Two-way Planar Array Radar with Diamond- and X-shaped Configurations for Sidelobe Suppression

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Abstract — The undesirable sidelobes in the pattern of a two-way radar antenna array is usually minimized by thinning several elements in the receive or transmit arrays. The thinning process is performed randomly on all array elements by using an optimization algorithm, with the computation time being significant due to a large number of combinations that need to be examined. In this paper, sidelobe suppression in a two-way array pattern is achieved by properly structuring the received array's elements into a diamond- or X-shape, such that its far-field pattern has exact null regions toward the directions of the sidelobe regions of the transmit array pattern. Then, multiplication of the null regions of one pattern with the sidelobe regions of another pattern results in a great reduction in the sidelobe levels of the resultant two-way array pattern. The transmit array structure was fixed as a standard rectangular shape, which has two dominant regions of the sidelobes along the horizontal and vertical lines on the array aperture. To obtain ultra-low sidelobes, the receive array structure should have nulls on these lines, and their sidelobe regions should be located on the diagonals of the array aperture. To meet these alignment conditions, the received array structure was designed as a diamond- or X-shaped structure. It was observed that the proposed configurations offer potential to suppress the sidelobe levels to more than –51 dB and the complexity ratio was lowered to 43%, with both values being much lower than the ones available in the literature.

Keywords — array antenna, sidelobe suppression, two-way radar antenna array

1. Introduction

Array tapers are usually used to reduce the undesirable sidelobe levels in radar antennas. It is a process of designing the weight vector for an antenna array by controlling the phase-only, amplitude-only, or amplitude and phase simultaneously in order to obtain a synthesized pattern with the required sidelobe level (SLL) [1]–[4]. In other approaches, two or more levels of weight vectors were also used to reduce SLL [5]–[7]. The main drawbacks of applying these methods include wider beamwidth, lower directivity, and poorer efficiency [8]–[10].

In the two-way radar antenna array, which is the product of a transmit array pattern and a receive array pattern, the SLL was reduced to more than –26 dB by aligning the first null direction of the receive array pattern in the same direction as the first sidelobe peak of the transmit array, while both arrays have the same number of elements and are excited uniformly [11]. This reduction in SLL can be further improved to more than –31 dB if the number of receive array elements is reduced to 71.4 % of the number of transmit array elements [12]. This reduction was achieved by thinning the edge elements of the receive array only.

Many other works used iterative-based stochastic optimization algorithms to randomly thin the elements of transmit or receive arrays [13]–[19]. However, all these iterative-based optimization algorithms need a huge number of iterations to examine all the possible combinations of the active and inactive elements in transmit and receive arrays. Thus, they are characterized as slow convergence algorithms, especially when applied to larger planar antenna arrays.

In [19], the receiving array in the two-way radar system was designed and analyzed with only two elements, while in [20], a plus-shaped coarray approach was used to simplify the design configurations of a 3D medical ultrasound system.

In this paper, several new designs structures for the receive array in a two-way radar system with novel X- and diamond-shaped structures are proposed. The unique shape, enabling their null regions to be placed at the exact positions with respect to the sidelobe regions of the transmit array patterns, is the decisive feature of the solution. The null regions of these receive array patterns are along the horizontal and vertical axes of the array aperture, while the sidelobe regions of the transmit array are along the diagonals. Thus, ultralow sidelobes can be obtained with the proposed structures.

Moreover, the number of the active elements in these proposed receive structures is much lower than that of the transmit array elements. In other words, all elements in the two-way radar system are transmitters, while only a small subset of elements arranged in a diamond or X shape are receivers. Thus, a great reduction in the complexity of the overall array was also achieved by adopting the proposed approach.

2. Problem Formulation

Consider two rectangular arrays. The first one consists of $T_x = N_t \times M_t$ elements and has the form of a uniform transmit array, while the other consists of $R_x = N_r \times M_r$ elements and is a uniform receive array. The overall two-way array pattern is the product between the far-field patterns of the transmit and receive arrays and may be described as follows:

$$AF_{\text{Two-Way}}(u,v) = AF_T(u,v) \times AF_R(u,v)\ , \tag{1}$$

where:

$$AF_T(u,v) = \frac{1}{N_t \times M_t} \sum_{n=1}^{N_t} a_n e^{-j(n-1)(kd_{xt}u)} \times \sum_{m=1}^{M_t} a_m e^{-j(m-1)(kd_{yt}v)}\ , \tag{2}$$

$$AF_R(u,v) = \frac{1}{N_r \times M_r} \sum_{n=1}^{N_r} a_n e^{-j(n-1)(kd_{xr}u)} \times \sum_{m=1}^{M_r} a_m e^{-j(m-1)(kd_{yr}v)}\ , \tag{3}$$

where $u = \sin\theta\cos\phi$, $v = \sin\theta\sin\phi$, θ is the elevation angle, ϕ is the azimuth angle, $k = \frac{2\pi}{\lambda}$, λ is the wave length, and d_{xt}, d_{yt}, d_{xr}, and d_{yr} are the inter-element spacing along the x-axis and y-axis in the transmit and receive arrays, respectively.

Since both transmit and receive arrays are uniform, then a_n and a_m have unit amplitudes for all transmit and receive elements.

For a rectangular structure with $T_x = R_x$, the two-way array structure and the corresponding array patterns for both transmit and receive arrays are shown in Fig. 1. From the array contour pattern, there are only two obvious sidelobe regions, marked using green and yellow, along the horizontal and vertical axes of the array aperture, while the null regions, marked blue, are positioned symmetrically in four quadrants. Here, since the sidelobe regions of the transmit and receive arrays are exactly aligned with each other, the SLL of the resultant two-way planar array is equal to the peak sidelobe level of the uniform transmit pattern times the peak sidelobe level of the uniform receive pattern. In decibels, this is equivalent to –13.2 × 2 = –26.4 dB.

A better reduction in SLL can be obtained when $T_x > R_x$ by a factor of 1.4, i.e., the number of elements in the receive array equals 66.67% of the number of elements in the transmit array [11]. This helps change the direction of the first null of one array to match the direction of the first sidelobe of the other array. However, this alignment is only limited to the first null and first sidelobe peak; therefore, only the first sidelobe level in the resultant two-way array pattern was suppressed [12].

3. Proposed Two-way Array Structure

In the proposed planar array structures, the number of active elements in the receive array can be greatly reduced while achieving an ultra-low SLL in the resulting two-way array pattern. The best SLL reduction may be obtained by aligning the null regions of the receive array pattern in the same positions as the sidelobe regions of the transmit array pattern.

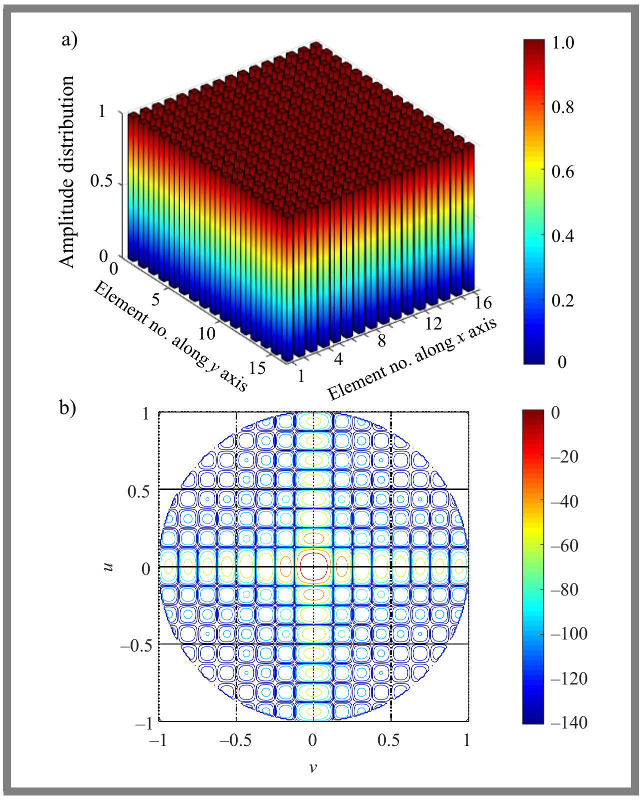

Fig. 1. Conventional two-way planar antenna array structure (16 × 16) with all elements transmuting and receiving simultaneously, and the relevant contour pattern.

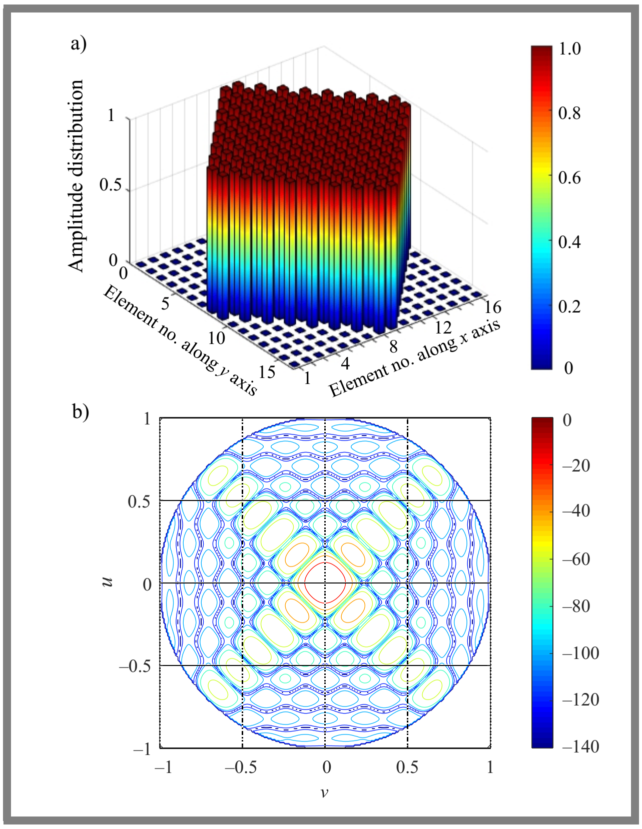

Fig. 2. Proposed diamond-shaped receive array structure and its corresponding contour pattern.

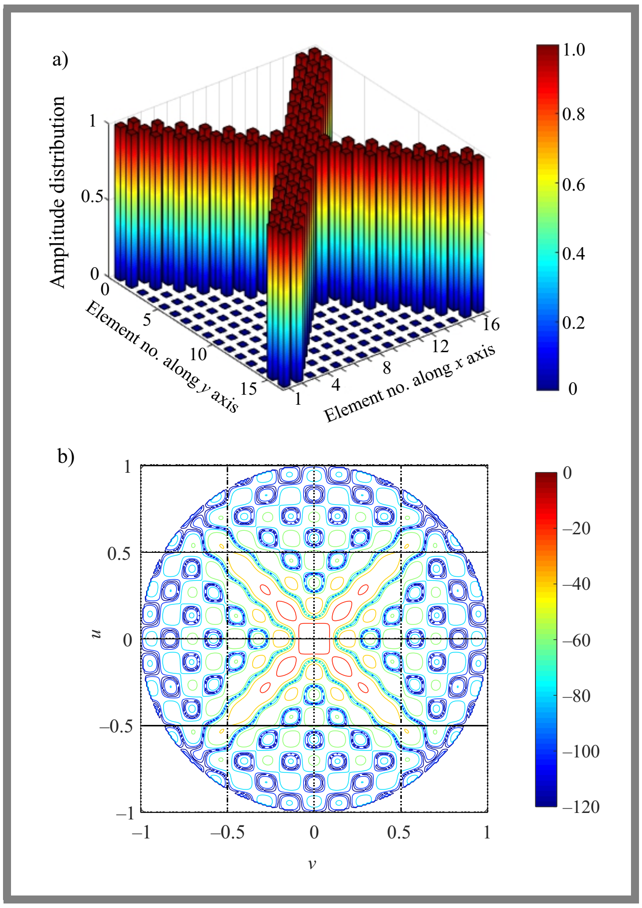

Fig. 3. Proposed X-shaped receive antenna array structure and its corresponding contour pattern.

To ensure such an alignment between the null regions and the sidelobe regions, the structure of the receive array should be changed.

Below, several structures are proposed for a receive array whose null regions are in perfect alignment with the sidelobe regions of the transmit array pattern. The diamond-shaped structure is one of the best solutions that meets these alignment requirements (see Fig. 2). X-shaped structure is another solution that perfectly meets the alignment requirement, as shown in Fig. 3.

The number of active elements in these proposed receive array structures is much lower than that of the transmit array. Noticeably, all elements in the two-way radar system are transmits, while only a small subset of active X- or diamond-shaped elements are receiving. Thus, a significant reduction in the overall complexity of the array is achieved.

Additionally, a plus-shaped structure was considered as well. The receive array with this structure is shown in Fig. 4. The size and the shape of the array aperture in the case of the plus-shaped structure remains fixed, just as for the standard 16 × 16 square array shown in Fig. 1. The sidelobe regions of the transmit and receive arrays do not change and remain aligned with each other, just as shown in Fig. 1. Therefore, the SLL of the resultant two-way plus-shaped planar array is reduced to only –26.4 dB.

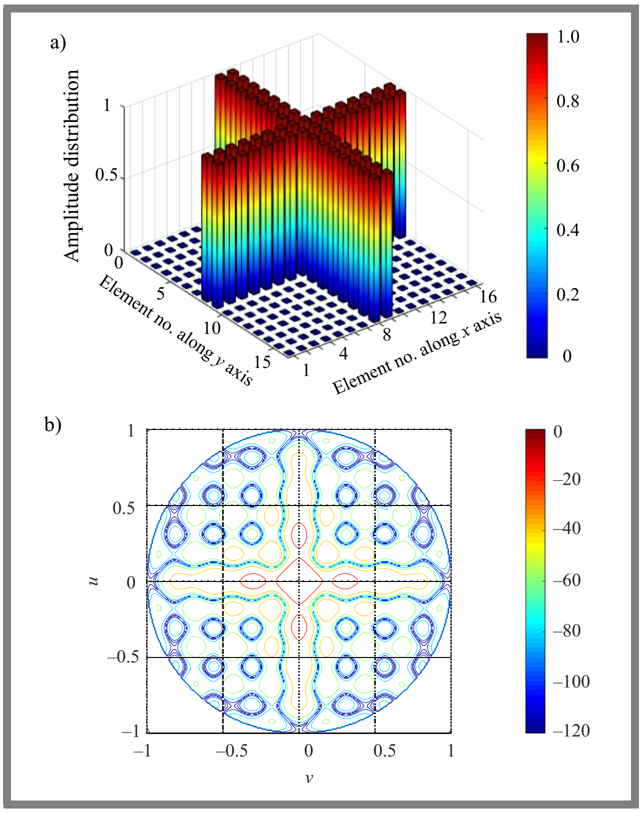

Fig. 4. Proposed plus-shaped receive array and its corresponding contour pattern.

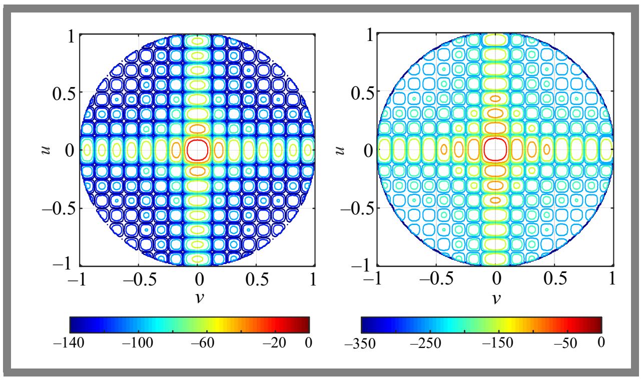

Fig. 5. Array patterns for the method from [11]: a) transmit and receive, and b) resultant two-way.

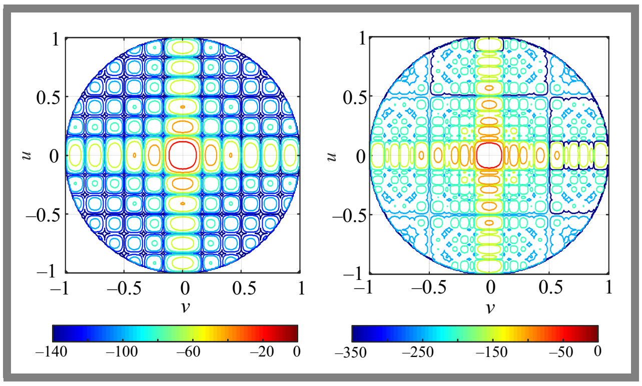

Fig. 6. Array patterns for the method proposed in [12]: a) receive and b) resultant two-way.

Tab. 1. Performance measures of the tested methods.

Method	Receive configuration	T_x	R_x	Complexity ratio [%]	SLL [dB]	Directivity [dB]
[11]	Square	256	256	100	–26.46	23.69
[12]	Square with thinned edges	256	142	55.47	–30.44	22.66
Proposed 1	Diamond	256	112	43.75	–51.00	23.16
Proposed 2	X-shaped	256	88	34.38	–47.47	20.93
Proposed 3	Plus-shaped	256	60	23.44	–26.46	23.69

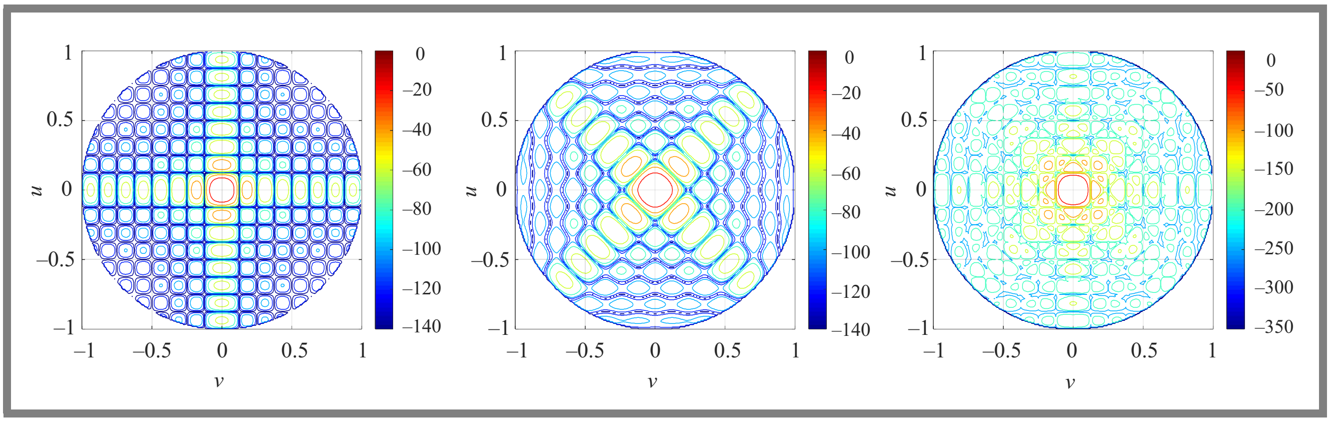

Fig. 7. Array patterns for the diamond-shaped structure: a) transmit, b) receive, and c) resultant two-way.

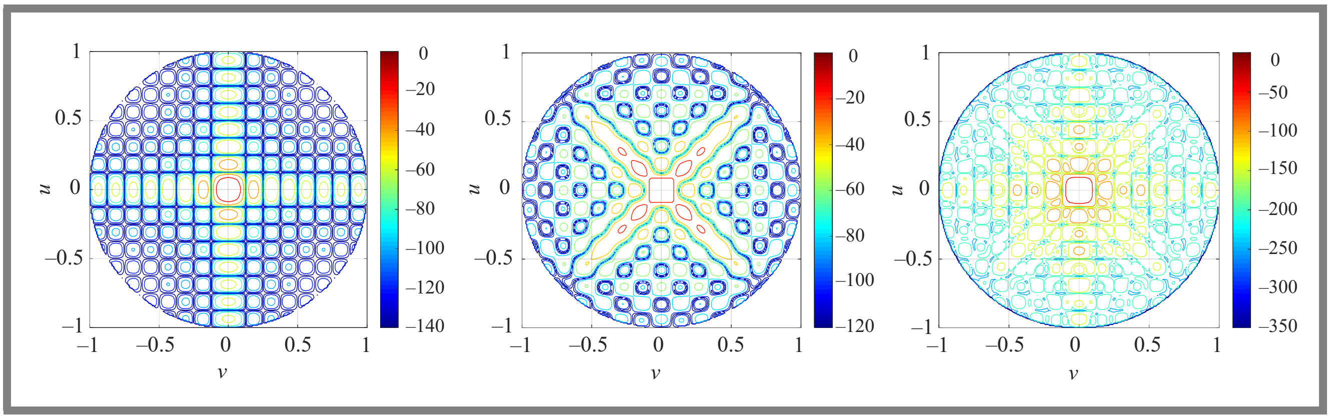

Fig. 8. Array patterns for the X-shaped antenna structure: a) transmit, b) receive, and c) resultant two-way.

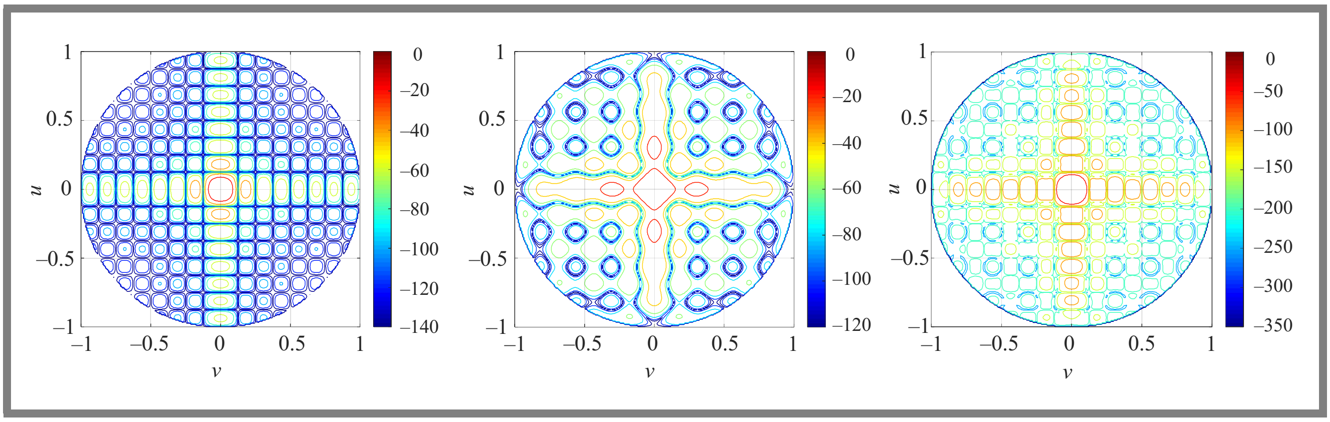

Fig. 9. Array patterns for the plus-shaped structure: a) transmit, b) receive, and c) resultant two-way.

3.1. Simulation Results

The effectiveness of the proposed two-way planar antenna array structures is demonstrated under several scenarios. The conventional two-way array method from [11] and the method described in [12] are also covered, for comparison.

In all the considered methods, all the elements in the transmit and receive arrays are uniformly excited with unit amplitudes and zero phases. The number of elements in the transmit arrays was $T_x = 16 \times 16$, and $d_{xt} = d_{yt} = 0.5\lambda$, whereas the number of elements in the receive arrays R_x was as given. For the comparison to be fair, the array patterns of the tested methods depicted in the following figures are normalized.

Two-way array directivity is the first performance measure of the tested methods. It is defined by:

$$Directivity|_{\text{dB}} = 10 \log_{10} \frac{4\pi\, U_{Two-Way}(u,v)}{P_{rad}} \,, \quad (4)$$

where

$$U_{Two-Way}(u,v) = \left[AF_{Two-Way}(u,v)\right]^2$$

is the radiation intensity of the resultant two-way array pattern given by Eq. (1) and P_{rad} is its radiated power.

Peak sidelobe level is the second performance measure. System complexity, defined as the ratio of the number of active elements in the receive and transmit arrays, is another important measure:

$$Complexity = \frac{R_x}{T_x} \times 100 \ [\%] \,. \quad (5)$$

The performance measures of the three methods [11], [12] and the proposed structures are shown in Tab. 1 and Figs. 5 – 9. According to this table, the SLLs of the X-shaped and diamond structures are the lowest. Directivity of the diamond-shaped structure is higher than that of the X structure.

However, the three complexity ratios of the proposed structures are lower than the same parameter of the conventional ones. The array patterns of the proposed X- and diamond-shaped structures shown in Figs. 7 and 8 indicate that the positions of the null regions in the receive array patterns are precisely aligned with the positions of the sidelobe regions in the transmit array patterns; thus, most of the sidelobes in the resultant two-way patterns were effectively suppressed.

The variations of SLL and complexity ratio of the diamond structure versus the diamond aperture size (i.e., the number of active receive elements R_x) is analyzed in Tab. 2. The deepest reduction in SLL occurs when $R_x = 112$ elements, while at this aperture size, the complexity ratio becomes 43.75%.

4. Conclusions

The simulation results confirm the effectiveness of the proposed two-way array structures with diamond- and X-shaped receive antenna arrays in obtaining ultralow sidelobe levels, reducing system complexity, and retaining undistorted directivities. The obtained values of the suppressed SLL, equaling –51.0 dB, and the complexity ratio of 43.75% (for the proposed diamond-shaped structure) are much better than those of conventional two-way methods. These values could be further improved when using smaller diamond sizes. Moreover, the proposed two-way planar structures may be enhanced further by including clustered configurations rather than elemental level counterparts.

Tab. 2. Variations in SLL and complexity ratio for the diamond structure versus R_x.

Receive configuration	T_x	R_x	Complexity ratio [%]	SLL [dB]	Directivity [dB]
Diamond 1	256	144	56.25	–43.42	23.69
Diamond 2	256	112	43.75	–51.0	23.16
Diamond 3	256	84	32.81	–47.89	22.66
Diamond 4	256	60	23.44	–45.34	22.20
Diamond 5	256	40	15.63	–43.26	21.75
Diamond 6	256	24	9.38	–41.63	21.33

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