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Two-Way Array Radar with Only Two-Elements Receiving Array and Improved Performance

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ABSTRACT: Two-way array factor is the product of array factors of transmitting array and receiving array in a radar antenna system. One of the major disadvantages of antenna arrays is undesirable high sidelobes near the main beam, which causes ground clutter and interference in the radar system. Furthermore, increasing the number of array elements in the transmitting/receiving modules results in a high complexity, cost, size, and weight. In this paper, a two-way radar structure with a receiving array that has only two elements is proposed to solve these aforementioned problems. Noticeably, all the existing receiving arrays have a number of elements that are much greater than two elements, and it is usually equal to or less than the number of transmitting array elements. Thus, this is the first time to produce such an extremely simple receiving array structure that has the capability to provide low sidelobes and improved directivity in the resultant two-way array pattern. To demonstrate the flexibility and generality of the proposed two-way array structure, it is applied to a uniform array and a nonuniform excitation array such as Dolph-Chebyshev, as well as to electronic scanned arrays. Simulation results confirm the effectiveness and superiority of the proposed two-way structure where the highest sidelobe level reached -26.47 dB; the directivity was 25.96 dB; and the complexity of the receiving array was significantly reduced to only 12.5% when two separate non-existing elements were deployed, and it was completely eliminated when two existing elements from the transmitting array were reused.

1. INTRODUCTION

Nowadays, antenna arrays play a crucial role in numerous practical applications, especially in radar detection, 5G and beyond wireless communications [1–3]. The directionality of radiated electromagnetic fields generated by an antenna array is typically described by radiation patterns. By adjusting the spatial position of array elements and their excitation currents, some key performance metrics of the radiation pattern, such as main-beam shape, sidelobe level (SLL), and directivity, can be effectively controlled. This process is commonly referred to as array pattern synthesis.

The conventional analytical synthesis methods that depend on the use of amplitude tapers, such as the Dolph-Chebyshev method [4, 5], Taylor method [4, 6], and the Woodward-Lawson method [4, 6], hold a significant interest in this field. These methods excel in high computational efficiency because they use explicit mathematical expressions to establish the direct relationship between array excitation currents and the performance metrics of the array radiation pattern. However, these methods are often constrained by pre-specified mathematical models, and thus their radiation patterns typically exhibit specific shapes, showing their lack of flexibility [7]. In contrast, techniques based on numerical optimization such as Genetic Algorithm (GA) [8, 9], Particle Swarm Optimization (PSO) [10, 11], and Differential Evolution (DE) [12, 13] offer higher degrees of freedom in reconfiguring the array radiation patterns. The optimization objective function in these methods usually represents the difference between the actual radiation pattern and targeted pattern (sometimes it is also called mask constraint), which should approach zero [14, 15]. By designing objective functions with distinct formulations, iterative-based stochastic optimization algorithms can be systematically configured to achieve the desired synthesis shape for diverse radiation pattern geometries. After several rounds of iterations, iteration-based optimization algorithms can gradually find the best solution in the list of candidate solutions that minimize the objective function, achieving the synthesized pattern that best matches the targeted requirements [16].

All the above-mentioned analytical and numerical methods can be applied to the two-way radar antenna systems that consist of transmitting and receiving arrays. Usually, transmitting and receiving arrays have the same number of elements where they are relatively large and use separate excitation weights. Thus, these structures are most complex and expensive in terms of their feeding networks [17]. To reduce the cost and complexity, some authors suggested to use either transmitting or receiving arrays with a smaller number of excitation elements [18]. Clearly, simpler structures with these smaller arrays can be obtained. Some other researchers suggested using three-level excitation weights [19, 20]. The peak sidelobe level in such multilevel excitation weights can be greatly reduced, and thus, the radar antennas are capable of resisting jamming effects by reducing the background noise and interfering signals.

In this paper, a new structure for the receiving array in the two-way radar antenna system that consists of only two ele-

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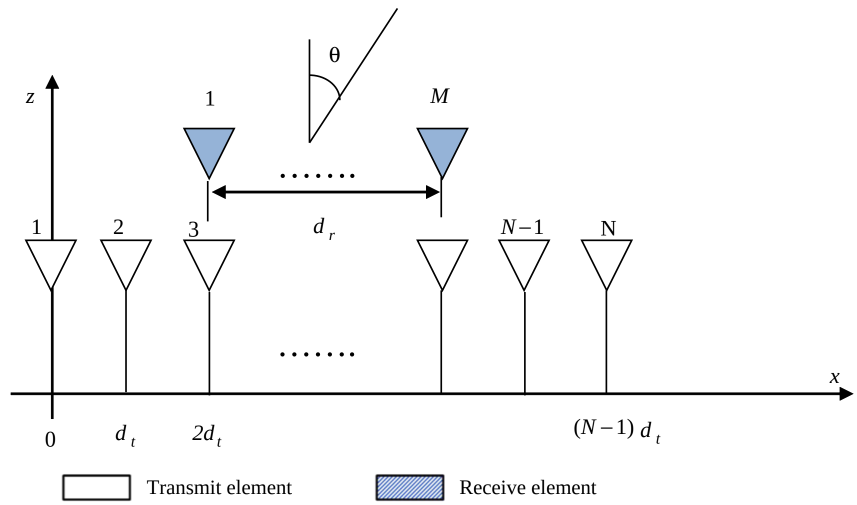

FIGURE 1. Conventional two-way array structure.

ments is proposed. The array factor properties in terms of null directions and peak sidelobe angular positions of this receive array can be changed by properly choosing the separation distance between these two elements. This separation distance may be quite wide (i.e., equal to or larger than the transmitting array aperture), thus, its array factor may have distinctive radiation characteristics such as multiple sidelobes with equal amplitudes even within the main beam region and two nulls between adjacent sidelobes. These nulls and sidelobes of the receiving array can be used to align with those of the transmitting array for sidelobe suppression during the multiplication process of the resultant two-way array factor. Moreover, the proposed array reduces the sidelobes that are near the main beam, which causes ground clutter and interference in the radar system.

2. THE TWO-WAY ARRAY RADAR ANTENNA

2.1. The Conventional Two-Way Array Structure

Figure 1 shows the structure of the conventional two-way array radar with N elements transmitting array and another M elements receiving array. The number of elements in these arrays can fall into one of the following three cases ($N = M, N > M$, or $N < M$). In the conventional two-way array structure presented in [17, 18], the number of elements in the transmitting array and receiving array was $N = M$, and the excitation weights of both arrays were assumed to be uniform (i.e., unit-amplitudes). The main achievement was a significant reduction in the peak sidelobe level of the resultant two-way array pattern where it has been reduced from -13.26 dB to -26.46 dB. In other words, the peak sidelobe level of the resultant two-way array pattern is exactly equal to the peak sidelobe level of the transmitting pattern times the peak sidelobe level of the receive pattern. Noticeably, this reduction comes under the assumption that all the elements in both arrays have unit amplitudes. This is because the resulting two-way array factor is the product of array factors of the transmitting and receiving arrays as follows [17, 18]

$$AF_{Two\text{-}Way} = AF_T \times AF_R \tag{1}$$

where

$$AF_T(\theta) = \frac{1}{N}\sum\nolimits_{n=1}^{N} a_n e^{j(n-1)(kd_t\cos\theta+\beta)} \tag{2}$$

$$AF_R(\theta) = \frac{1}{M}\sum_{m=1}^{M} a_m e^{j(m-1)(kd_r\cos\theta+\beta)} \tag{3}$$

where θ is the direction of arrival angle from the broadside; $k = \frac{2\pi}{\lambda}$, λ is the wave length; a_n and a_m are the amplitude excitations of the transmitting and receiving elements; d_t and d_r are the inter-element spacing in the transmitting and receiving arrays, respectively. For electronic scanning of the main beams, β, which is the progressive phase between succeeding elements in both transmitting and receiving arrays, is included in the above-mentioned equations.

A two-way array structure with $a_n = a_m = 1$ for all elements, $\beta = 0$, and $N = M$ is referred to as an unscanned uniform two-way array with equal apertures (This configuration is simply referred to as a conventional two-way array). As mentioned, the SLL reduction in this method was -26.46 dB. However, a better reduction in the SLL could be obtained when $N > M$ is chosen with a certain ratio equal to $\frac{N}{M} = 1.4$. Here, the number of elements in the transmitting array remains constant while that of the receiving array has its elements about 66.67% of the transmitting array. Reducing the number of elements in the receiving array has small impact on the receiving array factor, but it has a great impact on the resultant two-way array factor, where the SLL could be further lowered from -26.46 dB to -31.6 dB. In these two methods, the number N is equal to or higher than the number M, and more importantly, the number of M elements in the receiving array is much higher than two elements. It is well known that the two-element array (i.e., $M = 2$) produces a cosine pattern, which has many desirable features that can be efficiently exploited to improve the performance of the resulting two-way overall array system, as illustrated in the following subsection.

As mentioned in the previous subsection, the number of elements in the receiving array may be greatly reduced while

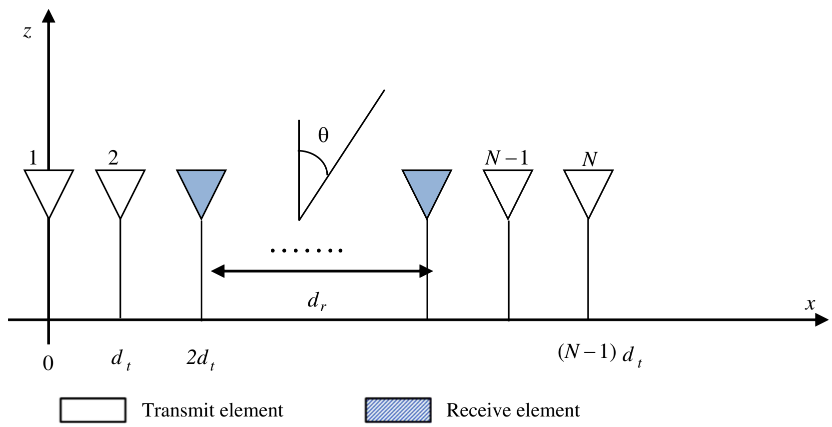

FIGURE 2. Proposed two-way array structure.

achieving a low sidelobe level in the resultant two-way array radar, especially those sidelobes that are near the main beam. A great reduction in these sidelobes of the resulting two-way array factor can be obtained when the angular locations of the sidelobe peaks in the transmitting array pattern coincide with the null directions in the receiving array pattern. Clearly, a great reduction in the SLL is achieved as a result of multiplying those sidelobe peaks of the transmitting array with those nulls of the receiving array.

In the proposed structure, the number of elements in the receiving array is chosen to be only two. The separation distance between these two elements is chosen to be wide enough to produce several nulls in the receiving array factor and at the same time to place these nulls at directions of the sidelobe peaks of the transmitting array factor. Even though the two-element receiving pattern has equal sidelobe levels rather than one main beam, as well as a lower directivity than the transmitting array pattern, the overall main-beam shape of the resultant two-way array pattern does not change.

To proceed, let us find the null directions of the receiving array for M elements, in general, and the excitation weights are assumed to be unit-amplitudes as follows

$$\theta_{null(m)} = \cos^{-1}\left[\frac{\lambda}{2\pi d_r}\left(-\beta \pm \frac{2m\pi}{M}\right)\right]$$
$$\text{where } m = 1, 2, \ldots \tag{4}$$

While the directions of the sidelobe peaks of the transmitting array pattern occur at

$$\theta_{sll(n)} = \cos^{-1}\left[\frac{\lambda}{2\pi d}\left(-\beta \pm \frac{(2n+1)\pi}{N}\right)\right]$$
$$\text{where } n = 1, 2, \ldots \tag{5}$$

Note that the values of m in (4) determine the order of the nulls (where $m = 1$ corresponds to the first null; $m = 2$ corresponds to the second null; and so on). More importantly, the number of nulls is a function of inter-element spacing d_r and progressive phase β. Thus, when only two elements that are separated are chosen by a relatively wide distance $d_r > d_t$, several nulls can be obtained. Also, the values of n in (5) determine the order of the sidelobe peaks (where $n = 1$ corresponds to the first sidelobe peak; $n = 2$ corresponds to the second sidelobe peak; and so on).

To obtain the required coincidence between the nulls of the receiving array and sidelobe peaks of the transmitting array, (4) and (5) should be equal. Then, after some simplification, we can get

$$\frac{1}{d_{r_r}}\left(\frac{2m}{M}\right) = \frac{1}{d_t}\left(\frac{(2n+1)}{N}\right) \tag{6}$$

To obtain the coincidence between the first null, $m = 1$, and the first sidelobe peak, which is the nearest one to the main beam, $n = 1$, the separation distance, d_r, is given by

$$d_r = 0.6667 \times \frac{N}{M} \times d_t \tag{7}$$

For $m = 2$ and $n = 2$, we get $d_r = 0.8 \times \frac{N}{M} \times d_t$. Also for $m = 3$ and $n = 3$, we get $d_r = 0.8571 \times \frac{N}{M} \times d_t$ and so on.

Another strategy for selecting the two elements of the receiving array is to reuse elements from the excited elements of the transmitting array. In this case, the separation distance of the two-element receiving array becomes an integer multiple of d_t which is fixed at $d_t = 0.5\lambda$. Accordingly, the two receiving elements are directly reused from the existing elements of the transmitting array. This further simplifies the proposed two-way array structure as shown in Fig. 2.

2.2. Simulation Results

The effectiveness and superiority of the proposed two-way array structure are demonstrated through several scenarios in this section. The conventional two-way array method in [17] and the method in [18] are also demonstrated for comparison purposes. The array structure of the method in [17] has the following design parameters: all the elements in the transmitting and receiving arrays are uniformly excited with unit-amplitudes, $N = M$, and $d_r = d_t = 0.5\lambda$, whereas the structure of the method in [18] has the following design parameters: all the elements in the transmitting and receiving arrays are uniformly excited with unit-amplitudes, $M = round(0.6667 \times N)$, $d_t =$

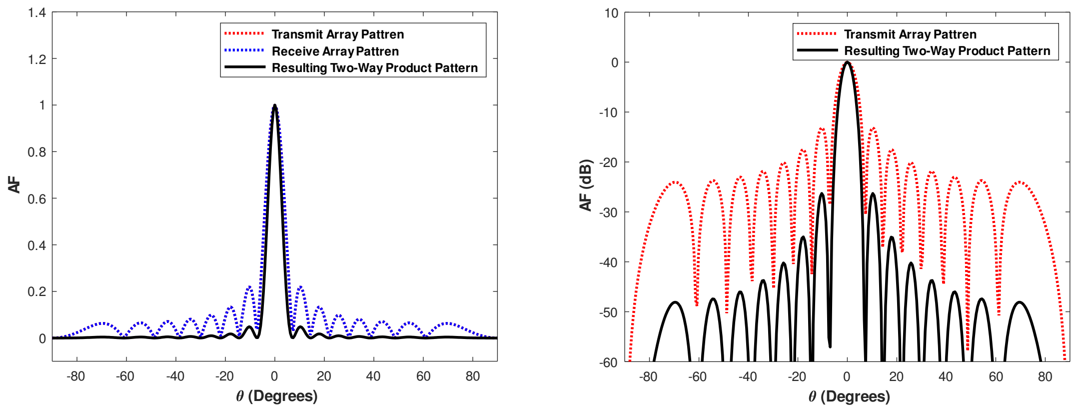

FIGURE 3. Two-way array patterns for $N = M = 16$ elements, $d_r = d_t = 0.5\lambda$ and uniform excitation weights.

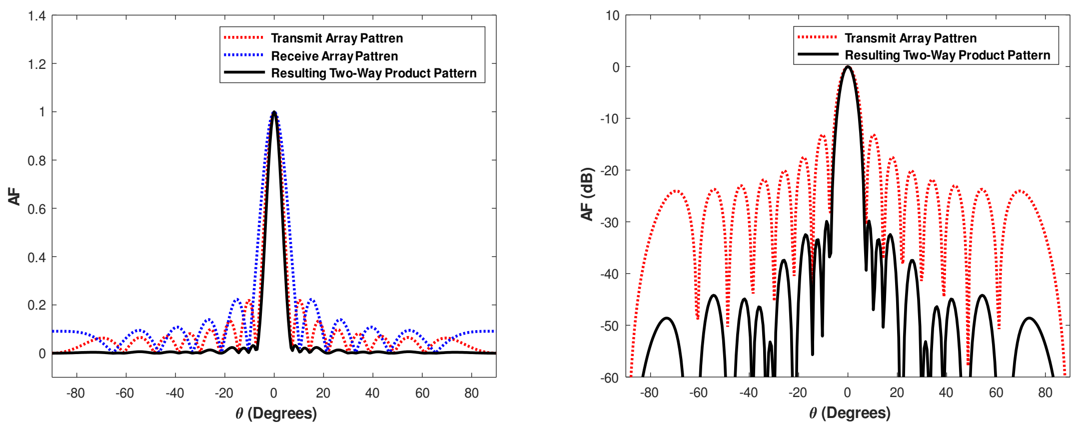

FIGURE 4. Two-way array patterns for $N = 16$, $M = 11$ elements, $d_r = d_t = 0.5\lambda$ and uniform excitation weights.

TABLE 1. Performance measures of the tested methods.

The Method	N	M	d_t	d_r	First sidelobe [dB]	Directivity [dB]	Complexity [%]
Method in [17]	16	16	0.5λ	0.5λ	-26.76	27.70	100
Method in [18]	16	11	0.5λ	0.5λ	-29.83	26.33	68.75
This method	16	2	0.5λ	2.6667λ	-26.47	25.69	12.5

0.5λ, and $d_r = i \times d_t$ where $i = 1, 2, 3, \ldots (N-1)$. For fair comparison, the array factors of the tested methods depicted in the following figures are normalized. The first performance measure of the proposed two-way array structure is the two-way array directivity, which is computed by:

$$Directivity|_{\text{dB}} = 10\text{Log}_{10}\left(\frac{4\pi U_{Two\text{-}Way}(\theta)}{P_{rad}}\right) \quad (8)$$

where $U_{Two\text{-}Way}(\theta) = [AF_{Two\text{-}Way}(\theta)]^2$ is the radiation intensity of the resultant two-way array factor given by (1), and P_{rad} is its radiated power.

The second performance measure is the magnitude of the first sidelobe of the resultant two-way array pattern, which is the nearest one to the main beam. Another important performance measure is the system complexity in terms of the actual needed number of active elements in the receiving array

$$\text{System Complexity} = \frac{M}{N} \times 100\% \quad (9)$$

In the first example, the performance measures of the method in [17], the method in [18], and the proposed two-way array method are studied and compared as shown in Table 1 and Fig. 3–Fig. 5. From this table, it can be seen that the first sidelobe levels and the directivities of these three tested methods are nearly equal. On the other hand, the array complexity of the proposed two-way structure is the lowest one. From the array factor of the proposed structure shown in Fig. 5, it can be seen that the direction of the first null in the receiving array pattern exactly matched the direction of the first sidelobe peak in the transmitting array pattern according to the principles presented in (6) and (7), thus, the first sidelobe near the main beam was greatly reduced while others were not.

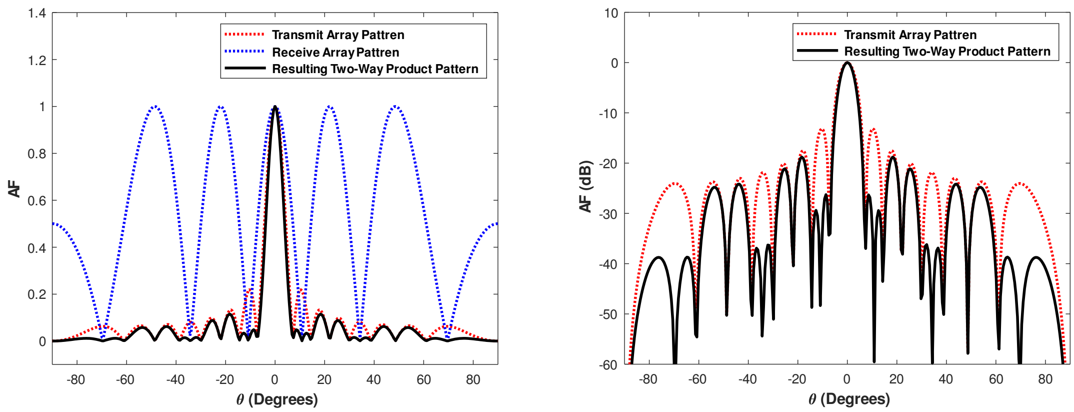

FIGURE 5. Two-way array patterns for $N = 16$, $M = 2$ elements, $d_t = 0.5\lambda$, $d_r = 2.666\lambda$ and uniform excitation weights.

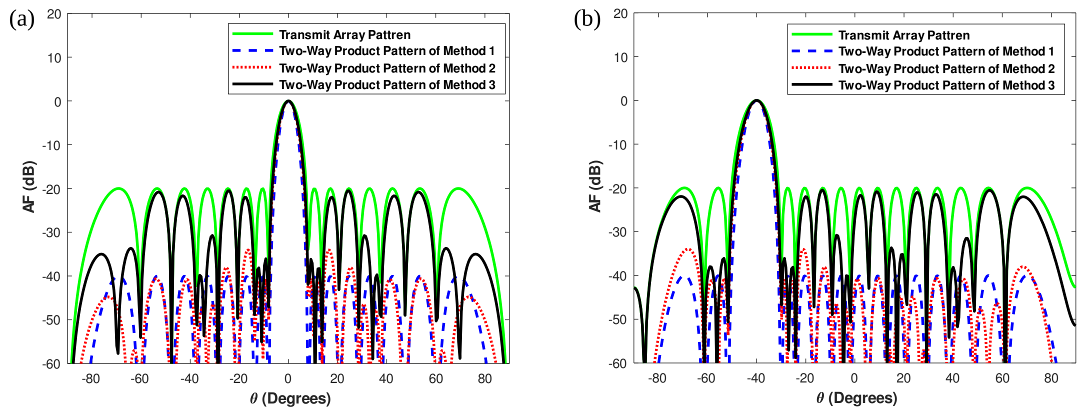

FIGURE 6. Two-way array patterns of the tested methods for nonuniform Dolph excitation weights and (a) un-scanned and (b) scanned main beam.

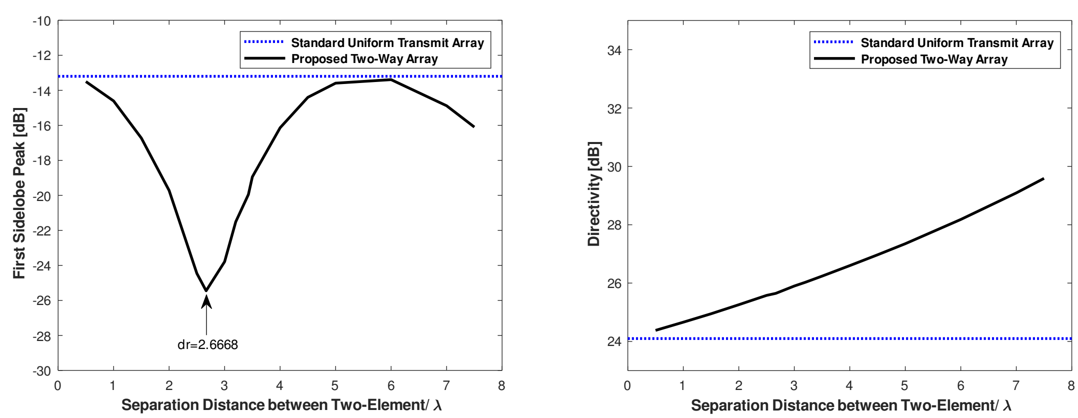

FIGURE 7. Variations of first sidelobe peak and directivity versus separation distance between two-element receiving array.

In the next example, the performances of these three tested methods are investigated under nonuniform Dolph-Chebyshev excitation weights and scanned main beams. The results are shown in Fig. 6. In this case, the directivities of the method in [17], the method in [18], and the proposed two-way array were 27.06 dB, 25.94 dB, and 25.24 dB, respectively, whereas the first sidelobe levels of these methods were -40.0 dB, -40.64 dB, and -36.0 dB.

Finally, the variations of the first sidelobe peak and the directivity of the proposed array as functions of the separation distance between the two receiving elements are analyzed as shown in Fig. 7. From this figure, it can be seen that the deepest reduction in the first sidelobe peak occurs when $d_t = 0.5\lambda$ and $d_r \cong 2.5\lambda$. It means that the two elements of the receiving array can be reused from existing elements of the transmitting array. This is another advantage for the proposed two-way array, in which it results in a zero complexity according to (9). Another feature of the proposed two-way array can be observed from Fig. 7, where its directivity is always proportional to the increased inter-element separation distance.

3. CONCLUSIONS

The simulation results fully confirm the effectiveness of the proposed two-way array structure with only a two-element receiving array for reducing the sidelobes that are near the main beam and at the same time retaining the directivity undistorted. Although the obtained values of the first sidelobe level (-26.47 dB) and the directivity (25.96 dB) for the proposed two-way array were not as high as those of the method of an equal number of elements in transmitting and receiving arrays, its array complexity was extremely low (12.5%) when two separate non-existing elements were used for receiving array, and it could reach zero when reusing two existing elements from the transmitting array.

The proposed two-way linear array may be further extended to the planar arrays where all rectangular elements are transmitting and only a certain subset of elements arranged in a specific shape is receiving.

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