on Antennas and Propagation*, Vol. 67, No. 10, 6677–6679, 2019.
7. Le Bihan, P., et al., "Dual-polarized aperture-coupled patch antennas with application to retrodirective and monopulse arrays," *IEEE Access*, Vol. 8, 7549–7557, 2019.
8. Ali, A. A., H. B. El-Shaarawy, and H. Aubert, "Millimeter-wave substrate integrated waveguide passive Van Atta reflector array," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 3, 1465–1470, 2012.
9. Mandal, J., M. K. Mandal, M. Kahar, S. Chakrabarty, and R. Jyoti, "An active retro-directive array with different transmit and receive frequencies," *2019 IEEE MTT-S International Microwave and RF Conference (IMARC)*, 1–5, IEEE, 2019.
10. Alharbi, M., M. A. Alyahya, S. Ramalingam, A. Y. Modi, C. A. Balanis, and C. R. Birtcher, "Metasurfaces for reconfiguration of multi-polarization antennas and van atta reflector arrays," *Electronics*, Vol. 9, No. 8, 1262, 2020.
11. Polehn, D. L. and F. Weisbrod, "Retro-directive metamaterial array antenna system," ed: Google Patents, 2019.
12. Zhu, Z.-B., et al., "A high-precision terahertz retrodirective antenna array with navigation signal at a different frequency," *Frontiers of Information Technology & Electronic Engineering*, Vol. 21, 377–383, 2020.
13. Miyamoto, R. Y., G. S. Shiroma, B. T. Murakami, and W. A. Shiroma, "A high-directivity

transponder using self-steering arrays," *2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No. 04CH37535)*, Vol. 3, 1683–1686, IEEE, 2004.

14. Buchanan, N. B., V. F. Fusco, and M. van der Vorst, "SATCOM retrodirective array," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 64, No. 5, 1614–1621, 2016.
15. Wei, X., L. He, and L. Chen, "Retrodirective antenna for inter-satellite data transmission," *IEEE Access*, Vol. 8, 89720–89726, 2020.
16. Chiu, L., T. Yum, W. Chang, Q. Xue, and C. Chan, "Retrodirective array for RFID and microwave tracking beacon applications," *Microwave and Optical Technology Letters*, Vol. 48, No. 2, 409–411, 2006.
17. Ren, Y.-J. and K. Chang, "New 5.8-GHz circularly polarized retrodirective rectenna arrays for wireless power transmission," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, No. 7, 2970–2976, 2006.
18. Re, P. D. H., S. K. Podilchak, S. A. Rotenberg, G. Goussetis, and J. Lee, "Circularly polarized retrodirective antenna array for wireless power transmission," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 4, 2743–2752, 2019.
19. Fairouz, M. and M. A. Saed, "A complete system of wireless power transfer using a circularly polarized retrodirective array," *Journal of Electromagnetic Engineering and Science*, Vol. 20, No. 2, 139–144, 2020.
20. Rodenbeck, C. T., M.-Y. Li, and K. Chang, "A phased-array architecture for retrodirective microwave power transmission from the space solar power satellite," *2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No. 04CH37535)*, Vol. 3, 1679–1682, IEEE, 2004.
21. Lim, S., K. M. Leong, and T. Itoh, "Adaptive power controllable retrodirective array system for wireless sensor server applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 12, 3735–3743, 2005.
22. Leong, K. M. and T. Itoh, "Mutually exclusive data encoding for realization of a full duplexing self-steering wireless link using a retrodirective array transceiver," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 12, 3687–3696, 2005.
23. Leong, K. M. and T. Itoh, "Full-duplex retrodirective array using mutually-exclusive uplink and downlink modulation schemes," *2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No. 04CH37535)*, Vol. 3, 1695–1698, IEEE, 2004.
24. Van Atta, L. C., "Electromagnetic reflector," ed: Google Patents, 1959.
25. Sharp, E. and M. Diab, "Van Atta reflector array," *IRE Transactions on Antennas and Propagation*, Vol. 8, No. 4, 436–438, 1960.
26. Withers, M., "An active Van Atta array," *Proceedings of the Institution of Electrical Engineers*, Vol. 111, No. 5, 982–984, IET, 1964.
27. Chung, S.-J., S.-M. Chen, and Y.-C. Lee, "A novel bi-directional amplifier with applications in active Van Atta retrodirective arrays," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, No. 2, 542–547, 2003.
28. Pon, C., "Retrodirective array using the heterodyne technique," *IEEE Transactions on Antennas and Propagation*, Vol. 12, No. 2, 176–180, 1964.
29. Ang, P. and G. V. Eleftheriades, "A passive redirecting Van Atta-type reflector," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 4, 689–692, 2018.
30. Zuo, J. and D. Piao, "Effect of loss tangent on the performance of retrodirective array based on microstrip patch," *2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, 1–3, IEEE, 2019.
31. Uluisik, C., G. Cakir, M. Cakir, and L. Sevgi, "Radar cross section (RCS) modeling and simulation, part 1: A tutorial review of definitions, strategies, and canonical examples," *IEEE Antennas and Propagation Magazine*, Vol. 50, No. 1, 115–126, 2008.
32. Gross, F., *Smart Antennas with Matlab: Principles and Applications in Wireless Communication*, McGraw Hill Professional, 2015.